METALS HANDBOOK

1948 EDITION

A 37985

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1948 EDITION

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TAYLOR LYMAN

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FOREWORD

THE 1948 EDITION OF THE METALS HANDBOOK is more than a revision of the 1939 edition, which it supersedes. It is a new book, in a new form.

The 1939 edition has had to be completely revised. The ink was hardly dry on that edition before World War II threw the whole world into a frenzy of activity that called for the greatest ingenuity of which the metallurgical profession was capable. There was no time for publication of new theories and new developments; indeed many of these were of such a high order of originality and so important as assets in the hands of the nations at war that a cloak of secrecy was thrown about them. Nevertheless the demand for metallurgical information was so great that the Society found it necessary to reprint the 1939 edition in 1942 and again in 1944. Normally, a revision of the text would have preceded reprinting, but such a burden could not have been carried by the hundreds of collaborators necessary for such a task, along with the press of wartime production, nor could the war effort countenance the expenditure of effort in that direction.

The release of restricted matter, the organization of committees to undertake the gathering together of the latest material bearing on the various branches of metallurgy covered by the Handbook, and the preparation of the material in suitable form for publication followed immediately the cessation of war activities in 1945, and culminated in this new 1948 edition.

So extensive have been the coverage, the rewriting and the revisions that the continuation of the 6-by-9-inch page size of the previous editions would have made the 1948 edition unhandy. It has thus been necessary not only to undertake a complete revision of the text but also to make a radical change in the physical make-up of the book.

The metallurgical profession and the Society are indebted to all those who have contributed their time and effort to this vast undertaking.

FRANCIS B. FOLEY
President, American Society for Metals

PREFACE

THE 1948 EDITION OF THE METALS HANDBOOK represents a fresh attack on the problem of providing an authoritative reference volume about metals. The Handbook presented here is the seventh in a series that began in 1924 as looseleaf data sheets and continued with the publication of bound volumes in 1929, 1930, 1933, 1936, and 1939. The 1948 edition is a thorough revision and substantial enlargement of the 1939 edition.

The aim of the Metals Handbook Committee has been to provide a single volume that will serve the needs of those who wish to know the accurate facts, the specific meaning and the real significance of metallurgical subjects. To include every item that might answer a query would make a morgue of little-used details and defeat easy use of the book. Therefore the plan of this work has been to stress the fundamental or essential aspects of the various subjects by means of explanatory articles, rather than merely to display opaque facts in a solid array.

The body of technical knowledge enlarges with each passing year. Information multiplies. As the number and diversity of metallurgical subjects have increased, the range of authorship of the Metals Handbook has widened correspondingly until, in the present edition, 68 subcommittees and more than 500 individuals are named as contributors. The accuracy and authority of the material included in this volume are assured by the names of the contributors. All are specialists who represent the best metallurgical learning of the day.

In the present revision, more than two-thirds of the 1939 edition has been completely rewritten and much new material has been added. The 1948 edition is almost 40% larger than the 1939 edition. Important changes have been made in the scope, form and arrangement of the subject matter.

THE NEW BOOK is divided into four principal sections: General, Ferrous Metals, Nonferrous Metals, and Constitution of Alloys.

General Section. In this section have been grouped 74 articles that deal with metals, processes, or methods in general — or with both ferrous and nonferrous metals. Forty-six of these articles are entirely new; most of the others have been completely revised. Included for the first time are sections dealing with the mechanical testing and nondestructive inspection of metallic materials. A group of articles on industrial heating is almost entirely new. The articles on dilatometry, wear, oxidation, stress corrosion, relief of residual stress, and service failures have not appeared in previous editions. The glossary of definitions starting on page 1 has been expanded greatly.

Ferrous Metals. This section contains 131 articles, of which 62 are new and most of the rest extensively revised. Notable changes include a correlated set of ten articles on the alloying elements in steel, a completely new section on hardenability, and a greatly expanded treatment of the cast and wrought materials that are used at high temperature or in corrosive environments. The eight articles dealing with the manufacture of iron and steel have been rewritten and information on the iron blast furnace process has been added. The articles on tool steel have been co-ordinated through a new classification of principal types of tool steel.

Nonferrous Metals. The Nonferrous Section has been almost entirely rewritten and has been expanded and changed greatly in form. The new section contains 102 articles and 220 data sheets. Eighty per cent of the articles and all the data sheets are new.

For the first time, discussions of melting, shaping, treating, and corrosion are a prominent part of the Nonferrous Section. Such articles have been given three times as much space as before, and five times as many authors have contributed.

Specific data for 220 nonferrous metals and alloys have been presented according to a new, semitabular arrangement. This data sheet form has been used so that the reader can easily find information of the same kind for various alloys by following key numbers, which are the same throughout the Nonferrous Section. A guide to the use of the data sheets and a list of the key numbers are printed on the inside of the back cover.

A new section is included for the eight precious metals, and another for twenty miscellaneous metals not discussed elsewhere.

Constitution of Alloys. The first extensive collection of alloy phase diagrams to be published in America is a part of this edition of the Metals Handbook.

In previous editions, articles about the constitution of binary and ternary alloys were distributed throughout the several ferrous and nonferrous sections of the book. For the present edition, all such articles, with the included phase diagrams, have been placed in a single section and prepared according to a uniform style.

Index. Much time and effort have been expended in order to increase the usefulness of the index, which now contains five times as many entries as before.

TAYLOR LYMAN, *Editor*

SUGGESTIONS FOR USING THE METALS HANDBOOK

TO ENJOY your Metals Handbook, and to profit from it, you must use it. The suggestions offered here will help you to use the Handbook to your greatest advantage. While you are reading this folder, have the 1948 Handbook nearby, so that you can consult the pages mentioned.

The Metals Handbook was designed to be a useful working whole — not merely a collection of articles, tables, data sheets, and diagrams. To be readily and effectively usable, such a volume must have aids that will direct the reader into the book. The following aids are a part of the 1948 Metals Handbook:

Condensed Table of Contents
Front flyleaf
Complete Table of Contents
Pages vii to xi
Guide to the Nonferrous Data Sheets
Inside back cover
Guide to the Phase Diagrams
Page 1145
Index (of subjects)
Pages 1269 to 1331
Index of Important Reference Tables
Front flyleaf
Index of Government Specification Numbers
Page 1332

Systematic use of these indexes, guides, and tables of contents will enable you to find the available information in a minimum time.

Condensed Table of Contents

On the flyleaf just inside the front cover, you will find a Condensed Table of Contents that lists all the principal sections of the Handbook. Note first that there are four main divisions:

GENERAL SECTION *(pages 1 to 305)*
FERROUS METALS *(pages 307 to 736)*
NONFERROUS METALS *(pages 739 to 1144)*
CONSTITUTION OF ALLOYS *(pages 1146 to 1268)*

Under these four headings are listed the 37 sections of the Handbook. *Take 90 seconds now to read these section titles.*

This list of section titles will often provide a short-cut to the page of text that is wanted. For instance, after you have used the TOOL STEELS SECTION a few times, you will become familiar with the way it is organized, and frequently you will be able to find the information you are seeking as soon as you have located that section of the book. The Condensed Table of Contents tells you at a glance that the TOOL STEELS SECTION begins on page 653.

Complete Table of Contents

The complete Table of Contents (pages vii to xi) lists the titles of all articles in the Handbook. There are 803 titles, and it would take you about 30 minutes to read them all. However, in half that time you can get a fair idea of the way the articles are grouped in sections. As the arrangement is somewhat different from that in the previous editions, it would probably be worth while to spend ten minutes surveying the Table of Contents.

General Section. When you examine page vii, which is the Contents for the GENERAL SECTION, you will see that in this part of the Handbook have been grouped articles, tables and definitions that deal with metals, processes, or methods in general — or with both ferrous and nonferrous metals. Note the glossary of metallurgical terms starting on page 1. These definitions have been increased twofold in the 1948 edition.

Ferrous Metals. Page viii is the Contents for the FERROUS METALS SECTION, which is the longest of the four principal parts of the Handbook. Don't be surprised to find a few alloys in here that have less than 50% iron. For instance, some of the heat-resisting alloys and magnetic materials contain more nickel or cobalt than iron, but it is most convenient for the reader to have these materials discussed with the iron-base alloys used for similar purposes.

Nonferrous Metals. In looking over pages ix and x (the Contents for the NONFERROUS METALS SECTION) you will note that the seven principal nonferrous metals are discussed in alphabetic order, with sections concerning precious metals and miscellaneous metals at the end.

Each section about a nonferrous metal has a similar pattern: *first*, a group of explanatory articles; *second*, compilations of properties for individual alloys.

The explanatory articles follow the same sequence in each nonferrous section: general survey (The *X* Industry), melting and casting, mechanical working, heat treatment, joining, machining, finishes, corrosion, and metallography.

Nonferrous Data Sheets

In this edition of the Metals Handbook, nearly all the data about properties of nonferrous metals and alloys have been presented according to a new, semitabular arrangement. These compilations will be called data sheets. Turn now to page 832 in the Handbook, where you will find a typical data sheet for an aluminum casting alloy (Al–4.5 Cu). Note that each item of data is preceded by a letter and number (A2, B1, D6, etc.). By following these key symbols, which are the same throughout the NONFERROUS METALS SECTION, you can easily find information of the same kind for various alloys.

Note especially item K, Mechanical Properties. These properties include hardness, tensile strength, yield strength, elongation, modulus of elasticity, compressive strength, shear strength, impact, creep, fatigue, and other relationships between stress and strain. Because of the large number of mechanical properties reported in the data sheets, various tabular and graphical arrangements have been used instead of a multiplicity of subordinate symbols under item K.

The outline, with the key symbols, was made inclusive enough so that there would be a place for every type of information that might be important for some metal or alloy. Thus, in any one data sheet, numerous omissions occur in the sequence of numbers.

Key symbols for the items most frequently used throughout the nonferrous data sheets are listed on the inside of the back cover of the Handbook. You can read this list in about two minutes and become familiar with the outline.

Phase Diagrams

All of the 284 phase diagrams that are included in the 1948 Metals Handbook have been placed in a single section, which occupies the last text pages in the book (pages 1145 to 1268). The alloy systems are listed in the Contents, on page xi. Note that they are arranged in the alphabetic order of the chemical symbols of the components. For example, silver-aluminum is listed under "Ag", iron-carbon under "C". Consequently, this section of the book is self-indexing.

The form of the phase diagrams has been standardized to a considerable extent. In the following explanation the letters refer to corresponding notations on the cobalt-iron diagram *(see cut on the next page)*. Note first that the co-ordinates are in weight percentage and degrees Centigrade. Atomic percentages are marked on the top and degrees Fahrenheit on the right of each diagram.

(A) All binary phase diagrams are reproduced to a scale of 10 weight per cent equals one centimeter.

(B) The temperature scale has been drawn so that either 25, 50, 100, 200, or 400 degrees Centigrade equals one centimeter. Thus, both weight percentages and degrees Centigrade can be read directly from each binary diagram by using a centimeter scale.

(C) The component having alloys of the greater commercial importance in the binary system appears at the left side of the diagram.

(D) Temperatures of reaction horizontals are indicated in Centigrade, with a plain degree sign.

(E) Compositions at line intersections are shown in weight per cent, with the per cent sign omitted.

(F) A dashed line signifies doubt concerning the position of the line in question.

(G) Dotted lines show the temperatures of magnetic changes.

(H) A dot-dash line indicates the existence of an ordered structure (superstructure).

(I) Melting points of the pure components are shown according to the temperatures given in the table of Physical Properties of the Elements, on page 20.

(J) Polymorphic transformation in an element is shown as occurring at the same temperature in each diagram involving that element.

(K) The magnetic changes in iron, nickel and cobalt are shown consistently also.

The Index

The 1948 Metals Handbook has been thoroughly indexed. The index, printed on green paper, is the last 64 pages in the book (pages 1269 to 1331). You will be able to use this index efficiently if you meet the index-maker part way in understanding the problems involved in compiling an index for a large, technical book.

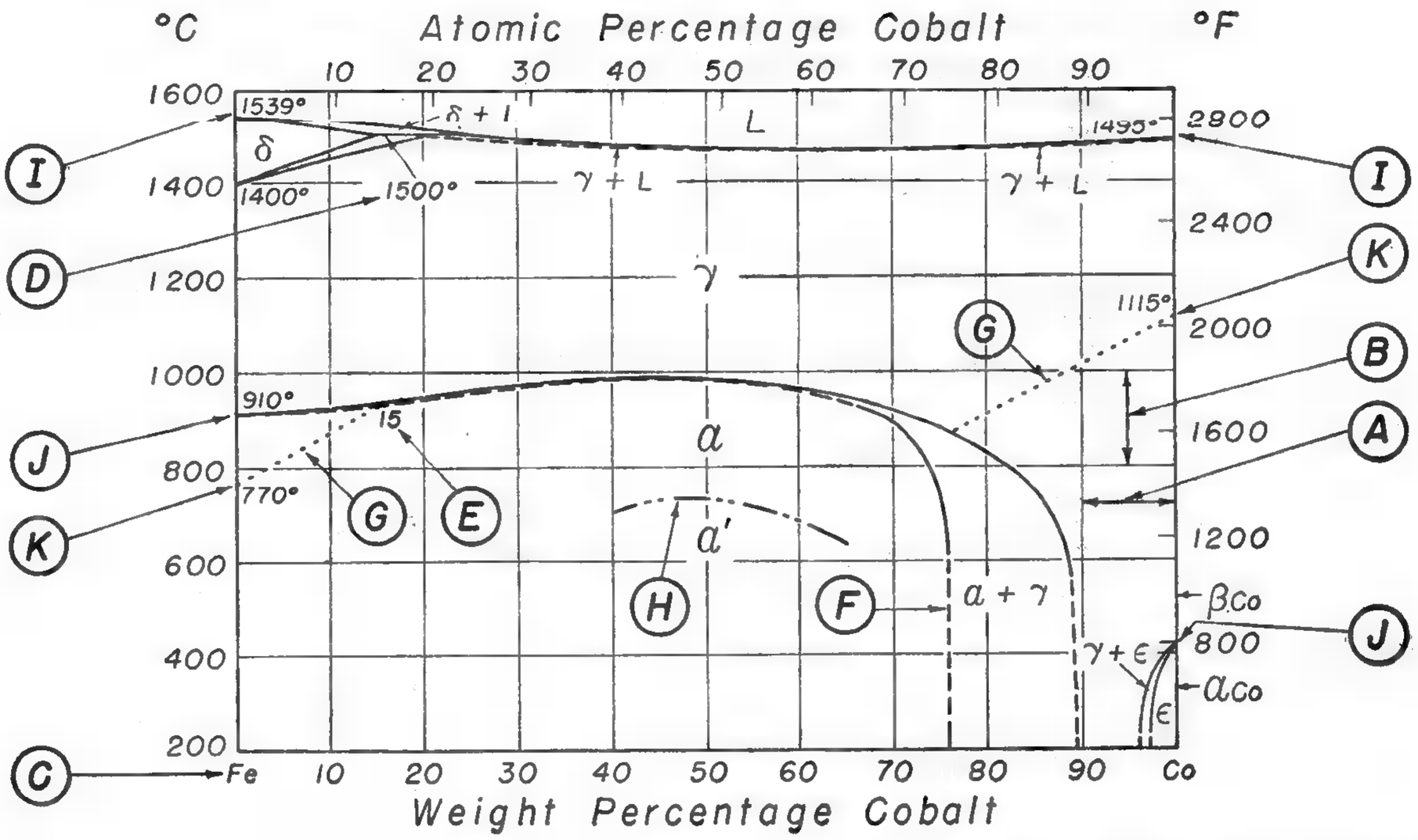
Probably the most useful fact to remember about the Handbook index is this:

> ***The Metals Handbook is a book about* metals, *and most subjects are indexed under the names of* metals (*or alloys*).**

Suppose, for example, that you want to know the value for the electrical resistivity of cartridge brass. Look under the name of the metal, *Cartridge brass,* not under *Electrical* or *Resistivity.* You will find the index entry:

Cartridge brass,
properties 915–917

The subentry *properties* sends you to the data sheet for cartridge brass (70 Cu–30 Zn). Being familiar with the outline of the nonferrous data sheets, you will know that electrical resistivity is always given as item E2, and you can easily find the line of print you are seeking on page 915.



Phase diagram for the cobalt-iron system (W. C. Ellis and E. S. Greiner, 1948 Metals Handbook, page 1192)
For explanation of the features marked, see top of column 2 on the preceding page of this folder.

Perhaps an engineer or purchasing agent of your acquaintance has the habit of telephoning you for miscellaneous information of this sort. Now that you know the secrets of the data sheets and the index, you can cope with such an individual rather easily. You can give him the answers to his questions in less than 60 seconds, if you keep the Handbook in close juxtaposition with the telephone. Gradually you will build up a reputation for this kind of service, and your telephone will be ringing most of the time.

What Are *the Names of Metals?* As the names of metals are important in the index, a few words about metallurgical nomenclature are in order.

Suppose you want information about the ferrous alloy containing 1.2% carbon and 12% manganese. This is *austenitic manganese steel.* However, it is also called *Hadfield's manganese steel,* and sometimes *high-manganese steel,* or simply *manganese steel.* In the Handbook, the term preferred is *austenitic manganese steel,* and under that main heading in the index you will find 31 subentries of the following form:

Austenitic manganese steel 526–534
  applications 529–531, 533, 534
    based on magnetic properties 531
    based on wear resistance 529–531
  creep (F) 531
  etching reagents (T) 395, 532
  low-temperature properties 212, 531
  machining (F) 533

[The letter (T) or (F) in parentheses after an index entry means that the information is in a Table or Figure.]

But suppose you had looked instead under one of the other names. You would have found:

Hadfield's manganese steel 526–534
High-manganese steel, austenitic 526–534
Manganese steel, austenitic 526–534
Steel, austenitic manganese 526–534

It would not be feasible to print the 31 subentries five times in the index. Therefore the "second-choice" items simply refer you to the inclusive pages 526–534 where the article on austenitic manganese steel is given. Note that in these second-choice entries you are not asked to "See also *Austenitic manganese steel.*" The purpose of the index is to get you into the Handbook as soon as possible — not to give you exercise as an index-athlete, hurdling back and forth in the green pages. Wherever possible, cross references have been omitted in favor of a direct reference to the text.

Of course, some cross references are necessary or decidedly helpful; for instance, the following:

Bronze
  See also *Aluminum bronze, Architectural bronze, Commercial bronze, Leaded tin bronze, Manganese bronze, Phosphor bronze, Silicon bronze,* etc.

Carbon steel
  See also *High-carbon steel, Low-carbon steel, Carbon tool steel.*

Now for another example. Suppose you have a commercial specification for a copper casting alloy that contains 83% copper, 4% tin, 6% lead and 7% zinc, and you want to find some infor-

mation about the properties and uses of this alloy. The rule is: Look under the name of the metal. But you may have forgotten that the "common name" of this alloy is *leaded red brass* or that it is sometimes called *hydraulic bronze*. Does this mean that you will need to thumb through the entire COPPER SECTION of the Handbook looking for this particular alloy? No, it does not. If you don't know the name of this alloy, look under *Copper-tin-lead-zinc alloys*. You will find the following entry, which sends you to the data sheet you are looking for:

Copper-tin-lead-zinc alloys
Cu – 4 Sn – 6 Pb – 7 Zn, properties 938

Most alloys are indexed in this way (under the names of the components, with the base metal given first) as well as under the common names.

What About Numbers? Suppose you are looking for data on the case hardening of 1020 steel. The rule is still: Look under the name of the metal. But since the name of this metal is a number, you will need to know how numbers are indexed. The general rule is: Numerical trade designations are grouped under the name of the base metal. Numerical steel designations are listed under *Steel, SAE-AISI*. Thus:

Steel, SAE-AISI trade designations,
1020,
approximate solubility of
carbon in austenite (F) 678
case depth and carbon content 695
case depth–time–temperature (F) 696
cyaniding 695, 696

For the numerical designations of stainless steels, both cast and wrought, look under *Stainless steel, trade designations* or *Heat-resisting alloys, trade designations*. If the alloy number is 17S, referring to an aluminum alloy, look under *Aluminum alloys, trade designations*.

And now for a final example of alloy names. Suppose you have a blueprint calling for QQ-B-611a, Comp E. Your first reaction to this assembly of signs may be nerve-shattering fear. But don't be alarmed. This is simply the way the U. S. Government spells *cartridge brass*. This is the language of Federal specifications. To help you translate these designations, we have indexed about 300 of them on the last page of the index, page 1332.

Processes and Methods. Several times we have repeated the suggestion that, when using the index, you should look under the name of the metal about which you want data. Now we must tell you that the index doesn't always work that way. For instance, when you are seeking a general discussion of some process or method, you *should not* look under the name of any metal. Processes and methods have been indexed as such. For example, if you look for *Precision casting* in the index you will find:

Precision casting 54, 55
advantages and limitations 55
applications 54
process and equipment 54

These are all references to the article on precision casting that appears in the GENERAL SECTION of the Handbook. The information in this article relates to precision casting in general, and there are no specific data about casting particular metals. But if you look again in the index, you will see a second group of headings under *Precision casting*:

Precision Casting of
aluminum alloys 765, 766
cobalt-base high-temperature alloys 580
copper alloys 853, 854
precious metals 1098–1101

This second group of entries refers you to information about casting specific metals. You could have found the same page references if you had looked under the names of the metals for the subentry *precision casting*. In other words, this particular information is indexed twice. So is a lot of other information in the Handbook, but it is not practicable to index everything twice. That is why we have been recommending that, when you are looking for specific information about a definite metal, you should look first under the name of the metal.

It Pays to Use the Index. This last example is supposed to have as a moral: *Don't get reckless and by-pass the index*. We are imagining that you have the problem of making a small hand hammer and you want to find out what steel to use and what hardness is recommended.

Your first reaction may be that a hammer is a tool and that you should look in the TOOL STEELS SECTION for the information. So you turn directly to that section of the book but, hunt as you will, you can find virtually nothing about hammers. However, you haven't used the index. Before you give up, look for *Hammers* in the index. There you'll find a reference to page 633, which, surprisingly enough, is not in the TOOL STEELS SECTION at all. Hammers are not ordinarily made of tool steel. They are usually made of an open hearth grade of carbon steel, and page 633, which is in the article on heat treatment of carbon steels, gives you some information about heat treating a hammer. On page 633, column 1, line 46, you will read that the final hardness on the striking face is usually Rockwell C 50 to 58, and on the claws, 40 to 47. Does that answer your question?

TAYLOR LYMAN
Editor, Metals Handbook

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DEFINITIONS AND PHYSICAL DATA

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Definitions of Metallurgical Terms

THE DEFINITIONS included in this glossary have been prepared by four committees. In determining the usage of various terms, these committees have consulted numerous technical publications and have been aided greatly by discussions with many other metallurgists. The contributions of the four committees were as follows:

The Joint AFA-ASM-ASTM-SAE Committee on Definitions of Terms Relating to Heat Treatment* has defined 64 terms concerning the heat treatment of metals. These terms are indicated in the glossary by a superscript star(*).

The ASM Committee on Powder Metallurgy* has prepared definitions of 110 terms in this field. In the glossary these definitions are indicated by the sign *Powd met* immediately after the term being defined.

The definitions of metallurgical terms that appeared in the 1939 edition of this Handbook—approximately 200 terms relating chiefly to the metallurgy of iron and steel—have been revised by the Committee on Definitions Relating to Ferrous Metallurgy.†

The remainder of the glossary—approximately 500 terms—has been compiled by the Committee on Definitions Relating to Nonferrous Metallurgy.‡ The majority of the definitions formulated by this committee relate to physical metallurgy and mechanical metallurgy generally; those that relate specifically to nonferrous metals are designated as such by the wording of the definition or by *Nonfer met.*

Definitions of terms used in X-ray metallography are republished from the 1939 edition, with minor changes, in a separate glossary beginning on page 16.

* Starred terms have been defined by the Joint AFA-ASM-ASTM-SAE Committee on Definitions of Terms Relating to Heat Treatment. The members of the committee are H. Bornstein, *Chairman* (Deere & Company), R. H. Aborn (United States Steel Corporation), J. R. Adams (The Midvale Company), O. W. Ellis (Ontario Research Foundation), L. H. Fry, *Vice Chairman* (Steam Locomotive Research Institute, Inc.), T. S. Fuller (General Electric Company), V. O. Homerberg (Massachusetts Institute of Technology), Taylor Lyman, *Secretary* (Metals Handbook Committee), G. A. Roberts (Vanadium-Alloys Steel Company), R. B. Schenck (Buick Motor Division, General Motors Corporation) and J. S. Vanick (International Nickel Company, Inc.).

* The members of the Committee on Powder Metallurgy are F. N. Rhines, *Chairman* (Carnegie Institute of Technology), C. W. Balke (Fansteel Metallurgical Corporation), J. J. Cordiano (Hardy Metallurgical Corporation), R. P. Koehring (Moraine Products Division, General Motors Corporation), C. H. Samans (American Optical Company), Alexander Squire (Westinghouse Electric Corporation), N. E. Woldman (Upper Montclair, N. J.), F. E. Wormser (Metal Powder Association) and L. L. Wyman (General Electric Company).

† The members of the Committee on Definitions Relating to Ferrous Metallurgy are R. H. Aborn (United States Steel Corporation), V. O. Homerberg (Massachusetts Institute of Technology), Taylor Lyman (American Society for Metals) and G. A. Roberts (Vanadium-Alloys Steel Company).

‡ The members of the Committee on Definitions Relating to Nonferrous Metallurgy are R. M. Brick, *Chairman* (University of Pennsylvania), R. S. Busk (Dow Chemical Company), A. H. Geisler (General Electric Company), E. N. Skinner, Jr. (International Nickel Company, Inc.) and F. H. Wilson (The American Brass Company).

A

acicular powder. *Powd met.* Needle-shaped particles.

acid bottom and lining. In a melting furnace, the inner bottom and lining composed of materials that have an acid reaction in the melting process—either sand, siliceous rock or silica bricks.

acid brittleness. The brittleness induced in steel, especially wire or sheet, when it is pickled in dilute acid to remove scale, or during electroplating. Commonly attributed to absorption of hydrogen.

acid steel. Steel melted in a furnace that has an acid bottom and lining, and under a slag that is dominantly siliceous.

activation energy. In metallurgical processes, the energy required for initiating or continuing a reaction; important in theoretical analyses of flow, diffusion and other processes.

* **age hardening.** A process of aging that increases hardness and strength and ordinarily decreases ductility. Age hardening usually follows rapid cooling or cold working. See *aging.*

* **aging.** In a metal or alloy, a change in properties that generally occurs slowly at atmospheric temperature and more rapidly at higher temperatures. See also *age hardening, precipitation hardening* and *strain aging.*

aging. *Nonfer met.* See *precipitation heat treatment, interrupted aging, progressive aging.*

air classification. *Powd met.* The separation of powder into ranges of particle size by means of a controlled stream of air.

air-hardening steel. An alloy steel that is hardened by cooling in air from a temperature higher than the transformation range. Also called *self-hardening steel.*

alclad. The common name for a type of clad wrought aluminum products, such as sheet and wire, with coatings of high-purity aluminum or of an aluminum alloy different from the core alloy in composition. The coatings are anodic to the core so they protect exposed areas of the core electrolytically during exposure to corrosive environments.

alkali metals. Metals of group IA of the periodic system, including lithium, sodium, potassium, rubidium, cesium and francium.

alkaline earth metals. Metals of group IIA of the periodic system, including calcium, strontium, barium and radium.

alligatoring. The longitudinal splitting of flat slabs in a plane parallel to the rolled surface. Also called "fishmouthing".

allotriomorphic crystal. See *idiomorphic crystal.*

allotropy. See *polymorphism.*

alloy. A substance that has metallic properties and is composed of two or more chemical elements of which at least one is a metal.

alloying elements. Chemical elements constituting an alloy; in steels, usually limited to the metallic elements added to modify the properties of the steel.

alloy powder. *Powd met.* A powder, each particle of which is composed of the same alloy of two or more metals.

alpha iron. The form of iron that is stable below Ae_3 (910 C, 1670 F) and characterized by a body-centered cubic crystal structure. See *transformation temperature* for definition of Ae_3.

alternate-immersion test. A type of corrosion test in which the specimen is immersed cyclically in the corrosive medium, held for a definite period, and removed at intervals.

alumel. A nickel-base alloy containing about 2.5% Mn, 2% Al and 1% Si, used chiefly as a component of pyrometric thermocouples.

amalgam. A mercury-base alloy.

amalgamation process. A process in which finely divided gold or silver ore, suspended in water, is carried over a surface of liquid mercury, so as to form recoverable amalgams.

amorphous. Noncrystalline.

angle of nip. In the rolling of sheet, the angle between the radius of the rolls at the point of initial contact and the normal to the sheet surface at this point.

* **annealing.** A process involving heating and cooling, usually applied to induce softening. The term also refers to treatments intended to alter mechanical or physical properties, produce a definite microstructure, or remove gases. When applicable, the following more specific terms should be used:

black annealing	isothermal annealing
blue annealing	malleablizing
box annealing	process annealing
bright annealing	spheroidizing
full annealing	stabilizing annealing
graphitizing	

Definitions of the above terms are given in their alphabetical positions in this glossary. When applied to ferrous alloys, the term "annealing", without qualification, implies full annealing. Any process of annealing will usually reduce stresses, but if the treatment is applied for the sole purpose of such relief, it should be designated as "stress relieving".

annealing. *Nonfer met.* A heat treatment designed to effect: (1) softening of a cold worked structure by recrystallization or grain growth or both; (2) softening of an age hardened alloy by causing a nearly complete precipitation of the second phase in relatively coarse form; (3) softening of certain age hardenable alloys by dissolving the second phase and cooling rapidly enough to obtain a supersaturated solution (this usage is generally applied to nickel-base and copper-base alloys; the treatment should be called more precisely a *solution heat treatment*); (4) relief of residual stress and change in properties induced during the thermal flattening of magnesium alloy sheet at slightly elevated temperatures.

annealing twin bands. Bands found in wrought and annealed metals with face-centered cubic structures; for example, copper, brass, nickel, 18-8 stainless steel. In unstrained crystals, the bands have straight parallel sides that represent the *twinning plane,* which is the octahedral plane for these face-centered cubic structures. The orientation relationship between band and matrix is fixed; one may be converted to the other by a rotation of 180 deg about the normal to the *twinning plane.* These twins originate during annealing for recrystallization of a previously strained crystal or during straining at an elevated temperature.

anode copper. Specially shaped slabs of copper cast from a fire-refining (anode) furnace and used as anodes in electrolytic refining.

anode effect. A sudden increase in voltage across an aluminum reduction cell, associated with the decrease of the concentration of the alumina in the fused electrolyte while the metal is being produced.

anode mud. Deposit of insoluble residue formed in an electroplating or electrorefining cell during solution of the anode; sometimes called "anode slime".

anodic coating. A coating or film of a metal compound, usually oxide, formed on metals by an electrolytic oxidation treatment.

anodic treatment. A cleaning, polishing or oxidizing treatment in which the specimen or work is made the anode in a suitable electrolyte; an inert metal is used as cathode and a potential is applied.

anodizing. *Nonfer met.* Subjecting metal to anodic oxidation.

apparent density. *Powd met.* The weight of a unit volume of powder, determined by a specified method of loading and usually expressed in grams per cubic centimeter.

arborescent powder. See *dendritic powder.*

arc welding. Welding accomplished by using an electric arc that may be formed between a metal or carbon electrode and the metal being welded; between two separate electrodes, as in *atomic hydrogen welding*; or between the two separate pieces being welded, as in *flash welding.*

artificial aging. An aging treatment above room temperature. See *precipitation heat treatment* and compare with *natural aging.*

atomization. *Powd met.* The dispersion of a molten metal into particles by a rapidly moving stream of gas or liquid.

* **austempering.** A trade name for a patented heat treating process that consists in quenching ■ ferrous alloy from a temperature above the transformation range, in a medium having a rate of heat abstraction sufficiently high to prevent the formation of high-temperature transformation products; and in maintaining the alloy, until transformation is complete, at ■ temperature below that of pearlite formation and above that of martensite formation.

austenite. A solid solution in which gamma iron is the solvent; characterized by a face-centered cubic crystal structure.

* **austenitizing.** The process of forming austenite by heating a ferrous alloy into the transformation range (partial austenitizing) or above the transformation range (complete austenitizing).

autofrettage. A process for manufacturing gun tubes and pressure vessels, in which the inner surface layers of a plain tube are initially stressed by expansion beyond the yield strength, so that residual compressive stresses are created.

autogenous welding. A method of uniting two pieces of metal by melting their edges together without solder or any added welding metal.

B

baghouse. A large chamber for holding bags that are used in the filtration of gases from a furnace in order to recover metal oxides and similar solids suspended in the gases.

ball mill. A mill in which material is finely ground by rotation in a steel drum along with pebbles or steel balls. The grinding action is provided by the collision of the balls with one another and with the shell of the mill.

banded structure. A segregated structure of nearly parallel bands aligned in the direction of working.

bark. The decarburized skin or layer just beneath the scale that results from heating steel in an oxidizing atmosphere.

base bullion. Argentiferous lead containing 10 to 60% silver with or without some gold.

basic bottom and lining. In a melting furnace, the inner lining and bottom composed of materials that have a basic reaction in the melting process—either crushed burned dolomite, magnesite, magnesite bricks or basic slag.

basic steel. Steel melted in a furnace that has a basic bottom and lining, and under a slag that is dominantly basic.

basin. See *pouring basin.*

Bauschinger effect. The phenomenon by which plastic deformation of a metal raises the yield strength in the direction of plastic flow and decreases the yield strength in the opposite direction.

Bayer process. The process for extracting alumina from bauxite ore before the electrolytic reduction. The bauxite is digested in a solution of sodium hydroxide, which converts the alumina to soluble aluminate. After the "red mud" residue has been filtered out, an aluminum hydrate is precipitated from the filtrate. Then the hydrate is filtered out and calcined to alumina.

beading. Raising a ridge on sheet metal.

beating. (1) Producing very thin sheet by hammering. (2) Forming sheet by hammering into or over a form of the desired shape, usually made of wood. See *hammering.*

bending rolls. Three staggered rolls adjusted to put the desired curvature in plate or used for coiling and uncoiling strip or wire.

bend radius. The radius corresponding to the curvature of a bent specimen or bent area of a formed part, and measured on the inside of a bend.

bend tests. Various tests used to determine the ductility of sheet or plate that is subjected to bending. These tests may include determination of the minimum radius or diameter required to make a satisfactory bend and the number of repeated bends that the material can withstand without failure when it is bent through a given angle and over a definite radius.

Bessemer process. A process for making steel by blowing air through molten pig iron contained in a suitable vessel, and thus causing rapid oxidation, mainly of silicon and carbon.

beta structure. Structurally analogous body-centered cubic phases, or electron compounds (similar to beta brass) that have ratios of three valence electrons to two atoms.

Betts process. A process for the electrolytic refining of lead by use of an electrolyte that contains lead fluosilicate and fluosilicic acid.

billet. *Nonfer met.* (1) A section of ingot, hot worked by forging, rolling or extrusion. (2) A casting suitable for rolling or extrusion. See *extrusion billet.*

billet. *Fer met.* See *bloom.*

billet mill. See *blooming mill.*

binary alloy. An alloy containing two principal elements.

binder. *Powd met.* A cementing medium; either a substance added to the powder to increase the strength of the compact and dispelled during sintering, or a substance (usually a relatively low-melting constituent) added to a powder mixture in order to cement together powder particles that alone would not sinter into a strong body.

biscuit. An upset blank from which a forging is produced.

* **black annealing.** A process of box annealing or pot annealing ferrous alloy sheet, strip or wire after hot working and pickling. See *box annealing.*

blank. *Powd met.* A pressed, presintered or fully sintered compact, usually in the unfinished condition and requiring cutting, machining or some other operation to produce the final shape.

blank holder. The tool that prevents the rim of a sheet metal blank from wrinkling while it is being deep drawn.

blanking. Shearing out a piece of sheet metal in preparation for deep drawing.

blast furnace. *Fer met.* A shaft furnace supplied with an air blast (usually hot) and used for producing pig iron by smelting iron ore in a continuous operation. The raw materials (iron ore, coke and limestone) are charged at the top, and the molten pig iron and slag, which collect at the bottom, are tapped out at intervals.

blast furnace. *Nonfer met.* A shaft type of vertical furnace used for smelting coarse copper, lead and tin ores; similar to the type used for smelting iron, but smaller.

blasting. A process for cleaning or finishing metal objects by use of an air blast that blows particles of an abrasive against the surfaces of the work pieces. Small, irregular particles of steel are used as the abrasive in *grit blasting,* sand in *sandblasting,* and steel balls in *shot blasting.*

blending. *Powd met.* The thorough intermingling of different batches of powder of the same substance, to adjust physical characteristics.

blister. A raised spot on the surface of metal, caused by expansion of gas in a subsurface zone during heat treatment. Very fine blisters are called "pinhead" or "pepper blisters".

blister copper. The metal produced when copper *matte* is "blown" in a converter. This metal, which contains 98.5% to 99.5% Cu, is subsequently refined electrolytically.

blocker. A forging die used for giving ■ forging an approximation of the final shape. The *blocker* imparts more detail than either the *edger* or the *fuller.*

bloom (slab, billet). *Fer met.* Semifinished products hot rolled from ingots and rectangular in cross section, with rounded corners. The chief differences are in cross-sectional area, in ratio of width to thickness, and in the intended uses. The American Iron and Steel Institute Steel Products Manual, Section 2 (1943) classifies general usage thus:

Type	Width, in.	Thickness, in.	Cross-Sectional Area, sq in.
Bloom	Width generally equals thickness		36 + (min)
Billet	1½ (min)	1½ (min)	2¼ to 36
Slab .....2 × thickness (min)		1½ (min)	16 (min) [a]

(a) Generally

Blooms, slabs and billets of rerolling quality are intended for hot rolling into common products such as shapes, plates, strip, bars, wire rod, sheet and black plate. Blooms, slabs and billets of forging quality are intended for conversion into forgings or other products to be heat treated.

blooming mill. *Fer met.* A mill that is used to reduce ingots to blooms, billets, slabs or sheet bars. Depending on the product, the mill is called a "blooming mill" ("cogging mill" in England), ■ "billet mill", or a "slabbing mill".

blowhole. A hole produced in a casting when gas, entrapped while the mold is being filled, or evolved during the solidification of metal, fails to escape and is held in pockets.

*** blue annealing.** A process of softening ferrous alloys in the form of hot rolled sheet, by heating in the open furnace to a temperature within the transformation range and then cooling in air. The formation of a bluish oxide on the surface is incidental.

blue brittleness. Reduced ductility occurring as a result of strain aging, when certain ferrous alloys are worked between 300 and 700 F. This phenomenon may be observed at the working temperature or subsequently at lower temperatures.

blue powder. A mixture of metallic zinc dust and zinc oxide obtained as a by-product in the distillation of zinc.

*** bluing.** A treatment for improving the appearance and resistance to corrosion of ferrous alloys by subjecting the surface, initially free from scale, to the action of air, steam, chemicals or other agents at a suitable temperature, thus forming a thin blue film of oxide.

NOTE: This term is ordinarily applied to sheet, strip or finished parts. It is used also to denote the heating of springs after fabrication, in order to reduce the residual stress caused by coiling and forming.

board hammer. A type of drop hammer in which boards attached to the ram are lifted between rollers.

book mold. A split mold that is hinged at the side.

bosh. In a blast furnace (1) the section where the diameter increases to a maximum above the tuyeres; (2) a lining of quartz that is built up during pyritic smelting of copper, narrowing down the internal dimensions at the tuyeres.

bossing. The roughening of roll surfaces to improve their bite on the bar in hot rolling.

bottom board. A flat base for holding the flask in making sand molds.

bowing. Lack of flatness in sheet or strip metal in which the longitudinal or transverse section forms an arc.

*** box annealing.** A process of annealing ■ ferrous alloy in a suitable closed metal container, with or without packing material, in order to minimize oxidation. The charge is usually heated slowly to a temperature below the transformation range, but sometimes above or within it, and is then cooled slowly. This process is also called "close annealing" or "pot annealing". See *black annealing.*

brake. A piece of equipment used for bending sheet; also called a "bar folder". If operated manually, it is called a "hand brake"; if power driven, it is called a "press brake".

brale. A diamond penetrator, conical in shape, used with a Rockwell hardness tester for hard metals.

brasses. Copper-base alloys in which zinc is the principal added element.

brazing. Joining metals by fusion of nonferrous alloys that have melting points above 800 F but lower than those of the metals being joined. This may be accomplished by means of a torch (torch brazing), in ■ furnace (furnace brazing) or by dipping in a molten flux bath (*dip* or *flux brazing*). The filler metal is ordinarily in rod form in torch brazing; whereas in furnace and dip brazing the work material is first assembled and the filler metal may then be applied as wire, washers, clips, bands, or may be integrally bonded, as in *brazing sheet.*

brazing sheet. A clad type of sheet product, coated on one or both surfaces with an alloy that has a melting point lower than the melting point of the core alloy. During brazing, only the coating melts and flows to form fillets in the preassembled article.

bridging. Local freezing across a mold before the metal below solidifies.

bridging. *Powd met.* In ■ powder mass, the formation of arched cavities, which may result in voids or uneven density in a compact, or which may result in stopping or interrupting the flow of powder through a funnel or other feeding device.

*** bright annealing.** A process of annealing usually carried out in a controlled furnace atmosphere so that surface oxidation is reduced to a minimum and the surface remains relatively bright.

bright dip. An acid solution into which articles are dipped to obtain a clean, bright surface.

brightener. Material added to an electroplating bath to give the deposited metal a highly reflective surface.

briquette. See *compact.*

brittleness. A tendency to fracture without appreciable deformation.

broach. (1) A rod inserted into a pierced tube when the tube is reduced by a reciprocating rolling process. (2) A tool employed for broaching.

broaching. Multiple shaving, accomplished by pushing ■ tool with stepped cutting edges along the work, particularly through holes.

buckling. The bending of sheets or plates under a compressive load.

buff. A polishing wheel usually consisting of a large number of treated or untreated muslin disks sewed together.

built-up plate. A pattern plate with the *cope* pattern mounted on or attached to one side and the *drag* pattern on the other. See *matchplate.*

bulging. Local expansion of tubes or shells by internal hydraulic pressure or by compression of a rubber cylinder.

bull block. A power-driven reel for drawing heavy-gage wire through a die.

bullion. An alloy containing sufficient precious metal to make *parting* profitable.

bumper. A machine for ramming sand in a flask by repeated jarring or jolting.

burnishing. Plastic smearing such as may occur on metallic surfaces during buffing.

*** burnt.** A term applied to a metal permanently damaged by having been heated to a temperature close to the melting point.

burr. A rough or sharp edge left on metal by a cutting tool.

bus bar. A metal bar for conducting high-amperage electric current.

button. A globule of metal remaining in an assaying crucible or cupel after fusion has been completed.

butt welding. Joining two edges or ends by placing one against the other and welding them.

C

cake. *Powd met.* A coalesced mass of unpressed metal powder.

cake. A copper ingot rectangular in cross section. See *wedge cake.*

calcination. The heating of ores or concentrates to cause decomposition of carbonates or hydrates.

camber of rolls. The increased diameter at the middle of rolls, designed to counterbalance the bending of the rolls when they are subjected to high pressures during rolling.

camber of sheet. Curvature in the plane of rolled sheet or strip.

capped steel. See *rimmed steel.*

carat. A twenty-fourth part, used to designate the fineness of gold. Thus "14-carat gold" means 14 parts gold, 10 parts base metal.

carbide. A compound of carbon with one or more metallic elements.

***carbonitriding.** A process in which a ferrous alloy is case hardened by first being heated in a gaseous atmosphere of such composition that the alloy absorbs carbon and nitrogen simultaneously, and then being cooled at a rate that will produce desired properties.

carbonization. Coking or driving off the volatile matter from fuels such as coal and wood. (Should not be confused with "carburization".)

carbon steel. Steel that owes its properties chiefly to the presence of carbon, without substantial amounts of other alloying elements; also termed "ordinary steel", "straight carbon steel", "plain carbon steel".

carbonyl powder. *Powd met.* Particles prepared by the thermal decomposition of a metal carbonyl.

*** carburizing.** A process that introduces carbon into a solid ferrous alloy by heating the metal in contact with a carbonaceous material—solid, liquid or gas—to a temperature above the transformation range and holding at that temperature. Carburizing is generally followed by quenching to produce a hardened case.

*** case.** In a ferrous alloy, the surface layer that has been made substantially harder than the interior or *core* by a process of *case hardening.*

*** case hardening.** A process of hardening a ferrous alloy so that the surface layer or *case* is made substantially harder than the interior or *core.* Typical case-hardening processes are *carburizing* and *quenching, cyaniding, carbonitriding, nitriding, induction hardening* and *flame hardening.*

casting. (1) Pouring molten metal into a mold. (2) The metal object produced by such pouring.

casting cracks. See *shrinkage cracks.*

casting shrinkage. See *solidification shrinkage.*

casting strains. Strains resulting from the cooling of a casting and accompanied by residual stresses.

cast steel. Any object made by pouring molten steel into molds.

cast structure. The structure, on a macroscopic or microscopic scale, of a cast alloy that consists of cored dendrites and, in some alloys, a network of other constituents.

cathode copper. The product of electrolytic refining of copper, which is used to charge furnaces in preparation for the final casting of copper and copper alloys.

cathodic protection. The use of a particular metal as cathode in the corrosion cell as a means of protecting that metal against *electrochemical corrosion.* This may be accomplished by the attachment of a more anodic metal or by the use of an applied potential.

caustic dip. Immersion in a solution of sodium hydroxide to clean the surface or, when working with aluminum alloys, to reveal the macrostructure.

cavitation erosion. Damage to a material in contact with a moving liquid, associated with the formation and collapse of cavities in the liquid at the solid-liquid interface.

cell. (1) A combination of two electrodes immersed in an electrolyte. Such a cell may set up an electromotive force, and if the electrodes are connected externally, an electric current will flow. (2) A unit for the electrodeposition of metals from an electrolyte.

cell feed. The material supplied to the cell in the electrolytic production of metals.

*** cementation.** A process of introducing elements into the outer layer of metal objects by means of diffusion at high temperature.

cementation. A process for obtaining a metal from a solution of one of its compounds through displacement by ■ more electropositive element. See *electromotive series.*

cementite. A compound of iron and carbon known as "iron carbide", which has the approximate chemical formula Fe_3C and is characterized by an orthorhombic crystal structure.

centrifugal casting. A casting technique in which the mold is rotated during solidification of the casting. Unusually sound castings may be produced by the action of centrifugal force pressing toward the periphery.

chafing fatigue. Accelerated fatigue caused by the stress-raising effect of frictional contacts.

chaplets. Metal supports for holding the cores of sand molds in place.

Charpy test. A pendulum type of impact test in which a specimen, supported at both ends as a simple beam, is broken by the impact of the falling pendulum. The energy absorbed in breaking the specimen, as determined by the decreased rise of the pendulum, is a measure of the impact strength of the metal. See *Izod test.*

check marks. On the surface of copper wire, defects in the form of V's, which are found in a line and point in the direction of drawing. Also called "crowfeet" and "fishhooks".

cheeks. The intermediate sections of a flask that are inserted between cope and drag to decrease the difficulty of molding unusual shapes or to fill a need for more than one parting line.

chemical deposition. The precipitation of one metal from a solution of its salt by the addition of another metal or reagent to the solution.

Chempur tin. Commercial tin of high purity, for example 99.991%.

chill-cast pig. Pig iron cast into metal molds or chills. If a machine is used the product is known as "machine-cast pig".

chills. Metallic inserts located in positions in sand molds where rapid cooling is desired.

Chinese script. A configuration typical of the constituents in cast aluminum alloys containing specific amounts of iron and silicon. This term applies also to a similar structure found in magnesium alloys containing silicon.

chipping. A method for removing seams and other surface defects with chisel or gouge so that such defects will not be worked into the finished product. Chipping is often employed also to remove metal that is excessive but not defective. Removal of defects by gas cutting is known as "deseaming" or "scarfing".

chlorination. (1) The roasting of prepared ore in contact with a chloride, usually common salt, to convert certain metals into the more easily separated chloride. (2) The degassing or purification of molten metals by fluxing with chlorine.

chrome pickle. A chemical treatment for magnesium in a nitric acid, sodium dichromate solution. The treatment gives some protection against corrosion by producing a film that is also a base for paint.

cladding. A process for covering one metal with another. Usually the surfaces of fairly thick slabs of two metals are brought carefully into contact and are then subjected to co-rolling so that a clad composition results. In some instances a thick electroplate may be deposited before rolling.
classification. *Powd met.* Separation of a powder into fractions according to particle size.
cleavage plane. A crystallographic plane on which fracture occurs in a crystal or grain of metal. A substance may fracture on more than one crystallographic plane.
close annealing. See *box annealing.*
closed dies. Forging dies in which the compressive force is applied to the whole surface of the forging. In *open* dies, there is no constraint to lateral flow in some directions.
closed passes. Grooves in rod rolls designed so that they restrain the metal from forming fins between the rolls.
cloth. *Powd met.* Metallic or nonmetallic fabric used for screening or classifying powders.
cloudburst treatment. Surface hardening by impingement of steel balls.
cluster mill. A rolling mill where each of the two working rolls of small diameter is supported by two or more back-up rolls.
coalesced copper. The product of a patented process for deposition of brittle copper cathodes and subsequent sintering of briquettes of the pieces of broken-up cathodes. The sintered briquettes can be worked into an oxide-free copper of good physical properties.
coalescence. (1) The growth of particles of a dispersed phase by solution and reprecipitation. (2) The growth of grains by absorption of adjacent undistorted grains.
coated particles. *Powd met.* Metal particles of which the surfaces have been covered with another metal.
cockles. Waviness at the edge of sheet metal. See *riffles.*
coercive force. The magnetizing force that must be applied in the direction opposite to that of the previous magnetizing force in order to remove residual magnetism; thus, an indicator of the "strength" of magnetically hard materials.
cogging. *Fer met.* Rolling or forging ingots to blooms or billets.
cogging hammer. *Fer met.* A forging hammer used to reduce ingots to blooms or billets.
cohesive strength. A term used with one of the following meanings: (1) The maximum stress required in order to cause tensile fracture in the absence of any deformation, when two of the three principal stresses equal zero; that is, with an unnotched bar. Sometimes called "initial cohesive strength". (2) The maximum principal stress required in order to cause tensile fracture when triaxial stresses are present; that is, by using a notched test bar. This is frequently called the "technical cohesive strength" and is variable, depending on the relative magnitude of the three principal stresses, the amount of plastic deformation preceding fracture, and the temperature and rate of straining. (3) See *disruptive strength.*
coinage metals. Alloys of gold or silver with nickel or copper, used for minting coins.
coining. A process of impressing images or characters of the die and punch onto a plane metal surface. See also *sizing* for *Powd met* usage.
coin silver. An alloy, standard in the United States, containing 900 parts of silver and 100 parts of copper.
cold pressing. *Powd met.* Forming a compact at room temperature.
cold short. The characteristic of metals that are brittle at ordinary or low temperatures.
cold shut. (1) A discontinuity that appears on the surface of cast metal as a result of two streams of liquid meeting and failing to unite. Pouring the metal when it is too cold may cause such a discontinuity. (2) On a forging, a portion of the surface that is separated by oxide from the main body of metal.
cold work. Plastic deformation at such temperatures and rates that substantial increases occur in the strength and hardness of the metal. Visible structural changes include changes in grain shape and, in some instances, mechanical twinning or banding.
cold working. Deforming a metal plastically at such a temperature and rate that strain hardening occurs. The upper limit of temperature for this process is the *recrystallization temperature.*
columnar structure. A coarse structure of parallel columns of grains, which is caused by highly directional solidification resulting from sharp thermal gradients.
combined carbon. The carbon that is combined with iron or alloying elements to form carbide in cast iron or steel.
comminution. See *pulverization.*
compact. *Powd met.* An object produced by the compression of metal powders with or without the inclusion of nonmetallic constituents. Synonymous with *briquette.*
components. (1) The least number of chemical substances or metals required to create the system under consideration. (2) The individual parts of a stress or strain vector as referred to a system of co-ordinates.
composite compact. *Powd met.* A metal powder compact consisting of two or more adhering layers of different metals or alloys, with each layer retaining its original identity.
compound compact. *Powd met.* A metal powder compact consisting of mixed metals, the particles of which are joined by pressing or sintering or both, with each metal particle retaining substantially its original composition.
compression ratio. *Powd met.* The ratio of the volume of the loose powder to the volume of the compact made from it by the application of a specified pressure in a specified die at a specified pressing speed.
compressive strength. Yield. The maximum stress that a metal, subjected to compression, can withstand without a predefined amount of deformation. **Ultimate.** The maximum stress that a brittle material can withstand without fracture when subjected to compression.
congruent transformation. A solid state or solid-liquid phase change involving no change in composition.
constant-deflection test. A stress-corrosion-cracking or mechanical test in which the specimen is stressed by bending to a definite and constant curvature.
constant-load test. A stress-corrosion-cracking or mechanical test in which the specimen is stressed by applying a dead load.
constituent. A micrographically distinguishable part of an alloy or mixture.
constitution diagram. See *phase diagram.*
continuous casting. A casting technique in which the ingot is continuously solidified while it is being poured, and the length is not determined by mold dimensions.
continuous electrode. In an electric-arc furnace, a type of electrode that is replenished as it is consumed.
continuous phase. In alloys containing more than one phase, the phase that forms the matrix or background in which the other phase or phases are present as isolated units.
★ **controlled cooling.** A process of cooling from an elevated temperature in a predetermined manner, to avoid hardening, cracking or internal damage, or to produce a desired microstructure. This cooling usually follows the final hot forming operation.
converter. A furnace in which air is blown through the molten bath of crude metal or matte for the purpose of oxidizing impurities.
cooling curve. A curve showing the relation between time and temperature during the cooling of a metal sample. Since most phase changes involve evolution or absorption of heat, there may be abrupt changes in the slope of the curve.
cooling stresses. Stresses developed by uneven contraction or external constraint of metal during cooling; also those stresses resulting from localized plastic deformation during cooling, and retained.
cope. The upper or topmost section of a flask, mold or pattern.
core. (1) A body of sand or other material placed in a mold to produce a cavity in a casting. (2) A tubular defect that comes from the surface of a billet and appears at the back end of extruded rod. (3) The center or base portion of a clad product.
★ **core.** In a ferrous alloy, the interior portion that is substantially softer than the surface layer or *case*, after *case hardening.*
cored bar. *Powd met.* A compact of bar shape heated, by its own electrical resistance, to a temperature that melts its interior.
core rod. *Powd met.* The part of a die used to produce a hole in a compact.
coring. Variable composition in solid-solution dendrites; the center of the dendrite is richer in one element, as shown by the pertinent solidus-liquidus lines in a phase diagram.
corrosion. Gradual chemical or electrochemical attack on a metal by atmosphere, moisture or other agents.
corrosion embrittlement. The embrittlement caused in certain alloys by exposure to a corrosive environment. Such material is usually susceptible to the intergranular type of corrosion attack.
corrosion fatigue. The repeated cyclic stressing of a metal in a corrosive medium, resulting in more rapid deterioration of properties than would be encountered as a result of either cyclic stressing or of corrosion alone.
couple. Two dissimilar conductors in electrical contact. An electromotive force is created under proper electrolytic influences or during heating.
coupon. An extra piece of metal (for example, on a casting) from which a specimen for physical or mechanical testing is cut or machined.
creep. The flow or plastic deformation of metals held for long periods of time at stresses lower than the normal yield strength. The effect is particularly important if the temperature of stressing is in the vicinity of the recrystallization temperature of the metal.
creep limit. The maximum stress that will result in creep at a rate lower than an assigned rate.
critical point. *Transformation temperature* is the term preferred.
★ **critical range or critical temperature range.** Synonymous with *transformation range,* which is preferred.
critical strain. The percentage strain at which, or immediately higher than which, large grain growth occurs during heating.
critical temperature. *Transformation temperature* is the term preferred.
crop. The end or ends of an ingot that contain the pipe or other defects to be cut off and discarded; also termed "crop end" and "discard".
cross rolling. The rolling of sheet so that the direction of rolling is changed about 90 deg from the direction of the previous rolling.
crown. In the center of metal sheet or strip, thickness greater than at the edge.
crucible. A ceramic pot or receptacle made of graphite and clay, or clay or other refractory material, and used in the melting of metal. The term is sometimes applied to pots made of cast iron, cast steel or wrought steel.
crystal. A physically homogeneous solid in which the atoms, ions or molecules are arranged in a three-dimensional repetitive pattern.
crystallization. The formation of crystals by the atoms assuming definite positions in a crystal lattice. This is what happens when a liquid metal solidifies. (Fatigue, the failure of metals under repeated stresses, is sometimes falsely attributed to crystallization.)
cup fracture. The type of fracture in which the exterior portion is extended and the interior is relatively depressed, resembling a cup. When only a part of the exterior is extended, the term "half-cupped" or "quarter-cupped" is used.
cupellation. Oxidizing fusion of lead that contains silver and gold, in order to remove the base metal entirely. The process is used also in the manufacture of lead oxide.
cupping. The breaking of wire with a cup fracture accompanied by very little reduction of area; observed during cold drawing. Also the forming of sheet into cuplike objects such as shells, by deep drawing.
curling. Rounding the edge of sheet metal into a closed or partly closed loop.
cut. See *fraction.*
cyanide slimes. Gold precipitated from cyanide solutions used in extracting gold from ores.
★ **cyaniding.** A process of case hardening a ferrous alloy by heating in a molten cyanide, thus causing the alloy to absorb carbon and nitrogen simultaneously. Cyaniding is usually followed by quenching to produce a hard case.

D

damping capacity. The ability of a metal to absorb vibrations, changing the mechanical energy into heat. See *internal friction.*
D. C. (Direct Chill) ingot casting practice. A continuous method of casting ingots for sheet or extrusion by pouring the metal into a short mold that is gradually lowered while the metal solidifies. The mold has no fixed bottom, but the movable platform serves at the start of the operation or "drop". When the platform is gradually lowered, the frozen shell of metal acts as a retainer for the liquid

metal. The ingot is usually cooled by the impingement of water directly on the mold or on the walls of the ingot being lowered.

dead roast. A roasting process for complete elimination of sulfur.

decalescence. The decrease that is caused in temperature when the rate of absorption of heat during transformation exceeds the rate of input of heat while heating steel through the transformation range.

* **decarburization.** The loss of carbon from the surface of a ferrous alloy as a result of heating in a medium that reacts with the carbon.

deep drawing. Forming cup-shaped articles or shells by using a punch to force sheet metal into a die.

deep etching. Macro-etching; etching, for examination at a low magnification, in a reagent that attacks the metal to a much greater extent than normal for microscopic examination. Gross features may be developed—abnormal grain size, segregation, cracks or grain flow.

deformation bands. Bands within individual cold worked crystals. The bands and matrix differ variably in orientation.

degrees of freedom. The number of independently variable quantities (such as temperature, pressure, and concentration within the phases present) that may be altered at will without causing alteration in the number of phases in a system; or, the number of such variables that must be fixed arbitrarily in order to define the system completely.

dendrite. A crystal formed usually by solidification and characterized by a treelike pattern composed of many branches; also termed "pine tree" and "fir tree" crystal.

dendritic powder. *Powd met.* Particles, usually of electrolytic origin, with typical "pine tree" structure. Synonym, *arborescent powder*.

density ratio. *Powd met.* The determined density of a green or sintered compact, divided by the absolute density of metal of the same composition; usually expressed as a percentage.

deseaming. See *chipping*.

dezincification. Corrosion of an alloy containing zinc (usually brass), involving loss of zinc and a surface residue or deposit of one or more less active components (usually copper).

diamagnetic. A material that has less magnetic permeability than a vacuum. The material would be repelled weakly by a magnet.

dichromate treatment. A chemical treatment for magnesium alloys in a boiling sodium dichromate solution, resulting in a surface film that resists corrosion.

die. *Powd met.* The part or parts making up the confining form into which a powder is pressed. The parts of the die may include some or all of the following: die body, punches, core rods. Synonym, *mold*.

die body. *Powd met.* The stationary or fixed part of a die.

die casting. Casting metals into final shapes in metal molds; usually alloys that have relatively low melting points, such as zinc, lead, tin, aluminum or magnesium base alloys. If the metal is forced into the mold, the process is called "pressure die casting"; otherwise, "gravity or permanent mold die casting".

die forging. See *drop forging*.

die insert. *Powd met.* A removable liner or part of a die body or punch.

die lines. Lines or markings caused on drawn or extruded products by minor imperfections in the surface of the die.

die plates. Plates of steel or iron with tapered holes of several sizes for drawing wire.

die radius. The radius on the exposed edge of a deep drawing die, over which the sheet flows in forming drawn shells.

die scalping. Drawing through a sharp-edged die to cut off the surface.

die set. *Powd met.* The parts of a press that hold the die and locate it in proper relation to the punches.

die sinking. Forming or machining a depressed pattern in a die.

differential flotation. A flotation process for separating a complex ore into two or more valuable minerals and gangue.

* **differential heating.** A heating process by which the temperature is varied within the object so that, after cooling, various parts may have different properties as desired.

diffusion. A movement of atoms within a solution. The net movement is usually in the direction from regions of high concentration toward regions of low concentration in order to achieve homogeneity of the solution, which may be a liquid, solid or gas.

diffusion coefficient. A factor of proportionality representing the amount of substance in grams diffusing in one second across an area of one square centimeter through a unit concentration gradient.

diffusion zone. In the clad type of products, the zone between coating and core, in which diffusion between the two has occurred.

dilatometer. An instrument for measuring the expansion or contraction caused in a metal by changes in temperature or structure.

dimpling. A process of cupping sheet so as to permit the use of rivets that have countersunk heads. Dimpling differs from countersinking in that it is a cupping operation and no metal is cut away after the rivet hole has been drilled.

direct extrusion. Extrusion through a die placed at the opposite end of the billet from the ram.

directional properties. Anisotropic condition where physical and mechanical properties vary, depending on the relation of the test axis to a specific direction of the metal; a result of preferred orientation or of fibering of inclusions during the working.

* **direct quenching.** A process of quenching carburized parts directly from the carburizing operation.

discard. See *crop*.

disintegration. *Powd met.* Reduction of massive material to powder.

dislocations. Postulated vacant atom sites in metal crystals. These vacant sites may move under stress or alloy concentration gradients, and such movements are employed to explain plastic deformation, creep, diffusion and other phenomena.

dispersoid. Finely divided particles of a relatively insoluble constituent, apparent in the microstructure of certain alloys.

disruptive strength. The maximum strength of a metal when subjected to three principal tensile stresses at right angles to one another and of equal magnitude.

doré silver. Crude silver containing a small amount of gold, obtained after removing lead in a cupeling furnace, during the processing of slimes from copper anodes.

Dow process. A process for the production of magnesium by electrolysis of molten magnesium chloride.

draft. (1) The amount of taper in the side walls of die impressions. (2) The taper given to the sides of a pattern to enable it to be withdrawn easily from the mold.

drag. The lower or bottom section of a mold or pattern.

drawbench. The stand that holds the die and drawhead used in drawing wire, rod and tubing.

drawing. See *tempering*.

drawing or cupping tools. Major tools involved in deep drawing, such as the *die*, *punch*, *blank holder* and *knockout*.

drawn shells. Articles formed by deep drawing sheet into rectangular, cylindrical, hemispherical or odd shapes.

drop forging. Forming metal, usually under impact, by compression within dies designed to produce the required shape. The term is ordinarily used synonymously with *hot die forging*.

drop hammer. A forging machine that employs the impact resulting from the action of gravity, with or without added steam or air pressure, on a falling ram.

dross. Metal oxides in or on molten metal.

dry cyaniding. Synonymous with *carbonitriding*.

dry sand mold. A casting mold of sand, which is thoroughly dried before being filled with liquid metal.

ductility. The property that permits permanent deformation before fracture by stress in tension.

dummy. Stock that has been given a preliminary rough shaping before being placed between dies for drop forging complicated shapes.

dummy block. A free cylinder that transmits pressure from the ram to the billet in the extrusion of metals.

duralumin. The trade name applied to the first aluminum-copper-magnesium type of age-hardenable alloy (17S), which contains nominally 4% Cu, ½% Mn and ½% Mg. The term is sometimes used to include the class of wrought aluminum-copper-magnesium alloys that harden during aging at room temperature.

Durville process. A casting process that involves rigid attachment of the mold in an inverted position above the crucible. The melt is poured by tilting the entire assembly, causing the metal to flow along a connecting launder and down the side of the mold.

dusting. Applying an agent such as powdered sulfur to prevent the burning of molten magnesium alloys during pouring.

E

ear. A wavy projection formed in the course of deep drawing, as a result of directional properties or anisotropy of the sheet.

edger. The portion of a die used for preliminary forging that distributes the metal in the general proportions of the shape to be forged.

elastic aftereffect. A slight contraction that occurs slowly while metal is standing with no load, subsequent to plastic tensile flow and immediate elastic recovery. *Microscopic stresses*, acting in compression, are responsible for this as well as for the Bauschinger effect.

elastic constants. In the general form of Hooke's law, the elastic moduli, which vary in individual crystals with the direction of test.

elastic deformation. Temporary changes caused in dimensions by stress. The material returns to the original dimensions after removal of the stress.

elastic hysteresis. Energy absorbed by reversed deformation, represented by the closed loop of stress-strain curves in the elastic range, formed by curves for loading and unloading.

elastic limit. The maximum stress that a material will withstand without permanent deformation. (Almost never determined experimentally; *yield strength* is customarily determined.)

electrochemical corrosion. Localized corrosion that results from exposure of an assembly of dissimilar metals in contact or coupled with one another; or of a metal containing macroscopic or microscopic areas dissimilar in composition or structure. The dissimilar elements form short-circuited electrodes, the corrosive medium is the electrolyte, and an electric current is induced, which results in the dissolution of the electrode that has the more anodic solution potential, while the other is unattacked. The same condition may result from local differences within the corroding medium.

electrode potential. See *solution potential*.

electroforming. Production or reproduction of articles by electrolytic deposition.

electrolytic brightening. See *anodic treatments*.

electrolytic deposition. *Powd met.* The production of a metal from a solution of its salts by the passage of an electric current through the solution.

electrolytic oxidation. See *anodic treatments*.

electrolytic polishing. See *anodic treatments*.

electrolytic protection. Protection from electrochemical corrosion by use of the protected material as cathode in the corrosion cell. See also *cathodic protection*.

electromotive (force) series. A list of elements arranged according to their *standard electrode potentials*.

electron microscope. A microscope that utilizes electron beams of short wave length and magnetic fields instead of the visible light and glass lenses utilized in ordinary microscopes. However, since the electron beams will not reflect in the same way as visible light, a thin replica of polished and etched metal surfaces is employed. Magnifications of the replica from ×5000 to 50,000 are readily obtained.

electron valence ratios. In structurally analogous compounds, the ratio of valence electrons to atoms; 3:2, 7:4 and 21:13 are common.

elinvar. An iron-base alloy containing about 36% Ni and 12% Cr, used for its constancy of elastic modulus with temperature.

elongation. The amount of permanent extension in the vicinity of the fracture in the tension test; usually expressed as a percentage of the original gage length, as 25% in 2 in. Elongation may also refer to the amount of extension at any stage in any process that elongates a body continuously, as in rolling.

embossing. Raising a design in relief against a surface.

endurance limit. The maximum stress that a metal will withstand without failure during a specified large number of cycles of stress. If the term is employed without qualification, the cycles of stress are usually such as to produce complete reversal of flexural stress.

endurance ratio. The ratio of the endurance limit for cycles of reversed flexural stress to the tensile strength.

epsilon structure. Structurally analogous, close-packed phases or electron compounds that have ratios of 7 valence electrons to 4 atoms.

equilibrium. A dynamic condition of balance between atomic movements, where the resultant is zero and the condition appears to be one of rest rather than change.

equilibrium diagram. See *phase diagram*.

Erichsen test. A ductility or cupping test in which the depth of impression at fracture, made by forcing a cone-shaped, spherical-end plunger into the sheet specimen, is measured in millimeters.
erosion. The abrasion of metal or other material by liquid or gas, usually accelerated by pressure of solid particles of matter in suspension, and sometimes by corrosion.
etch figures. Markings caused by an etchant on a crystal surface and usually related geometrically to the crystal structure.
etching. In metallography, the process of revealing structural details by the preferential attack of reagents on a metal surface.
eutectic (1) The isothermal reversible reaction of a liquid that forms two different solid phases (in a binary alloy system) during cooling. (2) The alloy composition that freezes at constant temperature, undergoing the eutectic reaction completely. (3) The alloy structure of two (or more) solid phases formed from the liquid eutectically.
eutectic alloy. In an alloy system, the composition at which two descending liquidus curves in a binary system or three descending liquidus surfaces in a ternary system meet at a point. Thus such an alloy has a lower melting point than neighboring compositions. More than one eutectic composition may occur in a given alloy system.
eutectic melting. Melting of local micro areas that are the same as the eutectic in average composition. On cooling rapidly, these areas solidify into a typical eutectic structure. See *rosette*, 1.
eutectoid reaction. The isothermal reversible reaction of a solid that forms two new solid phases (in a binary alloy system) during cooling. As with *eutectic*, the word *eutectoid* can also refer to an alloy composition or structure associated with the reaction.
eutectoid steel. A steel of the eutectoid composition (composition *S* on the iron-carbon diagram). This composition in pure iron-carbon alloys is 0.80% C, but variations from this composition are found in commercial (impure) steels, and particularly in alloy steels, in which the carbon content of the eutectoid is usually lower.
exfoliation. A type of corrosion that progresses parallel to the outer surface of the metal, causing layers of the metal to be elevated by the formation of corrosion product. See also *spalling*.
explosive rivet. A type of blind fastener in which a hollow-shank rivet is used, containing an explosive charge. The rivet shank is expanded by exploding the charge after the rivet has been inserted.
extensometer. Device, usually mechanical, for indicating the deformation of metal while it is subjected to stress.
extrusion. Shaping metal into a chosen continuous form by forcing it through a die of appropriate shape.
extrusion defect. See *core*.
extrusion ingot or billet. Cast or preworked metal used as starting stock in extrusion.

F

fatigue. The tendency for a metal to break under conditions of repeated cyclic stressing considerably below the ultimate tensile strength.
fatigue crack or failure. A fracture starting from a nucleus where there is an abnormal concentration of cyclic stress and propagating through the metal. The surface is smooth and frequently shows concentric (sea shell) markings with a nucleus as a center.
fatigue limit. The maximum stress that a metal will withstand without failure for a specified large number of cycles of stress. Usually synonymous with *endurance limit.*
faying surfaces. The contacting surfaces of overlapped metal in a lapped joint.
feeder head. See *riser*.
ferrite. A solid solution in which alpha iron is the solvent, and which is characterized by a body-centered cubic crystal structure.
ferro-alloy. An alloy of iron that contains a sufficient amount of one or more chemical elements—such as manganese, chromium, or silicon —to be useful as an agent for introducing these elements into steel by admixture with molten steel.
fiber, fibre. (1) A characteristic of wrought metal that indicates directional properties and is revealed by the etching of a longitudinal section or is manifested by the fibrous or woody appearance of a fracture. Fiber is caused chiefly by the extension of the constituents of the metal, both metallic and nonmetallic, in the direction of working. (2) The pattern of preferred orientation of metal crystals after a given deformation process (usually wiredrawing); see "fibering" in the Glossary of Terms Used in X-Ray Metallography. See *preferred orientation.*
fiber stress. Local stress at a point or line on a section over which stress is not uniform, such as on the cross section of a beam under a bending load.
filler metal. In brazing or welding, the added metal melted by the arc or flame and acting to bind edges or fill empty zones.
fillet. A concave junction of two (usually perpendicular) surfaces.
fin. See *flash*.
fineness. Parts per 1000 of gold or silver.
fines. *Powd met.* The portion of a powder composed of particles smaller than a specified size, currently less than 44 microns.
fines. See *shorts*.
finished steel. Steel that is ready for the market without further work or treatment. Blooms, billets, slabs, sheet bars, and wire rods are termed "semifinished".
finisher. Die for making the final impression in forging an article.
finishing temperature. The temperature at which hot mechanical working of metal is completed.
fire scale. Copper oxide subscale formed just under the surface of silver-copper alloys when annealed in air.
fir tree crystal. See *dendrite*.
fishmouthing. See *alligatoring*.
fishtail. An overlapping at the back end of rolled sheet.
flake powder. *Powd met.* Flat or scale-like particles, relatively thin.
flakes. Internal fissures in ferrous metals. In a fractured surface these fissures may appear as sizeable areas of silvery brightness and coarse texture; in wrought products such fissures may appear as short discontinuities on an etched section. Also called "shatter cracks", "chrome checks", "fish eyes" and "snowflakes".
★ **flame annealing.** A process of softening a metal by the application of heat from a high-temperature flame.
★ **flame hardening.** A process of hardening a ferrous alloy by heating it above the transformation range by means of a high-temperature flame, and then cooling as required.
flange. (1) A projection of metal on formed objects. (2) The parts of a channel at right angles to the central section or web.
flapping. An operation that precedes poling in the fire-refining of copper. The surface of the slag is broken by striking with a rabble blade, and the melted metal is exposed to the air in order to hasten oxidation.
flash. A thin fin of metal formed at the sides of a forging or weld when a small portion of metal is forced out between the edges of the forging or welding dies.
flask. The outer metal or wood frame, consisting of the cope and drag, used to hold the sand around the pattern in making a sand mold.
flat sheet. Sheet rolled as pieces of convenient size and then flattened or leveled, usually by stretching. This operation may produce properties slightly different from those of *coiled sheet*.
floating plug. A plug that locates itself inside a tube during drawing, in such a way that the tube is reduced in thickness between the plug and the die.
flotation. The concentration of valuable minerals from ores by agitation of the ground ore with water, oil and flotation chemicals. Normally the valuable minerals are wetted by the oil, are lifted to the surface by air bubbles and are then floated off.
flow rate. *Powd met.* The time required for a powder sample of standard weight to flow through an orifice in a standard instrument according to a specified procedure.
flow stress. The shear stress required to cause plastic deformation of solid metals.
fluidity. The ability of a liquid metal to flow readily, as measured by the length of a standard spiral casting.
fluting. Kinking or breaking caused by the curving of metal strip on a radius so small, in relation to thickness, as to stretch the outer surface well beyond its elastic limit.
flux-coated electrode. A rod of filler metal on which a coating of flux has been baked for use in arc welding.
fluxing. Applying ■ solid or gaseous material to molten metal in order to remove oxide dross and other foreign materials. The treatment of molten magnesium alloys with flux is frequently called *refining*.
fly ash. A finely divided product of combustion, which may appear as inclusions in metal melted in the open hearth type of furnace.
fog quenching. A method of quenching in which a fine vapor or mist is used as the quenching medium. See also *spray quenching*.
foil. Metal in any width but no more than about 0.005 in. thick.
folds. Defects caused in metal by continued fabrication of overlapping surfaces.
forging rolls. Rolling mills that forge comparatively uniform shapes by using variable radii around the circumference of rolls that rotate in the opposite direction from those ordinarily used for rolling.
forging strains. Differential strains that result from forging or from cooling from the forging temperature, and that are accompanied by residual stresses.
fraction. *Powd met.* That portion of ■ powder sample which is between two stated particle sizes or two stated screen-mesh sizes. Synonymous with *cut*.
fracture stress. The maximum principal true stress (fracture load divided by fracture area). See *cohesive strength*.
fracture test. *Fer met.* Breaking a piece of metal for the purpose of examining the fractured surface to determine the structure or carbon content of the metal or to detect the presence of internal defects.
fragmentation. Imperfection of the crystal structure of grains in a metal as the result of working. The fragments differ slightly from one another in orientation, and tend to rotate to a stable orientation.
free ferrite. Ferrite formed from austenite during cooling, without simultaneous formation of carbide.
free machining. The property that makes machining easy because of the forming of small chips, a characteristic imparted to steel by sulfur, to brass by lead, to aluminum alloys by lead and bismuth, to nickel alloys by sulfur or carbon, and so on.
fretting corrosion. Corrosion at the interface between two contacting surfaces, accelerated by vibration between the two sufficient to produce localized deformation.
★ **full annealing.** A softening process in which a ferrous alloy is heated to a temperature above the transformation range and, after being held for a sufficient time at this temperature, is cooled slowly to a temperature below the transformation range. The alloy is ordinarily allowed to cool slowly in the furnace, although it may be removed and cooled in some medium that ensures a slow rate of cooling.
fuller. In preliminary forging, the portion of a die that reduces the cross-sectional area between the ends of the stock and permits the metal to move outward.

G

galling. The damaging of one or both metallic surfaces by removal of particles from localized areas during sliding friction.
galling. *Powd met.* The impairment caused on the surface of a compact or of die parts by adhesion between the die wall and the metal powder. Synonymous with *seizing*.
galvanic corrosion. See *electrochemical corrosion*.
gamma iron. The form of iron stable between Ae_3 and Ae_4 (910 and 1400 C; 1670 and 2550 F) and characterized by a face-centered cubic crystal structure. See *transformation temperature* for definitions of Ae_3 and Ae_4.
gamma structure. Structurally analogous phases or electron compounds that have ratios of 21 valence electrons to 13 atoms; generally a large complex cubic structure.
gangue. In an ore, the commercially undesirable portion that must be removed before further processing.
gas cyaniding. Synonymous with *carbonitriding*.
gaseous reduction. *Powd met.* The conversion of metal compounds to metallic particles by the use of a reducing gas.
gassing. (1) The absorption of gas by ■ metal. (2) The evolution of gas from a metal.
gassing of copper. See *hydrogen embrittlement*.
gas welding. Manual or automatic torch welding of metals, in which the heating is accomplished by an oxyacetylene or oxyhydrogen flame.
gate. (1) The point where molten metal enters the casting cavity. (2) The assembly of *pouring basin*, *sprue*, and *runner*, forming a channel for pouring liquid metal into a casting mold.
gated pattern. Mold patterns designed to permit two or more castings, joined by connecting channels, to be made in one mold.

German silver. An alloy of copper, zinc and nickel, containing no silver and probably not originating in Germany. See *nickel silver.*

germinative conditions. The presence of a critical amount of cold work in a metal, which leads to the development of a very coarse grain structure as a result of heating. See *critical strain.*

globular powder. *Powd met.* Particles approximately spherical.

gold-filled. Consisting of base metal mechanically covered with a layer of gold alloy and used as a substitute for solid gold. The quality of gold-filled articles is controlled by federal authority.

gold leaf. Gold beaten or rolled extremely thin and used for gilding. Imitation gold leaf is made of brass.

grained metal. Metal of a fine particle size produced by stirring or otherwise breaking up the metal while it is cooling through the freezing range.

grain growth. An increase in the grain size of metal.

grain refiner. Any material added to a liquid metal for the purpose of producing a finer grain size in the subsequent casting, or of retaining fine grains during the heat treatment of wrought structures.

grains. Individual crystals in metals.

grain size. In many nonferrous metals, particularly alpha brasses, grain size is expressed in millimeters average diameter and is determined by comparison with standards at 75 diameters in magnification. The grain size may also be expressed in terms of the number of grains per unit area or volume.

granular powder. *Powd met.* Particles that have approximately equidimensional, nonspherical shapes.

granulated metal. Metal in small pellets formed by allowing thin streams of the liquid metal to fall into water. The streams are usually formed by pouring the metal on wire mesh. Another process involves a rotating disk from which the liquid metal is dispersed by centrifugal force.

granulation. *Fer met.* The recrystallization of columnar crystals and dendrites in freshly solidified steel to form more or less equiaxed grains at temperatures near the solidus.

granulation. *Powd met.* The production of coarse metal particles by pouring the molten metal through a screen into water or by agitating the molten metal violently while it is solidifying.

graphitic embrittlement. Reduction in ductility of a metal or alloy, associated with the occurrence of graphite in the grain boundaries.

*** graphitizing.** A heating and cooling process by which the combined carbon in cast iron or steel is transformed, wholly or partly, to graphitic or free carbon. See *temper carbon.*

gravity segregation. Variable composition caused in a casting by the settling of the heavier constituents.

green. *Powd met.* Unsintered.

grizzly. A device consisting of approximately parallel bars used for the coarse separation or screening of ores.

growth. *Powd met.* The increase that may occur in the dimensions of a compact during the sintering operation.

Guerin forming. A method of forming in which the metal is forced to conform to the shape of a male die by the application of a hydrostatic force of confined rubber.

Guinier-Preston zones. In a structure precipitating from solid solution, the two-dimensional platelets that produce streaks on Laue X-ray photograms. These platelets form on specific crystallographic planes of the matrix lattice and produce the first discernible evidence of decomposition of a supersaturated solid solution.

H

Hall process. The usual process of winning aluminum from alumina by electrolytic reduction of a fused bath of alumina dissolved in cryolite.

hammer forging. A forging process in which the work is deformed by repeated blows. Compare with *press forging.*

hammering. Beating metal sheet into a desired shape either over a form or on a high-speed mechanical hammer, in which the sheet is moved between a small curved hammer and a similar anvil to produce the required dishing or thinning.

Hansgirg process. A method for producing magnesium by reduction of magnesium oxide with carbon.

hard drawn. A temper produced in wire, rod, or tube by cold drawing.

***hardenability.** In a ferrous alloy, the property that determines the depth and distribution of hardness induced by quenching.

hardener. A preliminary alloy, of composition high in one or more alloying elements, which is added in making a melt and which permits closer control of composition than is possible with the addition of the pure metals. Also referred to as *rich alloy* or *master alloy.*

*** hardening.** Any process for increasing the hardness of metal by suitable treatment, usually involving heating and cooling.

hard head. A tin-iron alloy obtained in the smelting of slags from the first treatment of tin concentrates in either the blast furnace or the reverberatory furnace.

hardness. Defined in terms of the method of measurement. (1) Usually the resistance to indentation. (2) Stiffness or temper of wrought products. (3) Machinability characteristics.

Hazelett process. A method for casting liquid metal continuously into rolls for sheet or plate.

heading. An upsetting process used to form rivet, screw and bolt heads in making these products from wire or rod.

hearth. In a reverberatory furnace, the portion that holds the molten metal or bath.

heat tinting. Heating in air a specimen with a suitable surface, in order to develop the structure by oxidizing or otherwise affecting the different constituents.

heat treatable alloy. An alloy hardenable by heat treatment.

heat treating film. A thin oxide coating or film formed on the surface of metals during thermal treatments.

*** heat treatment.** A combination of heating and cooling operations, timed and applied to a metal or alloy in the solid state in a way that will produce desired properties. Heating for the sole purpose of hot working is excluded from the meaning of this definition.

heterogeneous structure. A metallic structure with more than one phase.

Heyn stresses. See *microscopic stresses.*

high-temperature oxidation. Preferential attack on certain alloy constituents in light metal alloys during solution heat treatment. See *internal oxidation.*

hold down. The tool that exerts pressure normal to a sheet blank during deep drawing, in order to prevent wrinkling and to cause uniform circumferential compression while the large circumference of the blank is reduced to that of the shell.

holding furnace. A small furnace for maintaining molten metal, from a larger melting furnace, at the right casting temperature.

homogeneous. Usually defined as having identical characteristics throughout. However, *physical* homogeneity may require only an identity of lattice type throughout, while *chemical* homogeneity requires uniform distribution of alloying elements.

*** homogenizing.** A process of heat treatment at high temperature intended to eliminate or decrease chemical segregation by diffusion.

homogenizing treatment. A heat treatment, usually for a long time at a high temperature, designed to make metal chemically homogeneous.

homopolar crystals. Crystals where neighboring atoms share electrons; for instance, diamond, where the four outer (valence) electrons of each carbon atom are shared with its four nearest neighbors, thus completing an outer shell of eight electrons per atom.

Hooker process. A process of cold extrusion in a crank press, employed in making small arms cartridge cases and small thin-walled seamless tubes.

Hooke's law. Stress is proportional to strain in the elastic range.

Hoopes process. An electrolytic refining process for aluminum, in which three liquid layers are used in the reduction cell.

hot bed. A large enclosed area containing closely spaced rolls or rails for holding hot, partially rolled metal.

hot forming. Working operations, such as bending and drawing sheet and plate, forging, pressing, and heading, performed on metal heated to temperatures above room temperature.

hot pressing. *Powd met.* The simultaneous forming and heating of a compact.

hot shortness. Brittleness in hot metal.

hot top. See *sinkhead.*

*** hot quenching.** A process of quenching in a medium at a temperature substantially higher than atmospheric temperature.

hot working. Plastic deformation of metal at such a temperature and rate that strain hardening does not occur. The lower limit of temperature for this process is the recrystallization temperature.

humectant. Any material added to foundry sand to retain moisture.

hydrogen embrittlement. (1) In oxygen-bearing copper, silver, and similar metals, a condition of low ductility resulting from absorption of hydrogen at high temperature, internal reduction of cuprous or corresponding metallous oxide, and creation of intergranular holes or cracks by the accompanying generation of steam. (2) A condition of low ductility resulting from hydrogen absorption and internal pressure developed subsequently.

hydrogen loss. *Powd met.* The loss caused in the weight of metal powder or of a compact when a representative sample is heated for a specified time and temperature in an atmosphere of purified hydrogen; broadly, a measure of the oxygen content of the sample when the test is applied to materials that contain only such oxides as are reducible with hydrogen, and no other hydride-forming element.

hypereutectoid steel. A steel containing more than the eutectoid percentage of carbon. See *eutectoid steel.*

hypoeutectoid steel. A steel containing less than the eutectoid percentage of carbon. See *eutectoid steel.*

I

idiomorphic crystal. A perfect crystal exhibiting geometric arrangement of plane faces, observed occasionally with certain constituents or intermetallic compounds in the microstructure of cast alloys. The normal crystals, generally called "grains" in metallography, are of the imperfect or *allotriomorphic* type, since the outward form is determined more or less by the surroundings.

immersion coating. Coating a metal with a second metal by immersing the first in a solution containing ions of the second.

impact extrusion. A cold forming process in which the metal is forced by impact to flow around the punch, forming a tube with a solid bottom.

impact test. A test to determine the energy absorbed in fracturing a test bar at high velocity. The test may be in tension or in bending, or it may properly be a *notch* test if a notch is present, creating multiaxial stresses.

impoverishment. Loss of any constituent from an alloy or from localized areas of an alloy by oxidation, liquation, volatilization or changes in the solid state. The term "depletion" is also used, particularly in referring to the lowering of the concentration of solute in a solid solution, around particles precipitated from solid solution.

impregnation. *Powd met.* (1) The process of filling the pores of a sintered compact, usually with a liquid such as a lubricant. (2) The process of mixing particles of a nonmetallic substance in a matrix of metal powder, as in diamond-impregnated tools. (3) The process of filling the pores of a sintered or unsintered compact with a metal or alloy of lower melting point.

inclusions. Particles of impurities (usually oxides, sulfides, silicates and such) that are held mechanically, or are formed during solidification or by subsequent reaction within the solid metal.

indentation hardness. The resistance of a material to indentation. This is the usual type of hardness test, in which a pointed or rounded indenter is pressed into a surface under a substantially static load.

indirect extrusion (inverted). An extrusion process in which the metal is forced back inside a hollow ram that pushes the die.

*** induction hardening.** A process of hardening a ferrous alloy by heating it above the transformation range by means of electrical induction, and then cooling as required.

*** induction heating.** A process of heating by electrical induction.

ingot. A casting intended for subsequent rolling or forging.

ingot iron. An open hearth iron very low in carbon, manganese and most other impurities.

inhibitor. (1) A material such as fluoride, boric acid or sulfur, used to inhibit the burning of molten magnesium alloys. (2) An agent added to pickling or other solutions to minimize corrosion.

initial creep. The early part of the time-elongation curve for creep, in which extension increases at a rapid rate.

inoculation. The addition to molten metal of substances designed to form nuclei for crystallization.

inserts. Parts formed from a second material, usually a metal, which are placed in the mold and appear as integral structural parts of the final casting.
insoluble anode. In electrodeposition, an anode that does not go into solution during the electrolytic process.
intercept method. A method of determining surface or volume grain size by counting the number of grains per unit length, intersected by lines parallel to and at right angles to the direction of working. Multiplication of counts along two perpendicular lines gives the surface grain size for the plane defined by the lines, while multiplication of counts along three mutually perpendicular lines gives the volume grain size.
intercommunicating porosity. *Powd met.* In a sintered compact, the type of porosity that connects the pores in such a way that a fluid may pass from one to another through the entire compact.
intercrystalline cracking. Cracks or fractures that follow along grain boundaries in the microstructure of metals and alloys.
interdendritic attack. A type of electrochemical corrosion that sometimes occurs in as-cast alloys or alloys that have had very little working. The attack progresses preferentially through areas around the dendrites and dendritic arms, as a result of composition (coring) gradients.
intergranular corrosion. A type of electrochemical corrosion that progresses preferentially along the grain boundaries of an alloy, usually because the grain boundary regions contain material anodic to the central regions of the grains.
intermediate annealing. An annealing treatment given to wrought materials before fabrication to final gage and final thermal treatment.
intermetallic compound. A compound of two or more metals that has a characteristic crystal structure and may have a definite composition or a range of compositions corresponding to a solid solution.
internal friction. Ability of a metal to transform vibratory energy into heat. Internal friction generally refers to low stress levels of vibration; *damping* has a broader connotation since it may refer to stresses approaching or exceeding the yield strength.
internal oxidation. Preferential oxidation of certain phases or components of alloys before the oxidation of the matrix; a condition encountered when some alloys are heated to high temperatures in certain types of oxygen-containing atmospheres.
internal stress. A misnomer for *residual stress.*
interrupted aging. The aging of an alloy at two or more temperatures by steps, and cooling to room temperature after each step. Compare with *progressive aging.*
* **interrupted quenching.** A process of quenching in which the metal object being quenched is removed from the quenching medium while the object is at a temperature substantially higher than that of the quenching medium.
intracrystalline failures. Fractures across the grains in metal.
inverse segregation. A concentration of certain alloy constituents that have lower melting points, in the region corresponding to that first solidifying; caused by interdendritic flow of enriched liquid through channels where the pressure drops with contraction of dendrites. The internal evolution of hydrogen may also give a positive pressure, aiding this flow and causing a *liquated surface* or *tin sweat.*
investment compound. A refractory used for molds formed around wax patterns.
ion. An atom that is charged electrostatically as a result of losing or gaining an outer electron.
ionic crystal. A crystal where electron transfer results in some atoms having residual positive charges while others have residual negative electrical charges. Found in compounds of strongly electronegative and electropositive elements, for example, sodium chloride.
ironing. Thinning the walls of deep drawn articles by reducing the clearance between punch and die.
irregular powder. *Powd met.* Particles lacking symmetry.
isomorphous. Literally, "of like form"; phases with crystal structures of the same type.
* **isothermal annealing.** A process in which a ferrous alloy is heated to produce a structure partly or wholly austenitic, and is then cooled to and held at a temperature that causes transformation of the austenite to a relatively soft ferrite-carbide aggregate.
* **isothermal transformation.** The process of transforming austenite in a ferrous alloy to ferrite or a ferrite-carbide aggregate at any constant temperature within the *transformation range.*
Izod test. A pendulum type of impact test, in which the specimen is supported at one end as a cantilever beam and the energy required to break off the free end is used as a measure of impact strength. See *Charpy test.*

K

keyhole specimen. A type of notched impact test specimen in which a hole-and-slot notch, shaped like a keyhole, gives multiaxial stresses.
killed steel. Steel deoxidized with a strong deoxidizing agent such as silicon or aluminum in order to reduce the oxygen content to a minimum so that no reaction occurs between carbon and oxygen during solidification.
kiln. A furnace for calcining ores or concentrates.
kip. A load of 1000 lb or 453.59 kg.
knockout. (1) A mechanism for removing work from the die after completion of forming operations, such as deep drawing, forging or stamping. (2) The operation of removing sand cores from castings.
Knoop hardness. Microhardness determined from the resistance of the metal or of individual microconstituents to indentation by a diamond indenter making a rhombohedral impression with one long and one short diagonal.
knurling. Impressing a design into a metallic surface, usually by means of small, hard rollers that carry the design on their surfaces.
Krause rolling mill. A sheet rolling mill using a reciprocating action that accomplishes a high reduction in metal sheet during a single passage through the mill.

L

laminations. Defects resulting from the presence of blisters, seams or foreign inclusions aligned parallel to the worked surface of a metal.
lap. A surface defect appearing as a seam, caused by folding over hot metal, fins or sharp corners and then rolling or forging them into the surface, but not welding them.
lap weld. A term applied to a weld formed by lapping two pieces of metal and then pressing or hammering, and applied particularly to the longitudinal joint produced by a welding process for tubes or pipe, in which the edges of the skelp are beveled or scarfed so that when they are overlapped they can be welded together.
latent heat. Thermal energy absorbed or released when a substance changes state; that is, from one solid phase to another, or from solid to liquid, or the like.
launder. A channel for conducting molten metal.
leaching. Extracting a soluble material from a heterogeneous solid by dissolving out the soluble material in water or in a chemical solution, such as a dilute acid. The solution may be treated later to recover a metal or to analyze for a substance.
lead. Antimonial or hard. Lead containing antimony.
Soft. Lead made from relatively pure ores and containing very small amounts of impurities.
Desilverized. Lead made from argentiferous ores, often of low purity, and purified by the Parkes or Betts electrolytic processes.
ledeburite. The cementite-austenite eutectic structure that forms at point *C* on the iron-carbon diagram.
leveling. Flattening rolled metal sheet. See *roller flattening.*
levigation. Separation of fine powder from coarser material by suspension in liquid.
light metals. Metals and alloys that have a low specific gravity, such as beryllium, magnesium and aluminum.
lineage structure. Deviations from perfect alignment of parallel arms of columnar dendrites growing from a liquid. This type of imperfection may vary from a few minutes to as much as two degrees of arc difference in orientation from one part of the cast crystal to another.
liner. The slab of coating metal that is placed on the core alloy and is subsequently rolled down to clad sheet as a composite.
liquated surface. A surface of an ingot that exhibits exudations or protuberances as a result of inverse segregation. See *tin sweat.*
liquation. The partial melting of an alloy, which can be used to effect a separation of two or more constituents.
liquid gold, silver or platinum. Liquid preparations used for decorating pottery and porcelain. Firing produces bright metallic deposits.
liquidus. A line on a binary phase diagram or a surface on a ternary phase diagram, representing the temperatures at which freezing begins during cooling or melting ends during heating under equilibrium conditions.
loading. *Powd met.* The filling of the die cavity with powder.
loam. A coarse, strongly bonded molding sand used for making loam and dry sand casting molds.
local action. Electrochemical corrosion resulting from chemical or physical differences within the same alloy. Certain microscopic and macroscopic areas may be anodic to other areas and consequently may dissolve.
longitudinal direction. The direction in a wrought metal product parallel to the direction of working (drawing, extruding, rolling).
lost wax process. A precision casting process in which a wax pattern is used. The wax pattern is invested in a plaster slurry; then after the mold is dry, the wax is melted and poured out of the mold cavity.
lower punch. *Powd met.* The lower part of a die, which forms the bottom of the die cavity, and which may or may not move in relation to the die body.
lubricating. *Powd met.* Mixing some agent with a powder or incorporating an agent into a powder to facilitate the pressing and ejecting of the compact from the die body; applying a lubricant to the die walls or punch surface, or both.
Lüder's lines (stretcher strains, flow figures). Elongated markings that appear on the surface of some materials, particularly iron and low-carbon steel, when deformed just past the yield point. These markings lie approximately parallel to the direction of maximum shear stress and are the result of localized yielding. They consist of depressions when produced in tension and of elevations when produced in compression. They may be made evident by localized roughening of a polished surface or by localized flaking from an oxidized surface.
lute. (1) A mixture of fire clay used to seal cracks between crucible and cover or between container and cover when heat is to be applied. (2) To seal with clay or other plastic material.

M

machine-cast pig. See *chill-cast pig.*
macrograph. A photographic reproduction of any object that has not been magnified more than ten times.
macroscopic. Visible either with the naked eye or under low magnification (as great as about 10 diameters).
macroscopic stresses. Residual stresses of such scope that relatively large areas of the material or the whole specimen are involved. These stresses are accompanied by strain measurable with ordinary extensometers under appropriate test conditions.
macrostructure. The structure of metals as revealed by macroscopic examination.
magclad. A name that has been applied to magnesium alloy sheet clad with layers of a more anodic magnesium alloy.
magnetic separator. A device used to separate magnetic materials from less magnetic or nonmagnetic materials. The crushed material is separated while traveling on a conveyer belt past a magnet.
malleability. The property that determines the ease of deforming a metal when the metal is subjected to rolling or hammering. The more malleable metals can be hammered or rolled into thin sheet more easily than others.
* **malleablizing.** A process of annealing white cast iron in such a way that the combined carbon is wholly or partly transformed to graphitic or free carbon or, in some instances, part of the carbon is removed completely. See *temper carbon.*
mandrel. (1) A rod used to retain the cavity in hollow metal products during working. (2) A metal bar around which other metal may be cast, bent, formed or shaped.
Mannesmann process. A process used for piercing tube billets in making seamless tubing. The billet is rotated between two heavy rolls mounted at an angle, and is forced over a fixed mandrel.
* **martempering.** The process of quenching an austenitized ferrous alloy in a medium at a temperature in the upper portion of the temperature range of martensite formation, or slightly above that range,

and holding in the medium until the temperature throughout the alloy is substantially uniform. The alloy is then allowed to cool in air through the temperature range of martensite formation.

martensite. An unstable constituent in quenched steel, formed without diffusion and only during cooling below a certain temperature known as the M_s (or Ar'') temperature. The structure is characterized by its acicular appearance on the surface of a polished and etched specimen. Martensite is the hardest of the transformation products of austenite. Tetragonality of the crystal structure is observed when the carbon content is greater than about 0.5%.

master alloy. See *hardener*.

match plate. A plate of metal or other material, on which patterns, split along the parting line, are mounted back to back with the gating system to form an integral piece.

matrix. The principal phase in which another constituent is embedded.

matrix metal. *Powd met.* The continuous phase of a polyphase alloy or mechanical mixture; the physically continuous metallic constituent in which separate particles of another constituent are embedded.

matte. An impure metallic sulfide product obtained from the smelting of sulfide ores of metals such as copper, lead and nickel.

mechanical metallurgy. The science concerned with the relationships among the measured mechanical properties of metals and their mechanical behavior in service, and with the way these properties and service characteristics vary with chemical composition, structure and temperature. The field also includes mechanical processing such as rolling, drawing and the like.

mechanical properties. Those properties of a material that reveal the elastic and inelastic reaction when force is applied, or that involve the relationship between stress and strain; for example, the modulus of elasticity, tensile strength and fatigue limit. These properties have often been designated as "physical properties", but the term "mechanical properties" is much to be preferred.

mechanical testing. Methods of determining *mechanical properties*.

mechanical twins. Lens-shaped or narrow band markings found in body-centered cubic, close-packed hexagonal and other crystal types (excepting the face-centered cubic). These may be formed during plastic deformation by shearing movements of successive planes of atoms, resulting in a fixed and sudden change in orientation at the interface or *twinning plane*. Compare with *annealing twin bands*.

mechanical working. Subjecting metal to pressure exerted by rolls, dies, presses, or hammers, to change its form or to affect the structure and consequently the mechanical and physical properties.

Medart straightener. A roller straightener that bends and straightens rods and tubes by means of ■ concave roll.

melting range. The range of temperature in which an alloy melts; that is, the range between solidus and liquidus temperatures.

mesh. *Powd met.* The screen number of the finest screen of a specified standard screen scale through which almost all the particles of a powder sample will pass. Frequently, but not necessarily, a part of the sample may pass finer screens. Also called "mesh size".

metal leaf. Extremely thin metal sheet.

metallic binding forces. The attraction of the positive ions constituting metallic crystals for the negative electrons that form a "gas" permeating the structure. This attraction holds the structure together and balances the repulsive forces of the ions for one another and electrons for other electrons. The electrons move freely through the lattice and provide good thermal and electrical conductivity.

metallography. The science concerning the constitution and structure of metals and alloys as revealed by the microscope.

metal spraying. A process for applying a coating of metal to an object. The metal, usually in the form of wire, is melted by an oxy-hydrogen or oxyacetylene blast or by an electric arc and is projected at high speed by gas pressure against the object being coated.

metastable. A state of pseudoequilibrium.

metatectic. See *peritectoid*.

microhardness. The hardness of microscopic points within an alloy. The hardness of individual constituent particles and of localized areas of the solid solution matrix can be determined. See *Knoop* or *Tukon hardness*.

micron. A linear distance of 0.001 mm.

microporosity. Extremely fine porosity caused in castings by shrinkage or gas evolution and apparent on radiographic films as mottling.

microradiography. The process of passing X-rays through a thin section of an alloy in contact with a photographic emulsion, and then magnifying the radiograph 50 to 100 times to observe the distribution of alloying constituents and voids.

microscopic stresses. Stresses that are balanced over distances of the order of magnitude of grain diameters; also known as Heyn stresses.

microsegregation. See *coring*.

microstructure. The structure of polished and etched metal and alloy specimens as revealed by the microscope.

microtome. A piece of equipment ordinarily used to prepare thin sections of biological substances for microscopic examination by transmission. In metallurgy, the microtome is sometimes used as a hand-driven shaper to produce a flat surface on relatively soft specimens before metallographic polishing and etching.

middlings. A product of specific gravity intermediate between that of the concentrate and the tailings, which is obtained in the jigging of crushed ores and which, recrushed to a finer size, is then re-treated to obtain a concentrate.

mill finish. A surface finish produced on sheet and plate, characteristic of the ground finish on the rolls used in fabrication.

milling. *Powd met.* The mechanical treatment of material, as in a ball mill, to produce particles or alter their size or shape, or to coat one component of a powder mixture with another.

minus mesh. *Powd met.* The portion of a powder sample that passes through a screen of stated size.

mischmetal. An alloy of rare earth metals containing about 50% cerium with 50% lanthanum, neodymium and similar elements.

misruns. Cast metal that was poured too cold so that it solidified before filling the mold completely.

mixing. *Powd met.* The thorough intermingling of powders of two or more substances.

modification. A process in which the eutectic temperature, structure and composition of aluminum-silicon alloys are apparently altered by the addition of small amounts of a third element, such as sodium. A similar phenomenon can be effected by chill casting.

modulus of elasticity. The slope of the elastic portion of the stress-strain curve in mechanical testing. The stress is divided by the unit elongation. The tensile or compressive elastic modulus is called "Young's modulus"; the torsional elastic modulus is known as the "shear modulus" or "modulus of rigidity".

modulus of rigidity. In a torsion test, the ratio of the unit shear stress to the displacement caused by it per unit length in the elastic range. This modulus corresponds to the modulus of elasticity in the tension test.

modulus of rupture. The ultimate strength or the breaking load per unit area of a specimen tested in torsion or in bending (flexure). In tension, it is the tensile strength.

modulus of strain hardening. When the true stress (σ) is plotted against true strain (δ) in tensile testing, the slope of the tangent to the curve in the plastic range is sometimes called the "strain hardening modulus". A better expression would be "rate of strain hardening", defined as $d\sigma/d\delta$.

mold. A form or cavity into which molten metal is poured to produce a desired shape.

mold. *Powd met.* See *die*.

molder's rule. A ruler used in making patterns for castings, on which the graduations are expanded to account for thermal and solidification contraction of the metal being cast.

mold wash. Usually an aqueous emulsion containing various compounds, such as graphite, silica flour and the like, used to coat the face of the cavity in the casting mold.

Mond process. A process for extracting and purifying nickel. The main features consist of forming nickel carbonyl by reaction of the finely divided reduced metal with carbon monoxide, and decomposing the nickel carbonyl, with deposition of nickel on small nickel pellets.

monotectic. An isothermal reversible reaction in a binary system where a liquid, during cooling, forms a solid and a second liquid of different composition.

monotron hardness test. An indentation type of hardness test for measuring the load required to indent a standard spherical penetrator to a standard depth.

mosaic structure. A structure of units, intermediate between unit cell size and grain size, which is presumed to exist in metals and alloys. Unit blocks are believed to be about 10^{-4} to 10^{-5} cm along an edge.

mossy zinc. Particles of zinc obtained by pouring molten zinc into water. See *granulated metal*.

muffle furnace. A furnace in which the heating is indirect and the charge is contained in a refractory container or crucible heated from the outside. The products of combustion are not in direct contact with the charge, as in the *open hearth* or reverberatory furnace.

N

natural aging. Spontaneous aging of a supersaturated solid solution at room temperature.

necking down. Reduction in area concentrated at the subsequent fracture when a ductile metal is tested in tension.

needles. *Powd met.* Elongated rodlike particles.

network structure. A structure in which the grains or crystals of one constituent are partly or entirely enveloped in another constituent. An etched section through the crystals resembles a network.

Neumann bands. Narrow bands differently oriented within a grain of ferrite. Ordinarily these bands are formed only on deformation by impact, but in some alloys (silicon ferrite, for example) and particularly at low temperatures the bands are formed more readily, as in ordinary cold working processes.

ni-carbing. Synonymous with *carbonitriding*.

nickel silver. A copper-base alloy that contains 17 to 32% Zn and 10 to 30% Ni.

***nitriding.** A process of case hardening in which a ferrous alloy, usually of special composition, is heated in an atmosphere of ammonia or in contact with nitrogenous material to produce surface hardening by the absorption of nitrogen, without quenching.

noble metals. Elements with metallic surfaces that are permanent in air, as gold, silver, platinum and palladium.

nodular powder. *Powd met.* Irregular particles that have knotted, rounded or other similar shapes.

***normalizing.** A process in which a ferrous alloy is heated to a suitable temperature above the transformation range and is subsequently cooled in still air at room temperature.

normal segregation. Concentration of alloying constituents that have low melting points, in those portions of a casting that solidify last. Compare with *inverse segregation*.

notch brittleness. Susceptibility of a material to brittleness in areas containing a groove, scratch, sharp fillet or notch.

notched ingots. Castings with deep grooves designed to facilitate breaking for remelting.

notch fatigue factor. The reduction caused in fatigue strength by the presence of ■ sharp notch in the stressed test section.

notch sensitivity. The reduction caused in nominal strength, impact or static, by the presence of a stress concentration, usually expressed as the ratio of the notched to the unnotched strength.

nowel. A colloquial term for drag mold (castings).

nucleus. The first structurally determinate particle of a new phase or structure that may be about to form. Applicable in particular to solidification, recrystallization and transformations in the solid state.

nugget. A small mass of a metal such as gold or silver, as found in nature. See *weld nugget*.

O

Olsen ductility test. A cupping test in which a piece of sheet, restrained except at the center, is deformed by a standard steel punch with a hemispherical end. This test measures the depth of the impression required to fracture the metal.

open hearth furnace. A furnace for melting metal, in which the bath is heated by the convection of hot gases over the surface of the metal and by radiation from the roof.

operating stress. The stress to which a structural unit is subjected during service.

orange peel effect. A surface roughening encountered in forming products from metal stock that has a coarse grain size, also referred to as "*pebbles*" and "alligator skin".

ordering. A reaction or transformation in certain solid solutions in which a random arrangement of solvent and solute atoms in the crystal is replaced by a regular or ordered arrangement of the different atoms on preferred lattice sites. See *superlattice.*

ore. A mineral from which the metal can be extracted profitably.

ore dressing. The concentration of raw ore and its conversion into a product from which the metal or metals can be recovered at a profit.

orientation. The angular relationship between the axes of a crystal and an external reference system. The orientation of individual crystals is most conveniently represented by poles of simple planes plotted stereographically. Compare *pole figure.*

osmiridium. A natural osmium-rich alloy of osmium and iridium.

overaging. Aging under conditions of time and temperature greater than those required to obtain maximum strength.

overbending. Allowance for spring-back when bending metal to a desired angle.

overdraft. A tendency of metal to curve upwards when leaving rolls, because of lower surface speed of the upper roll.

* **overheated.** A term applied when, after exposure to an excessively high temperature, a metal develops an undesirably coarse grain structure but is not permanently damaged. Unlike a *burnt* structure, the structure produced by overheating can be corrected by suitable heat treatment, by mechanical work, or by a combination of the two.

oversize powder. *Powd met.* Particles coarser than the maximum permitted by a given specification for particle size.

overstressing. Permanently deforming a metal by subjecting it to stresses that exceed the elastic limit.

P

packing material. *Powd met.* Any material in which compacts are embedded during the presintering or sintering operation.

pack rolling. Rolling two or more pieces of thin sheet at the same time, a method usually practiced in rolling sheet into thin foil. This method permits more accurate control of thickness than individual rolling.

paramagnetic. A material that is slightly more permeable than a vacuum and is approximately independent of the magnetizing force.

Parkes process. A process used to recover precious metals from lead, and based on the principle that if 1 to 2% Zn is stirred into the melted lead, a compound of zinc with gold and silver separates out and can be skimmed off.

particle size. *Powd met.* The controlling lineal dimension of an individual particle, as determined by analysis with screens or other suitable instruments.

particle size distribution. *Powd met.* The percentages by weight of the fractions into which a powder sample has been classified according to particle size.

parting. (1) In the recovery of precious metals, the separation of silver from gold. (2) The zone of separation between the cope and drag portions of mold or flask in sand casting.

parting line. A line on a pattern or casting corresponding to the separation between the cope and drag portions of a sand mold.

parting sand. Finely ground sand for dusting on surfaces that are to be separated in making a sand mold.

pass. The opening between rolls. This term is also used more generally to indicate the process of putting metal through a rolling mill.

* **patenting.** In wire making, a heat treatment applied to medium-carbon or high-carbon steel before the drawing of wire or between drafts. This process consists in heating to a temperature above the transformation range, and then cooling to a temperature below that range, in air or in a bath of molten lead or salt maintained at a temperature appropriate to the carbon content of the steel and to the properties required of the finished product.

pattern. (1) A form, frequently of wood, around which sand is packed to make ■ mold for casting metals. (2) A full-scale reproduction of a part used as a guide in cutting. (3) A regular array of characters, such as an X-ray diffraction pattern.

Pattinson process. A process for separating silver from lead, in which the melted lead is slowly cooled so that crystals poorer in silver solidify out and are removed, leaving the melt richer in silver.

pearlite. The lamellar aggregate of ferrite and carbide.

NOTE: It is recommended that this word be reserved for the microstructures consisting of thin plates or lamellae—that is, those that may have a pearly luster in white light. The lamellae can be very thin and resolvable only with the best microscopic equipment and technique.

pebbles. The grain pattern visible at an unconstrained surface when metal of appreciable grain size is deformed. See *orange peel.*

percussion welding. An electric-resistance butt-welding process in which the weld area is upset or forged at the moment of welding.

peritectic reaction. An isothermal reversible reaction in binary alloy systems, in which a solid and a liquid phase react during cooling to form a second solid phase.

peritectoid reaction. An isothermal reversible reaction in binary alloy systems, in which two solid phases react during cooling to form a new solid phase. (The inverse of ■ *eutectoid,* a peritectoid is sometimes called a metatectic.)

permalloy. Nickel alloys containing about 20 to 60% Fe, used for their high magnetic permeability and electrical resistivity.

permanent mold. A mold, ordinarily of metal, that is used repeatedly for the production of many castings of the same form. Liquid metal is poured in by gravity. Not an ingot mold.

permanent set. Inelastic deformation.

permeability. (1) Magnetic permeability, the ratio of the magnetic induction to the intensity of the magnetizing field. (2) In a mold, the porosity of foundry sands and the ability of trapped gases to escape through the sand.

perminvar. A nickel-base alloy with about 22.5% Fe and 7.5% Co, of high magnetic permeability.

pewter. A series of alloys of tin with 5 to 15% Sb, 0 to 3% Cu and 0 to 15% Pb. Also called *britannia metal* or *white metal.*

phase. A physically homogeneous portion of a material system.

phase diagram. A graphical representation of the equilibrium temperature and composition limits of phase fields and phase reactions in an alloy system. In a binary system, temperature is usually the ordinate and composition the abscissa. Ternary and more complex systems require several two-dimensional diagrams to show the temperature-composition variables completely. In metal systems, pressure is usually considered constant, although it may be treated as an additional variable.

photomicrograph. A photographic reproduction of any object magnified more than 10 diameters. The term *micrograph* may be used.

physical metallurgy. The science concerned with the physical and mechanical characteristics of metals and alloys.

physical properties. Those properties familiarly discussed in physics, exclusive of those described under *mechanical properties;* for example, density, electrical conductivity, coefficient of thermal expansion. This term has often been used to describe mechanical properties, but this usage is not recommended. See *mechanical properties.*

physical testing. Testing methods by which physical properties are determined. This term is also used inadvisedly to mean the determination of the mechanical properties.

pickle. Chemical or electrochemical removal of surface oxides.

Pidgeon process. A method for the production of magnesium by the use of ferrosilicon to reduce magnesium oxide.

piercing. The process of spinning and rolling a billet over ■ mandrel in such a way that a hole is opened in the center. Also, opening a hole through a billet by hot punching.

piezoelectricity. Electric charges of opposite signs developed during mechanical stressing of certain hemimorphic crystals; that is, crystals having axes of symmetry that differ at their two ends.

pig. An ingot of virgin or secondary metal to be remelted for use.

pig iron. Iron produced by reduction of iron ore in the blast furnace.

Pilger tube-reducing process. A process of rolling for decreasing the diameter of a pierced tube bloom in making tubing. The rolls have a groove tapered to a decreased diameter over part of their surface while the remainder will permit free passage of the bloom. The bloom, with an inserted mandrel or broach, is forced into the rotating rolls and is advanced and rotated specific amounts at intervals corresponding to passage of the decreased-diameter part of the rolls. A short section of the bloom is reduced during each revolution.

pinch pass. A pass of sheet through rolls that are set to give a very light reduction.

pine tree crystals. See *dendrite.*

pin expansion test. A test to determine the capacity of tubes for expansion by forcing a tapered pin into the open end of a sample.

pinhead blister. See *blister.*

pinhole porosity. Very small holes scattered through a casting, possibly by microshrinkage or gas evolution during solidification.

pipe. A cavity formed by contraction in metal (especially ingots) during solidification of the last portion of liquid metal.

pit. A sharp depression in the surface of metal.

planimetric method. A method of measuring grain size, in which the grains within a definite area are counted.

plastic deformation. Permanent distortion of a material under the action of applied stresses.

plasticity. The ability of a metal to be deformed extensively without rupture.

plate. A flat rolled steel product. See *sheet* for size limitation.

plates. *Powd met.* Flat powder particles that have considerable thickness. See *flake powder.*

plating. Deposition of a thin film of a second metal or alloy on a base object, from a solution containing ions of the plating metal.

platinum black. Finely divided platinum metal obtained by cementation.

platinum solders. White alloys of high melting point, containing palladium and gold, used for soldering platinum-base alloys.

plug. (1) A rod or mandrel over which a pierced tube is forced. (2) A rod or mandrel that fills a tube as it is drawn through a die.

plumbago. Graphite in powdered form. Plumbago crucibles are made from this graphite plus clay.

plus mesh. *Powd met.* The portion of a powder sample retained on a screen of stated size.

ply metals. Sheet consisting of bonded layers of dissimilar metals. See *cladding.*

pointing. The process of reducing the diameter of wire, rod or tubing, over a short length at the end, by swaging or hammer forging to facilitate entry into a drawing die and gripping in the drawhead.

Poisson's ratio. The ratio of the transverse contraction of a strained test specimen to its longitudinal elongation; essentially a statement of constancy of volume during deformation.

pole figure. A stereographic projection representing the statistical average distribution of poles of a specific crystalline plane in a polycrystalline metal, with reference to an external system. In an isotropic metal, that is, in one having a completely random distribution of orientations, the pole density is stereographically uniform; preferred orientation is shown by an increased density of poles in certain areas. This representation is more informative than the description of preferment in terms of one or more ideal orientations.

poling. In the fire refining of copper, the molten metal is rabbled or blown with air to obtain "dry" or "set" copper. Then a carbonaceous material, such as coke, is distributed on the surface of the liquid and the metal is stirred with a green wooden pole, thus reducing the oxygen content to produce tough pitch copper. The nature of solidification of sample buttons, taken at logical intervals, indicates the *set* of the surface; the appearance of the fracture, when the buttons are broken, indicates the degree of reduction of oxygen content.

overpoling is indicated by a convex swollen surface caused by the liberation of excessive amounts of gas, probably sulfur dioxide or water vapor.

underpoling is indicated by a concave surface and a fracture more brittle and redder than is desired.

polycrystalline. Consisting of more than one crystal.

polymorphism. The ability of a material to exist in more than one crystallographic structure. Numerous metals change in crystallographic structure at transformation temperatures during heating or cooling. (If the change is reversible, it is allotropy.)

pore. *Powd met.* A minute cavity in a compact. Synonym, *void.*

pore-forming material. *Powd met.* In a powder mixture, an included substance that volatilizes during sintering and thereby produces a desired kind of porosity in the finished compact.

porosity. Unsoundness caused in cast metals by the presence of blowholes and shrinkage cavities.

porosity. *Powd met.* A multiplicity of pores in a compact.

porthole die. A type of extrusion die consisting of two or more sections and used to extrude shapes that have unusual contours. The metal is extruded as several different streams, which are welded, when they leave the die, to form tubing and intricate closed shapes without requiring the use of separate mandrels.

* **postheating.** A process used immediately after welding, whereby heat is applied to the weld zone either for tempering or for providing a controlled rate of cooling, in order to avoid a hard or brittle structure.

pot. A vessel for holding molten metal. Also used to refer to the electrolytic *reduction cell* employed in winning certain metals, such as aluminum, from a fused electrolyte.

pot annealing. See *box annealing*.

pouring. The transfer of molten metal from the ladle into ingot molds or other types of molds; for example, in castings.

pouring basin. Reservoir into which liquid metal is poured, on top of the gate of a casting.

powder. *Powd met.* Particles of matter characterized by small size, usually within the range of 1 to 1000 microns.

powder metallurgy. *Powd met.* The art of producing metal powders and of utilizing metal powders for the production of massive materials and shaped objects.

power reels. Drums that coil strip and pull it through rolls that are not driven. See *Steckel mill*.

precious metals. Scarce and costly metals that do not form stable oxides at atmospheric pressures; specifically, gold, silver, and metals of the platinum group.

* **precipitation hardening.** A process of hardening an alloy in which a constituent precipitates from a supersaturated solid solution. See also *age hardening* and *aging*.

precipitation heat treatment *Nonfer met.* Any of the various aging treatments conducted at elevated temperatures to improve certain of the mechanical properties through precipitation from solid solution. See *artificial aging, interrupted aging,* and *progressive aging*.

preferred orientation. In a polycrystalline structure, a departure from crystallographic randomness.

preforming. *Powd met.* The initial pressing of a metal powder to form a compact that is to be subjected to a subsequent pressing operation other than coining or sizing. Also, the preliminary shaping of a refractory metal compact after presintering and before the final sintering.

* **preheating.** (1) A general term used to describe heating applied as a preliminary to some further thermal or mechanical treatment. (2) A term applied specifically to tool steel to describe a process in which the steel is heated slowly and uniformly to a temperature below the hardening temperature and is then transferred to a furnace in which the temperature is substantially above the preheating temperature.

preheating. *Nonfer met.* Heating a metal to a relatively high temperature for a relatively long time in order to change the structure before working. Ingots are homogenized by preheating.

presintering. *Powd met.* The heating of a compact to a temperature lower than the normal temperature for final sintering, usually to increase the ease of handling or forming the compact or to remove a lubricant or binder before sintering.

press. *Powd met.* A machine used to form or size a compact by pressure.

pressed density. *Powd met.* The weight per unit volume of an unsintered compact. Sometimes called "green density".

press forging. The forging process in which metal stock is formed between dies, usually by hydraulic pressure. Press forging is an operation that employs a single, slow stroke. Compare with *hammer forging*.

pressing. A term that ordinarily refers to forming sheet or plate by a shallow drawing process. The term is used also to indicate the press forging of thin sections in closed dies.

pressing. *Powd met.* Applying pressure to a powder or compact.

pressing crack. *Powd met.* See *slip crack*.

pressure die casting. The usual die-casting process in which the liquid metal is forced into the mold under pressure.

pressure-tight. A term that describes a casting free from porosity of the type that would permit leaking.

primary crystals. The first dendritic crystals that form in an alloy during cooling below the liquidus temperature.

primes. Metal products, such as sheet and plate, of the highest quality and free from visible surface defects.

principal stresses. Normal stresses along rectilinear co-ordinates that are so chosen in direction that shearing stresses are zero.

prismatic plane. In noncubic crystals, any plane that is parallel to the *C* or principal axis.

* **process annealing.** In the sheet and wire industries, a process by which a ferrous alloy is heated to a temperature close to, but below, the lower limit of the transformation range and is subsequently cooled. This process is applied in order to soften the alloy for further cold working.

process metallurgy. The science of obtaining metals from their ores.

progressive aging. An aging process in which the temperature of the alloy is continuously increased during the aging cycle. The temperature may be increased in steps or by any other progressive method. Compare with *interrupted aging*.

proof stress. In a test, stress that will cause a specified permanent deformation in a material, usually 0.01% or less.

proportional limit. The greatest stress that the material is capable of sustaining without a deviation from the law of proportionality of stress to strain (*Hooke's Law*).

pseudobinary (quasi-binary) system. A three-component or ternary alloy system in which an intermediate phase containing two of the metals in fixed proportions (that is, an intermetallic compound) acts as a single element. A certain vertical section through the ternary diagram is similar to a binary diagram.

puffed compact. *Powd met.* A compact expanded by internal gas pressure.

pull cracks. Cracks caused in a casting by thermal contraction when two portions become anchored as a result of an irregular shape.

pulverization. *Powd met.* The reduction of matter to powder by mechanical means; a specific type of disintegration. Synonymous with *comminution*.

punch. The movable part that forces the metal into the die in equipment for sheet drawing, blanking, coining, embossing and the like.

punch. *Powd met.* Part of a die assembly that is used to transmit pressure to the powder in the die cavity.

punching. Shearing holes in sheet metal with punch and die.

punch radius. The radius on the bottom end of the punch, over which the sheet is bent in deep drawing. This radius is independent of the shape of the punch.

push bench. Equipment used for drawing heavy-gage tubes by cupping sheet and forcing it through a die by pressure against the bottom of the cup.

pyramidal plane. Any plane that intersects all three axes in noncubic crystals.

pyrometallurgy. Process metallurgical operations employing heat, such as roasting and smelting.

pyrometer. An instrument of any of various types used for measuring temperatures.

pyrophoric alloys. Alloys that throw off sparks when struck or abraded, usually iron-cerium alloys; used in cigarette lighters and such.

Q

quaternary alloy. An alloy that contains four principal elements.

* **quench hardening.** A process of hardening a ferrous alloy of suitable composition by heating within or above the transformation range and cooling at a rate sufficient to increase the hardness substantially. The process usually involves the formation of martensite.

* **quenching.** A process of rapid cooling from an elevated temperature by contact with liquids, gases or solids.

quenching crack. A fracture resulting from thermal stresses induced during rapid cooling or quenching. Frequently encountered in alloys that have been overheated and liquated and are thus "hot short".

Q-value. *Powd met.* A "figure of merit" commonly used to designate the ratio of the inductive reactance to the effective resistance of electrical cores made from iron and other powders. This value is determined by means of a Q-meter and a specified procedure.

R

rabbling. A raking or stirring operation performed on a charge of ore or semimolten metal either by hand or mechanically.

radioactive metals. A group of metals with high atomic weights and with atomic nuclei that decompose slowly, giving off continual radiations of positively charged alpha particles, which are relatively slow; negatively charged beta particles, which are faster and lighter; and gamma rays. The gamma rays are similar to X-rays but are more penetrating and are used for radiography of very thick sections. Bombardment by neutrons can make any metal radioactive and small concentrations of such metals are used as "tracers" in the study of diffusion and other phenomena.

radiography. A nondestructive method of internal examination in which metal objects are exposed to a beam of X-ray or gamma radiation. Differences in thickness, density or absorption, caused by internal defects or inclusions, are apparent in the shadow image either on a fluorescent screen or on photographic film placed behind the object.

ramming. The process of packing sand in making a sand mold.

rare earth metals. The group of similar, trivalent metals that have atomic numbers 57 to 71.

rate of oil flow. *Powd met.* The rate at which a specified oil will pass through a sintered porous compact under specified test conditions.

recalescence. The increase in temperature caused when the rate of liberation of heat during transformation exceeds the rate of dissipation of heat during the cooling of steel through the transformation range.

recovery. (1) The removal of residual stresses by localized plastic flow as the result of low-temperature annealing operations; performed on cold worked metals without altering the grain structure or strength properties substantially. (2) In process metallurgy, the proportion of the valuable component obtained from an ore in processing.

recrystallization. A process whereby the distorted grain structure of cold worked metals is replaced by a new, strain-free grain structure during annealing above a specific minimum temperature.

recrystallization temperature. The lowest temperature at which the distorted grain structure of a cold worked metal is replaced by a new, strain-free grain structure during prolonged annealing. Time, purity of the metal, and prior deformation are important factors.

recuperator. A piece of equipment for recovering heat from hot, spent gases and using it for the preheating of incoming fuel or air. This is a continuous operation, in which the incoming materials pass through pipes surrounded by a chamber through which the outgoing gases pass.

red mud. A residue high in iron oxide, resulting from the purification of alumina from bauxite by the *Bayer process*.

red shortness. Brittleness in steel when it is red hot.

red stain. Stain formed on brass by volatilization of zinc during annealing or by redeposition of copper during pickling.

reduction cell. A pot or tank in which a water solution of a metallic salt or a fused salt electrolyte is electrolytically reduced to form free metals. See *reduction pot* and *electrolytic bath*.

reduction in area. The difference between the original cross-sectional area and that of the smallest area at the point of rupture; usually stated as a percentage of the original area; also called "contraction of area".

refining. The operation of purifying crude metals. See also *fluxing*.

refining temperature. A temperature, usually just higher than the transformation range, employed in the heat treatment of steel to refine the structure—in particular, the grain size.

reflector sheet. An alclad product containing on one side a surface layer of high-purity aluminum superimposed on a core or base alloy of commercial-purity aluminum or an aluminum-manganese alloy. The high-purity coating imparts good polishing characteristics and the core gives adequate strength and formability.

refractory. A heat-resistant material, usually nonmetallic, which is used for furnace linings and such.

regenerator. Equipment used for recovering heat from hot, spent gases from a furnace. The regenerator differs from the *recuperator* in that the hot spent gases are used to heat a brick checkerwork; then after

the flow of exhaust gases has been turned off, the gases to be preheated are passed through the checkerwork.

regulus. (1) Metal that separates as a large mass from the slag in a furnace or crucible. (2) Refined antimony.

reheating. A thermal operation designed solely to heat the work back to hot forming temperatures. In general, no structural changes are intended.

relaxation. Relief of stress as the result of creep. Some types of tests are designed to provide diminution of stress by relaxation at constant strain, as frequently occurs in service.

re-pressing. *Powd met.* The pressing of a previously pressed and sintered compact, for the purpose of altering physical properties or size.

residual stress. Macroscopic stresses that are set up within a metal as the result of nonuniform plastic deformation. This deformation may be caused by cold working or by drastic gradients of temperature from quenching or welding.

resilience. The tendency of a material to return to its original shape after the removal of a stress that has produced elastic strain.

resistance thermometer. A pyrometer that functions on the principle that the electrical resistance of metal changes with temperature. The change in resistance of a coil of fine wire, usually platinum, is calibrated with temperature.

resistance welding. A type of welding process in which the work pieces are heated by the passage of an electric current through the contact. Such processes include *spot welding, seam* or *line welding* and *percussion welding. Flash* and *butt welding* are sometimes considered as resistance welding processes.

resolved shear stress. The vectorial component of load acting on the shear plane, divided by the shear plane area.

restriking. Cold striking of a finished forging to remove distortions after it has been quenched.

retort. A vessel or crucible used for distilling volatile metals.

reverberatory furnace. See *open hearth furnace.*

rich alloys. See *hardener.*

riddle. A device, operated by hand or power, for removing large particles of sand or foreign material from foundry sand.

riffles. Waviness at the edge of sheet or strip.

rimmed steel. An incompletely deoxidized steel normally containing less than 0.25% C and having the following characteristics: (*a*) During solidification an evolution of gas occurs sufficient to maintain a liquid ingot top ("open" steel) until a side and bottom rim of substantial thickness has formed. If the rimming action is intentionally stopped shortly after the mold is filled, the product is termed *capped steel.* (*b*) After complete solidification, the ingot consists of two distinct zones—a rim somewhat purer than when poured and a core containing scattered blowholes, a minimum amount of pipe and an average percentage of metalloids somewhat higher than when poured and markedly higher in the upper portion of the ingot.

riser. A reservoir of excess molten metal at the top of the heaviest section or sections of a casting, designed to supply metal in compensation for shrinkage that cannot be fed properly from the gate.

roasting. A process used for treating certain ores by heating to produce a chemical change such as oxidation, or to eliminate a volatile component.

rocking shear. An improved type of guillotine shear that uses a curved blade and a rocker movement to cut across metal.

rod mill. (1) A mill for fine grinding, somewhat similar to the *ball mill,* but employing long steel rods instead of balls as the grinding medium. (2) A mill for rolling metal rod.

roll coating. A mixture of finely divided aluminum and aluminum oxide that may form, under certain conditions, on rolls used to make aluminum alloy sheet.

roll compacting. *Powd met.* The progressive compacting of metal powders by the use of a rolling mill.

rolled gold. Similar to filled gold but of a lower quality. Compare *gold filled.*

roller flattening. The process in which a series of staggered rolls of small diameter is used to remove bow and waves from sheet. While passing through the rolls, the sheet is bent back and forth slightly and is delivered approximately flat.

roller stamping die. An engraved roller used for stamping designations and markings on either circular or flat work.

roller straightening. A process involving a series of staggered rolls of small diameter, between which rod, tubing and shapes are passed for the purpose of straightening. The process consists of a series of bending operations.

roll forming. (1) An operation used in forming sheet. Strips of sheet are passed between rolls of definite settings that bend the sheet progressively into structural members of various contours, sometimes called "molded sections". (2) A process of coiling sheet into open cylinders.

roll table. A conveyer-type table surface that contains a series of small rolls over which metal products pass during processing.

roll threading. Applying a thread to a bolt or screw by rolling the piece between two grooved die plates, one of which is in motion, or between rotating grooved circular rolls.

rosette. (1) Rounded configuration of eutectiferous constituents in the microstructure of an alloy, indicative of *eutectic melting* during heat treatment. (2) Strain gages arranged to indicate at a single position strains in three different directions.

rotary press. *Powd met.* A machine fitted with a rotating table that carries multiple dies in which a material is pressed.

rotary shear. A cutting machine with sharpened circular blades or disk-like cutters used for trimming edges and slitting sheet and foil.

rotary swager. A machine used for pointing wire rod and tubing and for initial working of moderately brittle metals and alloys in which a pair of tapered dies is used. The dies are rotated and are pressed intermittently against the work material by an eccentric action.

roughing stand. The rolls used for breaking down the ingot or billet in the preliminary rolling of metal products.

runner. A channel through which molten metal or slag is passed from one receptacle to another; in a casting mold, the portion of the gate assembly that connects the downgate or sprue with the casting.

runner box. Device for distributing molten metal around a mold by dividing it into several streams.

runout. Escape of molten metal from a furnace, mold or melting crucible.

runout table. In a rolling mill, a plane area at the receiving end, for holding rolled metal. See *hot bed.*

rupture stress. The stress given by dividing the load at the moment of incipient fracture, by the area supporting that load.

S

salt spray test. An accelerated corrosion test in which the metal specimens are exposed to a fine mist of salt water solution either continuously or intermittently.

sand burning. The formation of a hard surface on a sand casting by the reaction between the sand of the mold and the hot metal.

sand control. Procedure whereby various properties of foundry sand, such as fineness, permeability, green strength and moisture content, are adjusted to obtain castings free from blows, scabs, veins and similar defects.

sands. In a crushed material, a size of particles that will settle easily in water. The particle size of sands is coarser than that of *slimes.*

sandwich rolling. The rolling of dissimilar metals together to form composite sheet. See *ply metals* and *cladding.*

scab (scabby). A blemish caused on a casting by eruption of gas from the mold face, or by uneven mold surfaces; or occurring where the skin from a blowhole has partly burned away and is not welded.

scaling. Surface oxidation caused on metals by heating in air or in other oxidizing atmospheres.

scalping. Machining the surface layers from ingots, billets and slabs before fabrication.

scarfing. Cutting surface areas of metal objects, ordinarily by using a gas torch. The operation permits surface defects to be cut from ingots, billets, or the edges of plate that is to be beveled for butt welding. See *chipping.*

scleroscope test. A hardness test where the loss in kinetic energy of a falling metal "tup", absorbed by indentation upon impact of the tup on the metal being tested, is indicated by the height of rebound.

scorification. The oxidizing fusion of impure lead containing precious metals, carried out in the presence of fluxes, in order to concentrate the precious metals by partial removal of the base metal impurities before cupellation.

scrap. Material unsuitable for direct use but usable for reprocessing.

screen. A perforated metal screen placed between the gate and the runner of a casting mold for the purpose of separating entrapped oxides or gases during the pouring.

screen analysis. *Powd met.* Distribution of particle size expressed in terms of the percentage of weight retained on each of a series of standard screens decreasing in mesh size, and the percentage passed by the screen of finest mesh.

screen classification. *Powd met.* The separation of powder into ranges of particle size by the use of a series of graded sieves.

screening. *Powd met.* Separating powder according to particle size, by passing it over cloth of the desired mesh size.

screw stock. Metal in the form of wire or rod, ordinarily a free-machining type of alloy, used for making screw-machine products.

scruff. A mechanical mixture of tin oxide and iron-tin alloy formed as dross on a tin coating bath.

sealing. A process used to render anodic coatings on metals nonabsorbent.

seam. On the surface of metal, a crack that has been closed but not welded; usually produced by some defect either in casting or in working, such as blowholes that have become oxidized or folds and laps that have been formed during working. Seam also refers to lap joints, as in *seam welding.*

seaming. Joining sheet metal by multiple bends.

seam welding. An electric-resistance type of welding process, in which the lapped sheet is passed between electrodes of the roller type while a series of overlapping *spot welds* is made by the intermittent application of electric current.

season cracking. A term used in the copper industry for *stress-corrosion cracking* that involves only residual stresses and specific corrosive agents (usually ammonia or compounds of ammonia).

secondary creep. The second portion of the creep curve following the *initial creep* stage and in which the rate of creep has reached a rather constant value.

* **secondary hardening.** Tempering certain alloy steels at certain temperatures so that a hardness is obtained greater than that resulting from the tempering of the same steel at some lower temperature for the same time.

secondary metal. Metal recovered from scrap by remelting.

seed charge. A quantity of a material added to a supersaturated solution for the purpose of nucleating precipitation; for example, aluminum hydrate, which is added to the aluminate solution in the Bayer process, to precipitate aluminum trihydrate.

segment die. *Powd met.* A die made of parts that can be separated for the ready removal of the compact. Synonymous with *split die.*

segregation. In an alloy object, concentration of alloying elements at specific regions, usually as a result of the primary crystallization of one phase with the subsequent concentration of other elements in the remaining liquid. *Microsegregation* refers to *normal segregation* on a microscopic scale whereby material richer in alloying element freezes in successive layers on the dendrites (*coring*) and in the *constituent network. Macrosegregation* refers to gross differences in concentration (for example, from one area of an ingot to another) which may be *normal, inverse* or *gravity segregation.*

seizing. Damaging of a metal surface by rubbing with another metal surface. See *galling.*

* **selective heating.** A process by which only certain portions of an object are heated, in a way that will produce desired properties after cooling.

* **selective quenching.** A process by which only certain portions of an object are quenched.

self-hardening steel. A steel containing sufficient carbon or alloying element, or both, to form martensite either through air hardening or, as in welding and induction hardening, through rapid removal of heat from a locally heated portion by conduction into the surrounding cold metal. See also *air-hardening steel.*

semikilled steel. Steel incompletely deoxidized, to permit evolution of sufficient carbon monoxide to offset solidification shrinkage.

semipermanent mold. A permanent mold in which sand cores are used.

set copper (dry copper). Copper that contains about 6% cuprous oxide at the end of the oxidizing part of the fire-refining cycle. A button sample shows a brick-red brittle fracture and a deep depression with a bulb at its base.

set (pitch). The shape, concavity or convexity, of the solidifying surface of cast copper.

settling. (1) In general, separation of a denser solid from a liquid by gravity. (2) A process for removing iron from liquid magnesium alloys by holding at a low temperature after the addition of manganese.

shake-out. The operation of removing castings from the mold.

shank. The handle attached to a small ladle.

shaving. Trimming heavy-gage blanks to remove uneven sheared edges.

shear. (1) A type of cutting operation in which the metal object (sheet, wire, rod, or such) is cut by means of a moving blade and fixed edge or by a pair of moving blades that may be either flat or curved. (2) A type of deformation in which parallel planes in metal crystals slide so as to retain their parallel relation to one another, resulting in block movement.

shear crack. A diagonal, transgranular crack caused by shear stresses.

shear modulus. See *modulus of rigidity*.

shear stress. The component of stress acting on the plane of shear.

sheet. A flat rolled product. *Sheet, strip, plate* and *bar* are defined in the American Iron and Steel Institute Steel Products Manual, Section 11 (1946), according to size limitations, as follows:

Hot Rolled Carbon Steel

Width, inches	Thickness, inch: 0.2500 and thicker	0.2499 to 0.2031	0.2030 to 0.1875	0.1874 to 0.0568
To 3½ inclusive	Bar	Bar	Strip	Strip
More than 3½, to 6 inclusive	Bar	Bar	Strip	Strip
More than 6, to 12 inclusive	Plate	Strip	Strip	Strip
More than 12, to 32 inclusive	Plate	Sheet	Sheet	Sheet
More than 32, to 48 inclusive	Plate	Sheet	Sheet	Sheet
More than 48	Plate	Plate	Plate	Sheet

Width, inches	Thickness, inch: 0.0567 to 0.0344	0.0343 to 0.0255	0.0254 to 0.0142	0.0141 and thinner
To 3½ inclusive	Strip	Strip	Sheet	Sheet
More than 3½, to 6 inclusive	Strip	Sheet	Sheet	Sheet
More than 6, to 12 inclusive	Sheet	Sheet	Sheet	Sheet
More than 12, to 32 inclusive	Sheet	Sheet	Sheet	Black Plate
More than 32, to 48 inclusive	Sheet	Sheet	Sheet	Sheet
More than 48	Sheet	Sheet	Sheet	.....

Cold Rolled Carbon Steel

Width, inches	Thickness, inch: 0.2500 and thicker	0.2499 to 0.0142	0.0141 and thinner
To 12 inclusive	Bar	Strip[c]	Strip[c]
More than 12, to 24 inclusive	Strip[a]	Strip[a]	Strip[a]
More than 12, to 24 inclusive	Sheet[b]	Sheet[b]	Black Plate[b]
More than 24, to 32 inclusive	Sheet	Sheet	Black Plate
More than 32	Sheet	Sheet	Sheet

(a) When a particular temper, as defined in ASTM Specification A109, or a special edge, or special finish is specified.

(b) When no special temper, edge or finish is specified.

(c) When the width is greater than the thickness but does not exceed ½ in.; when the cross-sectional area does not exceed 0.05 sq. in., and the edges are rolled or prepared, the material is "flat wire".

shell. (1) An article formed by deep drawing. (2) The metal sleeve remaining when a billet is extruded with a dummy block of somewhat smaller diameter.

shielded-arc welding. Electric-arc welding in which the metal is protected from the air atmosphere. An inert gaseous atmosphere may be used or *flux-coated electrodes*.

shift. A casting defect caused by mismatch of *cope* and *drag*.

Shore hardness test. See *scleroscope hardness*.

shortness. Brittleness in metal.

shorts. In the screening of crushed ores, the product remaining on the screen or sieve (as opposed to *fines*, which pass through).

shotting. A process in which molten metal is dropped from a height to form rounded metal pellets or shot. The droplets freeze into spherical particles before reaching the water tank at the bottom of the fall.

shrinkage. *Powd met.* The decrease that may occur in the dimensions of a compact during sintering.

shrinkage cavity. A void left in cast metals as a result of solidification shrinkage and the progressive freezing of metal towards the center.

shrinkage cracks. Cracks that form in metal as a result of the pulling apart of grains by thermal contraction before complete solidification.

shrinkage rule. See *molder's rule*.

silky fracture. A steel fracture that has a very smooth fine grain or silky appearance.

silver solders. Alloys of silver, copper, zinc and other metals, melting between 650 and 875 C, used for making strong joints that resist corrosion.

single-acting hammer. A forging hammer in which the head is raised by a steam cylinder and piston and the blow is delivered by the free fall of the head. (With the double-acting hammer, the blow is delivered by admitting steam above the piston and employing it also on the downward stroke.)

single-action press. A forming press that operates with a single function, such as moving a punch into a die with no simultaneous action for holding down the blank or ejecting the formed work.

single crystal. A piece of metal consisting of a single crystallographic grain instead of the usual *polycrystalline* mass.

sinkhead or hot top. A reservoir insulated to retain heat and to hold excess molten metal on top of an ingot mold, in order to feed the shrinkage of the ingot. Also called "shrink head" or "feeder head".

sinking tubing. Drawing tubing through a die without use of an interior tool.

sintering. *Powd met.* Bonding adjacent surfaces of particles in a mass of powder or a compact by heating.

sizing. *Powd met.* A final pressing of a sintered compact to secure the desired size. Synonymous with *coining*.

skelp. A plate of steel or wrought iron from which pipe or tubing is made by rolling the skelp into shape longitudinally and welding the edges together.

skimgate. See *screen*.

skimmer. A tool for removing scum and dross from molten metal.

skin. A thin surface layer that is different from the main mass of a metal object, in composition, structure or other characteristics.

skull. A film of metal or dross remaining in a pouring vessel after the metal has been poured.

slab. See *bloom*.

slabbing mill. See *blooming mill*.

slag. A product resulting from the action of a flux on the nonmetallic constituents of a processed ore, or on the oxidized metallic constituents that are undesirable. Usually slags consist of combinations of acid oxides with basic oxides, and neutral oxides are added to aid fusibility.

slenderness ratio. Length of a test specimen divided by the square root of the cross-sectional area.

slime. Material of extremely fine or colloidal particle size, encountered in ore treatments and electrolytic refining. See *anode mud*.

slip. A process of plastic deformation by the irreversible shear displacement of one part of a metal crystal relative to another, in a definite crystallographic direction and usually on a specific crystallographic plane. It is sometimes postulated that the slip process involves migration of "dislocations".

slip bands. A series of parallel lines produced across a crystal grain by deforming the body *after* polishing the surface on which these lines appear. They are traces of the slip planes, or planes joining the displaced crystalline blocks or lamellae, and may be distinguished from twin markings by repolishing and etching. Twin markings will reappear, but slip lines will not.

slip crack. *Powd met.* A rupture caused in the pressed compact by mass slippage of a part of the compact. Synonym, *pressing crack*.

slip direction. Direction of slip in an individual crystal.

slip interference. In a ductile metallic structure, resistance to deformation offered by a hard phase dispersed in the matrix. The resistance to deformation has been found to be proportional to the logarithm of the average length of a straight path through the continuous phase.

slip lines. The line markings evident on a polished surface if the metal is deformed after being polished. These surface displacements are frequently called *slip bands*.

slip plane. The crystallographic plane of slip in an individual crystal. See *slip bands*.

slip plane precipitate. A precipitate formed from solid solution preferentially along planes upon which slip has occurred as a result of quenching stresses or cold working after solution heat treatment.

slush casting. A casting made of an alloy that has a low melting point and freezes within a wide range of temperature. The metal is poured into the mold, and brought into contact with all surfaces so as to form an inner shell of frozen metal; then the excess metal is poured out. Castings that consist of completely enclosed shells may be made by using a definite quantity of metal and a closed mold.

smelting. A metallurgical thermal processing operation in which the metal or matte is separated in fused form from nonmetallic materials or other undesired metals with which it is associated.

***soaking.** Prolonged heating of a metal at a selected temperature.

solder embrittlement. Reduction in ductility of a metal or alloy, associated with local penetration by molten solder along grain boundaries.

soldering. Joining metals by fusion of alloys that have relatively low melting points—most commonly, lead-base or tin-base alloys, which are the soft solders. Hard solders are alloys that have silver, copper, or nickel bases and use of these alloys with melting points higher than 800 F is generally termed *brazing*.

solidification shrinkage. The decrease in size accompanying the freezing of a molten metal.

solid solubility limit. The limit for the amount of alloying element that can be present in the solid metal without forming a second phase.

solid solutions.

(a) *Continuous series.* Condition of complete solubility, a single phase for all compositions of two alloying elements at temperatures lower than the "solidus".

(b) *Intermediate.* Alloy phases that are separated, in the phase diagram, from the pure metals or terminal solid solutions by heterogeneous fields.

(c) *Interstitial.* Solid solutions in which atoms of the alloying element (being very small) occupy spaces between atoms of the solvent element, which retain their original lattice positions.

(d) *Substitutional.* Solid solutions in which atoms of the alloying element occupy atom sites previously filled by atoms of the pure metal. The distribution of unlike atoms is usually random but may be ordered. See *superlattice*.

(e) *Terminal.* Solid solutions of which one boundary in the phase diagram is a pure metal.

solidus line. A line on a binary phase diagram, or a surface on a ternary phase diagram, representing the temperatures at which freezing ends during cooling, or melting begins during heating, under equilibrium conditions.

solute. In a solution, a metal or substance present in minor amounts.

***solution heat treatment.** A process in which an alloy is heated to a suitable temperature, is held at this temperature long enough to allow a certain constituent to enter into solid solution and is then cooled rapidly to hold the constituent in solution. The metal is left in a supersaturated, unstable state and may subsequently exhibit *age hardening*.

solution potential. The difference in potential of a material and of a reference electrode in a solution. For purposes of comparison standard electrodes and solutions are ordinarily used.

solvent. The base metal or major constituent in a solution.
solvus. A name that has been applied to solid solubility curves of alloy equilibrium diagrams.
sorbite. Tempered martensite that has a microstructure of distinctly granular appearance. Further tempering causes the appearance of clearly resolvable carbide particles (spheroidite).
spalling. The cracking and flaking of metal particles from a surface.
specific gravity. A numerical value representing the weight of a given substance as compared with the weight of an equal volume of water, for which the specific gravity is taken as 1.0000.
specific heat. Equivalent to thermal capacity, or the quantity of heat required to produce a unit change in the temperature of a unit mass.
specific surface. *Powd met.* The surface area of the particles in one gram of powder, usually expressed in square centimeters.
spectrograph. An optical instrument for determining the presence or concentration of minor metallic constituents in a material by indicating the presence and intensity of specific wave lengths of radiation when the material is thermally or electrically excited.
speculum metal. A copper-base alloy containing tin and zinc, hard and brittle but capable of taking a high polish and therefore satisfactory for reflectors and mirrors.
speiss. Metallic arsenides and antimonides that result from smelting metal ores, such as those of cobalt.
spelter. Crude zinc obtained by smelting.
spelter solders (brazing solders). Copper-zinc alloys that have low melting points and are used for joining.
spheroidite. An aggregate of globular carbide and ferrite. The terms "spheroidized pearlite", "granular pearlite", "globular pearlite" and "divorced pearlite" should be avoided, even when the structure is undoubtedly the result of spheroidizing a pearlitic structure.
***spheroidizing.** Any process of heating and cooling that produces a rounded or globular form of carbide in steel. Spheroidizing methods frequently used are:

1 Prolonged holding at a temperature just below Ae_1.
2 Heating and cooling alternately between temperatures that are just above and just below Ae_1.
3 Heating to a temperature above Ae_1 or Ae_3 and then cooling very slowly in the furnace, or holding at a temperature just below Ae_1.
4 Cooling at a suitable rate from the minimum temperature at which all carbide is dissolved, to prevent the re-formation of a carbide network, and then reheating in accordance with method 1 or 2 above (applicable to hypereutectoid steel containing a carbide network.)

spiegeleisen (also spiegel). A pig iron containing 15 to 30% Mn and 4.5 to 6.5% C.
spinning. The procedure of making sheet metal disks into hollow shapes by pressing a tool against a rotating form (spinning chuck).
split die. See *segment die.*
sponge. A sintered metallic aggregate of platinum or palladium, sponge-like in appearance, resulting from the thermal decomposition of the metal ammonium chloride.
sponge iron. *Powd met.* The material produced by the reduction of iron oxide with carbon, without melting.
spongy. *Powd met.* A term applied to powder particles (usually reduced oxides) in which a porous condition exists.
spot welding. An electric-resistance welding process in which the fusion is limited to a small area. The pieces being welded are pressed together between a pair of water-cooled electrodes through which an electrical current is passed during a very short interval so that fusion occurs over a small area at the interface between the pieces.
spray quenching. After solution heat treating, a mode of quenching in which a spray of water is directed upon material just removed from the furnace. This method is more effective than *fog quenching.* Both methods are designed to reduce distortion that may attend water bath quenching.
spring-back. An indicator of elastic stresses, frequently measured as the increase in diameter of a curved strip after removing it from the mandrel about which it was held. The measurement is employed as an indicator of the extent of recovery or relief of residual stresses that has been achieved by the transformation of elastic strain to plastic strain during heating or *stress relieving.*
springing. Reversed overbending to straighten, or to reduce residual stresses.
spring temper. See *temper.*
sprue. In casting practice, the vertical channel connecting the *pouring basin* with the *skimming gate,* if any, and the *runner* to the mold cavity, all of which together may be called the *"gate".* In top-poured castings the sprue may also act as *riser.*
***stabilizing anneal.** A treatment applied to austenitic stainless steels that contain titanium or columbium. This treatment consists of heating to a temperature below that of a full anneal in order to precipitate the maximum amount of carbon as titanium carbide or columbium carbide. This eliminates precipitation at lower temperatures, which might reduce the resistance of the steel to corrosion.
stabilizing treatment. A thermal treatment designed to precipitate material from solid solution, in order to improve the workability, to decrease the tendency of certain alloys to age harden at room temperature, or to obtain dimensional stability under service at slightly elevated temperatures.
stamping. A process used to cut lines of letters, figures and decorations on smooth metal surfaces. The impact of a punch with comparatively sharp projecting outlines impresses the characters into the surface of the metal. Stamping is also used to refer to various press-forming operations—*coining, embossing, blanking,* and *pressing.*
standard electrode potential. The potential of a metallic element in equilibrium with a solution containing simple ions of that element at a concentration corresponding to unit activity. The standard potential for hydrogen is assigned the value zero. (A negative sign is used before the potentials of elements that show a larger decrease in free energy than hydrogen shows, while forming ions in solution.)
standard gold. A legally adopted alloy for coinage of gold. In the United States the alloy contains 10% copper; in Great Britain it contains 8.33% copper.
starting sheet. A thin sheet of metal used as cathode in electrolytic refining.
Stead's brittleness. A condition of brittleness that yields rectangular transcrystalline fractures in the coarse grain structure produced by prolonged annealing of thin sheets of steel very low in carbon and rolled previously at a relatively low temperature (lower than 1300 F).
Steckel mill. A rolling mill in which the power is applied to a reel that draws strip through undriven rolls.
stepped extrusion. A type of metal extrusion in which the size of the contour changes abruptly in order to decrease the amount of machining necessary to make tapered members.
sterling silver. An alloy of 925 parts silver and 75 parts copper. Accepted standard for silverware in the United States and England.
Stiefel mill. A machine for making tubes by hot piercing billets. The rolls of the machine have cantilever supports.
stopping-off. (1) Protecting desired areas from chemical action, such as carburizing or electroplating, by an appropriate coating of such areas with a material that is unaffected by the chemical action. (2) Filling part of a mold with sand to keep out molten metal.
strain. Deformation expressed as a pure number or ratio. (1) Ordinarily expressed as epsilon (ϵ), equivalent to the change in length divided by original length. (2) *True* strain (δ or ϵ) is the logarithm of the ratio of the length at the moment of observation, to the original length. True strain δ does not differ much from ϵ until above 20%.
***strain aging.** Aging induced by cold working. See *aging.*
strain hardening. An increase in hardness and strength caused by plastic deformation at temperatures lower than the recrystallization range.
strain hardening exponent. The constant "n" in the expression

$$\sigma = \sigma_0 \delta^n$$

σ = true stress
σ_0 = stress at unit strain
δ = true strain.

Straits tin. Tin metal made from Malay district ores.
streamline tubing. Extruded or drawn tubing of which the cross section is shaped like a teardrop.
stress. The load per unit of area. Ordinarily stress-strain curves do not show the true stress (load divided by area at that moment) but a fictitious value obtained by using always the original area.
stress-corrosion cracking. Spontaneous failure of metals by cracking under combined action of corrosion and stress, residual or applied.
stress raisers. Factors such as sharp changes in contour or surface defects, which concentrate stresses locally.
***stress relieving.** A process of reducing residual stresses in a metal object by heating the object to a suitable temperature and holding for a sufficient time. This treatment may be applied to relieve stresses induced by casting, quenching, normalizing, machining, cold working, or welding.
stretcher flattening. A process for removing bow and warpage from sheet by applying a uniform tension at the ends so that the piece is elongated to a definite amount of permanent set.
stretcher straightening. A process for straightening rod, tubing and shapes by the application of tension at the ends of the stock. The products are elongated a definite amount to remove warpage.
stretch forming. A process of forming panels and cowls of large curvature by stretching sheet over a form of the desired shape. This method is more rapid than *hammering* and *beating.*
stringer. A microstructural configuration of alloy constituents or foreign material lined up in the direction of working.
strip. A flat rolled steel product. See *sheet* for size limitation.
stripper punch. *Powd met.* A punch that serves as top or bottom of the die cavity and later moves further into the die to eject the compact.
stripping. Removing coated or electrolytically deposited metal or oxides from the base.
sub-boundary structure. A network of boundaries which, after etching, appears within the main crystals of the metal structure. The granules within the sub-boundaries seem to have a uniform orientation. The structure may be caused by more intense precipitation at preferred places within grains.
subsieve fraction. *Powd met.* Particles all of which will pass through a 325-mesh screen.
sulfur dome. An inverted container holding a high concentration of sulfur dioxide; used over a pot of molten magnesium in connection with the die casting of magnesium.
supercooling. Lowering the temperature of a molten metal below its liquidus during cooling.
superfines. *Powd met.* The portion of a powder that is composed of particles smaller than a specified size, currently less than 10 microns.
superheating. A process of refining the grains in certain magnesium alloy castings by heating the molten metal between 1500 and 1700 F.
superlattice (superstructure). A crystal structure that exists in a solid solution when atoms of the different types fall into an orderly arrangement in relation to one another. See *ordering.*
supersaturated. Metastable solution in which the dissolved material exceeds the amount the solvent can hold in normal equilibrium at the temperature and under the other conditions that prevail.
surface checking. General breaking and cracking of the surface, which may result from a variety of causes, such as over-rolling, overforming, or atmospheric attack at grain boundaries.
swaging. See *rotary swaging.*
sweating. *Powd met.* The appearance, on the surface of a compact, of some or all of the constituents that have low melting points.
sweating out. On the surface of a solid mass of a mixture or alloy, the appearance, usually in small globules, of one constituent that has a relatively low melting point.
sweeps. Floor and table sweepings containing precious metal.
synthetic. In a binary alloy system, an isothermal reversible reaction whereby two liquids form a solid phase during cooling.

T

tailings (tails). The worthless portion of a crushed ore, separated during concentration.
tangent modulus. The slope of the stress-strain curve of a metal at any point along the curve in the plastic region. In the elastic region the tangent modulus is equivalent to *Young's modulus.*
tap density. *Powd met.* The apparent density of a powder, obtained when the volume receptacle is tapped or vibrated during loading under specified conditions.

tapping. Transferring molten metal from melting furnace to ladle.
tarnish. Surface discoloration on a metal, usually from a thin film of oxide or sulfide.
Taylor process. A method for making extremely fine wire by inserting common wire into a glass tube and stretching the two together at a high temperature.
technical cohesive strength. See *cohesive strength*, (2).
teeming. Pouring metal into ingot molds. See *pouring*.
temper. *Nonfer met.* A condition produced in a metal or alloy by mechanical or thermal treatment and having characteristic structure and mechanical properties. A given alloy may be in the fully softened or *annealed temper*, or it may be cold worked to the *hard temper*, or further to *spring temper*. Intermediate tempers produced by cold working (rolling or drawing) are called "quarter-hard", "half-hard" and "three-quarters hard", and are determined by the amount of cold reduction and the resulting tensile properties. In addition to the *annealed temper*, conditions produced by thermal treatment are the *solution heat treated temper* and the *heat treated and artificially aged temper*. Other tempers involve a combination of mechanical and thermal treatments and include that temper produced by cold working after heat treating, and that produced by artificial aging of alloys that are as-cast, as-extruded, as-forged and heat treated, and worked.
* **temper brittleness.** Brittleness that results when certain steels are held within, or are cooled slowly through, a certain range of temperature below the transformation range. The brittleness is revealed by noched-bar impact tests at room temperature or lower temperatures.
* **temper carbon.** The free or graphitic carbon that comes out of solution, usually in the form of rounded or equiaxed nodules in the structure, during the *graphitizing* or *malleablizing* of white cast iron.
* **tempering.** A process of reheating quench-hardened or normalized steel to a temperature below the transformation range, and then cooling at any rate desired.
Templin grip. A spherically seated grip of the wedge type, used in the tension testing of metals.
tensile strength. The value obtained by dividing the maximum load observed during tensile straining by the specimen cross-sectional area before straining. Also called "ultimate strength".
ternary alloy. An alloy that contains three principal elements.
texture. The pattern of preferred orientation occurring in wrought or cast metal.
thermal analysis. The determination of equilibrium conditions and phase relationships in metals by means of thermal arrests shown on heating and cooling curves.
thermal electromotive force. The electromotive force generated when the junction of two dissimilar metals is heated.
thermal stresses. Stresses in metal, resulting from nonuniform distribution of temperature.
thermit reactions. Exothermic, self-propagating processes in which finely divided aluminum powder is used to reduce metal oxides to free metals by direct oxidation of aluminum to aluminum oxide, with accompanying reduction of the less stable metal oxide.
thermocouple. A device for measuring temperatures by the use of two dissimilar metals in contact; the junction of these metals gives rise to a measurable electrical potential with changes in temperature. See *thermal electromotive force*.
throwing power. The ability of an electroplating solution to deposit metal uniformly on a cathode of irregular shape.
tilt-mold ingot. An ingot made by a casting practice employing a book-type mold that has its bottom nearly vertical at the start of the pouring and is gradually tilted back to a normal horizontal position during pouring. The object of such a practice is to reduce the amount of agitation while the metal stream is being poured into the mold and thus to reduce the tendency toward formation of oxide film and entrapment. See *Durville process*.
tin cry. The peculiar crackling sound heard when pure tin is bent. Assumed to be related to mechanical twinning of crystals.
tinning. Coating with tin, most commonly by immersion into molten tin; electrodeposition and metal spraying are also used.
tin pest. The tendency of tin cooled to low temperatures, specifically lower than 56 F, to crumble into a powder known as "gray tin", an allotropic modification.
tin sweat. The beads of tin-rich low-melting phase that are found on the surface of bronze castings when the molten metal contained appreciable amounts of hydrogen.
tolerance limit. (1) The permissible deviation from the desired value. (2) As applied to magnesium alloys, the specific critical amount of an impurity element which, if exceeded, results in a great increase in rate of corrosion in salt solutions.
top-and-bottom process. Separation of copper and nickel, in molten sulfide form, by the addition of sodium sulfide, which causes the separation of two liquid layers. The lower holds most of the nickel.
torsion. Strain created in a material by a twisting action. Correspondingly, the stress within the material resisting the twisting.
tossing (tin). Purifying tin by pouring from a ladle into a kettle, so as to expose thin sheets of the liquid metal to the air, forming oxide dross.
toughness. Property of absorbing considerable energy before fracture; usually represented by the area under a stress-strain curve, and therefore involving both ductility and strength.
tough pitch copper. Refined copper (usually from electrolytic cells) that has been remelted under conditions producing a final oxygen content from 0.02 to 0.05% by weight. It has been found that copper, poled to the point where it solidifies to a flat set surface, exhibits a high degree of toughness.
trace. Extremely small quantity of an element, usually too small to determine quantitatively.
transcrystalline. Literally, across the crystal. See *intracrystalline*.
* **transformation range or transformation temperature range.** The temperature interval within which austenite forms while ferrous alloys are being heated. Also the temperature interval within which austenite disappears while ferrous alloys are being cooled. The two ranges are distinct, sometimes overlapping but never coinciding. The limiting temperatures of the ranges depend on the composition of the alloy and on the rate of change of temperature, particularly during cooling. See *transformation temperature*.
* **transformation temperature.** The temperature at which a change in phase occurs. The term is sometimes used to denote the limiting temperature of a transformation range. The following symbols are used for iron and steel:

Ac_1. The temperature at which austenite begins to form during heating.
Ac_3. The temperature at which transformation of ferrite to austenite is completed during heating.
Ac_{cm}. In hypereutectoid steel, the temperature at which the solution of cementite in austenite is completed during heating.
Ar_1. The temperature at which transformation of austenite to ferrite or to ferrite plus cementite is completed during cooling.
Ar_3. The temperature at which austenite begins to transform to ferrite during cooling.
Ar_{cm}. In hypereutectoid steel, the temperature at which precipitation of cementite starts during cooling.
A_4. The temperature at which austenite transforms to delta ferrite during heating; the reverse process occurs during cooling.
M_s (or Ar''). The temperature at which transformation of austenite to martensite starts during cooling.
M_f. The temperature at which transformation of austenite to martensite is completed during cooling.

NOTE: All these changes (except the formation of martensite) occur at lower temperatures during cooling than during heating, and depend on the rate of change of temperature. The temperatures of phase changes at equilibrium are denoted by the symbols Ae_1, Ae_3, Ae_{cm} and Ae_4.

transition lattice. An intermediate, unstable crystallographic configuration that forms during solid metal reactions, such as precipitation from solid solution and eutectoid decomposition.
transition point. The temperature of transformation from one solid crystalline form of a substance to another. More broadly, the point where different phases can exist in equilibrium.
transverse. Literally "across", signifying a direction or plane perpendicular to the direction of working.
triple point. The temperature and pressure at which three phases of any substance exist in equilibrium.
trommel. A revolving, cylindrical screen used in grading coarsely crushed ore.
troostite. Tempered martensite that etches rapidly, usually appears dark, and is not resolved by the microscope.

NOTE: Two entirely different structures are frequently confused and called troostite: (1) The nodular, quickly etching microconstituent, found in steels that are cooled just too slowly to be fully martensitic, can be resolved into very fine pearlite. (2) "Temper troostite", the first product of the tempering of martensite, consists of submicroscopic particles of carbide in ferrite, and is frequently indistinguishable from a quickly etching fine pearlite in general appearance. The word "troostite" or "quenching" or "nodular troostite" should not be used to denote the first structure. If the word "troostite" is to be retained it should be reserved for temper troostite.

tube reducer. A machine in which a pair of rolls is used for cold rolling tubing and rod. These rolls have a tapered groove around part of their surface, corresponding to the intended change in outside dimension of the tube or rod. The stock is rotated between working strokes. This process is somewhat different from the *Pilger Process* in that the stock moves in the same direction, as rolling proceeds; the axes of the rolls move back and forth parallel to the stock; and the direction of rotation of the rolls changes between the forward working stroke and the backward return stroke. A fixed mandrel is used in rolling tubing.
Tukon hardness test. A method for determining microhardness by using a Knoop diamond indenter or Vickers square-base pyramid indenter.
tumbling. Cleaning articles by rotating them in a cylinder with cleaning materials.
Turk's-head rolls. Four undriven working rolls arranged in a square that serves as a die for drawing strip or wire to a rectangular section.
twin bands. In a polished and etched section, a band across a crystal grain, brought into relation with the main body of the grain by twinning.
twin crystals (twins, twinned crystals). A crystal grain in which the crystal lattices of two parts are related to each other in orientation as mirror images across the interface known as the "twinning plane".
type metal. A series of alloys containing 54 to 95% Pb, 2 to 28% Sb and 2 to 20% Sn, used to make printing type.

U

ultimate strength. See *tensile strength*.
undercooling. See *supercooling*.
underdraft. The tendency of metal to curve downward when leaving rolls, because of lower surface speed of the lower roll.
undermining pitting. A type of corrosion attack in which pitting develops on the exposed surface and spreads out beneath the surface.
underpoling. See *poling*.
upper punch. *Powd met.* The member of a die assembly that moves downward into the die body to transmit pressure to the powder contained in the die cavity.
upsetting. (1) A metal working operation similar to forging. (2) The process of axial flow under axial compression of metal, as in forming heads on rivets by flattening the end of wire.

V

vacuum refining. Melting in a vacuum, usually by electrical induction, to remove gaseous contaminants from the metal.
valve effect. A characteristic of certain materials to pass electric current in one direction only, thus qualifying these materials for applications in electric rectifiers.
Vegard's law. The lattice parameters of substitutional solid solutions vary linearly with composition expressed in atomic percentage.
veining. See *sub-boundary structure*.
vents. Narrow openings in closed molds to provide escape for gases.
Vickers hardness test. An indentation hardness test employing a 136-deg diamond pyramid indenter and variable loads enabling the use of one hardness scale from very soft lead to tungsten carbide.
virgin metal. Metal obtained directly from ore and not used before.

viscosity. The resistance of fluid substance to flowing, quantitatively characteristic for each individual substance at a given temperature and under other definite external conditions.
void. See *pore.*
volatility. The tendency of a substance to vaporize at the temperature under consideration.

W

wedge. A hardwood stick used as a forming tool in spinning.
wedge cake. A cast shape with slightly tapering sides, used principally for copper that is to be hot rolled to sheet.
weld bead. The built-up portion of a fusion weld, formed either from the filler metal or from the melting of the parent metal.
welding. A process used to join metals by the application of heat. *Fusion welding,* which includes *gas, arc,* and *resistance welding,* requires that the parent metals be melted. This distinguishes fusion welding from brazing. In *pressure welding* joining is accomplished by the use of heat and pressure without melting. The parts that are being welded are pressed together and heated simultaneously, so that recrystallization occurs across the interface.
welding stress. The stress resulting from localized heating and cooling of metal during welding.
weld nugget. The ellipsoidal melted area of a *spot weld.*
white gold. Gold alloyed with nickel, palladium or zinc.
white metal. (1) A general term covering alloys that are based on tin, lead or antimony, such as bearing, type and babbitt metals. (2) A copper matte of about 77% Cu obtained from the smelting of sulfide copper ores.
Widmanstätten structure. A structure characterized by a geometrical pattern resulting from the formation of a new phase along certain crystallographic planes of the parent solid solution. The orientation of the lattice in the new phase is related crystallographically to the orientation of the lattice in the parent phase. This type of structure is familiarly seen in cast steel and in overheated wrought steel that has been cooled rather rapidly, but it may occur in any alloy in which a phase change occurs. In steels exhibiting this structure, ferrite delineates the octahedral planes of austenite.
wire bar. A cast shape, particularly of tough pitch copper, which has a cross section approximately square with tapered ends, designed for hot rolling to rod for wire.
wire rod. A semifinished product from which wire is made. It is generally of circular cross section approximately ¼ in. in diameter.
woody fracture. Fractures having a fibrous appearance. See *fiber.*
woody or wood fiber structure. A structure found in extruded rods, particularly of aluminum alloys, which shows elongated surfaces of separation when fractured.
work hardness. Hardness developed in metal as a result of cold working. See *cold working.*
workability. The characteristic or group of characteristics that determines the ease of forming a metal into desired shapes.
worm. Solidifying copper is said to "throw a worm" when it forces a stream of molten copper through the top crust; high sulfur content is indicated.

Y

Y alloy. An aluminum-base casting alloy that contains about 4% Cu, 2% Ni, 1.5% Mg (142 alloy).
yellow gold. Gold alloys that possess the natural yellow color.
yield point. In mild or medium-carbon steel, the stress at which a marked increase in deformation occurs without increase in load. In other steels and in nonferrous metals this phenomenon is not observed. See *yield strength.*
yield strength. The stress at which a material exhibits a specified limiting deviation from proportionality of stress to strain. An offset of 0.2% is used for many metals such as aluminum-base and magnesium-base alloys, while a 0.5% total elongation under load is frequently used for copper alloys.
Young's modulus. The *modulus of elasticity* in tension or compression.

Definitions of Terms Used in X-Ray Metallography

By L. W. McKeehan*

THIS GLOSSARY is intended primarily for those who have occasion to consult publications in the field of X-ray metallography. The definitions may have secondary value to those who prepare such publications and who wish to use terms that are unambiguous. A part of the glossary has appeared in the Proceedings of the ASTM (Vol 26, Part 1, p 582, 1926) with a report by that society's Committee on X-Ray Metallography. It has been revised and extended here.

A (abbreviation). Angström unit, 10^{-8} cm; also written AU, Å, ÅU.
absorber (for X-rays). A sheet of material placed between the source of X-radiation and the place where it is detected or measured. When this sheet contains elements chosen especially to reduce the intensity of X-rays that have undesired wave lengths, the absorber is usually called a *filter.*
absorption coefficient (for X-rays in a substance). The rate of decrease, per unit distance traversed in a substance, of the natural logarithm of the intensity of a parallel beam; usually written μ.
absorption limit. See *limit.*
amorphous. Without crystal structure, so the X-ray diffraction pattern is like that of a liquid.
angle. See *glancing angle.*
Angström unit. A, 10^{-8} cm.
anisotropic. Having different properties in different directions.
anticathode (in X-ray tubes). The part of the anode that receives most of the cathode rays, and in which the target, if any, is mounted.
asterism (in X-ray diffraction patterns). The appearance of streaks or bands approximately along radii of the pattern.
axial ratio (in crystals). In the tetragonal system and in the hexagonal division of the hexagonal system, the ratio of the parameter for the principal crystallographic axis of highest multiplicity to the parameter for either one of the other principal axes, usually $C = c/a$; in less symmetrical systems the continued ratio of all three parameters, usually written a:b:c.
axis (crystal). One of three noncoplanar intersecting lines, fixed with respect to a crystal, which meet any crystal plane at points whose distances from the intersection of the axes, in terms of three parameters (a, b and c), one for each axis, are in the ratios of small integers. The principal crystal axes are those about which the symmetry is the highest possible to the crystal considered. Less properly, the length of an edge of the unit cell. See *parameter.*
axis of symmetry. In a crystal, a line about which a rotation through 360 deg/N (where N is 2, 3, 4 or 6), with or without a translation parallel to the line and with or without a reflection in a plane perpendicular to the line, replaces every element (point, line and plane) of the crystal by an equivalent element. The axis is said to be N-fold and is a rotation axis if neither translation nor reflection is involved; is a screw-axis if any other than a primitive translation is involved; and is a rotatory-reflection axis (N not equal to 3) if reflection is involved.

back reflection. X-ray diffraction at deviations near 180 deg, especially useful in precise measurement of interplaner distances.
balanced filters (for X-rays). A pair of filters adjusted to give the same absorption except in the range of wave lengths lying between their characteristic absorption limits. When these filters are used alternately, the difference in effect, if any, is due to X-rays that have wave lengths in this range.
basal plane. In tetragonal and hexagonal crystals, a plane perpendicular to the c-axis.
beam (X-ray). A nearly parallel pencil of X-rays from a common source.
body. See *bulb.*
body-centered (concerning space lattices). Having the equivalent lattice points at the corners of the unit cell, and at its center; sometimes called *centered,* or *space-centered.*
Bragg equation (for X-ray reflection). The equation $n\lambda = 2d \sin \theta$. See also *reflection.*
Bragg method (for X-ray or crystal analysis). A method using monochromatic or polychromatic X-rays and a single crystal of large size rotated through a small angle about an axis lying in a crystal face.
bulb (in X-ray tube). The part made of glass or other pressure-tight material; when made of metal, more usually called the "body".

calcite. Natural rhombohedral $CaCO_3$, the primary standard crystal used in X-ray spectrometry.
cassette (in X-ray spectrographs). A box for holding a photographic film or plate in position to receive the X-ray diffraction pattern.
cell. See *unit cell.*
centered (concerning space lattices). Body-centered.
channel (in X-ray spectrographs). A collimating system consisting of a hole through a thickness of metal, usually in two parts to permit cleaning.
chaotic. See *orientation.*
characteristic X-rays. Series of monochromatic X-rays that are emitted (in addition to heterochromatic X-radiation) by a particular element when that element is exposed to cathode rays or X-rays of sufficiently high energy.
close-packed (concerning atomic arrangement in crystals). Having one of the two possible arrangements, one cubic and one hexagonal, in which equal hard spheres can be made to occupy the least total volume; and, by extension, having any of the hexagonal arrangements derived from the second of these by expansion or contraction of the hexagonal axis. See *face-centered* and *hexagonal close-packed.*
coefficient. See *absorption coefficient, mass-absorption coefficient, mass-scattering coefficient.*
collimate. To isolate a parallel, or nearly parallel, beam of rays, as by slits, pinholes or a channel.
continuous spectrum. Heterochromatic X-rays.
Coolidge tube. A type of X-ray tube that has a high vacuum and a hot wire cathode.
covering operation. A general name for translations, symmetry operations, and their combinations in extended structures, by which every element (point, line and plane) of the structure is replaced by an equivalent element. Besides translations and symmetry operations there are screw rotations about screw axes and glide reflections in glide-reflection planes.
critical (concerning voltage, wave length or frequency). Limiting. See *limit.*
cross direction (in rolled metal). The direction parallel to the axes of the rolls during rolling.
crystal. A coherent piece of matter all parts of which have the same anisotropic arrangement of atoms; in metals, usually synonymous with "grain" and "crystallite".
crystal analysis. The determination of crystal structure.
crystalline. Composed of crystals.
crystal unit. Unit of structure.
cube-centered (concerning space lattices). Body-centered cubic.

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cubic (concerning crystals). Having nonparallel 3-fold axes of symmetry, with other elements of symmetry. Sometimes called "isometric" or "regular". The typical cubic crystal has three equivalent axes (2-fold or 4-fold) mutually perpendicular, and the common parameter is usually written a (or a_0).

dashed (concerning X-ray diffraction patterns from crystal aggregates). Made up of separately distinguishable images of the source.
Debye-Scherrer method (for X-ray crystal analysis). A method using a monochromatic (or polychromatic) X-ray beam defined by pinholes, an aggregate of small crystals oriented more or less completely at random and a photographic film bent into an almost complete cylinder with axis perpendicular to the X-ray beam at the crystalline specimen; almost indistinguishable from the Hull method; sometimes called the *powder method*.
define (X-rays). To limit in angle, as by slits or pinholes; to collimate.
deviation (X-ray). The angle between the direction of incidence produced through the substance, and the direction of diffraction; twice the glancing angle of incidence; usually written 2θ.
diagram (for X-ray diffraction patterns). A representation, either a photograph as taken, or a projection therefrom; for example, the *index diagram*.
diamond cubic (concerning atomic arrangements). Similar to the diamond in having two face-centered cubic arrangements of atom centers, either of which is displaced with respect to the other by one-fourth of the diagonal of the unit cube.
diffraction (X-ray). The deviation of an X-ray beam by scattering from atoms that have some regularity of arrangement or spacing.
diffraction pattern (X-ray). The totality of the intersections, with a plane or other surface, of the beams diffracted by a crystal or by a crystalline aggregate.
discontinuity (in absorption). The ratio between absorption coefficients at a limit.
doublet (in characteristic X-ray spectra). A pair of lines from the same element that differ little in wave length; for example, the K*a*-doublet, Ka_1 and Ka_2.

end-centered (concerning orthorhombic space lattices). Having equivalent points at the corners of the unit cell and at the centers of the pair of opposite faces perpendicular to the c-axis. Same as *side-centered*, with a different choice of axes.
equivalent (concerning points, lines, planes and atoms). Interchangeable by the covering operations appropriate to the structure.
excite (X-rays). To cause to be emitted.
exposure (to X-rays). The time integral of the intensity; with X-ray tubes of the same kind and operated under the same conditions, the exposure is proportional to the product of the electron current through the tube by the time of operation.

face (crystal). A natural surface, or a cut surface parallel to a possible natural surface.
face-centered (concerning cubic space lattices). Having equivalent points at the corners of the unit cell and at the centers of its six faces. A face-centered cubic space lattice is characteristic of one of the close-packed arrangements of equal hard spheres.
family (of crystal planes). The planes in any one crystal that have common indices.
fiber axis. See *fibering*.
fiber diagram. An X-ray diffraction pattern, or a chart prepared therefrom, showing the existence of fibering or measuring its completeness.
fibering. The state of a crystalline aggregate in which the preferred orientations are obtained by rotation about a line, the fiber axis. If fibering is complete, all azimuths about the fiber axis are equally probable. If fibering is incomplete, the preferred orientations may decrease to a small number and the concept of fibering loses its value. Besides simple fibering there may be a helical fibering in which the fiber axis has all the orientations assumed by the tangent to a helix of constant pitch. In ring fibering, the pitch of the helix is zero.
filter (for X-rays). A sheet of material that selectively absorbs secondary or other undesired X-rays. See also *balanced filters*.
fluorescent screen (for X-rays). A sheet of material (usually mounted on paper or other nonabsorbent material) that emits visible or actinic light when exposed to X-rays.
fluorescent X-rays. Characteristic X-rays excited by X-rays.
focus (in X-ray tubes). The spot on the target where the cathode rays are concentrated and which is therefore the principal source of X-rays; its shape and size are controllable by design.
focusing (concerning methods of X-ray or crystal analysis). Using such a shape and position of sample and position of source that the diffracted X-rays from many or all parts of the sample fall close together in the diffraction pattern. Such methods permit the use of wide beams and require relatively short exposures. See *Bragg method* and *Seemann-Bohlin method*.
form (for equivalent crystal planes or lines). Having the same indices, except for sign or order; for example, the planes (110), (101) in a cubic crystal are both of the form {110}; the planes (110), (101) in a tetragonal crystal are not of the same form. The lines [210], [120], [012] in a cubic crystal are of the form $<210>$.
frequency (X-ray). Measured by the equation $\nu = c/\lambda$, wherein c is the velocity of propagation of light (3×10^{10} cm per sec) and λ is the wave length, in centimeters.
frequency factor (for crystal planes of a form). The number of different families of planes having the same form.

general (concerning X-radiation). Heterochromatic.
glancing angle. The angle between the incident X-ray beam and the crystal planes from which reflection takes place, however these may be inclined to the bounding surface of the crystal; usually written θ.
glide-reflection plane. See *plane of symmetry*.
gnomonic projection. A projection in which each plane of a crystal is represented by the point in which the perpendicular allowed to fall upon it from a fixed point meets the plane of the projection.
goniometer. An instrument for measuring angles or for setting objects in known orientations. *Spectrographs* and *spectrometers* are goniometers of a special sort.
grating constant (in crystals). Interplanar distance.
grating space (in crystals). Interplanar distance.

halo (in X-ray diffraction patterns). A diffuse circular band.
hard (concerning X-rays). Having great penetrating power, short wave length, high frequency
hemihedral (concerning crystals). Having only one-half of the symmetry elements possible to the crystal system in which the crystal belongs; having different properties in opposite directions, or on opposite faces, or lacking symmetrically opposite faces.
heterochromatic (concerning X-rays). Having a continuous series of wave lengths, as from a tube operated at less than the critical voltage for its target.
heterogeneous (concerning X-rays). Heterochromatic.
hexagonal (concerning crystals). Having parallel 6-fold rotation axes of symmetry, or a single set of parallel 3-fold rotation axes of symmetry with planes of symmetry perpendicular thereto, and with or without other symmetry elements. The typical hexagonal crystal has two equal axes, b = a, inclined at an angle of 120 deg and a third axis, c, perpendicular to their plane.
hexagonal close-packed (concerning atomic arrangements in crystals). Having atoms at the corners of the hexagonal unit cells, which are right prisms with rhombic bases, and at the centers of those (equilateral) triangular prisms that are similarly located halves of the hexagonal unit cells. The two sets of atoms are not crystallographically equivalent. If the atoms are arranged like hard equal spheres in contact, c = 1.633 or $2\sqrt{6}/3$.
holohedral (concerning crystals). Having all the symmetry elements possible to the crystal system in which the crystal belongs.
homogeneous (concerning matter). Having the same properties in every small region containing many atoms (but not necessarily isotropic).
homogeneous (concerning X-rays). Monochromatic.
Hull method (for X-ray crystal analysis). A method using a monochromatic (or polychromatic) X-ray beam defined by slits or pinholes, an aggregate of small crystals oriented more or less completely at random and a photographic plate or a photographic film (if a film, bent around a cylinder with its axis perpendicular to the X-ray beam at the crystalline specimen); virtually indistinguishable from the Debye-Scherrer method; sometimes called the *powder method*.

identity period (along a crystal line). A primitive translation.
image (in X-ray diffraction patterns). By analogy with optics, a recognizable copy of the source of X-rays or of any aperture defining the X-ray beam.
index diagram. A chart based on an X-ray diffraction pattern and permitting the assignment of indices to the families of planes responsible for the maxima of intensity in the pattern.
indices. See *Miller indices, Miller-Bravais indices, line indices*.
intensifier (for X-rays). A substance placed in, on or under a photographic emulsion or a fluorescent screen, or used in photographic development, to make the effects of X-rays more conspicuous.
intensifying factor (for X-ray intensifiers). The ratio between the exposure when no intensifier is used, and the exposure, for the same effect, when the intensifier is used, provided that all other conditions remain unaltered.
intensifying screen (in X-ray spectrographs). A separately mounted intensifier.
intensity (X-rays). The flux of energy per unit of time and per unit of cross section perpendicular to the direction of propagation.
interplanar distance (in crystals). The perpendicular distance between the nearest equivalent planes of a family; usually written d. The indices of the planes may be written as a subscript; for example, d_{100}.
inversion. A symmetry operation by which each point of a structure is replaced by a point at the same distance from a fixed point (the inversion center) but in the opposite direction therefrom. See also *symmetry operation*.
ionization method. Any method of X-ray or crystal analysis that depends on measuring the electrical conductivity of a gas exposed to the diffracted X-rays; great accuracy in angular measurement is possible, but not easy.
isometric (concerning crystals). Cubic.
isotropic. Having the same properties in every direction.

K. The letter that designates the series of characteristic X-rays having, for each element, the shortest wave lengths. Greek letters and Arabic subscripts are used to distinguish the lines of the K-series; for example copper Ka_1, molybdenum $K\beta$. L and M are used to designate characteristic groups of X-rays of successively greater wave length, but these are rarely used in crystal analysis.
kX (abbreviation). Kilo-X-unit. Differs slightly from an angström unit (10^{-8}cm). See *X*.

lattice. Space lattice. Lattice lines and lattice planes are lines and planes chosen so as to pass through collinear lattice points, and noncollinear lattice points, respectively.
Laue method (for crystal analysis). A method using heterochromatic X-rays, a small fixed crystal and a plane screen, usually a photographic plate; the Laue spot is the image (of a pinhole or of the small crystal itself) characteristic of the resulting diffraction pattern.
layer line (in *revolving-crystal* and *oscillating-crystal methods*). A row of spots caused by families of planes equally inclined to the axis of rotation or oscillation. Compare with *side spectrum, zero spectrum*.
limit (in voltage, wave length or frequency of X-rays). A value, characteristic of the particular chemical element in question, on the two sides of which excitation, absorption, photographic effect or the like, have sharply different values.
line (crystal). A possible edge of a crystal.
line (in X-ray diffraction patterns). A straight or slightly curved narrow region of maximal intensity.
line (X-ray). A group of monochromatic X-rays, not necessarily collimated.
line focus (in X-ray tubes). A focus having one dimension reduced to such an extent that the focus approximates a segment of a straight line on the target in the plane determined by the axis of the tube and the direction from the target to the irradiated object. This secures the advantages of a point source of X-rays without extreme local heating.
line indices. The smallest integers proportional to the co-ordinate differences, in terms of the parameters (a, b and c), between equivalent points lying on a crystal line; written, in general [HKL]; in

particular, for example, [210]. In cubic crystals the line [pqr] is perpendicular to the plane (pqr).

mass-absorption coefficient (for X-rays in a substance). The rate of decrease, per unit mass traversed, of the natural logarithm of the intensity of a parallel beam; usually written μ/ρ. It is often more convenient than the absorption coefficient because its use does not require knowledge of the density ρ. See also *mass-scattering coefficient.*

mass-scattering coefficient (for X-rays in a substance). The rate of decrease, per unit mass traversed, of the natural logarithm of the intensity of a parallel beam, caused by scattering alone; usually written σ/ρ; the excess of the mass-absorption coefficient, μ/ρ, over σ/ρ is called the true mass-absorption coefficient, μ'/ρ.

Miller indices (for crystal planes). The smallest integers proportional to the reciprocals of the intercepts, in terms of the parameters (a, b and c) of the plane on the three crystal axes; written, in general (hkl); in particular, for example (210); see also *form.*

Miller-Bravais indices (for crystal planes in the hexagonal division of the hexagonal system only). The smallest integers proportional to the reciprocals of the intercepts, in terms of the parameters (a, a, a, and c) of the plane on the four axes; written, in general (hjkl); in particular, for example (1120). The index for the hexagonal axis is always written last; $k = -(h + j)$ and may be replaced by a period; thus $(11\bar{2}0)$ and (11.0) are the same. Any two of the three equivalent axes 120 deg apart in the basal plane, together with the fourth axis, are crystallographically sufficient; but the use of four axes makes it easier to recognize planes of the same form.

monochromatic (concerning X-rays). Having a single wave length.

monoclinic (concerning crystals). Having only parallel 2-fold axes of symmetry, or parallel planes of symmetry, or both of these with the axes perpendicular to the planes. The typical monoclinic crystal has three unequal axes, only one of which is perpendicular to two others. The unique axis is usually taken as the b-axis.

multiplicity (for axes of symmetry). The value of N if the axis is N-fold.

order (in X-ray reflection). The integral value of n in the equation $n\lambda = 2d \sin \theta$.

orientation (crystal). Arrangement in space of the axes of a crystal. Every crystal must at every moment have a definite orientation; only aggregates, in space or time, can possess chaotic orientation; if the the orientation is not chaotic, some one or more orientations must be preferred.

orthohexagonal (concerning crystal axes). A set of mutually perpendicular axes for hexagonal crystals. In terms of the more usual hexagonal parameters (a, a, c) the orthohexagonal parameters are $a\sqrt{3}$, a, c.

orthorhombic (concerning crystals). Having only 2-fold axes of symmetry, with planes of symmetry parallel to the axes or perpendicular thereto. The typical orthorhombic crystal has three unequal axes mutually perpendicular.

oscillating-crystal method (for X-ray or crystal analysis). Using a single crystal rotating at constant speed, but alternately in both directions, through less than a complete rotation (usually much less).

parameter (in crystals). A characteristic magnitude defining the unit cell or the position of a point within it. The edges of the unit cell, a, b, c, and the angles, α (between ■ and c), β (between ■ and a), γ (between a and b), are its parameters. The edge of the unit cube, a_o, is the single parameter of a cubic lattice. When the fractional co-ordinates of a point within the unit cell may vary, the values of these fractions (x, y, z) are parameters of the structure.

pattern. *Diffraction pattern.*

photogoniometer. An X-ray goniometer with photographic registration.

pinhole. A small round hole used to define a beam of X-rays.

plane (crystal). A possible face of a crystal.

plane of symmetry. In a crystal, a plane in which a reflection, with or without a translation parallel to the plane, replaces every element (point, line and plane) of the crystal, by an equivalent element. The plane is a *reflection plane* if no translation is involved, and is a *glide-reflection plane* if translation is involved.

point-group. A limited group of points (from 1 to 48 in number) possessing the same symmetry elements as one of the 32 possible classes of crystals.

pole figure (for crystalline aggregates). A stereoscopic projection showing preferred orientations of the normals to planes of a given form.

polychromatic. Having several distinct wave lengths; for example, the characteristic X-rays from a single element.

powder method (for X-ray or crystal analysis). A method using a loose aggregate of small crystals with chaotic orientation; applied early, but somewhat illogically, to methods using solid metals composed of crystalline aggregates; see *Debye-Scherrer method, Hull method.*

preferred. See *orientation.*

primary (concerning X-rays). Emitted directly from the anticathode in the X-ray tube.

primitive. See *translation.*

principal spectrum (in *revolving-crystal* and *oscillating-crystal* patterns). *Zero spectrum.*

pseudocrystalline. Possessing regularities of structure that result in a diffraction pattern unlike that of a liquid or an amorphous solid, although true crystals are not present; for example, stretched rubber is pseudocrystalline.

radiography. The use of X-rays in studying the macrostructure of single objects or assemblies (internal boundaries, inclusions, variations in density or composition).

random (concerning orientation). Chaotic.

rating (for X-ray tubes). The product of the allowable current by the peak operating voltage.

ratio. See *axial ratio.*

reciprocal lattice (for a crystal). A group of points arranged about a center in such a way that the line joining each point to the center is perpendicular to a family of planes in the crystal, and the length of this line is inversely proportional to their interplanar distance.

reflection (X-ray). Diffraction considered to result from scattering by crystal planes as units. These are the reflecting planes. Monochromatic X-rays are reflected only when $n\lambda = 2d \sin \theta$, where n is order, λ wave length, d interplanar distance, and θ glancing angle of incidence on the planes considered.

reflection plane. See *plane of symmetry.*

regular (concerning crystals). Cubic.

revolving-crystal method (for crystal analysis). A method using a small single crystal that rotates uniformly through many complete rotations during the time of the exposure.

rhombohedral (concerning crystals). Having parallel 6-fold rotatory-reflection axes, or a single set of parallel 3-fold rotation axes, in either instance without planes of symmetry perpendicular thereto, and with or without other elements of symmetry. The typical rhombohedral crystal has three equal axes (c = a, b = a) mutually inclined at an angle ■ not usually equal to 90 deg.

rock salt. Natural (cubic) NaCl, the secondary standard crystal used in X-ray spectrometry.

Roentgen rays. See *X-rays.*

rolling direction (in rolled metal). The direction, in the plane of the sheet, perpendicular to the axes of the rolls during rolling.

rotation axis. See *axis of symmetry.*

rotation diagram. A chart used in assigning indices to families of planes that give spots in the diffraction patterns obtained in revolving-crystal or oscillating-crystal methods for crystal analysis.

rotatory-reflection axis. See *axis of symmetry.*

scattering (X-ray). The re-emission of X-rays from irradiated matter, without change of wave length (except as modified by the Compton effect, which is negligible in crystal analysis); scattering takes place in all directions with respect to the incident X-rays, but more intensely (or more often) in some directions than in others.

screen (in X-ray spectrographs). A flat or curved surface on which a diffraction pattern may be observed; for example, a fluorescent screen. Sometimes, but less properly, a shield.

screw axis. See *axis of symmetry.*

secondary (concerning X-rays). Emitted elsewhere than from the anticathode.

secondary spectrum (in revolving-crystal and oscillating-crystal patterns). *Side spectrum.*

Seemann-Bohlin method (for crystal analysis). A method using ■ monochromatic or polychromatic X-ray beam of wide angular aperture; an aggregate of small crystals oriented more or less completely at random and spread on a cylinder having an element that passes along the single slit defining the X-ray beam; and a photographic film bent to fit another segment of the same cylinder. This is a focusing method.

series (in X-ray spectra). A group of characteristic X-rays having the same excitation limit; distinguished as K-series and L-series. See also *K.*

shield (in X-ray spectrographs). A plate, block or the like that prevents X-rays (usually secondary) from reaching the measuring or detecting device; a complete *absorber.*

shutter (in X-ray spectrographs). A removable shield.

side-centered (concerning orthorhombic space lattices). Having equivalent points at the corners of the unit cell, and at the centers of the pairs of opposite faces perpendicular to the a-axis or to the b-axis; the same as end-centered, but with a different choice of crystallographic axes.

side spectrum (in *revolving-crystal* and *oscillating-crystal* patterns). A row of spots indicating planes equally inclined to the axis of rotation or oscillation, but not parallel thereto. Compare with *layer line, zero spectrum.*

simple (concerning space lattices). Having equivalent points only at the corners of the unit cell.

slit. A narrow opening with parallel sides, used to define a beam.

slit system. A series of slits used to define a beam and to shield against secondary X-rays.

slitless spectrograph. *Wedge spectrograph.*

soft (concerning X-rays). Having little penetrating power, long wave length, low frequency.

source (X-ray). See *focus.*

space-centered (concerning space lattices). *Body-centered.*

space group. A group of points infinitely extended and possessing the same elements of symmetry and the same translations as one of the 230 different arrangements theoretically possible for atoms in crystals. The great number of space groups as compared with point groups results from the fact that ■ different location in space for the same symmetry elements is possible in the space group but not in the point group.

space lattice (crystal). A system of equivalent points formed by the intersections of three sets of planes parallel to pairs of principal axes; the space lattice may be thought of as formed by the corners of the unit cells. See *translation group.*

spacing (between crystal planes). *Interplanar distance.*

spectrograph (X-ray). An instrument using an extended surface—a photographic plate or film, or a fluorescent screen—for receiving the X-ray diffraction pattern.

spectrometer (X-ray). An instrument using a movable measuring device for exploring the X-ray diffraction pattern.

spectrum (X-ray). A distribution of X-rays along a line in accordance with the wave length, or a group of X-rays that can be distributed in this way. The set of layer lines furnished by the revolving-crystal method is sometimes called the complete spectrum. See also *side spectrum, zero spectrum.*

stereographic projection. A projection in which each plane of a crystal is represented by the point at which ■ perpendicular, let fall upon it from a fixed point, meets a sphere centered at the fixed point; and these representative points on the sphere are then represented in turn by the points at which lines drawn to them from the pole of a great circle of the sphere meet the diametral plane through the great circle.

structure. The arrangement of parts; in crystals, especially, the shape and dimensions of the unit cell, and the number, kinds and positions of the atoms within it.

symmetry. See *axis of symmetry, inversion, plane of symmetry.*

symmetry element. A general name for axes of symmetry, planes of symmetry and centers of inversion.
symmetry operation. A geometrical operation that interchanges equivalent elements (points, lines and planes) of a rigid geometrical figure. The possible symmetry operations are rotations about rotation axes that pass through the center of the figure and reflections in reflection planes that pass through the same point. A rotatory reflection is a compound operation in which the rotation axis must be perpendicular to the reflection plane, except that an inversion is equivalent to a 2-fold rotatory reflection about any rotatory-reflection axis.
system (crystal). One of the 6 classes into which the 32 possible types of crystal and the 230 possible types of structure have been divided on the basis of symmetry. They are *triclinic, monoclinic, orthorhombic, tetragonal, hexagonal* (including *rhombohedral* and *hexagonal* divisions) and *cubic.*

target (in X-ray tubes). The part of the anticathode, wholly or predominantly of a single metal, or coated with a substance to be analyzed, where the focus lies.
tetartohedral (concerning crystals). Having only one-fourth of the symmetry elements possible to the crystal system in which the crystal belongs.
tetragonal (concerning crystals). Having 4-fold axes of symmetry but no 3-fold axes of symmetry. The typical tetragonal crystal has two equal axes (b = a) perpendicular to each other and to a third axis (c).
translation (in a crystal or space group). A displacement parallel to a crystal line. A primitive translation is one of the least translations, without accompanying rotation or reflection, which replaces every element (point, line and plane) by an equivalent element. Suitable aliquot parts of a primitive translation may be combined with rotation or reflection in screw rotations and glide reflections.
translation group. An infinitely extended group of points having the same translations as one of the 14 space lattices possible in crystals.
transmission method (for X-ray or crystal analysis). Having the diffracted X-rays emergent from a surface that does not face the source.
triclinic (concerning crystals). Having no symmetry elements, or only inversion centers. The typical triclinic crystal has three unequal axes, no two of which are perpendicular.

uniform (concerning X-ray diffraction patterns). Not *dashed.*
unit cell (in crystals). The least parallelopiped that possesses the full symmetry of the crystal, and repetition of which without change or orientation builds up a crystal of any size.
unit cube (in crystals). The unit cell in cubic crystals.
unit of structure (in crystals). The group of atoms included by the unit cell, especially if the arrangement of the group indicates chemical relations among its members.

wave length (X-ray). The value of λ in the equation, $\lambda = \frac{2d \sin \theta}{n}$; wherein d is the interplanar distance in a crystal that reflects the X-rays at the glancing angle θ in the nth order.
wedge spectrograph. An X-ray spectrograph (developed by Seemann) in which the beams of incident and diffracted X-rays are limited by a wedge brought into contact with a face of the crystal; also called *slitless spectrograph.*
Weissenberg photogoniometer. A photogoniometer with a cylindrical film, shielded and axially advanced in such a way during exposure that the spots of a single layer line are recorded consecutively along the direction of travel of the film.
white (concerning X-rays). Heterochromatic.

X (abbreviation). X-unit; also written **XU.** $1XU = 1.00202 \times 10^{-11}$ cm so that 1 kilo-X-unit, or 1kX = 1.00202 A.
X-radiation. X-rays in general, especially when their direction of propagation is not emphasized.
X-ray analysis. The measurement of X-ray wave lengths and intensities.
X-rays. Light rays, excited usually by the impact of cathode rays on matter, which have wave lengths between about 10^{-6} cm, and 10^{-9} cm; also written X-rays; same as *Roentgen rays.*
X-ray tube. An assembly of *cathode, anticathode,* and *bulb* (or body) suitable for the production of X-rays.

zero spectrum (in revolving-crystal and oscillating-crystal patterns). A row of spots resulting from planes parallel to the axis of rotation or oscillation. Sometimes called "zero line". Compare with *layer line, side spectrum.*
zone axis (in a crystal). A line parallel to several crystal planes. The planes to which it is parallel form its zone.

Some Physical Properties of the Elements*

The following table has been compiled from many sources. For the 36 metallic elements that are discussed elsewhere in this Handbook, the numbers given here have been selected by the same specialists who compiled the data on the mechanical and metallurgical properties of these metals. For the less common metals and for the nonmetallic elements, most of the data are from National Bureau of Standards Circular C447, 1943, page 459.

Atomic weights are from the 1947 Report of the International Commission on Atomic Weights. Nearly all the melting points are those most recently quoted by the National Bureau of Standards. Most of the boiling points were selected by K. K. Kelley (Bureau of Mines Bulletin 383, 1935) from smoothed curves of vapor pressure versus temperature.

Most of the lattice constants are those selected by Hume-Rothery in his 1945 edition of "The Structure of Metals and Alloys", Institute of Metals, London; the references he gives have been checked and a few corrections and substitutions have been made when data have been found that the committee judged to be more accurate. The lattice constants have been corrected to 20 C (68 F), when the correction was a minor one, by using the known coefficients of thermal expansion; measurements at very low temperatures are reported as such, uncorrected, with the temperature given. For the polymorphic gases the structure stable at the highest temperature is given.

All entries in this table are for elements of high purity. Impurities may have a great effect on certain properties, for example, on the melting point and electrical resistivity. Most of the data do not apply to commercial metals, which contain greater amounts of impurities than the elements considered here. For metals, most of the properties refer to annealed specimens. Cold working will change certain properties—for example, density and electrical resistivity. Grain size may also affect some properties.

It will be noted that the number of significant figures contained in the various values ranges from one to six. Such differences in the uncertainties of the quoted values may reflect the greater or lesser care that has been taken in measuring the properties. Certain properties are much more difficult to measure than others; for example, the moduli of elasticity of soft and ductile metals and the boiling points of many metals are difficult to determine precisely. It is not uncommon for different investigators to report different values for a given property, depending on the method of measuring; examples are thermal conductivity and latent heat of fusion. Because of these factors, some of the values are probably less accurate than would be inferred from counting the number of digits contained in the values listed.

In using this table, the reader should be guided by the above considerations concerning the probable accuracy of the numbers.

* Compiled under the supervision of the Subcommittee on Physical Properties of the Elements. The members of this subcommittee are R. L. Kenyon, *Chairman* (The American Rolling Mill Company), C. S. Barrett (University of Chicago), J. B. Johnson (Air Materiel Command) and H. W. Russell (Battelle Memorial Institute).

Footnotes for Table on pages 20 and 21

NOTES. (*) Ordinary form; other modifications known or probable. (†) The kX-unit (1000 X-units), used in all crystal structure measurements, differs slightly from an Angström (10^{-8}cm); the tabulated lattice dimensions should be multiplied by 1.00202 to put them in Angströms, as when calculating theoretical densities of elements. (Density is given by the equation $\rho = 1.66020\ \Sigma A/V$, where ΣA is the sum of the atomic weights of the atoms in the unit cell and V is the volume of the unit cell, in cubic Angströms.)

(a) Computed (b) For polycrystalline zinc; in single crystals, varies from 61.5 (parallel to hexagonal axis) to 15 (perpendicular to hexagonal axis (c) From 20 to 60 C (68 to 140 F) (d) At 36 atmospheres pressure (e) From 20 to 100 C (68 to 212 F) (f) At 30 atmospheres pressure (g) At minus 62 C (minus 80 F) (h) From 20 to 50 C (68 to 122 F) (i) Sublimes (j) From 20 to 200 C (68 to 392 F) (k) From 20 to 750 C (68 to 1382 F) (m) At 0 C (32F) (n) At 40 C (104 F) (o) From 0 to 100 C (32 to 212 F) (p) At 100 C (212 F) (q) Monoclinic sulfur (r) At 25 C (77 F) (s) For polycrystalline zinc; in single crystals, varies from 6.16 (parallel to hexagonal axis) to 5.89 (perpendicular to hexagonal axis) (t) Pure zinc has no clearly defined modulus of elasticity (u) The solid helium listed is stable only under pressure.

Element	Symbol	Atomic Number	Atomic Weight (1947)	Density at 20 C (68 F), g per cu cm	Density at 68 F (20 C), lb per cu in.	Atomic Volume, cu cm per g-atom	Melting Point, deg Cent	Melting Point, deg Fahr	Boiling Point, deg Cent	Boiling Point, deg Fahr	Specific Heat at 20 C, cal/g/°C	Heat of Fusion, cal per g	Heat of Fusion, Btu per lb
Actinium	Ac	89	227.05	....	.....	.....	[a]1600	[a]2900	....	....	....	....	....
Aluminum	Al	13	26.97	2.699	0.09751	9.993	660.2 ± 0.1	1220.4 ± 0.2	2060	3740	0.215	94.6	170
Americium	Am	95	241	....	.....	.....	.....	.....	....	....	....	....	....
Antimony	Sb	51	121.76	6.62	0.239	18.4	630.5 ± 0.1	1166.9 ± 0.2	1440	2620	0.049	38.3	68.9
Argon	A	18	39.944	1.6626×10^{-3}	0.060070×10^{-3}	.....	−189.4 ± 0.2	−308.9 ± 0.4	−185.8	−302.4	0.125	6.7	12
Arsenic	As	33	74.91	5.73	0.207	13.1	[d]814	[d]1497	[l]610	[l]1130	0.082	....	....
Astatine	At	85	211	....	.....	.....	.....	.....	....	....	....	....	....
Barium	Ba	56	137.36	3.5	0.13	39	704 ± 20	1300 ± 35	1640	2980	0.068	....	....
Beryllium	Be	4	9.02	1.82	0.0658	4.96	1280 ± 40	2340 ± 70	2770	5020	0.52	260	470
Bismuth	Bi	83	209.00	9.80	0.354	21.3	271.3 ± 0.1	520.3 ± 0.2	1420	2590	0.034	12.5	22.5
Boron	B	5	10.82	2.3	0.083	4.7	2300 ± 300	4200 ± 550	....	....	0.309	....	....
Bromine	Br	35	79.916	3.12	0.113	25.6	−7.2 ± 0.2	+19.0 ± 0.4	58	136	0.070	16.2	29.2
Cadmium	Cd	48	112.41	8.65	0.313	13.0	320.9 ± 0.1	609.6 ± 0.2	765	1409	0.055	13.2	23.8
Calcium	Ca	20	40.08	1.55	0.056	25.9	850 ± 20	1560 ± 35	1440	2625	[o]0.149	....	....
Carbon (graphite)	C	6	12.010	2.22	0.0802	5.41	3700 ± 100	6700 ± 180	4830	8730	0.165	....	....
Cerium	Ce	58	140.13	6.9	0.25	20	600 ± 50	1100 ± 90	....	....	0.042	....	....
Cesium	Cs	55	132.91	1.9	0.069	70	28 ± 2	82 ± 4	690	1275	0.052	3.8	6.8
Chlorine	Cl	17	35.457	....	.....	.....	−101 ± 2	−150 ± 4	−34.7	−30.5	0.116	21.6	38.9
Chromium	Cr	24	52.01	7.19	0.260	7.23	1890 ± 10	3430 ± 20	2500	4500	0.11	75.6	136
Cobalt	Co	27	58.94	8.9	0.32	6.6	1495 ± 1	2723 ± 2	2900	5250	0.099	58.4	105
Columbium	Cb	41	92.91	8.57	0.310	10.8	2415 ± 15	4380 ± 30	....	....	[m]0.065	....	....
Copper	Cu	29	63.54	8.96	0.324	7.09	1083.0 ± 0.1	1981.4 ± 0.2	2600	4700	0.092	50.6	91.1
Curium	Cm	96	242	.....	.....	.....	.....	.....	....	....	....	....	....
Dysprosium	Dy	66	162.46	[a]8.56	[a]0.309	[a]19.0	.....	.....	....	....	....	....	....
Erbium	Er	68	167.2	[a]9.16	[a]0.331	[a]18.3	.....	.....	....	....	....	....	....
Europium	Eu	63	152.0	[a]5.24	[a]0.189	[a]29.0	.....	.....	....	....	....	....	....
Fluorine	F	9	19.00	....	.....	.....	−223 ± 10	−370 ± 20	−188.2	−306.8	0.18	10.1	18.2
Francium	Fa	87	223	....	.....	.....	.....	.....	....	....	....	....	....
Gadolinium	Gd	64	156.9	[a]7.95	[a]0.287	[a]19.7	.....	.....	....	....	....	....	....
Gallium	Ga	31	69.72	5.91	0.214	11.8	29.78 ± 0.02	85.60 ± 0.04	2070	3760	0.079	19.2	34.6
Germanium	Ge	32	72.60	5.36	0.194	13.5	958 ± 10	1760 ± 20	....	....	0.073	....	....
Gold	Au	79	197.2	19.32	0.698	10.2	1063.0 ± 0.0	1945.4 ± 0.0	2970	5380	0.031	16.1	29.0
Hafnium	Hf	72	178.6	11.4	0.412	15.7	[a]1700	[a]3100	....	....	....	....	....
Helium	He	2	4.003	0.1664×10^{-3}	0.6012×10^{-5}	.....	[f]−271.4 ± 0.2	[f]−456.5 ± 0.4	−268.9	−452.0	1.25	....	....
Holmium	Ho	67	164.94	....	.....	.....	.....	.....	....	....	....	....	....
Hydrogen	H	1	1.0080	0.08375×10^{-3}	0.3026×10^{-5}	.....	−259.4 ± 0.1	−434.6 ± 0.2	−252.7	−422.9	3.45	15.0	27.0
Illinium	Il	61	147	....	.....	.....	.....	.....	....	....	....	....	....
Indium	In	49	114.76	7.31	0.264	15.7	156.4 ± 0.1	313.5 ± 0.2	....	....	0.057	....	....
Iodine	I	53	126.92	4.93	0.178	25.7	114 ± 1	237 ± 2	183	361	0.052	14.2	25.6
Iridium	Ir	77	193.1	22.5	0.813	8.58	2454 ± 3	4449 ± 5	5300	9600	0.031	....	....
Iron	Fe	26	55.85	7.87	0.284	7.10	1539 ± 3	2802 ± 5	2740	4960	0.11	65	117
Krypton	Kr	36	83.7	3.488×10^{-3}	0.126×10^{-3}	.....	−157 ± 0.5	−251 ± 0.9	−152	−242	....	....	....
Lanthanum	La	57	138.92	6.15	0.222	22.6	826 ± 5	1519 ± 9	....	....	0.045	....	....
Lead	Pb	82	207.21	11.34	0.4097	18.27	327.4 ± 0.1	621.3 ± 0.2	1740	3160	0.031	6.3	11.3
Lithium	Li	3	6.940	0.53	0.019	13	186 ± 5	367 ± 9	1370	2500	0.79	159	286
Lutecium	Lu	71	174.99	[a]9.74	[a]0.352	[a]18.0	.....	.....	....	....	....	....	....
Magnesium	Mg	12	24.32	1.74	0.0628	14.0	650 ± 2	1202 ± 4	1110	2030	0.25	89	160
Manganese	Mn	25	54.93	7.43	0.268	7.39	1245 ± 10	2273 ± 20	2150	3900	0.115	64	115
Mercury	Hg	80	200.61	13.55	0.4896	14.81	−38.87 ± 0.02	−37.97 ± 0.04	357	675	0.033	2.7	4.9
Molybdenum	Mo	42	95.95	10.2	0.369	9.41	2625 ± 50	4760 ± 90	4800	8670	0.061	70	126
Neodymium	Nd	60	144.27	7.05	0.255	20.5	840 ± 40	1540 ± 70	....	....	0.045	....	....
Neon	Ne	10	20.183	0.8387×10^{-3}	0.0303×10^{-3}	.....	−248.6 ± 0.3	−415.5 ± 0.5	−246.0	−410.8	....	....	....
Neptunium	Np	93	237	....	.....	.....	.....	.....	....	....	....	....	....
Nickel	Ni	28	58.69	8.90	0.322	6.59	1455 ± 1	2651 ± 2	2730	4950	0.105	74	133
Nitrogen	N	7	14.008	1.1649×10^{-3}	0.04209×10^{-3}	.....	−210.0 ± 0.1	−346.0 ± 0.2	−195.8	−320.4	0.247	6.2	11.2
Osmium	Os	76	190.2	22.5	0.813	8.46	2700 ± 200	4900 ± 350	5500	9900	0.031	....	....
Oxygen	O	8	16.0000	1.3318×10^{-3}	0.048118×10^{-3}	.....	−218.8 ± 0.1	−361.8 ± 0.2	−183.0	−297.4	0.218	3.3	5.9
Palladium	Pd	46	106.7	12.0	0.434	8.89	1554 ± 1	2829 ± 2	4000	7200	[m]0.058	34.2	61.6
Phosphorus (yellow)	P	15	30.98	1.82	0.0658	17.0	44.1 ± 0.1	111.4 ± 0.2	280	536	0.177	5.0	9.0
Platinum	Pt	78	195.23	21.45	0.7750	9.102	1773.5 ± 1	3224.3 ± 1.8	4410	7970	0.032	27	49
Plutonium	Pu	94	239	....	.....	.....	.....	.....	....	....	....	....	....
Polonium	Po	84	210	....	.....	.....	[a]600	[a]1100	....	....	....	....	....
Potassium	K	19	39.096	0.86	0.031	45	63 ± 1	145 ± 2	770	1420	0.177	14.5	26.1
Praseodymium	Pr	59	140.92	6.63	0.240	21.3	940 ± 50	1700 ± 90	....	....	0.048	....	....
Protoactinium	Pa	91	231	....	.....	.....	[a]3000	[a]5400	....	....	....	....	....
Radium	Ra	88	226.05	5.0	0.18	45	700	1300	....	....	....	....	....
Radon	Rn	86	222	[g]4.40	[g]0.159	[g]50.5	−71	−96	−61.8	−79.2	....	....	....
Rhenium	Re	75	186.31	20	0.72	9.3	3170 ± 60	5740 ± 110	....	....	0.033	....	....
Rhodium	Rh	45	102.91	12.44	0.4495	8.273	1966 ± 3	3571 ± 5	4500	8100	0.059	....	....
Rubidium	Rb	37	85.48	1.53	0.0553	55.9	39 ± 1	102 ± 2	680	1260	0.080	6.1	11.0
Ruthenium	Ru	44	101.7	12.2	0.441	8.33	2500 ± 100	4500 ± 180	4900	8850	[m]0.057	....	....
Samarium	Sm	62	150.43	7.7	0.28	19	>1300	>2370	....	....	....	....	....
Scandium	Sc	21	45.10	2.5	0.090	18	1200	2190	....	....	....	....	....
Selenium	Se	34	78.96	4.81	0.174	16.4	220 ± ▮	428 ± 9	680	1260	0.084	6.6	11.9
Silicon	Si	14	28.06	2.33	0.084	12.0	1430 ± 20	2605 ± 35	2300	4200	[m]0.162	337	607
Silver	Ag	47	107.880	10.49	0.3790	10.28	960.5 ± 0.0	1760.9 ± 0.0	2210	4010	[m]0.056	25	45
Sodium	Na	11	22.997	0.97	0.035	24	97.7 ± 0.2	207.9 ± 0.4	892	1638	0.295	27.5	49.5
Strontium	Sr	38	87.63	2.6	0.094	34	770 ± 10	1420 ± 20	1380	2520	0.176	25	45
Sulfur (yellow)	S	16	32.066	2.07	0.0748	15.5	[q]119.0 ± 0.5	[q]246.2 ± 0.9	444.6	832.3	0.175	9.3	16.7
Tantalum	Ta	73	180.88	16.6	0.600	10.9	2996 ± 50	5425 ± 90	....	....	[m]0.036	....	....
Technetium	Tc	43	99	....	.....	.....	[a]2700	[a]4900	....	....	....	....	....
Tellurium	Te	52	127.61	6.24	0.225	20.5	450 ± 10	840 ± 20	1390	2530	0.047	7.3	13.1
Terbium	Tb	65	159.2	[a]8.33	[a]0.301	[a]19.1	327 ± 5	621 ± 9	....	....	....	....	....
Thallium	Tl	81	204.39	11.85	0.4281	17.24	300 ± 3	572 ± 5	1460	2660	0.031	7.2	13.0
Thorium	Th	90	232.12	11.5	0.415	20.2	1800 ± 150	3300 ± 270	....	....	0.034	....	....
Thulium	Tm	69	169.4	[a]9.35	[a]0.338	[a]18.1	.....	.....	....	....	....	....	....
Tin	Sn	50	118.70	7.298	0.2637	16.26	231.9 ± 0.1	449.4 ± 0.2	2270	4120	0.054	14.5	26.1
Titanium	Ti	22	47.90	4.54	0.164	10.6	1820 ± 100	3300 ± 180	....	....	0.126	....	....
Tungsten	W	74	183.92	19.3	0.697	9.53	3410 ± 20	6170 ± 35	5930	10,700	0.032	44	79
Uranium	U	92	238.07	18.7	0.676	12.7	1130	2065	....	....	0.028	....	....
Vanadium	V	23	50.95	6.0	0.217	8.5	1735 ± 50	3150 ± 90	3400	6150	0.120	....	....
Xenon	Xe	54	131.3	5.495×10^{-3}	0.1985×10^{-3}	.....	−112 ± 1	−170	−108.0	−162.4	....	....	....
Ytterbium	Yb	70	173.04	[a]7.01	[a]0.253	[a]24.7	.....	.....	....	....	....	....	....
Yttrium	Y	39	88.92	5.51	0.199	16.1	1490 ± 200	2700 ± 350	....	....	....	....	....
Zinc	Zn	30	65.38	[r]7.133	[r]0.258	9.17	419.46	787.03	906	1663	0.0915	24.09	43.36
Zirconium	Zr	40	91.22	6.5	0.23	14	1750 ± 700	3200 ± 1300	...	....	0.066	....	....

(For footnotes, see page 19.)

Heat of Fusion, Btu per lb	Coefficient of Linear Thermal Expansion near 20 C, micro-in./°C	Coefficient of Linear Thermal Expansion near 68 F, micro-in./°F	Thermal Conductivity near 20 C, cal/sq cm/cm per deg Cent/sec	Electrical Resistivity, microhm-cm	Modulus of Elasticity in Tension, 10^6 psi	Crystal Structure	Lattice Constants at 20 C (68 F), kX-units† a	b	c or Axial Angle or Temp	Closest Approach of Atoms	Element
....	....	....	....	....	....	.....	.....	....	....	....	..... Actinium
170	(e)23.9	(e)13.3	0.53	2.655 (20 C)	10	Face-centered cubic	4.0408	....	....	2.856	... Aluminum
....	....	....	....	....	....	.....	.....	....	....	....	... Americium
68.9	(b)(c)8.5 to 10.8	(b)(c)4.7 to 6.0	0.045	39.0 (0 C)	11.3	Rhombohedral	4.4974	....	57°6.5′	2.898	.... Antimony
12	....	....	0.406 × 10^{-4}	....	....	Face-centered cubic	5.42	....	(−233 C)	3.83	..... Argon
....	4.7	2.6	....	35 (0 C)	....	Rhombohedral*	4.151	....	53°49′	2.50	..... Arsenic
....	....	....	....	....	....	.....	.....	....	....	....	..... Astatine
....	....	....	....	....	....	Body-centered cubic*	5.015	....	....	4.34	..... Barium
470	(j)12.4	(j) 6.9	0.38	5.9 (0 C)	37	Close-packed hexagonal*	2.2810	....	3.5771	2.221	.... Beryllium
22.5	13.3	7.4	0.020	106.8 (0 C)	4.6	Rhombohedral	4.7361	....	57°14.2′	3.105	..... Bismuth
....	(k)8.3	(k) 4.6	....	1.8 × 10^{12} (0 C)	....	Orthorhombic (?)	17.86	8.93	10.13	....	..... Boron
....	....	....	....	....	....	Orthorhombic	4.48	6.67	8.72 (−150 C)	2.27	..... Bromine
29.2	29.8	16.6	0.22	6.83 (0 C)	8	Close-packed hexagonal	2.9727	....	5.606	2.972	.... Cadmium
23.8	22	12	0.3	3.43 (0 C)	3	Face-centered cubic*	5.56	....	....	3.93	..... Calcium
....	(e)0.6 to 4.3	(e) 0.3 to 2.4	0.057	1375 (0 C)	0.7	Hexagonal*	2.4564	....	6.6906	1.42	..... Carbon (graphite)
....	....	....	....	78 (20 C)	....	Face-centered cubic*	5.143	....	....	3.64	..... Cerium
....	97	54	....	18.83 (0 C)	....	Body-centered cubic	6.05	....	(−173 C)	5.24	..... Cesium
6.8	....	....	0.172 × 10^{-4}	....	....	Tetragonal	8.56	....	6.12 (−185 C)	1.81	..... Chlorine
38.9	6.2	3.4	0.16	13 (28 C)	36	Body-centered cubic*	2.8787	....	....	2.493	.... Chromium
136	12.3	6.8	0.165	6.24 (20 C)	30	Close-packed hexagonal*	2.502	....	4.061	2.501	..... Cobalt
105	7.1	4.0	....	13.1 (18 C)	....	Body-centered cubic	3.2941	....	....	2.853	.. Columbium
....	16.5	9.2	0.94	1.673 (20 C)	16	Face-centered cubic	3.6080	....	....	2.551	..... Copper
91.1	....	....	....	....	....	.....	.....	....	....	....	..... Curium
....	....	....	....	....	....	Close-packed hexagonal	3.578	....	5.648	3.499	.. Dysprosium
....	....	....	....	....	....	Close-packed hexagonal*	3.532	....	5.589	3.459	..... Erbium
....	....	....	....	....	....	Body-centered cubic	4.573	....	....	3.960	.... Europium
18.2	....	....	....	....	....	.....	.....	....	....	....	..... Fluorine
....	....	....	....	....	....	.....	.....	....	....	....	.... Francium
....	....	....	....	....	....	Close-packed hexagonal	3.622	....	5.748	3.554	.. Gadolinium
34.6	18	10	....	53.4 (0 C)	....	One-face-centered orthorhombic	4.517	4.511	7.645	2.437	..... Gallium
....	....	....	....	89,000 (0 C)	....	Diamond cubic	5.647	....	....	2.445	.. Germanium
29.0	14.2	7.9	0.71	2.19 (0 C)	12	Face-centered cubic	4.0701	....	....	2.878	..... Gold
....	....	....	....	....	....	Close-packed hexagonal*	3.200	....	5.077	3.14	..... Hafnium
....	....	....	3.32 × 10^{-4}	....	....	Close-packed hexagonal (?)	3.57	....	5.83 (−271.5 C)	3.57	..... Helium
....	....	....	....	....	....	Close-packed hexagonal	3.557	....	5.620	3.480	..... Holmium
27.0	....	....	4.06 × 10^{-4}	....	....	Hexagonal	3.75	....	6.12 (−271 C)	....	.... Hydrogen
....	....	....	....	....	....	.....	.....	....	....	....	..... Illinium
....	33	18	0.057	8.37 (0 C)	....	Face-centered tetragonal	4.585	....	4.941	3.24	..... Indium
....	93	52	10.4 × 10^{-4}	1.3 × 10^{15} (20 C)	....	Orthorhombic	4.777	7.251	9.773	2.70	..... Iodine
25.6	6.8	3.8	0.14	5.3 (20 C)	75	Face-centered cubic	3.8312	....	....	2.709	..... Iridium
....	11.7	6.5	0.18	9.71 (20 C)	28.5	Body-centered cubic*	2.8606	....	....	2.476	..... Iron
117	....	....	0.21 × 10^{-4}	....	....	Face-centered cubic	5.68	....	(−191 C)	4.02	..... Krypton
....	....	....	....	59 (18 C)	....	Close-packed hexagonal*	3.754	....	6.063	3.73	.. Lanthanum
11.3	29.3	(e)16.3	0.083	20.65 (20 C)	2.6	Face-centered cubic	4.9395	....	....	3.493	..... Lead
286	56	31	0.17	8.55 (0 C)	....	Body-centered cubic	3.5019	....	....	3.033	..... Lithium
....	....	....	....	....	....	Close-packed hexagonal	3.509	....	5.559	3.439	..... Lutecium
160	25	(n)14	0.38	4.46 (20 C)	6.5	Close-packed hexagonal	3.2028	....	5.1998	3.190	.. Magnesium
115	23	12	....	185 (20 C)	23	Cubic* (complex)	8.894	....	....	2.24	... Manganese
4.9	....	....	0.0201	94.1 (0 C)	....	Rhombohedral	2.999	....	70°31.7′(−46 C)	2.999	..... Mercury
126	4.9	(e) 2.7	0.35	5.17 (0 C)	50	Body-centered cubic	3.140	....	....	2.720	. Molybdenum
....	....	....	....	79 (18 C)	....	Close-packed hexagonal*	3.650	....	5.890	3.62	.. Neodymium
....	....	....	0.00011	....	....	Face-centered cubic	4.52	....	(−268 C)	3.20	..... Neon
....	....	....	....	....	....	.....	.....	....	....	....	... Neptunium
133	13.3	(o) 7.4	0.22	6.84 (20 C)	30	Face-centered cubic	3.5167	....	....	2.486	..... Nickel
11.2	....	....	0.000060	....	....	Hexagonal*	4.03	....	6.59 (−234 C)	....	..... Nitrogen
....	4.6	2.6	....	9.5 (20 C)	80	Close-packed hexagonal	2.7298	....	4.3104	2.670	..... Osmium
5.9	....	....	0.000059	....	....	Cubic*	6.83	....	(−225 C)	....	..... Oxygen
61.6	11.8	6.6	0.17	10.8 (20 C)	17	Face-centered cubic	3.8824	....	....	2.745	.... Palladium
9.0	125	70	....	10^{17} (11 C)	....	Cubic*	7.17	....	(−35 C)	....	.. Phosphorus (yellow)
49	8.9	4.9	0.17	9.83 (0 C)	21	Face-centered cubic	3.9158	....	....	2.769	..... Platinum
....	....	....	....	....	....	.....	.....	....	....	....	.... Plutonium
....	....	....	....	....	....	(probably) Monoclinic ($\beta = 92°$)	7.42	4.29	14.10	3.4	.... Polonium
26.1	33	46	0.24	6.15 (0 C)	....	Body-centered cubic	5.333	....	....	4.618	.... Potassium
....	....	....	....	88 (18 C)	....	Close-packed hexagonal*	3.662	....	5.908	3.633	Praseodymium
....	....	....	....	....	....	.....	.....	....	....	....	Protoactinium
....	....	....	....	....	....	.....	.....	....	....	....	..... Radium
....	....	....	....	....	....	.....	.....	....	....	....	..... Radon
....	....	....	....	....	....	Close-packed hexagonal	2.7553	....	4.4493	2.734	..... Rhenium
....	8.3	(e) 4.6	0.21	4.5 (20 C)	42	Face-centered cubic*	3.7957	....	....	2.684	..... Rhodium
11.0	30	50	....	12.5 (20 C)	....	Body-centered cubic	5.62	....	(−173 C)	4.87	.... Rubidium
....	9.1	5.1	....	7.6 (0 C)	60	Close-packed hexagonal*	2.6984	....	4.2730	2.644	... Ruthenium
....	....	....	....	....	....	.....	.....	....	....	....	.... Samarium
....	....	....	....	....	....	Face-centered cubic*	4.532	....	....	3.205	.... Scandium
11.9	25	21	....	....	....	Hexagonal*	4.3552	....	4.9494	2.32	..... Selenium
607	7.3 to 7.3	1.6 to 4.1	0.20	10^5 (0 C)	16	Diamond cubic	5.4173	....	....	2.346	..... Silicon
45	10.7	(o)10.9	(m)1.0	1.59 (20 C)	11	Face-centered cubic	4.0774	....	....	2.882	..... Silver
49.5	32	39	0.32	4.2 (0 C)	....	Body-centered cubic	4.2820	....	....	3.708	..... Sodium
45	....	....	....	23 (20 C)	....	Face-centered cubic*	6.075	....	....	4.30	.... Strontium
16.7	64	36	6.31 × 10^{-4}	2 × 10^{23} (20 C)	....	Face-centered orthorhombic*	10.48	12.92	24.55	2.12	..... Sulfur (yellow)
....	8.5	3.6	0.13	12.4 (18 C)	27	Body-centered cubic	3.2959	....	....	2.854	.... Tantalum
....	....	....	....	....	....	.....	.....	....	....	....	.. Technetium
13.1	36.3	9.3	0.014	2 × 10^5 (19.6 C)	6	Hexagonal	4.4469	....	5.9149	2.86	.... Tellurium
....	....	....	....	....	....	Close-packed hexagonal	3.585	....	5.664	3.508	..... Terbium
13.0	28	16	0.093	18 (0 C)	....	Close-packed hexagonal*	3.450	....	5.514	3.401	..... Thallium
....	11.1	(c) 6.2	....	19 (20 C)	....	Face-centered cubic	5.077	....	....	3.59	..... Thorium
....	....	....	....	....	....	Close-packed hexagonal	3.523	....	5.564	3.446	..... Thulium
26.1	23	13	0.16	11.5 (20 C)	6	Body-centered tetragonal*	5.8194	....	3.1753	3.016	..... Tin
....	9.5	4.7	....	80 (0 C)	16.8	Close-packed hexagonal*	2.953	....	4.729	2.91	.... Titanium
79	4.3	2.4	0.48	5.5 (20 C)	50	Body-centered cubic*	3.1585	....	....	2.734	..... Tungsten
....	....	....	0.064	60 (18 C)	....	Orthorhombic*	2.852	5.865	4.945	2.76	..... Uranium
....	7.8	4.3	....	26 (20 C)	....	Body-centered cubic	3.033	....	....	2.627	.... Vanadium
....	....	....	1.24 × 10^{-4}	....	....	Face-centered cubic	6.24	....	(−185 C)	4.41	..... Xenon
....	....	....	....	....	....	Face-centered cubic	5.468	....	....	3.866	... Ytterbium
....	....	....	....	....	....	Close-packed hexagonal	3.663	....	5.814	3.59	..... Yttrium
43.36	30.2	22.1	0.27	(s)5.916 (20 C)	(t)	Close-packed hexagonal	2.659	....	4.935	2.659	..... Zinc
....	5	3	....	41.0 (0 C)	11	Close-packed hexagonal*	3.223	....	5.123	3.16	... Zirconium

(*For footnotes, see page 19.*)

Periodic Table of the Elements

	I							
	1 H 1.0080							2 He 4.003
O	I	II	III	IV	V	VI	VII	VIII
2 He 4.003	3 Li 6.940	4 Be 9.02	5 B 10.82	6 C 12.010	7 N 14.008	8 O 16.0000	9 F 19.00	10 Ne 20.183
10 Ne 20.183	11 Na 22.997	12 Mg 24.32	13 Al 26.97	14 Si 28.06	15 P 30.98	16 S 32.066	17 Cl 35.457	18 A 39.944

O	I a	II a	III a	IV a	V a	VI a	VII a	VIII a			I b	II b	III b	IV b	V b	VI b	VII b	VIII b
18 A 39.944	19 K 39.096	20 Ca 40.08	21 Sc 45.10	22 Ti 47.90	23 V 50.95	24 Cr 52.01	25 Mn 54.93	26 Fe 55.85	27 Co 58.94	28 Ni 58.69	29 Cu 63.54	30 Zn 65.38	31 Ga 69.72	32 Ge 72.60	33 As 74.91	34 Se 78.96	35 Br 79.916	36 Kr 83.7
36 Kr 83.7	37 Rb 85.48	38 Sr 87.63	39 Y 88.92	40 Zr 91.22	41 Cb 92.91	42 Mo 95.95	43 Tc 99	44 Ru 101.7	45 Rh 102.91	46 Pd 106.7	47 Ag 107.880	48 Cd 112.41	49 In 114.8	50 Sn 118.70	51 Sb 121.76	52 Te 127.61	53 I 126.92	54 Xe 131.3
54 Xe 131.3	55 Cs 132.91	56 Ba 137.36	57 La 138.92	58 to 71	72 Hf 178.6	73 Ta 180.88	74 W 183.92	75 Re 186.31	76 Os 190.2	77 Ir 193.1	78 Pt 195.23	79 Au 197.2	80 Hg 200.61	81 Tl 204.39	82 Pb 207.21	83 Bi 209.00	84 Po 210	85 At 211	86 Rn 222
86 Rn 222	87 Fa 223	88 Ra 226.05	89 Ac 227.05	90 Th 232.12	91 Pa 231	92 U 238.07	93 Np 237	94 Pu 239	95 Am 241	96 Cm 242								
0	1	2	3	4	5	6	7	8		9	10	11	12	13	14	15	16	17	18

58 Ce 140.13	59 Pr 140.92	60 Nd 144.27	61 147	62 Sm 150.43	63 Eu 152.0	64 Gd 156.9	65 Tb 159.2	66 Dy 162.46	67 Ho 164.94	68 Er 167.2	69 Tm 169.4	70 Yb 173.04	71 Lu 174.99	Rare Earth Metals

Linear Thermal Expansions of Metals and Alloys

THE NUMBERS in this table have been collected from the numerous articles and data sheets that record in detail the properties of metals in this Handbook. The values are collected here for the reader's convenience in making general comparisons. For more specific information concerning the expansion of SAE steels, the table on page 309 should be consulted. Additional data for nonferrous metals and alloys will be found under item D6 in the data sheets. Values given here are for as-cast, as-wrought or as-annealed material. The effects of thermal treatment, temperature range and other factors are indicated in the various places mentioned above.

Metal		Temperature, deg Cent	Coefficient of Expansion per deg Cent
	Aluminum and Aluminum Alloys		
			× 10⁻⁶
Aluminum (99.95%)		20 to 100	23.9
	Wrought		
2 S	99.0 Al	20 to 100	23.5
3 S	1.2 Mn	20 to 100	23.2
11 S	5.5 Cu, 0.5 Pb, 0.5 Bi	20 to 100	22.9
14 S	4.4 Cu, 0.8 Si, 0.8 Mn, 0.4 Mg	20 to 100	22.5
17 S	4 Cu, 0.5 Mn, 0.5 Mg	20 to 100	23.0
18 S	4 Cu, 2 Ni, 0.5 Mg	20 to 100	22.4
24 S	4.5 Cu, 1.5 Mg, 0.6 Mn	20 to 100	22.8
25 S	4.5 Cu, 0.8 Mn, 0.8 Si	20 to 100	22.8
32 S	12.5 Si, 1.0 Mg, 0.9 Cu, 0.9 Ni	20 to 100	19.4
A51 S	1.0 Si, 0.6 Mg, 0.25 Cr	20 to 100	23.1
53 S	2.5 Mg, 0.25 Cr	20 to 100	23.8
52 S	1.3 Mg, 0.7 Si, 0.25 Cr	20 to 100	22.9
56 S	5.2 Mg, 0.1 Mn, 0.1 Cr	20 to 100	24.3
61 S	1.0 Mg, 0.6 Si, 0.25 Cu, 0.25 Cr	20 to 100	23.5
75 S	5.5 Zn, 2.5 Mg, 1.5 Cu	20 to 100	23.2
	Cast		
43	5 Si	20 to 100	22.0
108	4 Cu, 3 Si	20 to 100	22.0
113	7 Cu, 2 Si, 1.7 Zn	20 to 100	22.0
122	10 Cu, 0.2 Mg	20 to 100	22.0
142	4 Cu, 2 Ni, 1.5 Mg	20 to 100	22.5
195	4.5 Cu	20 to 100	23.0
214	3.8 Mg	20 to 100	24.0
220	10 Mg	20 to 100	24.5
355	5 Si, 1.3 Cu, 0.5 Mg	20 to 100	22.0
356	7 Si, 0.3 Mg	20 to 100	21.5
A108	5.5 Si, 4.5 Cu	20 to 100	21.5
A132	12 Si, 2.5 Ni, 1.2 Mg, 0.8 Cu	20 to 100	19.0
B195	4.5 Cu, 2.5 Si	20 to 100	22.0
750	6.5 Si, 1 Cu, 1 Ni	20 to 100	23.1
13	12 Si	20 to 100	20.0
85	5 Si, 4 Cu	20 to 100	21.0
218	8 Mg	20 to 100	23.7
360	9.5 Si, 0.5 Mg	20 to 100	19.5
	Copper and Copper Alloys[a]		
Pure Copper		20 to 100	16.5
Electrolytic Tough Pitch Copper		20 to 300	17.7
Deoxidized Copper		20 to 300	17.7
	Wrought		
Gilding Metal, 95%		20 to 300	18.1
Commercial Bronze, 90%		20 to 300	18.4
Red Brass, 85%		20 to 300	18.7
Low Brass, 80%		20 to 300	19.1
Cartridge Brass, 70%		20 to 300	19.9
Muntz Metal		20 to 300	20.8
Leaded Commercial Bronze		20 to 300	18.4
Low-Leaded Brass		20 to 300	20.2
High-Leaded Brass		20 to 300	20.3
Free-Cutting Brass		20 to 300	20.5
Leaded Muntz Metal		20 to 300	20.8
Forging Brass		20 to 300	20.7
Architectural Bronze		20 to 300	20.9
Admiralty Metal		20 to 300	20.2
Naval Brass		20 to 300	21.2
Manganese Bronze		20 to 300	21.2
Aluminum Brass		20 to 300	18.5
Phosphor Bronze, 1.25% (E)		20 to 300	17.8
Phosphor Bronze, 5% (A)		20 to 300	17.8
Phosphor Bronze, 8% (C)		20 to 300	18.2
Phosphor Bronze, 10% (D)		20 to 300	18.4
Cupro-Nickel, 30%		20 to 300	16.2
Nickel Silver, 18% (A)		20 to 300	16.2
Nickel Silver, 18% (B)		20 to 300	16.7
Silicon Bronze, Type A		20 to 300	18.0
Silicon Bronze, Type B		20 to 300	17.9
Aluminum Bronze, 8%		20 to 300	18.2
Beryllium Copper		20 to 100	16.6
	Cast		
Leaded Tin Bronze		21 to 260	18.5
Leaded Tin Bearing Bronze		21 to 177	18.0
Ounce Metal		21 to 204	19.1
Leaded Yellow Brass		21 to 260	21.6
High Strength Yellow Brass		21 to 260	19.8
Leaded Manganese Bronze		21 to 204	20.5
Aluminum Bronze (89-1-10)		21 to 260	17.1
	Iron and Iron Alloys *See also page 309*		
			× 10⁻⁶
Pure Iron		20	11.7
Fe-C Alloys	0.06% C	20 to 100	11.7
	0.22% C	20 to 100	11.7
	0.40% C	20 to 100	11.3
	0.56% C	20 to 100	11.0
	1.08% C	20 to 100	10.8
	1.45% C	20 to 100	10.1
	1.97% C	20 to 100	9.9
	2.24% C	20 to 100	9.6
	3.66% C	20 to 100	8.6
Invar Fe, 36 Ni		r t	0 to 2
13 Mn, 1.2 C		r t	18
13 Cr, 0.35 C		20 to 100	10.0
12.3 Cr, 0.4 Ni, 0.09 C		20 to 100	9.8
17.7 Cr, 9.6 Ni, 0.06 C		20 to 100	16.5
18 W, 4 Cr, 1 V		[illegible] to 100	11.2
Gray Cast Iron		0 to 100	10.5
Malleable Iron		....	12
	Lead and Lead Alloys		
Pure Lead (99.73%)		17 to 100	29.3
1% Antimonial Lead		20 to 100	28.8
Hard Lead 96 Pb, 4 Sb		20 to 100	27.8
Hard Lead 94 Pb, 6 Sb		20 to 100	27.2
8% Antimonial Lead 92 Pb, 8 Sb		20 to 100	26.7
Grid Metal 91 Pb, 9 Sb		....	26.4
Lead-Base Babbitt 80 Pb, 15 Sb, 5 Sn		20 to 100	24.0
Lead-Base Babbitt 75 Pb, 15 Sb, 10 Sn		20 to 100	19.6
Tin-Lead Solder 95 Pb, 5 Sn		15 to 110	28.7
Tin-Lead Solder 80 Pb, 20 Sn		15 to 110	26.5
Half and Half 50 Pb, 50 Sn		15 to 110	23.4
	Magnesium and Magnesium Alloys[d]		
Pure Magnesium (99.80%)[d]		40	26
	Nickel and Nickel Alloys		
Pure Nickel (99.95 Ni + Co)		0 to 100	13.3
"A" Nickel (99.4 Ni + Co)		25 to 100	13.3
Cast Nickel 1.5 Si, 0.5 Mn, 0.5 C		25 to 100	13.0
"Z" Nickel 4.5 Al		0 to 100	13.0
Monel 30 Cu, 1.4 Fe, 1.0 Mn, 0.15 C		0 to 100	14.0
"K" Monel 29 Cu, 3 Al		25 to 100	14.0
"S" Monel 30 Cu, 4 Si, 2 Fe		21 to 100	12.2
Cast Monel 32 Cu, 1.6 Si, 0.2 C		25 to 100	12.9
Hastelloy A 20 Mo, 20 Fe		0 to 100	11.0
Hastelloy B 30 Mo, 5 Fe		0 to 100	10.0
Hastelloy C 17 Mo, 15 Cr, 5 W, 5 Fe		0 to 100	11.3
Hastelloy D 8 to 11 Si, 3 Cu		0 to 100	11.0
Inconel 14 Cr, 6 Fe		0 to 100	11.5
Chromel A 20 Cr		70 to 1000	17.6
Nichrome 24 Fe, 16 Cr		20 to 1000	17.0
Chromax 50 Fe, 15 Cr		20 to 500	15.8
Constantan 45 Ni		20 to 1000	18.8
	Tin and Tin Alloys		
Pure Tin		0 to 100	23.0
Soft Solder 70 Sn, 30 Pb		15 to 110	21.6
Eutectic Solder 63 Sn, 37 Pb		15 to 100	24.7
	Zinc and Zinc Alloys		
Pure Zinc		20 to 250	39.7
Zamak 3 4 Al, 0.04 Mg		20 to 100	27.4
Zamak 5 4 Al, 1 Cu, 0.04 Mg		20 to 100	27.4
Commercial Rolled Zinc 99 Zn, 0.08 Pb		20 to 40	32.5[b]
		20 to 40	23.[c]
Commercial Rolled Zinc 0.06 Pb, 0.06 Cd		20 to 40	32.5[b]
		20 to 40	23.[c]
Commercial Rolled Zinc 0.3 Pb, 0.3 Cd		20 to [illegible]	33.9[b]
		20 to 98	23.4[c]
	Miscellaneous Pure Metals		
Cadmium		20	29.8
Chromium		20	6.2
Cobalt		20 to 100	12.3
Gold		20	14.2
Molybdenum		25 to 100	4.9
Silver		0 to 100	19.7
Tungsten		20	4.3

(a) For compositions of copper alloys, see page 24. (b) With the grain. (c) Across the grain. (d) Approximately the same for all commercial magnesium alloys.

Densities of Metals and Alloys

THE NUMBERS in this table have been collected from articles and data sheets that record in detail the properties of metals in this Handbook. The values are collected here for the reader's convenience in making general comparisons. For further data on the densities of ferrous alloys, the table on page 312 should be consulted. Additional information concerning densities of nonferrous metals and alloys will be found under item C1 in the data sheets. Values listed here are for as-cast, as-wrought or as-annealed material. The effects of thermal treatment, mechanical working, temperature, and other factors are indicated in the various places mentioned above.

Metal and Composition		Density, g per cu cm	Density, lb per cu in.
Aluminum and Aluminum Alloys			
Wrought			
Aluminum	(99.996 Al)	2.699	0.09751
2 S	99.0+ Al	2.71	0.0979
3 S	1.2 Mn	2.73	0.0986
4 S	1.25 Mn, 1.0 Mg	2.72	0.0983
11 S	5.5 Cu, 0.5 Pb, 0.5 Bi	2.82	0.102
14 S	4.4 Cu, 0.8 Si, 0.8 Mn, 0.4 Mg	2.80	0.101
17 S	4 Cu, 0.5 Mg, 0.5 Mn	2.79	0.101
18 S	4 Cu, 2 Ni, 0.5 Mg	2.80	0.101
24 S	4.5 Cu, 1.5 Mg, 0.6 Mn	2.77	0.100
25 S	4.5 Cu, 0.8 Mn, 0.8 Si	2.79	0.101
32 S	12.5 Si, 1.0 Mg, 0.9 Cu, 0.9 Ni	2.69	0.0972
A51 S	1.0 Si, 0.6 Mg, 0.25 Cr	2.69	0.0972
52 S	2.5 Mg, 0.25 Cr	2.68	0.0968
53 S	1.3 Mg, 0.7 Si, 0.25 Cr	2.69	0.0972
56 S	5.2 Mg, 0.1 Mn, 0.1 Cr	2.64	0.0954
61 S	1.0 Mg, 0.6 Si, 0.25 Cu, 0.25 Cr	2.70	0.0975
75 S	5.5 Zn, 2.5 Mg, 1.5 Cu	2.80	0.101
R303	6.4 Zn, 2.5 Mg, 1.2 Cu	2.82	0.102
R301	4.5 Cu, 0.8 Si, 0.5 Mn, 0.4 Mg, clad	2.81	0.101
R317	4 Cu, 0.6 Mn, 0.6 Mg, 0.5 Bi, 0.5 Pb	2.81	0.101
Cast			
43	5 Si	2.69	0.0972
108	4 Cu, 3 Si	2.79	0.101
113	7 Cu, 2 Si, 1.7 Zn	2.91	0.105
122	10 Cu, 0.2 Mg	2.95	0.107
142	4 Cu, 2 Ni, 1.5 Mg	2.81	0.101
195	4.5 Cu	2.81	0.101
214	3.8 Mg	2.65	0.0957
220	10 Mg	2.58	0.0932
355	5 Si, 1.3 Cu, 0.5 Mg	2.70	0.0975
A355	5 Si, 1.4 Cu, 0.5 Mg, 0.7 Mn, 0.7 Ni	2.74	0.0990
Allcast	5 Si, 3 Cu	2.76	0.0997
356	7 Si, 0.3 Mg	2.68	0.0968
Red X-8	8 Si, 0.3 Mg, 0.3 Mn, 1.5 Cu	2.73	0.0986
40E	5.5 Zn, 0.6 Mg, 0.5 Cr, 0.2 Ti	2.81	0.101
A108	5.5 Si, 4.5 Cu	2.79	0.101
C113	7 Cu, 3.5 Si	2.91	0.105
A132	12 Si, 2.5 Ni, 1.2 Mg, 0.8 Cu	2.68	0.0968
Red X-13	1.5 Cu, 0.7 Mg, 0.7 Mn, 12 Si	2.7	0.098
B195	4.5 Cu, 2.5 Si	2.78	0.100
A214	3.8 Mg, 1.8 Zn	2.65	0.0957
750	6.5 Sn, 1 Cu, 1 Ni	2.89	0.104
13	12 Si	2.66	0.0961
85	5 Si, 4 Cu	2.78	0.100
218	8 Mg	2.53	0.0914
360	9.5 Si, 0.5 Mg	2.68	0.0968
380	8.5 Si, 3.5 Cu	2.76	0.0997
Cobalt and Cobalt Alloys			
Pure Cobalt		8.9	0.32
Cast			
"61" Alloy	23 Cr, 5 W, 2 Ni	8.54	0.309
Vitallium	27 Cr, 6 Mo, 2 Ni	8.30	0.300
"X-40" Alloy	23 Cr, 10 Ni, 7 W	8.61	0.311
"422-19" Alloy	23 Cr, 16 Ni, 6 Mo	8.31	0.300
"S-816" Alloy	20 Ni, 19 Cr, 4 W, 4 Mo, 4 Cb, 3 Fe	8.59	0.310
"6059" Alloy	32 Ni, 23 Cr, 6 Mo	8.21	0.297
Copper and Copper Alloys			
Pure Copper		8.96	0.324
Electrolytic Tough Pitch Copper	(99.92 Cu – 0.04 O)	8.92[a]	0.322[a]
Deoxidized or Phosphorized Copper	(99.94 Cu – 0.02 P)	8.94	0.323
Wrought			
Primer Gilding Metal	97 Cu, 3 Zn	8.89	0.321
Gilding Metal, 95%	95 Cu, 5 Zn	8.86	0.320
Commercial Bronze, 90%	90 Cu, 10 Zn	8.80	0.318
Red Brass, 85%	85 Cu, 15 Zn	8.75	0.316
Low Brass, 80%	80 Cu, 20 Zn	8.67	0.313
Brazing Brass, 75%	75 Cu, 25 Zn	8.59	0.310
Cartridge Brass, 70%	70 Cu, 30 Zn	8.53	0.308
Yellow Brass, 65%	65 Cu, 35 Zn	8.47	0.306
Muntz Metal, 60%	60 Cu, 40 Zn	8.39	0.303
Leaded Commercial Bronze	89 Cu, 1.75 Pb, 9.25 Zn	8.83	0.319
Leaded Red Brass	78.5 Cu, 1.5 Pb, 20 Zn	8.70	0.314
Low-Leaded Brass	67 Cu, 0.5 Pb, 32.5 Zn	8.50	0.307
Low-Leaded Brass	64.5 Cu, 0.5 Pb, 35 Zn	8.47	0.306
Medium-Leaded Brass	64.5 Cu, 1.0 Pb, 34.5 Zn	8.47	0.306
High-Leaded Brass	62.5 Cu, 1.75 Pb, 35.75 Zn	8.47	0.306
Extra-High-Leaded Brass	62.5 Cu, 2.5 Pb, 35 Zn	8.50	0.307
Free-Cutting Brass	61.5 Cu, 3 Pb, 35.5 Zn	8.50	0.307
Leaded Muntz Metal	60 Cu, 0.5 Pb, 39.5 Zn	8.41	0.304
Free-Cutting Muntz Metal	60.5 Cu, 1.1 Pb, 38.4 Zn	8.41	0.304
Forging Brass	60 Cu, Pb, 38 Zn	8.44	0.305
Copper and Copper Alloys (continued)			
Architectural Bronze	57 Cu, 3 Pb, 40 Zn	8.47	0.306
Admiralty Metal	71 Cu, 1 Sn, 28 Zn	8.63	0.308
Naval Brass	60 Cu, 0.75 Sn, 39.25 Zn	8.41	0.304
Leaded Naval Brass	60 Cu, 0.75 Sn, 1.75 Pb, 37.5 Zn	8.44	0.305
Manganese Bronze	58.5 Cu, 1 Sn, 1.4 Fe, 39 Zn, 0.1 Mn	8.53	0.308
Aluminum Brass	76 Cu, 22 Zn, 2 Al	8.33	0.301
Phosphor Bronze, 1.25% E	98.75 Cu, 1.25 Sn	8.89	0.321
Phosphor Bronze, 5% A	95 Cu, 5 Sn	8.86	0.320
Phosphor Bronze, 8% C	92 Cu, 8 Sn	8.80	0.318
Phosphor Bronze, 10% D	90 Cu, 10 Sn	8.78	0.317
Cupro-Nickel, 30%	70 Cu, 30 Ni	8.94	0.323
Nickel Silver, 18% A	65 Cu, 17 Zn, 18 Ni	8.73	0.315
Nickel Silver, 15%	Cu, 21 Zn, 15 Ni	8.69	0.314
Nickel Silver, 10%	65 Cu, 25 Zn, 10 Ni	8.68	0.313
Nickel Silver, 18% B	55 Cu, 27 Zn, 18 Ni	8.70	0.314
Nickel Silver, 15%	57 Cu, 28 Zn, 15 Ni	8.63	0.312
Nickel Silver, 25%	55 Cu, 20 Zn, 25 Ni	8.72	0.315
Nickel Silver, 30%	47 Cu, 23 Zn, 30 Ni	8.74	0.316
Silicon Bronze, Type A	97 Cu, 3 Si	8.53	0.308
Silicon Bronze, Type B	98.5 Cu, 1.5 Si	8.75	0.316
Aluminum Bronze, 5%	95 Cu, 5 Al	8.17	0.295
Cupro-Nickel, 15%	85 Cu, 15 Ni	8.94	0.323
Cupro-Nickel, 20%	80 Cu, 20 Ni	8.94	0.323
Constantan	55 Cu, 45 Ni	8.9	0.32
Cunife	60 Cu, 20 Fe, 20 Ni	8.61	0.311
Beryllium Copper	98 Cu, 2 Be	8.23	0.297
Cast			
Leaded Tin Bronze	88 Cu, 6 Sn, 1.5 Pb, 4.5 Zn	8.7	0.315
Leaded Tin Bearing Bronze	87 Cu, 10 Sn, 1 Pb, 2 Zn	8.80	0.318
High-Leaded Tin Bronze	85 Cu, 5 Sn, 9 Pb, 1 Zn	8.87	0.320
High-Leaded Tin Bronze	83 Cu, 7 Sn, 7 Pb, 3 Zn	8.93	0.323
High-Leaded Tin Bronze	80 Cu, 10 Sn, 10 Pb	8.80	0.318
High-Leaded Tin Bronze	78 Cu, 7 Sn, 15 Pb	9.25	0.334
High-Leaded Tin Bronze	70 Cu, 5 Sn, 25 Pb	9.30	0.336
Ounce or Composition Metal	85 Cu, 5 Sn, 5 Pb, 5 Zn	8.80	0.318
Leaded Red Brass	83 Cu, 4 Sn, 6 Pb, 7 Zn	8.6	0.311
Leaded Semi-Red Brass	81 Cu, 3 Sn, 9 Pb, 7 Zn	8.70	0.314
Leaded Semi-Red Brass	76 Cu, 3 Sn, 6 Pb, 15 Zn	8.6	0.311
Leaded Yellow Brass	71 Cu, 1 Sn, 3 Pb, 25 Zn	8.50	0.307
Leaded Yellow Brass	66 Cu, 1 Sn, 3 Pb, 30 Zn	8.4	0.303
Leaded Yellow Brass	60 Cu, 1 Sn, 1 Pb, 38 Zn	8.40	0.303
High-Strength Yellow Brass	62 Cu, 26 Zn, 3 Fe, 5.5 Al, 3.5 Mn	7.9	0.285
High-Strength Yellow Brass	58 Cu, 39.25 Zn, 1.25 Fe, 1.25 Al, 0.25 Mn	8.2	0.296
Leaded Manganese Bronze	59 Cu, 0.75 Sn, 0.75 Pb, 37 Zn, 1.25 Fe, 0.75 Al, 0.5 Mn	8.2	0.296
Nickel Silver	66 Cu, 5 Sn, 1.5 Pb, 2 Zn, 25 Ni	8.85[b]	0.320[b]
Nickel Silver, Dairy Bronze	64 Cu, 4 Sn, 4 Pb, 8 Zn, 20 Ni	8.85	0.320
Nickel Silver, Benedict Metal	57 Cu, 2 Sn, 9 Pb, 20 Zn, 12 Ni	8.95	0.323
Leaded Nickel Silver	60 Cu, 3 Sn, 5 Pb, 16 Zn, 16 Ni	8.95	0.323
Aluminum Bronze	89 Cu, 1 Fe, 10 Al	7.6	0.274
Aluminum Bronze	87.5 Cu, 3.5 Fe, 9 Al	7.4	0.267
Aluminum Bronze	86 Cu, 4 Fe, 10 Al	7.5	0.271
Iron and Iron Alloys			
See also page 312.			
Electrolytic iron		7.874	0.2845
Ingot iron		7.866	0.2842
Wrought iron		7.7	0.28
Gray cast iron		7.15[c]	0.258[c]
Malleable iron		7.27[d]	0.262[d]
0.06 Carbon steel		7.871	0.2844
0.23 Carbon steel		7.859	0.2839
0.435 Carbon steel		7.844	0.2834
1.22 Carbon steel		7.830	0.2829
18 Cr, 8 Ni stainless steel		7.93	0.286
25 Cr, 20 Ni stainless steel		7.98	0.288
12.5 Cr stainless steel		7.75	0.280
25 Cr stainless steel		7.60	0.273
18 W, 4 Cr, 1 V high speed steel		8.67	0.313
20 W, 4 Cr, 2 V, 12 Co high speed steel		8.89	0.321
6 W, 5 Mo, 2 V high speed steel		8.16	0.265
8 Mo, 1.5 W, 1 V high speed steel		7.88	0.285
Invar 36 Ni		8.00	0.289
Hipernik 50 Ni		8.25	0.298
4 Si		7.6	0.27
10.27 Si		6.97	0.252

(a) 8.89 to 8.94 g per cu cm and 0.322 to 0.323 lb per cu in.

(b) 8.80 to 8.90 g per cu cm and 0.318 to 0.322 lb per cu in.

(*continued on the next page*)

(continued)

Metal and Composition		Density g per cu cm	Density lb per cu in.
Lead and Lead Alloys			
Pure Lead (99.73+ Pb)		11.34	0.4097
Chemical Lead (99.90+ Pb)		11.34	0.4097
Cable Sheath Alloy	99.8 Pb, 0.028 Ca	11.34	0.4097
1% Antimonial Lead	99 Pb, 1 Sb	11.27	0.4071
Hard Lead	96 Pb, 4 Sb	11.04	0.3989
Hard Lead	94 Pb, 6 Sb	10.88	0.3931
8% Antimonial Lead	92 Pb, 8 Sb	10.74	0.3880
Grid Metal	91 Pb, 9 Sb	10.66	0.3848
ASTM-12 Bearing Metal	90 Pb, 10 Sb	10.67	0.3855
ASTM-11 Bearing Metal	85 Pb, 15 Sb	10.28	0 3714
Lead-Base Babbitt,	85 Pb, 10 Sb, 5 Sn	10.24	0.3700
"G" Lead-Base Babbitt	83 Pb, 12.75 Sb, 3 As, 0.75 Sn	10.1	0.365
"S" Lead-Base Babbitt	83 Pb, 15 Sb, 1 Sn, 1 As	10.1	0.365
ASTM-10 Bearing Metal	83 Pb, 15 Sb, 2 Sn	10.07	0.3638
Lead-Base Babbitt,	80 Pb, 15 Sb, 5 Sn	10.04	0.3627
Lead-Base Babbitt,	75 Pb, 15 Sb, 10 Sn	9.73	0.351
ASTM-6 Bearing Metal	63.5 Pb, 15 Sb, 20 Sn, 1.5 Cu	9.33	0.337
Tin-Lead Solder	95 Pb, 5 Sn	11.0	0.397
Tin-Lead Solder	80 Pb, 20 Sn	10.20	0.3685
50-50 Half and Half	50 Pb, 50 Sn	8.89	0.321
Magnesium and Magnesium Alloys			
Magnesium	(99.80)	1.74	0.0628
A10	10 Al, 0.1 Mn (w, sc, and pmc)	1.81	0.0654
AZ91	9 Al, 0.7 Zn, 0.2 Mn (die cast)	1.81	0.0654
AZ92	9 Al, 2 Zn, 0.1 Mn (sc and pmc)	1.82	0.0658
A8	8 Al, 0.2 Mn (sand cast)	1.80	0.0650
AZ61X	6 Al, 1 Zn, 0.2 Mn (wrought)	1.80	0.0650
AM244	4 Al, 0.2 Mn (sand cast)	1.76	0.0636
AM11	1.25 Al, 1 Mn (die cast)	1.70	0.0616
AZ80X	8.5 Al, 0.5 Zn, 0.15 Mn (wrought)	1.80	0.0650
AZ63	6 Al, 3 Zn, 0.2 Mn (sand cast)	1.84	0.0665
AZ51X	5 Al, 1 Zn, 0.25 Mn (wrought)	1.79	0.0647
AZ31X	3 Al, 1 Zn, 0.3 Mn (wrought)	1.78	0.0643
M1	1.5 Mn (wrought)	1.76	0.0636
TA54	5 Sn, 3 Al, 0.5 Mn (wrought)	1.84	0.0665
Mg-Al Alloys	98 Mg, 2 Al	1.75	0.0632
	96 Mg, 4 Al	1.77	0.0639
	94 Mg, 6 Al	1.78	0.0643
	92 Mg, 8 Al	1.80	0.0650
	90 Mg, 10 Al	1.81	0.0654
	88 Mg, 12 Al	1.82	0.0658
Nickel and Nickel Alloys			
Nickel	(99.95 Ni + Co)	8.902	0.3216
"A" Nickel	(99.4 Ni + Co)	8.885	0.3210
Cast Nickel	97 Ni, 1.5 Si, 0.5 Mn, 0.5 C	8.34	0.301
"D" Nickel	95.2 Ni, 4.5 Mn	8.78	0.317
"Z" Nickel	94 Ni, 4.5 Al	8.75	0.316
Monel	67 Ni, 30 Cu, 1.4 Fe, 1.0 Mn, 0.15 C	8.84	0.319
Cast Monel	63 Ni, 32 Cu, 1.6 Si, 0.2 C	8.63	0.312
"K" Monel	66 Ni, 29 Cu, 3 Al	8.47	0.306
"S" Monel	63 Ni, 30 Cu, 4 Si, 2 Fe	8.36	0.302
Hastelloy A	60 Ni, 20 Mo, 20 Fe	8.80	0.318
Hastelloy B	65 Ni, 30 Mo, 5 Fe	9.24	0.334
Hastelloy C	58 Ni, 17 Mo, 15 Cr, 5 W, 5 Fe	8.94	0.323
Hastelloy D	85 Ni, 8 to 11 Si, 3 Cu	7.8	0.28
Illium G	58 Ni, 22 Cr, 6 Cu, 6 Mo, 6 Fe, 0.2 C	8.58	0.310
Inconel	80 Ni, 14 Cr, 6 Fe	8.51	0.307
Cast Inconel	77.5 Ni, 13.5 Cr, 6 Fe, 2 Si	8.3	0.30
Chromel A	80 Ni, 20 Cr	8.4	0.30
Nichrome	60 Ni, 16 Cr, 24 Fe	8.25	0.298
Chromax	35 Ni, 15 Cr, 50 Fe	7.95	0.287
Constantan	45 Ni, 55 Cu (wrought)	8.9	0.32
	45 Ni, 55 Cu (cast)	8.6	0.31
Ni-Fe Alloys	90 Ni, 10 Fe	8.8	0.32
	80 Ni, 20 Fe	8.6	0.31
	70 Ni, 30 Fe	8.5	0.31
	60 Ni, 40 Fe	8.35	0.302
Permalloy	78 Ni, 22 Fe	8.6	0.31
Mumetal	76 Ni, 16 Fe, 6 Cu, 2 Cr	8.6	0.31
Tin and Tin Alloys			
Pure Tin		7.298	0.2637
Soft Solder:	70 Sn, 30 Pb	8.32	0.301
Soft Solder, Eutectic Solder	63 Sn, 37 Pb	8.42	0.304
Tin Babbitt, ASTM-1	91 Sn, 4.5 Sb, 4.5 Cu	7.34	0.265
Tin Babbitt, ASTM-2	89 Sn, 7.5 Sb, 3.5 Cu	7.39	0.267
Tin Babbitt, ASTM-3	83 Sn, 8.3 Sb, 8.3 Cu	7.46	0.269
Tin Babbitt, ASTM-4	75 Sn, 12 Sb, 10 Pb, 3 Cu	7.75	0.280
Tin Babbitt, ASTM-5	65 Sn, 15 Sb, 18 Pb, 2 Cu	7.52	0.272
Zinc and Zinc Alloys			
Pure Zinc		7.133	0.2577
Zamak 2, ASTM XXI (dc)	92 Zn, 4 Al, 3 Cu, 0.03 Mg	6.7	0.24
Zamak 3, ASTM XXIII	95 Zn, 4 Al, 0.04 Mg	6.6	0.24
Zamak 5, ASTM XXV	94 Zn, 4 Al, 1 Cu, 0.04 Mg	6.7	0.24
SAE 63, T-11 (cast)	86 Zn, 10 Cu, 4 Al	6.9	0.25
Commercial Rolled Zinc	99 Zn, 0.08 Pb	7.14	0.258
Commercial Rolled Zinc	99 Zn, 0.06 Pb, 0.06 Cd	7.14	0.258
Commercial Rolled Zinc	99 Zn, 0.3 Pb, 0.3 Cd	7.14	0.258
Zilloy 40 (rolled)	98 Zn, 1 Cu, 0.08 Pb	7.18	0.259
Zilloy 15 (rolled)	98 Zn, 1 Cu, 0.1 Pb, 0.01 Mg	7.18	0.259

(c) 6.95 to 7.35 g per cu cm and 0.251 to 0.265 lb per cu in.
(d) 7.20 to 7.34 g per cu cm and 0.260 to 0.265 lb per cu in.

Metal and Composition		Density g per cu cm	Density lb per cu in.
Sintered Carbides			
97 WC, 3 Co		15.25	0.5510
95.5 WC, 4.5 Co		15.05	0.5438
94 WC, 6 Co		14.85	0.5365
91 WC, 9 Co		14.60	0.5275
87 WC, 13 Co		14.15	0.5112
80 WC, 20 Co		13.55	0.4896
Predominantly WC with TaC and 13 Co		13.90	0.5022
Predominantly WC with TaC and 6 Co		14.70	0.5311
Predominantly WC with TiC and 6 Co		11.20	0.4047
Predominantly WC, less TiC and 8 Co		12.80	0.4625
Predominantly WC, TaC, TiC, 8 Co		11.7	0.423
Predominantly WC, TaC, TiC, 11 Co		11.6	0.419
Predominantly WC, TaC, TiC, 15 Co		11.4	0.412
Precious Metals			
Gold		19.32	0.6984
69 Au, 25 Ag, 6 Pt		16.11	0.5820
10-Carat	41.5 Au, 11.7 Ag, 46.8 Cu	11.2	0.405
	41.6 Au, 6.8 Ag, 44.3 Cu, 7.3 Ni	11.55	0.4173
	41.6 Au, 4.6 Ag, 43.4 Cu, 5.0 Ni, 5.4 Zn	11.60	0.4190
12-Carat	50.0 Au, 4.0 Ag, 37.1 Cu, 4.3 Ni, 4.6 Zn	12.17	0.4397
	50.0 Au, 42.0 Cu, 6.0 Ni, 2.0 Zn	12.19	0.4404
14-Carat	58.3 Au, 3.3 Ag, 31.0 Cu, 3.5 Ni, 3.9 Zn	12.37	0.4469
	58.3 Au, 4.9 Ag, 31.6 Cu, 5.2 Ni	13.08	0.4726
Iridium		22.5	0.813
Osmium		22.5	0.813
Palladium		12.02	0.4343
Pd, 4 to 5 Ru		12.0	0.434
Pd, 40 Ag		11.3	0.408
Pd, 40 Cu		10.6	0.383
Platinum		21.45	0.7750
Pt-Ru Alloys	Pt, 5 Ru	20.67	0.7468
	Pt, 10 Ru	19.94	0.7204
Pt-Ir Alloys	Pt, 5 Ir	21.49	0.7764
	Pt, 10 Ir	21.53	0.7779
	Pt, 25 Ir	21.66	0.7826
Pt-Rh Alloys	Pt, 3.5 Rh	20.9	0.755
	Pt, 18.74 Rh	18.74	0.6771
Pt-Ni Alloys	Pt, 1 Ni	21.1	0.762
	Pt, 2 Ni	20.8	0.751
	Pt, 5 Ni	20.0	0.723
96 Pt, 4 W		21.3	0.770
84 Pt, 10 Pd, 6 Ru		18.1	0.654
Rhodium		12.44	0.4495
Ruthenium		12.2	0.441
Silver		10.49	0.3790
Ag-Cd Alloys	Ag, 2.5 Cd	10.43	0.3768
	Ag, 5.0 Cd	10.387	0.3753
	Ag, 10 Cd	10.29	0.3718
	Ag, 15 Cd	10.18	0.3678
Ag-CdO Materials	Ag, 2.5 CdO	10.38	0.3750
	Ag, 5.0 CdO	10.24	0.3700
	Ag, 10 CdO	9.97	0.3602
	Ag, 15 CdO	9.75	0.352
Ag-Graphite	Ag, 1 graphite	9.9	0.36
	Ag, 2 graphite	9.65	0.349
	Ag, 4 graphite	9.0	0.325
	Ag, 7 graphite	8.0	0.29
Ag-Mo Alloys	Ag, 20 Mo	10.42	0.3765
	Ag, 40 Mo	10.38	0.3750
	Ag, 60 Mo	10.35	0.3739
	Ag, 80 Mo	10.27	0.3710
Ag-W Alloys	Ag, 10 W	10.95	0.3956
	Ag, 20 W	11.52	0.4162
	Ag, 30 W	12.2	0.441
	Ag, 40 W	12.87	0.4650
	Ag, 50 W	13.6	0.491
	Ag, 70 W	15.4	0.556
	Ag, 90 W	17.8	0.643
Silmanal	86.75 Ag, 8.8 Mn, 4.45 Al	8.996	0.3250
Miscellaneous Pure Metals			
Antimony		6.62	0.239
Beryllium		1.816	0.0658
Bismuth		9.8	0.35
Cadmium		8.65	0.313
Calcium		1.55	0.056
Chromium		7.19	0.260
Cobalt		8.9	0.32
Columbium		8.57	0.3096
Gallium		5.91	0.214
Lithium		0.53	0.019
Manganese		7.43	0.268
Molybdenum		10.2	0.369
Rhenium		20	0.72
Selenium		4.81	0.174
Silicon		2.33	0.0842
Strontium		2.6	0.094
Tantalum		16.6	0.600
Tellurium		6.24	0.225
Thallium		11.85	0.428
Thorium		11.5	0.415
Titanium		4.54	0.164
Tungsten		19.3	0.697
Uranium		18.7	0.676
Vanadium		6.0	0.217
Zirconium		6.5	0.234

Thermal Conductivities of Metals and Alloys

THE NUMBERS in this table have been collected from articles and data sheets that record in detail the properties of metals in this Handbook. The values are collected here for the reader's convenience in making general comparisons. For further data on the thermal conductivities of ferrous alloys, the table on page 314 should be consulted. Additional information concerning thermal conductivities of nonferrous metals and alloys will be found under item D16 in the data sheets. Values listed here are for as-cast, as-wrought or as-annealed material. The effects of thermal treatment, mechanical working, and other factors are indicated in the various sections.

Metal	Thermal Conductivity near Room Temperature, cal/sq cm/cm/°C/sec	watt/cm/°C	Btu/sq ft/in/°F/sec
Aluminum and Aluminum Alloys			
Wrought			
2 S (99.0+ Al)	0.53	2.2	0.43
3 S 1.2 Mn	0.46	1.9	0.37
11 S 5.5 Cu, 0.5 Pb, 0.5 Bi	0.37	1.55	0.30
14 S 4.4 Cu, 0.8 Si, 0.8 Mn, 0.4 Mg	0.46	1.9	0.37
17 S 4 Cu, 0.5 Mg, 0.5 Mn	0.41	1.7	0.33
18 S 4 Cu, 2 Ni, 0.5 Mg	0.46	1.9	0.37
24 S 4.5 Cu, 1.5 Mg, 0.6 Mn	0.45	1.9	0.36
25 S 4.5 Cu, 0.8 Mn, 0.8 Si	0.37	1.55	0.30
32 S 12.5 Si, 1.0 Mg, 0.9 Cu, 0.9 Ni	0.37	1.55	0.30
A51 S 1.0 Si, 0.6 Mg, 0.25 Cr	0.50	2.1	0.40
52 S 2.5 Mg, 0.25 Cr	0.33	1.4	0.27
53 S 1.3 Mg, 0.7 Si, 0.25 Cr	0.41	1.7	0.33
56 S 5.2 Mg, 0.1 Mn, 0.1 Cr	0.28	1.2	0.23
61 S 1.0 Mg, 0.6 Si, 0.25 Cu, 0.25 Cr	0.41	1.7	0.33
75 S 5.5 Zn, 2.5 Mg, 1.5 Cu	0.29	1.2	0.23
Cast			
43 5 Si	0.35	1.5	0.28
108 4 Cu, 3 Si	0.29	1.2	0.23
113 7 Cu, 2 Si, 1.7 Zn	0.28	1.2	0.23
122 10 Cu, 0.2 Mg	0.38	1.6	0.31
142 4 Cu, 2 Ni, 1.5 Mg	0.40	1.7	0.32
195 4.5 Cu	0.33	1.4	0.27
214 3.8 Mg	0.33	1.4	0.27
356 7 Si, 0.3 Mg	0.35	1.5	0.28
220 10 Mg	0.21	0.88	0.17
A108 5.5 Si, 4.5 Cu	0.34	1.4	0.27
A132 12 Si, 2.5 Ni, 1.2 Mg, 0.8 Cu	0.28	1.2	0.23
B195 4.5 Cu, 2.5 Si	0.33	1.4	0.27
A214 3.8 Mg, 1.8 Zn	0.31	1.3	0.25
13 12 Si	0.37	1.55	0.30
85 5 Si, 4 Cu	0.27	1.1	0.22
218 8 Mg	0.25	1.05	0.20
360 9.5 Si, 0.5 Mg	0.35	1.5	0.28
380 8.5 Si, 3.5 Cu	0.26	1.1	0.21
750 6.5 Sn, 1 Cu, 1 Ni	0.42	1.8	0.34
Copper and Copper Alloys			
Pure Copper	0.941	3.94	0.759
Electrolytic Tough Pitch Copper	0.934	3.91	0.753
Deoxidized Copper (99.94 Cu, 0.02 P)	0.81	3.4	0.65
Wrought			
Gilding Metal 95 Cu, 5 Zn	0.56	2.3	0.45
Commercial Bronze 90 Cu, 10 Zn	0.45	1.9	0.36
Red Brass 85 Cu, 15 Zn	0.38	1.6	0.31
Low Brass 80 Cu, 20 Zn	0.33	1.4	0.27
Cartridge Brass 70 Cu, 30 Zn	0.29	1.2	0.23
Yellow Brass 65 Cu, 35 Zn	0.29	1.2	0.23
Muntz Metal 60 Cu, 40 Zn	0.29	1.2	0.23
Leaded Commercial Bronze 89 Cu, 1.75 Pb, 9.25 Zn	0.43	1.8	0.34
Low-Leaded Brass 67 Cu, 0.5 Pb, 32.5 Zn	0.28	1.2	0.23
Medium-Leaded Brass 64.5 Cu, 1.0 Pb, 34.5 Zn	0.28	1.2	0.23
High-Leaded Brass 62.5 Cu, 1.75 Pb, 35.75 Zn	0.28	1.2	0.23
Free-Cutting Brass 61.5 Cu, 3 Pb, 35.5 Zn	0.28	1.2	0.23
Free-Cutting Muntz Metal 60.5 Cu, 1.1 Pb, 38.4 Zn	0.28	1.2	0.23
Forging Brass 60 Cu, 2 Pb, 38 Zn	0.28	1.2	0.23
Architectural Bronze 57 Cu, 3 Pb, 40 Zn	0.29	1.2	0.23
Admiralty Metal 71 Cu, 1 Sn, 28 Zn	0.26	1.1	0.21
Naval Brass 60 Cu, 0.75 Sn, 39.25 Zn	0.28	1.2	0.23
Manganese Bronze 58.5 Cu, 1 Sn, 1.4 Fe, 39 Zn, 0.1 Mn	0.26	1.1	0.21
Aluminum Brass 76 Cu, 22 Zn, 2 Al	0.24	1.0	0.19
Phosphor Bronze, 1.25% E 98.75 Cu, 1.25 Sn	0.49	2.05	0.39
Phosphor Bronze, 5% A 95 Cu, 5 Sn	0.19	0.79	0.15
Phosphor Bronze, 8% C 92 Cu, ▮ Sn	0.15	0.63	0.12
Phosphor Bronze, 10% D 90 Cu, 10 Sn	0.12	0.50	0.10
Nickel Silver, 18% A 65 Cu, 18 Ni, 17 Zn	0.09	0.38	0.07
Nickel Silver, 18% ▮ 55 Cu, 18 Ni, 27 Zn	0.07	0.29	0.06
Silicon Bronze, Type A 97 Cu, 3 Si	0.09	0.38	0.07
Silicon Bronze, Type B 98.5 Cu, 1.5 Si	0.14	0.59	0.11
Aluminum Bronze, 5% 95 Cu, ▮ Al	0.198	0.828	0.160
Aluminum Bronze 90 Cu, 10 Al	0.144	0.602	0.116
Aluminum Bronze 82.5 Cu, 2.5 Fe, 10 Al, 5 Ni	0.091	0.38	0.073
Cupro-Nickel, 15% 85 Cu, 15 Ni	0.112	0.468	0.0903
Cupro-Nickel, 20% 80 Cu, 20 Ni	0.087	0.36	0.070
Cupro-Nickel, 30% 70 Cu, 30 Ni	0.07	0.29	0.06
Beryllium Copper 98 Cu, ▮ Be	0.20	0.84	0.16
Cast			
Leaded Tin Bearing Bronze 87 Cu, 10 Sn, 1 Pb, 2 Zn	0.11	0.46	0.090
High-Leaded Tin Bronze 80 Cu, 10 Sn, 10 Pb	0.11	0.46	0.090
High-Strength Yellow Brass 62 Cu, 26 Zn, 5.5 Al, 3.5 Mn, 3 Fe	0.12	0.50	0.10
Aluminum Bronze 89 Cu, 10 Al, 1 Fe	0.13	0.54	0.105
Iron and Iron Alloys *See also page 314.*			
Pure Iron	0.178	0.745	0.144
Cast Iron 3.16 TC, 1.54 Si, 0.57 Mn	0.112	0.469	0.0903
Carbon Steel 0.23 C, 0.635 Mn	0.124	0.519	0.100
Carbon Steel 1.22 C, 0.35 Mn	0.108	0.452	0.0871
Alloy Steel 0.34 C, 0.55 Mn, 0.78 Cr, 3.53 Ni, 0.39 Mo, 0.05 Cu	0.079	0.33	0.064
Stainless Steel 410 12 Cr	0.057	0.24	0.046
Stainless Steel 304 18 Cr, 8 Ni	0.036	0.15	0.029
W-Cr-V Steel 0.715 C, 0.25 Mn, 4.26 Cr, 18.45 W, 1.075 V	0.058	0.24	0.047
Lead and Lead Alloys			
Pure Lead (99.73+ Pb)	0.083	0.347	0.067
1% Antimonial Lead 99 Pb, 1 Sb	0.080	0.33	0.067
Hard Lead 96 Pb, 4 Sb	0.073	0.30	0.059
Hard Lead 94 Pb, 6 Sb	0.069	0.29	0.056
8% Antimonial Lead 92 Pb, 8 Sb	0.065	0.27	0.052
Grid Metal, 91 Pb, 9 Sb	0.064	0.27	0.052
Lead-Base Babbitt, 15 Sb, 5 Sn	0.058	0.24	0.047
Lead-Base Babbitt 15 Sb, 10 Sn	0.057	0.24	0.046
Tin-Lead Solder 95 Pb, 5 Sn	0.085	0.35	0.068
Tin-Lead Solder 80 Pb, 20 Sn	0.089	0.38	0.072
Half and Half 50 Pb, 50 Sn	0.111	0.464	0.0895
Magnesium and Magnesium Alloys			
Pure Magnesium (99.80 Mg)	0.376	1.57	0.303
A10 10 Al, 0.1 Mn	0.17	0.71	0.14
AZ91 9 Al, 0.7 Zn, 0.2 Mn	0.17	0.71	0.14
AZ92 9 Al, 2 Zn, 0.1 Mn	0.17	0.71	0.14
A8 8 Al, 0.2 Mn	0.18	0.75	0.14
AZ61X 6 Al, 1 Zn, 0.2 Mn	0.19	0.79	0.15
AM244 4 Al, 0.2 Mn	0.23	0.96	0.19
AZ80X 8.5 Al, 0.5 Zn, 0.15 Mn	0.18	0.75	0.14
AZ63 6 Al, 3 Zn, 0.2 Mn	0.18	0.75	0.14
AZ51X 5 Al, 1 Zn, 0.25 Mn	0.21	0.88	0.17
AZ31X 3 Al, 1 Zn, 0.3 Mn	0.23	0.96	0.19
M1 1.5 Mn	0.30	1.25	0.24
Nickel and Nickel Alloys			
Pure Nickel (99.95 Ni + Co)	0.22	0.92	0.18
"A" Nickel (99.4 Ni + Co)	0.145	0.607	0.117
"D" Nickel 95.2 Ni, 4.5 Mn	0.115	0.481	0.0927
Monel 30 Cu, 1.4 Fe, 1.0 Mn	0.062	0.25	0.050
"K" Monel 66 Ni, 29 Cu, 3 Al	0.045	0.19	0.036
Hastelloy A 60 Ni, 20 Mo, 20 Fe	0.04	0.17	0.03
Hastelloy B 65 Ni, 30 Mo, 5 Fe	0.027	0.11	0.022
Hastelloy C 58 Ni, 17 Mo, 15 Cr, 5 W, 5 Fe	0.03	0.13	0.02
Hastelloy D 85 Ni, ▮ to 11 Si, 3 Cu	0.05	0.21	0.04
Inconel 80 Ni, 14 Cr, 6 Fe	0.036	0.15	0.029
Chromel A 80 Ni, 20 Cr	0.032	0.13	0.026
Nichrome 60 Ni, 24 Fe, 16 Cr	0.0325	0.136	0.0262
Constantan 55 Cu, 45 Ni	0.0546	0.228	0.0440
Chromax 35 Ni, 15 Cr, 50 Fe	0.031	0.130	0.025
Tin and Tin Alloys			
Pure Tin	0.157	0.657	0.127
Soft Solder 63 Sn, 37 Pb	0.121	0.506	0.0976
Tin Foil 92 Sn, 8 Zn	0.141	0.590	0.114
Zinc and Zinc Alloys			
Pure Zinc	0.27	1.1	0.22
Zamak 2 92 Zn, 4 Al, 3 Cu, 0.03 Mg	0.25	1.05	0.20
Zamak 3 95 Zn, 4 Al, 0.04 Mg	0.27	1.1	0.22
Zamak 5 94 Zn, 4 Al, 1 Cu, 0.04 Mg	0.26	1.1	0.21
Commercial Rolled Zinc 0.08 Pb	0.257	1.075	0.207
Commercial Rolled Zinc 0.06 Pb, 0.06 Cd	0.257	1.075	0.207
Zilloy 15 98 Zn, 1 Cu, 0.01 Mg	0.25	1.05	0.20
Precious Metals			
Gold	0.71	2.97	0.57
Palladium	0.168	0.703	0.135
Platinum	0.165	0.690	0.133
Silver	1.0	4.2	0.81

Heat Contents Above 25 C (77 F)

COMPILED BY K. K. KELLEY*

	deg Cent deg Fahr	100 212	200 392	300 572	400 752	500 932	600 1112	800 1472	1000 1832	1200 2192	1400 2552	1600 2912	1800 3272
		Calories per gram[a]											
Aluminum		16.2	39.2	63.4	88.6	115	143(*s*)	291(*l*)	343	....	....	....	....
Antimony		3.8	8.9	14.1	19.5	25.1	30.8(*s*)	82.0(*l*)	94.4	....	....	....	....
Argon		9.3	21.8	34.2	46.6	59.1	71.5	96.4	121	146	171	196	221
Arsenic		5.9	14.3	22.8	31.5	40.6	50.0	70.2	....	....	....	....	....
Beryllium		33.0	84.9	141	201	264	329	465	604	....	....	....	....
Bismuth		2.3	5.5(*s*)	20.8(*l*)	24.4	28.0	31.6	38.7	45.9	....	....	....	....
Boron		19.8	51.5	89.0	130	176	224	328	434	....	....	....	....
Bromine		4.1	9.6	15.1	20.7	26.3	31.9	43.2	54.6	65.9	....	....	....
Cadmium		4.2	10.0	16.1(*s*)	35.3(*l*)	41.6	47.9	60.6	....	....	....	....	....
Calcium		11.8	28.5	46.5	64.9(α) 67.7(β)	85.9	104	143	....	....	....	....	....
Carbon (graphite)		14.7	39.8	70.2	104	142	182	265	353	444	537	634	735
Cerium		3.5	8.4	13.8	19.6	25.8	....	....	....	....	....	....	....
Cesium		8.3(*l*)	14.3	....	....	....	....	....	....	....	....	....	....
Chlorine		8.7	20.6	32.6	44.9	57.2	69.6	94.6	120	145	170	195	220
Chromium		8.7	21.1	34.1	47.5	61.2	75.6	107	140	175	211(*s*)	329(*l*)	....
Cobalt		8.0	18.8	30.5	42.9	55.8	69.1	97.0	128	161	197(*s*)	298(*l*)	....
Columbium		4.8	11.3	17.9	24.7	31.6	38.5	52.6	67.4	82.6	98.0	114	....
Copper		6.9	16.5	26.3	36.3	46.5	56.9	78.7	101(*s*)	174(*l*)	197	221	....
Fluorine		15.1	36.1	57.8	79.9	102	125	171	217	263	310	356	403
Gallium		26.4(*l*)	36.1	....	....	....	....	....	....	....	....	....	....
Gold		2.3	5.5	8.7	11.9	15.2	18.6	25.5	32.8(*s*)	55.0(*l*)	62.1	....	....
Helium		93.1	217	341	465	590	714	962	1210	1459	1707	1955	2203
Hydrogen		257	604	950	1299	1648	2000	2714	3446	4200	4972	5764	6574
Indium		4.3(*s*)	17.3(*l*)	....	....	....	....	....	....	....	....	....	....
Iodine		4.0(*s*)	64.7(*g*)	68.2	71.7	75.2	78.7	85.8	92.8	99.8	....	....	....
Iridium		2.4	5.5	8.8	12.2	15.6	19.0	26.2	33.7	41.4	49.5	58.0	....
Iron		8.3	20.1	33.0	47.2	62.3	78.8(*a*)	123(β)	161(γ)	193	227(γ)	332(*l*)	....
Krypton		4.5	10.4	16.3	22.3	28.2	34.1	46.0	57.9	69.8	81.6	93.5	105
Lanthanum		3.6	8.6	13.6	18.8	24.0	....	....	....	....	....	....	....
Lead		2.3	5.5	8.8(*s*)	18.0(*l*)	21.3	24.6	31.2	37.7	....	....	....	....
Lithium		64.4	....	....	....	....	....	....	....	....	....	....	....
Magnesium		18.4	44.4	71.4	99.7	129	159(*s*)	267(*l*)	....	....	....	....	....
Manganese		9.2	21.7	34.9	48.8	63.5	79.0(*a*)	121(β)	154	209(δ)	313(*l*)	353	393
Mercury		2.5	5.8	9.1(*l*)	81.8(*g*)	84.2	86.7	91.7	....	....	....	....	....
Molybdenum		4.7	11.0	17.3	23.9	30.5	37.4	51.5	66.1	81.0	96.7	113	....
Neodymium		3.8	9.3	15.1	21.3	27.9	34.8	....	....	....	....	....	....
Neon		18.5	43.1	67.7	92.3	117	142	191	240	289	338	388	437
Nickel		8.2	20.1	33.3(*a*)	46.7(β)	59.4	72.2	98.4	126	155	185(β)	288(*l*)	....
Nitrogen		18.6	43.6	69.0	94.8	121	148	204	262	320	380	441	502
Osmium		2.4	5.5	8.7	12.0	15.4	18.8	25.6	32.6	39.9	47.4	55.0	....
Oxygen		16.5	39.2	62.7	86.8	111	137	189	242	296	351	407	463
Palladium		4.3	10.3	16.5	22.8	29.1	35.5	48.9	63.0	77.3	92.2	....	....
Phosphorus (white)		18.9(*l*)	....	....	....	....	....	....	....	....	....	....	....
Platinum		2.4	5.7	8.9	12.3	15.8	19.3	26.6	34.1	41.8	49.8	58.0	....
Potassium		28.9(*l*)	48.9	68.8	....	....	....	....	....	....	....	....	....
Radon		1.7	3.9	6.1	8.4	10.6	12.9	17.3	21.8	26.3	30.8	35.3	39.7
Rhenium		2.4	5.7	9.2	12.7	16.3	19.9	27.3	34.9	43.0	....	....	....
Rhodium		4.5	10.6	16.9	23.5	30.2	37.2	52.1	67.6	83.8	101	118	....
Rubidium		12.9(*l*)	....	....	....	....	....	....	....	....	....	....	....
Ruthenium		4.3	10.0	15.9	21.9	28.2	34.5	47.8	61.6(*a*)	76.4(β)	90.5(γ)	108(δ)	....
Selenium		5.9	15.2(*s*)	41.7(*l*)	....	....	....	....	....	....	....	....	....
Silicon		13.4	32.4	52.8	73.7	95.1	117	161	....	....	....	....	....
Silver		4.2	9.9	15.9	21.9	27.9	34.2	47.4(*s*)	87.6(*l*)	101	115	128	....
Sodium		49.6(*l*)	82.2	....	....	....	....	....	....	....	....	....	....
Sulfur		16.0(*m*)	48.0(*l*)	73.0	99.6	....	....	....	....	....	....	....	....
Tantalum		2.5	5.9	9.3	12.7	16.3	19.9	27.2	34.6	42.2	50.1	58.2	....
Tellurium		3.5	8.5	13.6	18.9	....	....	....	....	....	....	....	....
Thallium		2.4	5.4(*a*)	9.5(β)	18.5(*l*)	....	....	....	....	....	....	....	....
Thorium		2.5	6.0	9.5	13.1	16.7	20.5	28.5	37.2	46.6	....	....	....
Tin		4.2	10.1(*s*)	30.8(*l*)	36.9	43.1	49.2	61.5	73.8	....	....	....	....
Titanium		9.6	22.5	36.3	50.5	65.4	80.7	113(*a*)	165(β)	196	....	....	....
Tungsten		2.5	5.7	9.0	12.4	15.8	19.2	26.3	33.5	41.0	48.6	56.3	....
Uranium		2.1	....	....	....	....	....	....	....	....	....	....	....
Vanadium		9.0	21.5	34.2	47.1	60.4	74.0	102	132	164	200	238	....
Xenon		2.8	6.6	10.4	14.2	18.0	21.8	29.3	36.9	44.5	52.0	59.6	67.2
Zinc		7.0	16.7	26.9	37.4(*s*)	75.7(*l*)	87.2	110	133	....	....	....	....
Zirconium		5.0	12.0	19.2	26.9	35.0	43.5	....	....	....	....	....	....

(a) Multiply by 1.8 to convert to Btu per lb. (*s*) = solid, (*l*) = liquid, (*g*) = gas, (*m*) = monoclinic.

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The Greek Alphabet

Alpha	= A, α	= A, a
Beta	= B, β	= B, b
Gamma	= Γ, γ	= G, g
Delta	= Δ, δ	= D, d
Epsilon	= E, ε	= E, e
Zeta	= Z, ζ	= Z, z
Eta	= H, η	= E, e
Theta	= Θ, θ	= Th, th
Iota	= I, ι	= I, i
Kappa	= K, κ	= K, k
Lambda	= Λ, λ	= L, l
Mu	= M, μ	= M, m
Nu	= N, ν	= N, n
Xi	= Ξ, ξ	= X, x
Omicron	= O, ο	= O, o
Pi	= Π, π	= P, p
Rho	= P, ρ	= R, r
Sigma	= Σ, σ, ς	= S, s
Tau	= T, τ	= T, t
Upsilon	= Υ, υ	= U, u
Phi	= Φ, φ	= Ph, ph
Chi	= X, χ	= Ch, ch
Psi	= Ψ, ψ	= Ps, ps
Omega	= Ω, ω	= O, o

Vapor Pressures of the Elements*

Element	Pressure, atmospheres: 0.0001 °C	0.0001 °F	0.001 °C	0.001 °F	0.01 °C	0.01 °F	0.1 °C	0.1 °F	0.50 °C	0.50 °F	1.0 °C	1.0 °F
Aluminum	1110	2030	1263	2305	1461	2662	1713	3115	1940	3524	2056	3733
Antimony	759	1398	872	1602	1013	1855	1196	2185	1359	2478	1440	2624
Arsenic	308	586	363	685	428	802	499	930	578	1072	610	1130
Bismuth	914	1677	1008	1846	1121	2050	1254	2289	1367	2493	1420	2588
Cadmium	*(s)* 307	585	*(l)* 384	723	471	880	594	1101	708	1306	765	1409
Calcium	688	1270	(β) 802	1476	*(l)* 958	1756	1175	2147	1380	2516	1487	2709
Carbon	3257	5895	3547	6417	3897	7047	4317	7803	4667	8433	4827	8721
Chromium	*(s)* 1420	2588	*(l)* 1594	2901	1813	3295	2097	3807	2351	4264	2482	4500
Copper	1412	2574	1602	2916	1844	3351	2162	3924	2450	4442	2595	4703
Gallium	1178	2152	1329	2424	1515	2759	1751	3184	1965	3569	2071	3760
Gold	1623	2953	1839	3342	2115	3839	2469	4476	2796	5065	2966	5371
Iron	1564	2847	1760	3200	2004	3639	2316	4201	2595	4703	2735	4955
Lead	815	1499	953	1747	1135	2075	1384	2523	1622	2952	1744	3171
Lithium	592	1098	707	1305	858	1576	1064	1947	1266	2311	1372	2502
Magnesium	516	961	*(s)* 608	1126	*(l)* 725	1337	886	1627	1030	1886	1107	2025
Manganese	(γ) 1115	2039	*(l)* 1269	2316	1476	2889	1750	3182	2019	3666	2151	3904
Mercury	*(l)* 77.9	172.2	120.8	249.4	176.1	349.0	251.3	484.3	321.5	610.7	357	675
Molybdenum	2727	4941	3057	5535	3477	6291	4027	7281	4537	8199	4804	8679
Nickel	1586	2887	1782	3240	2025	3677	2321	4210	2593	4699	2732	4950
Platinum	2367	4293	2687	4869	3087	5589	3637	6579	4147	7497	4407	7965
Potassium	261	502	332	630	429	804	565	1051	704	1299	774	1425
Rubidium	223	433	288	550	377	711	497	927	617	1143	679	1254
Selenium	282	540	347	657	430	806	540	1004	634	1173	680	1256
Silicon	1572	2862	1707	3105	1867	3393	2057	3735	2217	4023	2287	4149
Silver	1169	2136	1334	2433	1543	2809	1825	3317	2081	3778	2212	4014
Sodium	349	660	429	804	534	993	679	1254	819	1506	892	1638
Strontium	....	....	*(s)*	....	*(l)* 877	1629	1081	1978	1279	2334	1384	2523
Tellurium	*(s)*	....	*(l)* 509	948	632	1170	810	1490	991	1816	1087	1989
Thallium	692	1277	809	1488	962	1764	1166	2131	1359	2478	1457	2655
Tin	....	....	....	....	....	....	*(l)* 1932	3510	2163	3925	2270	4118
Tungsten	3547	6417	3937	7119	4437	8019	5077	9171	5647	10197	5927	10701
Zinc	*(s)* 399	750	*(l)* 477	891	579	1074	717	1323	842	1548	907	1665

* K. K. Kelley, Bureau of Mines Bulletin 383, 1935. The symbols *l* and *s* refer to the liquid and solid states, respectively.

Properties of Refractories

THE PROPERTIES listed in Table I refer to pure materials and not to commercial refractories, which may differ because of impurities, bonding materials and process of manufacture. However, the data for specific heat, thermal expansion and thermal conductivity, in Table I, may be used for engineering purposes, especially the data marked with an asterisk(*), which were obtained from commercial products.

Table II presents some chemical and physical properties of certain refractories that are used commercially.

Table I. Properties of Refractory Materials, Except Fire Clay*

COMPILED BY STUART M. PHELPS

Material	Composition of the Pure Material: Formula	Percentage	Melting Point: °C	°F	True Specific Gravity	Hardness (Moh's scale)	Mean Specific Heat[a]	Thermal Expansion[b]	Thermal Conductivity[c]: 1000 F	1600 F	2400 F
Beryllium oxide	BeO	BeO 100	2530[d]	4586[d]	3.0	9	0.29	7.5 (25-800 C)	....	....	....
Chromite	$FeO.Cr_2O_3$[e]	Cr_2O_3 ..... 68 FeO 32	2180	3956	4.5	5.5	0.22*	8.0*	12.6*	12.7*	13.2*
Corundum	Al_2O_3	Al_2O_3 100	2050	3722	4.0[f]	9	0.304*	8.5	16.5*[g]	16.3*[g]	15.3*[g]
Diasporite (Diaspore)[i]	$Al_2O_3.H_2O$	Al_2O_3 .... 85.1 H_2O 14.9	2050	3722	3.4 to 3.5	6.5 to 7	0.26 Approx	6.5*	11.6*[j]	10.9*[j]	10.0*[j]
Dolomite	$CaCO_3.MgCO_3$	CaO ..... 30.4 MgO .... 21.9 CO_2 ..... 47.7	[k]	[k]	2.81 to 2.95	3.5 to 4.0	0.222[l]	14.0	....	....	....
Forsterite	$2MgO.SiO_2$	MgO .... 57.3 SiO_2 .... 42.7	1910	3470	3.22	6 to 7	0.22[l]	10.5*	11.3*	10.6*	9.7*
Graphite	C	C 100	>3000	>5432	2.25	1 to 2	0.29	2.2	4.5	3.1	2.2 (2000 F)
Kyanite[h]	$Al_2O_3SiO_2$	Al_2O_3 ...62.85 SiO_2 .... 37.15	1810	3290	3.6	4 to 7	1.7 Approx	5.4*	10.6*	11.0*	....
Magnesia spinel	$MgO.Al_2O_3$	MgO .... 28.2 Al_2O_3 ....71.8	2135	3875	3.6	8	0.257	8.5	12.2*	13.3*	14.5*
Mullite	$3Al_2O_3.2SiO_2$	Al_2O_3 .....71.8 SiO_2 .... 28.2	1830	3326	3.16	Probably 6 to 8	0.175[m]	5.3[n]	16.6[p]	14.2[p]	13.2[p] (2000 F)
Periclase (Magnesia)[q]	MgO	MgO 100	2800	5072	3.6	5.5 to 6.0	0.285	13.5[q]	27.6*[q]	22.9*[q]	20.0*[q]
Quartz[r] (Quartzite)	SiO_2	Silica 100	1400[s]	2552[s]	2.65	7	0.263*	32.6*[t] 4.6*[u]	9.6*	11.6*	14.4*
Silicon carbide	SiC	Si ..... 70 C 30	2250[v]	4082[v]	3.17 to 3.21	9 to 10	0.19[w]	5.2*[x]	75.5*[x]	82.5*[x]	92.3*[x]
Zircon (Zirconium silicate)	$ZrO_2.SiO_2$	ZrO_2 .... 67.1 SiO_2 .... 32.9	2500	4532	4.7	7.5	0.132[y]	4.5	19.9*	16.3*	14.2* (2000 F)
Zirconia (Zirconium oxide)	ZrO_2	Zr ..... 73.9 O_2 ..... 26.1	2700	4892	5.5 to 6.0	6.5	0.16	6.6[z]	12.0*	13.0*	14.0*

(*) Property of commercial product. Data not marked with an asterisk refer to pure materials.

(a) For the range 20 to 1000 C (68 to 1832 F) unless indicated otherwise by footnote.

(b) Mean reversible thermal expansion per °C times 10^{-6}, for the range 20 to 1000 C (68 to 1832 F) unless noted

(c) Thermal conductivity in Btu/sq ft/in./°F/hr, average from the more reliable data

(d) Approximate

(*notes continued at the bottom of page 29*)

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Table II. Chemical and Physical Properties of Commercial Refractories

COMPILED BY F. H. NORTON*

Material	Theoretical Composition	Reaction with Basic Fluxes[a]	Reaction with Acid Fluxes[a]	Resistance to Oxidation	Resistance to Reduction
Alumina (fused)	Al_2O_3	Fairly rapid with fluid slags. Slow in cement kilns	Fairly slow	Good	Not affected
Carbon	C	Slow	Slow	Low above red heat	Not affected
Chromite	$FeO.Cr_2O_3$	Slow	Slow	Low above red heat	Reduced to ferrochromium at high temp
Fire clay	$2SiO_2.Al_2O_3$	Rapid	Slow except at high temp	Good	Not affected
Forsterite	$2MgO.SiO_2$	Fairly slow	Fairly slow	Good	Not affected
Graphite	C	Slow	Slow	Good	Not affected
High alumina (diaspore)	$Al_2O_3.H_2O$	Fairly rapid with fluid slags. Slow in cement kilns	Slow at low and medium temp	Good	Same as alumina
Magnesite	MgO	Slow	Rapid except at low temp	Good	Reduced to Mg at high temp
Mullite	$2SiO_2.3Al_2O_3$	Rapid	Fairly slow	Good	Not affected
Porcelain (refractory)	$2SiO_2.3Al_2O_3$	Rapid	Fairly slow	Good	Not affected
Silica (fused)	SiO_2	Rapid	Slow	Good	Not affected except at high temp
Silica (ganister)	SiO_2	Rapid	Slow	Good	Same as fused silica
Silicon carbide	SiC	Fairly rapid	Slow	Fair above red heat	Not affected
Spinel	$MgO.Al_2O_3$	Slow	Fairly rapid	Good	Not affected
Zircon (electrically fused)	$ZrO_2.SiO_2$	Fairly rapid	Slow	Good	Not affected except at high temp
Zirconia (electrically fused)	ZrO_2	Fairly slow	Slow	Good	Forms carbides at high temp

Material	Fusion Point,[b] °F	Temp (°F) for 10% deformation under 25 psi	Mean Coef Linear Expansion between room temp and shrink. temp $\times 10^{-6}$/°F	Specific Gravity	Weight of a Std 9-in. Brick	Resistance to Spalling	Hardness (Moh's Scale)	Specific Heat (0–1200 F)
Alumina (fused)	3725	3100-3200	0.43	4.0	8.5	Fair	9	0.23
Carbon	Very high	.....	0.30	1.7-2.0	.....	Excellent	.....	0.30
Chromite	3450-3950	2550-2900	0.56	4.3-4.5	11	Poor	5.5	0.22
Fire clay	2730-3150	2550-2850	0.25-0.30	2.6-2.75	7.5-8.5	Good	2.5	0.23
Forsterite	3430	.....	.....	3.2-3.3	9.0	Fair	6-7	0.25
Graphite	Very high	.....	0.43	2.1-2.3	.....	Excellent	1-2	0.30
High alumina (diaspore)	3100-3350	2820	0.28	3.0-3.5	8.0	Good	6.5-7	0.23
Magnesite	3990-5070	2550 (sheared)	0.56-0.83	3.4-3.6	10.0	Poor	5-5.5	0.27
Mullite	3270	3150	0.30	3.0	8.5	Good	6-6.5	0.18
Porcelain (refractory)	2900-3250	.....	0.30	2.7-3.0	.....	Good	6-6.5	0.18
Silica (fused)	Devitrifies at 2000	.....	0.03	2.2	.....	Excellent	7	0.23
Silica (ganister)	3100-3180	3000	5.60-0.46	2.3-2.5	6.0	Good at high temp only	7	0.23
Silicon carbide	(decomposes)	3180	0.24	3.1-3.3	9	Excellent	9.5	0.20
Spinel	3450-3800	2700-2900	0.42	3.5	10	Poor	7.5-8	0.25
Zircon (electrically fused)	4000-4600	.....	0.22	4.7	12.5	Excellent	7.5	.....
Zirconia (electrically fused)	4500-4800	.....	0.30-0.80	5.7	15	Fair	6.5-7.5	0.20

Material	Thermal Conductivity,[c] Btu/sq ft/in./° F/hr							Electrical resistivity,[d] ohm-cm		
	200 F	400 F	800 F	1200 F	1600 F	2000 F	2400 F	1300 F	2200 F	2700 F
Alumina (fused)	19	20	22	24	27	30	32	.....	.....	.....
Carbon	25	....	....	....	....	....	....	.....	.....	.....
Chromite	5	6	7	8	10	11	12	.....	.....	.....
Fire clay	5	6	7	8	10	11	12	30,000	1,000	600
Forsterite	....	6	7	8	10	11	12	.....	.....	.....
Graphite	....	600	....	....	....	....	....	.....	.....	.....
High alumina (diaspore)	[illegible]	6	7	8	10	11	12	35,000	900	.....
Magnesite	45	40	35	31	27	25	24	.....	100,000	2,000
Mullite	....	8	9	10	12	13	14	.....	50,000	3,000
Porcelain (refractory)	....	14	15	17	18	19	20	80,000 500,000	.....	.....
Silica (fused)	14	....	....	....	....	....	....	10,000,000	500,000	.....
Silica (ganister)	6	7	8	9	11	12	13	80,000	16,000	5,000
Silicon carbide (recrystallized)	....	170	140	120	100	90	80	.....	2.5	1.6
Spinel	....	10	11	12	13	14	15	.....	.....	.....
Zircon	....	....	....	11 to 14		....	....	140,000	.....	.....
Zirconia	....	8	9	10	12	13	14	.....	2,000	400
Kaolin refractory insulator	1.2	1.3	1.6	2.0	2.6	3.1	3.2	.....	.....	.....
Block insulator	0.6	0.7	0.8	....	....	....	....	.....	.....	.....

(a) The slag resistance of a refractory is influenced by the physical as well as the chemical properties of the material. Therefore, a dense nonporous structure without flaws is desirable.

(b) The fusion point of refractories is sometimes reported in terms of cone numbers (PCE), but these numbers are not precise, and the use of the Fahrenheit scale is recommended for engineering work.

(c) The figures for thermal conductivity are not exact; there is considerable variation in the published results.

(d) The values for electrical resistivity are approximate; small amounts of impurities influence the resistivity greatly.

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Notes for Table I (continued)

(e) General chemical formula for chromite is $RO.R_2O_3$. The RO oxide is usually FeO and may be replaced in part by MgO; the R_2O_3 is mostly Cr_2O_3, but may be replaced in part by Al_2O_3 and Fe_2O_3.

(f) Alpha modification

(g) 90% alumina brick

(h) Other aluminum silicates of the same chemical composition are andalusite and sillimanite.

(i) Commercial diaspore is composed of diasporite grains bonded with clay.

(j) For diaspore brick containing 75% alumina, and having a porosity of about 30%

(k) Dissociates at very high temperatures

(l) For the range 20 to 100 C (68 to 212 F)

(m) For the range 20 to 800 C (68 to 1472 F)

(n) Synthetic, pure

(p) From a virtually pore-free body

(q) Magnesia is amorphous, or crystalline (periclase), depending on heat treatment. (Thermal expansion and conductivity data on commercial brick)

(r) Ganister is the commercial form used for refractories (about 98% silica).

(s) Cristobalite is the stable form of silica above 1470 C; melting point 1713 C (3115 F).

(t) Silica brick, mean expansion in range 20 to 300 C (68 to 572 F)

(u) Quartz, mean expansion in range 300 to 1135 C (572 to 2075 F)

(v) Dissociation temperature; oxidation may begin at 900 C (1652 F).

(w) Varies with temperature

(x) Clay-bonded silicon carbide

(y) For the range 21 to 51 C (70 to 124 F)

(z) Sintered pure material

Temperature Conversions

The general arrangement of this table was devised by Sauveur and Boylston more than 25 years ago. The middle column of figures (in bold-faced type) contains the reading (°F or °C) to be converted. If converting from degrees Fahrenheit to degrees Centigrade, read the Centigrade equivalent in the column headed "C". If converting from degrees Centigrade to degrees Fahrenheit, read the Fahrenheit equivalent in the column headed "F".

F		C	F		C	F		C	F		C	F		C
.....	−458	−272.22	.....	−308	−188.89	−252.4	−158	−105.56	+17.6	−8	−22.22	287.6	142	61.11
.....	−456	−271.11	.....	−306	−187.78	−248.8	−156	−104.44	+21.2	−6	−21.11	291.2	144	62.22
.....	−454	−270.00	.....	−304	−186.67	−245.2	−154	−103.33	+24.8	−4	−20.00	294.8	146	63.33
.....	−452	−268.89	.....	−302	−185.56	−241.6	−152	−102.22	+28.4	−2	−18.89	298.4	148	64.44
.....	−450	−267.78	.....	−300	−184.44	−238.0	−150	−101.11	+32.0	±0	−17.78	302.0	150	65.56
.....	−448	−266.67	.....	−298	−183.33	−234.4	−148	−100.00	+35.6	+2	−16.67	305.6	152	66.67
.....	−446	−265.56	.....	−296	−182.22	−230.8	−146	−98.89	+39.2	+4	−15.56	309.2	154	67.78
.....	−444	−264.44	.....	−294	−181.11	−227.2	−144	−97.78	+42.8	+6	−14.44	312.8	156	68.89
.....	−442	−263.33	.....	−292	−180.00	−223.6	−142	−96.67	+46.4	+8	−13.33	316.4	158	70.00
.....	−440	−262.22	.....	−290	−178.89	−220.0	−140	−95.56	+50.0	+10	−12.22	320.0	160	71.11
.....	−438	−261.11	.....	−288	−177.78	−216.4	−138	−94.44	+53.6	+12	−11.11	323.6	162	72.22
.....	−436	−260.00	.....	−286	−176.67	−212.8	−136	−93.33	+57.2	+14	−10.00	327.2	164	73.33
.....	−434	−258.89	.....	−284	−175.56	−209.2	−134	−92.22	+60.8	+16	−8.89	330.8	166	74.44
.....	−432	−257.78	.....	−282	−174.44	−205.6	−132	−91.11	+64.4	+18	−7.78	334.4	168	75.56
.....	−430	−256.67	.....	−280	−173.33	−202.0	−130	−90.00	+68.0	+20	−6.67	338.0	170	76.67
.....	−428	−255.56	.....	−278	−172.22	−198.4	−128	−88.89	+71.6	+22	−5.56	341.6	172	77.78
.....	−426	−254.44	.....	−276	−171.11	−194.8	−126	−87.78	+75.2	+24	−4.44	345.2	174	78.89
.....	−424	−253.33	.....	−274	−170.00	−191.2	−124	−86.67	+78.8	+26	−3.33	348.8	176	80.00
.....	−422	−252.22	−457.6	−272	−168.89	−187.6	−122	−85.56	+82.4	+28	−2.22	352.4	178	81.11
.....	−420	−251.11	−454.0	−270	−167.78	−184.0	−120	−84.44	+86.0	+30	−1.11	356.0	180	82.22
.....	−418	−250.00	−450.4	−268	−166.67	−180.4	−118	−83.33	+89.6	+32	±0.00	359.6	182	83.33
.....	−416	−248.89	−446.8	−266	−165.56	−176.8	−116	−82.22	+93.2	+34	+1.11	363.2	184	84.44
.....	−414	−247.78	−443.2	−264	−164.44	−173.2	−114	−81.11	+96.8	+36	+2.22	366.8	186	85.56
.....	−412	−246.67	−439.6	−262	−163.33	−169.6	−112	−80.00	+100.4	+38	+3.33	370.4	188	86.67
.....	−410	−245.56	−436.0	−260	−162.22	−166.0	−110	−78.89	+104.0	+40	+4.44	374.0	190	87.78
.....	−408	−244.44	−432.4	−258	−161.11	−162.4	−108	−77.78	107.6	42	5.56	377.6	192	88.89
.....	−406	−243.33	−428.8	−256	−160.00	−158.8	−106	−76.67	111.2	44	6.67	381.2	194	90.00
.....	−404	−242.22	−425.2	−254	−158.89	−155.2	−104	−75.56	114.8	46	7.78	384.8	196	91.11
.....	−402	−241.11	−421.6	−252	−157.78	−151.6	−102	−74.44	118.4	48	8.89	388.4	198	92.22
.....	−400	−240.00	−418.0	−250	−156.67	−148.0	−100	−73.33	122.0	50	10.00	392.0	200	93.33
.....	−398	−238.89	−414.4	−248	−155.56	−144.4	−98	−72.22	125.6	52	11.11	395.6	202	94.44
.....	−396	−237.78	−410.8	−246	−154.44	−140.8	−96	−71.11	129.2	54	12.22	399.2	204	95.56
.....	−394	−236.67	−407.2	−244	−153.33	−137.2	−94	−70.00	132.8	56	13.33	402.8	206	96.67
.....	−392	−235.56	−403.6	−242	−152.22	−133.6	−92	−68.89	136.4	58	14.44	406.4	208	97.78
.....	−390	−234.44	−400.0	−240	−151.11	−130.0	−90	−67.78	140.0	60	15.56	410.0	210	98.89
.....	−388	−233.33	−396.4	−238	−150.00	−126.4	−88	−66.67	143.6	62	16.67	413.6	212	100.00
.....	−386	−232.22	−392.8	−236	−148.89	−122.8	−86	−65.56	147.2	64	17.78	417.2	214	101.11
.....	−384	−231.11	−389.2	−234	−147.78	−119.2	−84	−64.44	150.8	66	18.89	420.8	216	102.22
.....	−382	−230.00	−385.6	−232	−146.67	−115.6	−82	−63.33	154.4	68	20.00	424.4	218	103.33
.....	−380	−228.89	−382.0	−230	−145.56	−112.0	−80	−62.22	158.0	70	21.11	428.0	220	104.44
.....	−378	−227.78	−378.4	−228	−144.44	−108.4	−78	−61.11	161.6	72	22.22	431.6	222	105.56
.....	−376	−226.67	−374.8	−226	−143.33	−104.8	−76	−60.00	165.2	74	23.33	435.2	224	106.67
.....	−374	−225.56	−371.2	−224	−142.22	−101.2	−74	−58.89	168.8	76	24.44	438.8	226	107.78
.....	−372	−224.44	−367.6	−222	−141.11	−97.6	−72	−57.78	172.4	78	25.56	442.4	228	108.89
.....	−370	−223.33	−364.0	−220	−140.00	−94.0	−70	−56.67	176.0	80	26.67	446.0	230	110.00
.....	−368	−222.22	−360.4	−218	−138.89	−90.4	−68	−55.56	179.6	82	27.78	449.6	232	111.11
.....	−366	−221.11	−356.8	−216	−137.78	−86.8	−66	−54.44	183.2	84	28.89	453.2	234	112.22
.....	−364	−220.00	−353.2	−214	−136.67	−83.2	−64	−53.33	186.8	86	30.00	456.8	236	113.33
.....	−362	−218.89	−349.6	−212	−135.56	−79.6	−62	−52.22	190.4	88	31.11	460.4	238	114.44
.....	−360	−217.78	−346.0	−210	−134.44	−76.0	−60	−51.11	194.0	90	32.22	464.0	240	115.56
.....	−358	−216.67	−342.4	−208	−133.33	−72.4	−58	−50.00	197.6	92	33.33	467.6	242	116.67
.....	−356	−215.56	−338.8	−206	−132.22	−68.8	−56	−48.89	201.2	94	34.44	471.2	244	117.78
.....	−354	−214.44	−335.2	−204	−131.11	−65.2	−54	−47.78	204.8	96	35.56	474.8	246	118.89
.....	−352	−213.33	−331.6	−202	−130.00	−61.6	−52	−46.67	208.4	98	36.67	478.4	248	120.00
.....	−350	−212.22	−328.0	−200	−128.89	−58.0	−50	−45.56	212.0	100	37.78	482.0	250	121.11
.....	−348	−211.11	−324.4	−198	−127.78	−54.4	−48	−44.44	215.6	102	38.89	485.6	252	122.22
.....	−346	−210.00	−320.8	−196	−126.67	−50.8	−46	−43.33	219.2	104	40.00	489.2	254	123.33
.....	−344	−208.89	−317.2	−194	−125.56	−47.2	−44	−42.22	222.8	106	41.11	492.8	256	124.44
.....	−342	−207.78	−313.6	−192	−124.44	−43.6	−42	−41.11	226.4	108	42.22	496.4	258	125.56
.....	−340	−206.67	−310.0	−190	−123.33	−40.0	−40	−40.00	230.0	110	43.33	500.0	260	126.67
.....	−338	−205.56	−306.4	−188	−122.22	−36.4	−38	−38.89	233.6	112	44.44	503.6	262	127.78
.....	−336	−204.44	−302.8	−186	−121.11	−32.8	−36	−37.78	237.2	114	45.56	507.2	264	128.89
.....	−334	−203.33	−299.2	−184	−120.00	−29.2	−34	−36.67	240.8	116	46.67	510.8	266	130.00
.....	−332	−202.22	−295.6	−182	−118.89	−25.6	−32	−35.56	244.4	118	47.78	514.4	268	131.11
.....	−330	−201.11	−292.0	−180	−117.78	−22.0	−30	−34.44	248.0	120	48.89	518.0	270	132.22
.....	−328	−200.00	−288.4	−178	−116.67	−18.4	−28	−33.33	251.6	122	50.00	521.6	272	133.33
.....	−326	−198.89	−284.8	−176	−115.56	−14.8	−26	−32.22	255.2	124	51.11	525.2	274	134.44
.....	−324	−197.78	−281.2	−174	−114.44	−11.2	−24	−31.11	258.8	126	52.22	528.8	276	135.56
.....	−322	−196.67	−277.6	−172	−113.33	−7.6	−22	−30.00	262.4	128	53.33	532.4	278	136.67
.....	−320	−195.56	−274.0	−170	−112.22	−4.0	−20	−28.89	266.0	130	54.44	536.0	280	137.78
.....	−318	−194.44	−270.4	−168	−111.11	−0.4	−18	−27.78	269.6	132	55.56	539.6	282	138.89
.....	−316	−193.33	−266.8	−166	−110.00	+3.2	−16	−26.67	273.2	134	56.67	543.2	284	140.00
.....	−314	−192.22	−263.2	−164	−108.89	+6.8	−14	−25.56	276.8	136	57.78	546.8	286	141.11
.....	−312	−191.11	−259.6	−162	−107.78	+10.4	−12	−24.44	280.4	138	58.89	550.4	288	142.22
.....	−310	−190.00	−256.0	−160	−106.67	+14.0	−10	−23.33	284.0	140	60.00	554.0	290	143.33

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F		C	F		C	F		C	F		C	F		C
557.6	292	144.44	870.8	466	241.11	1832.0	1000	537.78	3398.0	1870	1021.1	4964.0	2740	1504.4
561.2	294	145.56	874.4	468	242.22	1850.0	1010	543.33	3416.0	1880	1026.7	4982.0	2750	1510.0
564.8	296	146.67	878.0	470	243.33	1868.0	1020	548.89	3434.0	1890	1032.2	5000.0	2760	1515.6
568.4	298	147.78	881.6	472	244.44	1886.0	1030	554.44	3452.0	1900	1037.8	5018.0	2770	1521.1
572.0	300	148.89	885.2	474	245.56	1904.0	1040	560.00	3470.0	1910	1043.3	5036.0	2780	1526.7
575.6	302	150.00	888.8	476	246.67	1922.0	1050	565.56	3488.0	1920	1048.9	5054.0	2790	1532.2
579.2	304	151.11	892.4	478	247.78	1940.0	1060	571.11	3506.0	1930	1054.4	5072.0	2800	1537.8
582.8	306	152.22	896.0	480	248.89	1958.0	1070	576.67	3524.0	1940	1060.0	5090.0	2810	1543.3
586.4	308	153.33	899.6	482	250.00	1976.0	1080	582.22	3542.0	1950	1065.6	5108.0	2820	1548.9
590.0	310	154.44	903.2	484	251.11	1994.0	1090	587.78	3560.0	1960	1071.1	5126.0	2830	1554.4
593.6	312	155.56	906.8	486	252.22	2012.0	1100	593.33	3578.0	1970	1076.7	5144.0	2840	1560.0
597.2	314	156.67	910.4	488	253.33	2030.0	1110	598.89	3596.0	1980	1082.2	5162.0	2850	1565.6
600.8	316	157.78	914.0	490	254.44	2048.0	1120	604.44	3614.0	1990	1087.8	5180.0	2860	1571.1
604.4	318	158.89	917.6	492	255.56	2066.0	1130	610.00	3632.0	2000	1093.3	5198.0	2870	1576.7
608.0	320	160.00	921.2	494	256.67	2084.0	1140	615.56	3650.0	2010	1098.9	5216.0	2880	1582.2
611.6	322	161.11	924.8	496	257.78	2102.0	1150	621.11	3668.0	2020	1104.4	5234.0	2890	1587.8
615.2	324	162.22	928.4	498	258.89	2120.0	1160	626.67	3686.0	2030	1110.0	5252.0	2900	1593.3
618.8	326	163.33	932.0	500	260.00	2138.0	1170	632.22	3704.0	2040	1115.6	5270.0	2910	1598.9
622.4	328	164.44	935.6	502	261.11	2156.0	1180	637.78	3722.0	2050	1121.1	5288.0	2920	1604.4
626.0	330	165.56	939.2	504	262.22	2174.0	1190	643.33	3740.0	2060	1126.7	5306.0	2930	1610.0
629.6	332	166.67	942.8	506	263.33	2192.0	1200	648.89	3758.0	2070	1132.2	5324.0	2940	1615.6
633.2	334	167.78	946.4	508	264.44	2210.0	1210	654.44	3776.0	2080	1137.8	5342.0	2950	1621.1
636.8	336	168.89	950.0	510	265.56	2228.0	1220	660.00	3794.0	2090	1143.3	5360.0	2960	1626.7
640.4	338	170.00	953.6	512	266.67	2246.0	1230	665.56	3812.0	2100	1148.9	5378.0	2970	1632.2
644.0	340	171.11	957.2	514	267.78	2264.0	1240	671.11	3830.0	2110	1154.4	5396.0	2980	1637.8
647.6	342	172.22	960.8	516	268.89	2282.0	1250	676.67	3848.0	2120	1160.0	5414.0	2990	1643.3
651.2	344	173.33	964.4	518	270.00	2300.0	1260	682.22	3866.0	2130	1165.6	5432.0	3000	1648.9
654.8	346	174.44	968.0	520	271.11	2318.0	1270	687.78	3884.0	2140	1171.1	5450.0	3010	1654.4
658.4	348	175.56	971.6	522	272.22	2336.0	1280	693.33	3902.0	2150	1176.7	5468.0	3020	1660.0
662.0	350	176.67	975.2	524	273.33	2354.0	1290	698.89	3920.0	2160	1182.2	5486.0	3030	1665.6
665.6	352	177.78	978.8	526	274.44	2372.0	1300	704.44	3938.0	2170	1187.8	5504.0	3040	1671.1
669.2	354	178.89	982.4	528	275.56	2390.0	1310	710.00	3956.0	2180	1193.3	5522.0	3050	1676.7
672.8	356	180.00	986.0	530	276.67	2408.0	1320	715.56	3974.0	2190	1198.9	5540.0	3060	1682.2
676.4	358	181.11	989.6	532	277.78	2426.0	1330	721.11	3992.0	2200	1204.4	5558.0	3070	1687.8
680.0	360	182.22	993.2	534	278.89	2444.0	1340	726.67	4010.0	2210	1210.0	5576.0	3080	1693.3
683.6	362	183.33	996.8	536	280.00	2462.0	1350	732.22	4028.0	2220	1215.6	5594.0	3090	1698.9
687.2	364	184.44	1000.4	538	281.11	2480.0	1360	737.78	4046.0	2230	1221.1	5612.0	3100	1704.4
690.8	366	185.56	1004.0	540	282.22	2498.0	1370	743.33	4064.0	2240	1226.7	5702.0	3150	1732.2
694.4	368	186.67	1007.6	542	283.33	2516.0	1380	748.89	4082.0	2250	1232.2	5792.0	3200	1760.0
698.0	370	187.78	1011.2	544	284.44	2534.0	1390	754.44	4100.0	2260	1237.8	5882.0	3250	1787.7
701.6	372	188.89	1014.8	546	285.56	2552.0	1400	760.00	4118.0	2270	1243.3	5972.0	3300	1815.5
705.2	374	190.00	1018.4	548	286.67	2570.0	1410	765.56	4136.0	2280	1248.9	6062.0	3350	1843.3
708.8	376	191.11	1022.0	550	287.78	2588.0	1420	771.11	4154.0	2290	1254.4	6152.0	3400	1871.1
712.4	378	192.22	1040.0	560	293.33	2606.0	1430	776.67	4172.0	2300	1260.0	6242.0	3450	1898.8
716.0	380	193.33	1058.0	570	298.89	2624.0	1440	782.22	4190.0	2310	1265.6	6332.0	3500	1926.6
719.6	382	194.44	1076.0	580	304.44	2642.0	1450	787.78	4208.0	2320	1271.1	6422.0	3550	1954.4
723.2	384	195.56	1094.0	590	310.00	2660.0	1460	793.33	4226.0	2330	1276.7	6512.0	3600	1982.2
726.8	386	196.67	1112.0	600	315.56	2678.0	1470	798.89	4244.0	2340	1282.2	6602.0	3650	2010.0
730.4	388	197.78	1130.0	610	321.11	2696.0	1480	804.44	4262.0	2350	1287.8	6692.0	3700	2037.7
734.0	390	198.89	1148.0	620	326.67	2714.0	1490	810.00	4280.0	2360	1293.3	6782.0	3750	2065.5
737.6	392	200.00	1166.0	630	332.22	2732.0	1500	815.56	4298.0	2370	1298.9	6872.0	3800	2093.3
741.2	394	201.11	1184.0	640	337.78	2750.0	1510	821.11	4316.0	2380	1304.4	6962.0	3850	2121.1
744.8	396	202.22	1202.0	650	343.33	2768.0	1520	826.67	4334.0	2390	1310.0	7052.0	3900	2148.8
748.4	398	203.33	1220.0	660	348.89	2786.0	1530	832.22	4352.0	2400	1315.6	7142.0	3950	2176.6
752.0	400	204.44	1238.0	670	354.44	2804.0	1540	837.78	4370.0	2410	1321.1	7232.0	4000	2204.4
755.6	402	205.56	1256.0	680	360.00	2822.0	1550	843.33	4388.0	2420	1326.7	7322.0	4050	2232.2
759.2	404	206.67	1274.0	690	365.56	2840.0	1560	848.89	4406.0	2430	1332.2	7412.0	4100	2260.0
762.8	406	207.78	1292.0	700	371.11	2858.0	1570	854.44	4424.0	2440	1337.8	7502.0	4150	2287.7
766.4	408	208.89	1310.0	710	376.67	2876.0	1580	860.00	4442.0	2450	1343.3	7592.0	4200	2315.5
770.0	410	210.00	1328.0	720	382.22	2894.0	1590	865.56	4460.0	2460	1348.9	7682.0	4250	2343.3
773.6	412	211.11	1346.0	730	387.78	2912.0	1600	871.11	4478.0	2470	1354.4	7772.0	4300	2371.1
777.2	414	212.22	1364.0	740	393.33	2930.0	1610	876.67	4496.0	2480	1360.0	7862.0	4350	2398.8
780.8	416	213.33	1382.0	750	398.89	2948.0	1620	882.22	4514.0	2490	1365.6	7952.0	4400	2426.6
784.4	418	214.44	1400.0	760	404.44	2966.0	1630	887.78	4532.0	2500	1371.1	8042.0	4450	2454.4
788.0	420	215.56	1418.0	770	410.00	2984.0	1640	893.33	4550.0	2510	1376.7	8132.0	4500	2482.2
791.6	422	216.67	1436.0	780	415.56	3002.0	1650	898.89	4568.0	2520	1382.2	8222.0	4550	2510.0
795.2	424	217.78	1454.0	790	421.11	3020.0	1660	904.44	4586.0	2530	1387.8	8312.0	4600	2537.7
798.8	426	218.89	1472.0	800	426.67	3038.0	1670	910.00	4604.0	2540	1393.3	8402.0	4650	2565.5
802.4	428	220.00	1490.0	810	432.22	3056.0	1680	915.56	4622.0	2550	1398.9	8492.0	4700	2593.3
806.0	430	221.11	1508.0	820	437.76	3074.0	1690	921.11	4640.0	2560	1404.4	8582.0	4750	2621.1
809.6	432	222.22	1526.0	830	443.33	3092.0	1700	926.67	4658.0	2570	1410.0	8672.0	4800	2648.8
813.2	434	223.33	1544.0	840	448.89	3110.0	1710	932.22	4676.0	2580	1415.6	8762.0	4850	2676.6
816.8	436	224.44	1562.0	850	454.44	3128.0	1720	937.78	4694.0	2590	1421.1	8852.0	4900	2704.4
820.4	438	225.56	1580.0	860	460.00	3146.0	1730	943.33	4712.0	2600	1426.7	8942.0	4950	2732.2
824.0	440	226.67	1598.0	870	465.56	3164.0	1740	948.89	4730.0	2610	1432.2	9032.0	5000	2760.0
827.6	442	227.78	1616.0	880	471.11	3182.0	1750	954.44	4748.0	2620	1437.8	9122.0	5050	2787.7
831.2	444	228.89	1634.0	890	476.67	3200.0	1760	960.00	4766.0	2630	1443.3	9212.0	5100	2815.5
834.8	446	230.00	1652.0	900	482.22	3218.0	1770	965.56	4784.0	2640	1448.9	9302.0	5150	2843.3
838.4	448	231.11	1670.0	910	487.78	3236.0	1780	971.11	4802.0	2650	1454.4	9392.0	5200	2871.1
842.0	450	232.22	1688.0	920	493.33	3254.0	1790	976.67	4820.0	2660	1460.0	9482.0	5250	2898.8
845.6	452	233.33	1706.0	930	498.89	3272.0	1800	982.22	4838.0	2670	1465.6	9572.0	5300	2926.6
849.2	454	234.44	1724.0	940	504.44	3290.0	1810	987.78	4856.0	2680	1471.1	9662.0	5350	2954.4
852.8	456	235.56	1742.0	950	510.00	3308.0	1820	993.33	4874.0	2690	1476.7	9752.0	5400	2982.2
856.4	458	236.67	1760.0	960	515.56	3326.0	1830	998.89	4892.0	2700	1482.2	9842.0	5450	3010.0
860.0	460	237.78	1778.0	970	521.11	3344.0	1840	1004.4	4910.0	2710	1487.8	9932.0	5500	3037.7
863.6	462	238.89	1796.0	980	526.67	3362.0	1850	1010.0	4928.0	2720	1493.3	10,022.0	5550	3065.5
867.2	464	240.00	1814.0	990	532.22	3380.0	1860	1015.6	4946.0	2730	1498.9	10,112.0	5600	3093.3

Preferred Orientations

COMPILED BY C. S. BARRETT*

PREFERRED ORIENTATIONS (textures) are usually specified by the indices, in square brackets [ ], of the crystal direction parallel to the longitudinal axis of wires or rods, the axis of compression in uniaxial compression or forging, or the direction of rolling in rolled products. Textures in sheets are specified by naming also, in parentheses ( ), the crystal plane that is parallel to the surface of the sheet. The scatter around the principal orientations listed below is often considerable and is usually expressed by means of pole figures.

"Recrystallization textures" are often sensitive to impurities, alloy content, and the temperature and duration of annealing; some reported textures may have been altered by grain growth subsequent to recrystallization.

Deformation Textures

Metal	Crystal Structure	Texture
Wire Drawing and Swaging		
Al, Cu, Ag, Au, Ni, Pd, α brass, bronze	Fcc	[111] and [100]
Pb, (Al after severe reduction)	Fcc	[111]
α-Fe, Mo, W, alloyed ferrites	Bcc	[110]
Mg and Mg alloys, Zr	Hcp	[210]
Mg alloys worked at 450 C	Hcp	[110]
Zn (severe reductions)	Hcp	[001] 70° from wire axis
Rod Extrusion		
Like *wire drawing*, except as follows:		
Zn	Hcp	[001] both 0° and 90° to rod axis
Zn – 10 Al – 2 Cu – 0.03 Mg	Hcp	[001] 90° to rod axis
Cold Rolling (sheet and strip)		
Al, Cu, Ni, Au, Pt, Ag, Fe-Ni, α Cu-Sn, Au-Ag, constantan, Pb alloys	Fcc	(110) [112] (strong); also (112) [111] and weaker (001) [100], (110) [001], (236) [533]
α brass	Fcc	(110) [112] (strong) also (weaker) spread from [113] to [117] in rolling direction
Pb	Fcc	(001) [110]
Fe, alloyed ferrites, Mo	Bcc	(001) [110] with spread around rolling direction as an axis ± 55°, that is, to (1̄11) [110]
Mg, Zr, Co	Hcp	(001); modifications of this in some alloys
Zn, Cd, alloyed Zn	Hcp	(001) about 20° from surface, 70° from rolling direction; modifications of this in some alloys

Recrystallization Textures

Metal	Crystal Structure	Texture
After Wire Drawing		
Al	Fcc	[111]; or [111] + [100]; or sometimes [112]
Cu, α brass	Fcc	[111] + [100]; sometimes [112]
Fe, W, Mo, alloyed ferrites	Bcc	[110]
Zn – 1 Cu	Hcp	[001] 70° to wire axis
After Uniaxial Compression or Forging		
Al, Cu, α brass	Fcc	[110]
Fe	Bcc	[111]
Mg	Hcp	[001]
After Rolling (sheet and strip)		
Ag, Ag-Au (70% Ag), Ag-Zn (1% Zn), Cu-Zn (5–39% Zn), Cu-Sn (1–5% Sn), Cu-Be (0.5% Be), Cu-Cd (0.5% Cd), Cu-P (0.05% P)	Fcc	(113) [211]
Cu-Zn (30% Zn) after severe reduction and high-temperature anneal	Fcc	(110) [112] (Grain growth texture)
Ni, Cu, Au, Al, Fe-Ni (30–100% Ni), Cu-Zn (0-1% Zn), some Ni-Cu and Fe-Ni-Cu alloys	Fcc	(100) [001] (after severe cold rolling)
Cu alloyed with Sb, Mg, or Ni	Fcc	Complex, nearly random
Mg, Zn, Zn-Cd, Zn-Cu	Hcp	Same as cold rolling texture
Fe, low-carbon steel	Bcc	(100) parallel to rolling plane, [011] 15° from rolling direction
Fe-Si, with intermediate anneal and two cold reductions	Bcc	(110) [001]

* Professor of Metallurgy, Institute for the Study of Metals, University of Chicago, Chicago

Thermoelectric Data for Some Thermocouple Materials

COMPILED BY D. I. FINCH*

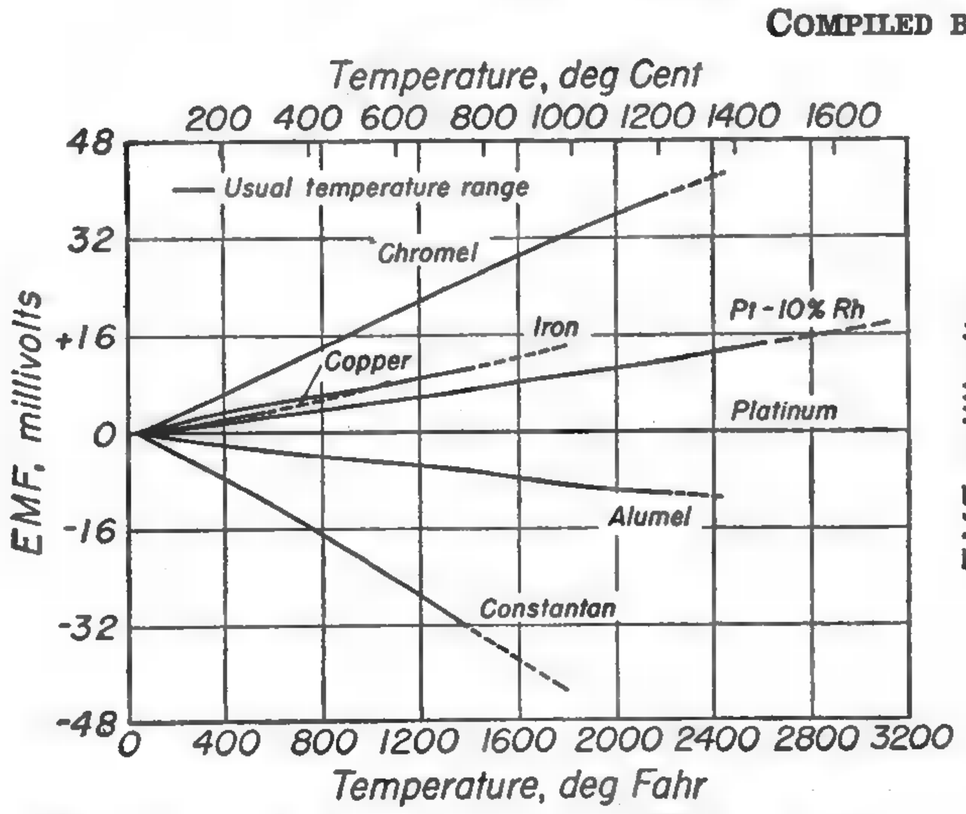

Fig. 1 Thermal emf versus temperature for the most common thermocouple materials, referred to platinum

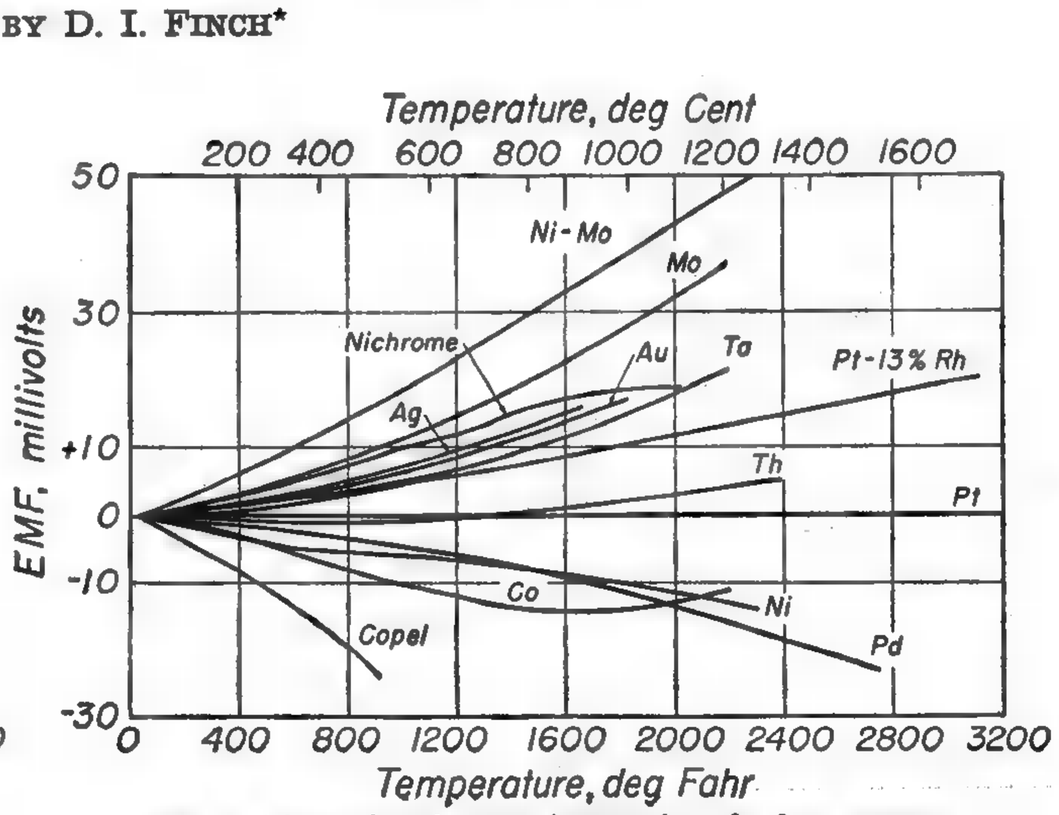

Fig. 2 Thermal emf versus temperature for less common thermocouple materials, referred to platinum

* Chief of Metallurgical Division, Research Department, Leeds & Northrup Company, Philadelphia

SHAPING OF METALS

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Forging by the Blacksmith

By William Telfer*

WHEN selecting material of the correct dimensions for a certain part, the blacksmith must first decide how the part is to be forged. One procedure would be to select stock a little larger than the largest dimension and to obtain the smaller dimensions by drawing down. If the forging is to be short, stock comparable with the smaller dimensions could be used, and the larger dimensions could be obtained by upsetting. In either instance it would be correct procedure to figure the approximate cubic contents or weight of the finished forging before selecting the stock, and to allow enough for squaring the end, and for loss caused by scaling. This loss varies with the number of reheatings and with the atmosphere and temperature of heating.

Blacksmith Tools. The tools used at the anvil with hand hammers or sledge hammers are swages, fullers, set hammers, flatters, punches and chisels, with tongs to hold the work. The swages, fullers, set hammers and flatters are usually made of 0.70 to 0.80% C steel, and the hot and cold chisels of 0.80 to 0.90% C steel. A 0.45 to 0.50% C steel could be used for the bottom fuller and swage which fit into the square hole of the anvil. Cast medium-carbon steel or a good gray iron will serve as a swage block.

Fullers. When shoulders are required on both sides, the forging is worked between the top and bottom fullers, the top being struck with a sledge. The top fuller is often used alone to make depressions on one side of the forging as it lies flat on the anvil. The radius of the depression or fillet will determine the size of the fullers to be used. Figure 1 shows a top and bottom fuller.

Swages. These tools (Fig. 2) are used for finishing round or semiround work at the anvil, after the work has been drawn nearly to size by the use of either the hand hammer, the sledge, or the power hammer.

The depth of the impression should be about one-third the diameter of the part of the forging to be swaged, and the edges should be well rounded. If the bottom swage is made to come flush with one or both sides of the anvil, it will have a greater range of usefulness.

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Prepared for the Subcommittee on Forging, with membership as follows: Adam Steever, *Chairman* (Columbia Tool Steel Company), W. W. Criley (The Ajax Manufacturing Co.), A. A. Handler (Deceased), G. R. Houghtaling (Rochester, N. Y.), Waldemar Naujoks (Forging Consultant), William Telfer (University of Michigan) and R. W. Thompson (Transue & Williams Steel Forging Corporation).

Set Hammer and Flatter. Both are used on flat surfaces, but if work is necessary on square shoulders or in depressions too small for the flatter, the set hammer usually answers the purpose. The set hammer and flatter are both shown in Fig. 3.

Cold Chisel. Some steels in the hot or cold worked condition can be notched all or part way around by the use of this chisel and a sledge, and then broken by a sharp blow (Fig. 4).

Hot Chisel. This is much thinner than the cold chisel (Fig. 4), and is used on steel at elevated temperatures. The cut is usually made all the way through.

Hardie. This tool should fit into the square hole in the anvil. It can be used on some steels both hot and cold. The metal is placed on the hardie and struck with a hand hammer (Fig. 4).

When belt, air or steam hammers are used, the tools are somewhat similar to those used for sledge hammering, but are modified to permit their use with power hammers.

Power Hammer Swages. Swages are usually made of 0.45 to 0.50% C steel, and the shape is obtained by sinking hot, through the use of either a round bar or some special shape. Most of the work done by swaging is round in cross section, but special shapes can be produced by using these tools. Where the forgings are of large diameter, the top and bottom swages are ordinarily not attached by spring handles because of the weight to be manipulated by the helper. Figures 5 and 6 show the hammer swages.

Power Hammer Fuller. The hammer fuller, shown in Fig. 7, is used for drawing short sections where the dies are too wide, and also for forging a taper. The rounded side of the fuller is used for breaking down or roughing, and the flat side could be called a "flatter" for finishing.

Power Hammer Cutters. Hot cutters (Fig. 8) usually consist of a straight blade with a handle about 3 to 8 ft long, depending on the size of the forging. Some are made with curved blades and others form an angle of 90 deg. The handle near the blade should be flat so as to act as a spring and prevent injury to the wrists or arms of the blacksmith.

Stocks. These are used for turning and handling the forgings at the hammer (Fig. 9).

When the quantity of forgings of the same kind justifies the making of dies, the blacksmith first makes one forging, taking special care with the shape and dimensions. This sample or master forging then is employed to sink the

die or dies. The die blanks are usually forged with handles drawn out. The next step is to heat the blanks to a high temperature, put the sample in between, and then force them together with heavy blows. Sometimes the dies are partly sunk before using the master forging. These dies or "swages", as they are sometimes called, are held in line by spring handles, guide pins or both, and are held on the bottom hammer die by the helper. The smith has used this method of increasing production for many years. It has been used for some time, on a much larger scale, by the producers of drop forgings.

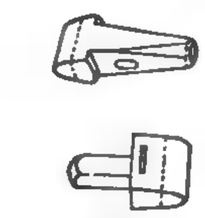

Fig. 1

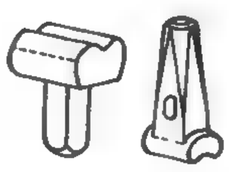

Fig. 2

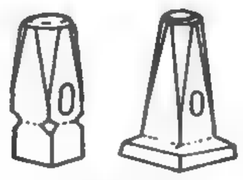

Fig. 3

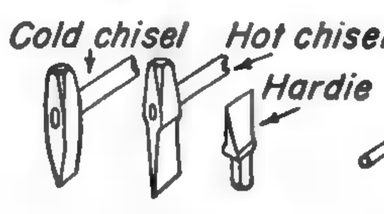

Fig. 4

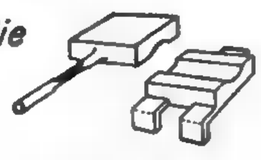

Fig. 5

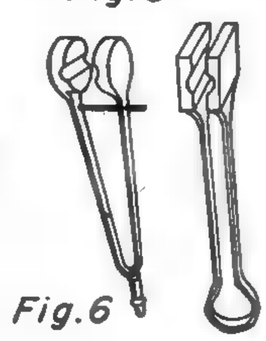

Fig. 6

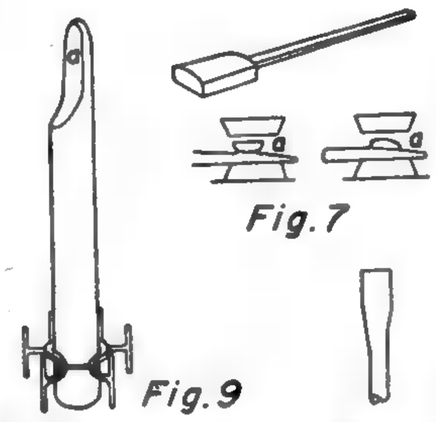

Fig. 7

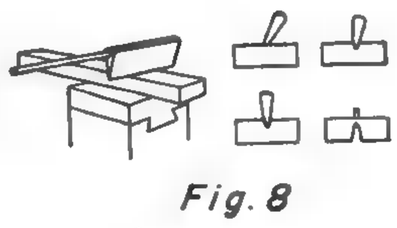

Fig. 8

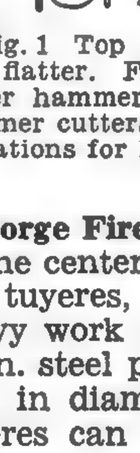

Fig. 9

Fig. 10

Fig. 1 Top and bottom fuller. Fig. 2 Swages. Fig. 3 Set hammer and flatter. Fig. 4 Cold chisel, hot chisel and hardie. Fig. 5 and 6 Power hammer swages. Fig. 7 Power hammer fuller. Fig. 8 Power hammer cutters. Fig. 9 Stocks for turning forgings. Fig. 10 Scarfing operations for lap welding.

Forge Fire. A cast-iron hearth with a bowl or depression in the center for the fire, and an opening in the bottom for the tuyeres, will answer the purpose for light work. For heavy work an inexpensive forge can be constructed from ⅛-in. steel plate formed into a square or a cylinder about 4 ft in diam and 2 ft, 6 in. in height. Space below the tuyeres can be filled with broken brick and ashes. The distance between the top of the hearth and the tuyeres should be about 10 in. for heavy work and about 4 in. for light work. Provision should be made for removing ashes from below the tuyeres. The clinkers can be removed from above. After the fire is started, wet coal is banked on both sides. This not only supplies coke for surrounding the metal to be heated, but acts somewhat like the firebrick wall of a furnace.

The object is to heat the steel uniformly to high temperature with as little oxidation as possible. This can be accomplished by keeping a good bed of coke between the tuyeres and the steel, to consume the oxygen in the blast. Also a good covering is necessary. Better control of the atmosphere and the temperature can be maintained in a furnace, but in a forge fire, the heat can be concentrated at some given point of the bar or forging.

In building a forge fire for medium and heavy work, a block of wood corresponding to the size of the fire required is placed on the tuyere, and wet coal is firmly packed around it to the necessary depth. Two boards are then used as forms to build the banks to required dimensions.

The fire is started by shoveling hot coke into the hole left after the wood is removed. The banks usually stand undisturbed for a half to a whole day, and hard coke, broken to a convenient size, is used as a fuel.

The banks of coal coke to a depth of several inches during the day; this coke is used along with the hard coke on the following day, after the fire is rebuilt.

Fine coal is more desirable for forge fires since, when wet, it packs much better than lump coal. The fuel for the forge is usually a good grade of bituminous coal, low in ash and sulfur, high in fixed carbon and having good coking qualities.

Hammer Size. During the forging of the steel, the size will determine the method of applying the force. If the temperature is close to the upper limit of the plastic range, a 1½-lb hammer will supply enough force for ⅝-in. diam low-carbon and ½-in. diam high-carbon steel, and a 14-lb sledge will answer the purpose up to 1¼ in. for low-carbon steel. Of course, the smith will save time by using a power hammer, if he has access to one.

Precautions in Heating and Forging Steel. Too rapid heating will cause uneven expansion of the metal, starting internal cracks. This is especially dangerous in high-carbon and high-alloy steels. When such steels must be heated near the upper limit of the plastic range, it is advisable to use a preheat furnace at temperatures between 1200 and 1400 F, depending on the composition, size and previous treatment.

Forging temperatures too high for the amount of work to be done will result in large grains in the finished forging. If temperatures reach the melting range, voids and oxide inclusions will result when the metal is forged. This is commonly called "burning".

Applying too little force will cause rupture of the steel by working the outer layers more than the inside metal. Sufficient force should be applied to affect the whole cross section, and this should be continued until the dimensions are close to those of the finished forging.

Continuing the forging at temperatures too low will leave the steel in a highly stressed state and, if not followed by some form of heat treatment, will result in short life for the machine part.

When a great reduction in size is necessary, the steel should be forged down on the square or rectangular shape. The stock should be turned so that the sides will form an angle of 90 deg. If the finished cross section is to be round, forging should be continued on the square until close to the finished dimension. The corners can then be forged to produce an octagonal shape, and little rolling is necessary to finish.

If the above procedure is not carried out, the metal may be in shear some of the time, instead of in compression, and if the steel is slightly rigid, because of low temperatures or a hard alloy steel, such as high speed steel, it will be ruptured.

Overlapping of the steel, forming cold shuts, is often caused by using hammer dies and tools with sharp corners.

The above applies both to forging on the anvil with a hand hammer and to forging between the flat dies of a power hammer or press.

Welding at the Forge. When wrought iron or steel is heated to high temperatures, such as are used in welding, and is exposed to the air, the metal oxidizes rapidly. In order to secure a good bond between two pieces, this oxide must be so fluid that it can be squeezed out from between the surfaces. The fusion point of the oxide is lowered by the use of fluxes.

Clean silica sand and borax are two common fluxes used at the forge. Borax, having a comparatively low fusion point, is used on high-carbon steel. After scarfing, it can be placed on the steel at low temperatures, supplying a protective coating. Also, it can be sprinkled on the steel while heating. Borax serves a double purpose, lowering the fusion point of the oxide and preventing further oxidation.

Sand has a high fusion temperature but when combined with iron oxide it becomes fusible at lower temperatures. It is generally sprinkled on when the metal is close to the welding temperature.

Silica sand, cheaper than borax, can be used on the low-carbon steels. Fluxes are not necessary in the forge welding of wrought iron and very low-carbon steel, because it is possible to melt the oxide without "burning" or melting the metal.

The operation of preparing the pieces for welding is known as "scarfing". Figure 10 shows the shape used in lap

welding. Other types of welds are known as: butt, V or split, T, corner, and jump.

Precautions in Forge Welding. Before the scarfs are shaped, the end of the pieces to be welded should be upset sufficiently and far enough back from the scarf to allow for mechanical working during and after welding.

The grain size of the metal in the weld and adjacent to the weld will depend on the amount of work it receives and the finishing temperature.

The scarf surfaces should be well rounded so that contact will be made in the center; the curved surfaces will force the liquid oxide or dirt out from between.

It is important to guard against excessive oxidation on heating, by keeping a good supply of coke in the bottom of the fire, and having the metal well covered with fuel. The scarfed ends should be face down in the fire.

When the work material has reached the welding temperature, enough speed should be used to get the pieces together before the oxide solidifies.

Blows should be heavy enough to work the metal uniformly. A power hammer should be used when necessary.

The metal in and adjacent to the weld may be annealed to produce a more homogeneous structure with greater ductility—a property usually low in forge welds.

The properties of a forge weld will depend on the following factors: (1) the skill of the welder, (2) the weldability of the material, (3) the fuel used (sulfur and ash will interfere), (4) the amount of flux used and the time of application, (5) uniformity of temperatures of pieces to be welded, (6) atmospheric condition of the fire or furnace, (7) amount of oxide or fuel ash trapped between the scarfs, (8) method of working (too much rolling on the anvil or between the dies of a power hammer, when welding round stock, will be detrimental), (9) force of the blow.

Swaging

By W. L. Bowen*

THE term "swaging" as used here refers only to rotary swaging (rotary reduction) and is not to be confused with coining or other types of presswork.

Construction and Operation of Swaging Machines. The modern swaging machine is simply a mechanical means for rapidly opening and closing two dies, or sometimes four dies. The dies are carried in a slot in the face of a revolving spindle and are held between a pair of steel blocks called "backers". Around the spindle is a circular roll cage containing loosely a number of hardened steel rolls.

The revolution of the spindle causes the backers and dies to pass between successive pairs of opposing rolls, thus forcing the dies together. With a spindle rpm of 500 and with 10 rolls, there would be approximately 3000 die blows per min. Actually, this is reduced somewhat because the roll cage rotates slowly, thus lessening the number of blows.

The dies are blocks of hardened steel, having upon their inner faces the impression of the shape or the diameter of the work to be produced. One end of the die groove is flared to allow the unreduced stock to enter (Fig. 1).

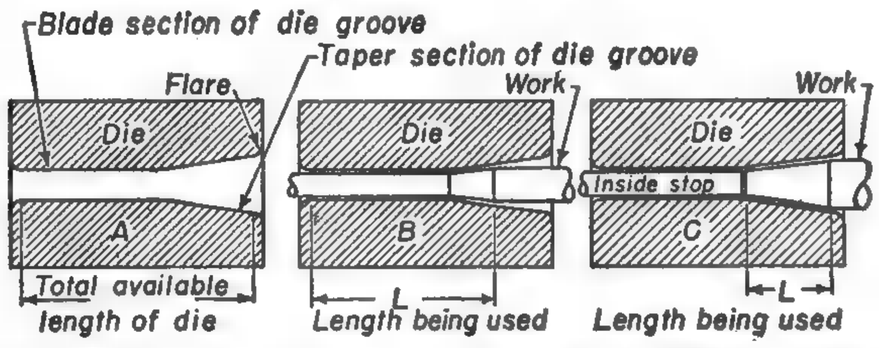

Fig. 1. Three views of the same die, showing different values for *L*. *A* shows the total available length, *L*, of the die. *B* and *C* show two different jobs as swaged with the same die. In *B*, the entire length of the blade section of the groove is used, plus approximately one-half the taper section of the groove. In *C*, only the length of the taper is being used.

Uses of Swaging. Since the dies rotate around the work, the swaged portion must assume a round cross section even though the original work can be of any regular cross section, such as square or hexagonal.

Swaging is the best method for tapering welded or seamless tubes or drawn steels. Rods, bars and wire are also reduced or tapered economically by swaging. Gold-plated wire, for instance, can be swaged with the plate kept intact and evenly distributed all the way to the end of the swaged section.

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Prepared for the Subcommittee on Forging, with membership as follows: Adam Steever, *Chairman* (Columbia Tool Steel Company), W. W. Criley (The Ajax Manufacturing Co.), A. A. Handler (Deceased), G. R. Houghtaling (Rochester, N. Y.), Waldemar Naujoks (Forging Consultant), William Telfer (University of Michigan) and R. W. Thompson (Transue & Williams Steel Forging Corporation).

Speed of Swaging. Naturally the speed of swaging depends on many factors, such as the kind of material, angle of taper, amount of reduction, or finish desired. In general, the speed varies from 1 in. per sec up to 4 in. or perhaps 5 in. per sec. Whether the work is fed into the dies automatically or by hand, influences the speed very little, although automatic feeding is always slower than hand feeding unless hydraulic equipment is used.

Physical Effect of Swaging. Swaging is actually performed more by pressure than by blows; hence there is a flow and readjustment of the grains of the swaged material.

Most metals tend to work harden when cold swaged, so annealing may often be necessary after one, two or three swaging passes, depending on the amount of reduction and type of material. This is particularly true of stainless steels.

Some extremely brittle metals, such as a cast or sintered tungsten bar, when hot swaged in a series of passes, are made so ductile that further reductions can be made by drawing.

Since the entire volume of the metal being swaged is not lessened to any appreciable extent, but rather is changed in shape, it follows that solid pieces, when swaged, tend to elongate. In work with tubing, swaging tends to thicken the wall, since a volume equal to only 10% of the cross section goes into elongation. The thickening of the wall is caused by the flowing metal following the line of least resistance.

Amount of Reduction. The amount of reduction in any one pass depends on various factors, such as type of material and angle of taper, but in general the maximum reduction in one swaging pass should not exceed 30% of the cross-sectional area.

Because the die pressure is in a radial direction around the work, steep angles or abrupt tapers are to be avoided. For easy commercial swaging, the included angle of taper should not be more than 10 to 12 deg or less, depending on the force available for feeding.

Swaging Machine Capacities. Various metals have different compressive strengths and therefore require different swaging pressures to obtain a given amount of reduction. For all practical purposes, flowing or swaging pressures may be considered to be 1.75 times the compressive strength of the material being cold swaged. No figures are given for comparative pressures for hot swaging because of the large number of variable factors.

It must be borne in mind that the factor 1.75 given above for swaging pressures does not hold good when the length of swage within the swaging dies exceeds ten times the diameter of the work (this applies to solid pieces only), because of the restriction of endwise flow of the work, resulting from surface friction between the dies and the work, which creates pressures greater than the strength of the dies.

To obtain the maximum capacity of any given swaging machine the following equation may be used:

$$D = \frac{T}{1.75\ (SL)}$$

where D = the diameter of the work, in inches
T = the total capacity of the machine, in pounds
S = the compressive strength of the work material, in pounds per square inch
L = the length of the die being used, in inches (*see* Fig. 1)

The value for S can be obtained from tables elsewhere in this Handbook and the value for T from the swaging machine producer. The value for L depends on the job.

Example. A manufacturer has some material of a certain diameter to be swaged and wants to know whether it can be handled without overloading his swager. The swaging machine has a total capacity of 400,000 lb with a die length of 3 in., all of which length is to be used (Fig. 1).

The material to be swaged has a compressive strength of 150,000 lb, so the example is solved as follows:

$$\frac{400{,}000}{1.75\ (150{,}000)\ (3)} = 0.507 \text{ in. in diam}$$

Hence 0.507-in. diam work could be swaged safely.

From the above equation, it is obvious that as S is reduced, D is increased and vice versa, so the allowable projected area in the swaging die grooves (the length of taper times the average diameter of taper) varies inversely with the compressive strength of the metal being swaged.

Similarly, when only a part of the available length of the swaging die is used, larger diameter work can be safely handled (Fig. 1*C*).

The limiting factor for D is the actual width of the dies. For instance, if it were required to determine the maximum diameter of zinc or a similar material that could be swaged on a certain machine, the value for S, 70,000, might be so low as to cause the value for D (diameter of the work) to be greater than the width of the swaging dies.

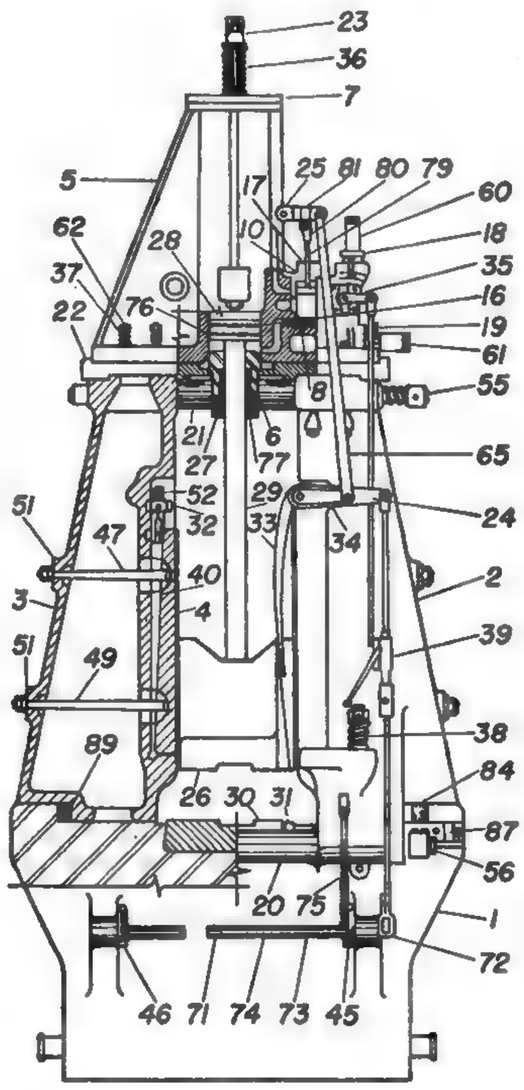
Drop Forging

By R. W. Thompson*

DIE forging done under a hammer, in impression dies, is most commonly referred to as "drop forging". It is the operation of forming metal into a desired shape by repeated blows on a hot bar or billet (or on a slug cut therefrom) between a set of dies which have the desired impression of the finished forging shape. Drop forgings, also known as closed-die or impression-die forgings, are produced from carbon and alloy steels and various alloys of copper, aluminum, nickel, and magnesium.

The drop forging hammer has a moving ram, which carries a die operating in a vertical plane, and has also an anvil block in which is keyed a stationary die. The two dies are matched together, with perfect alignment of the impressions in both, so that the impact of the top die striking on the bottom die compels the metal to fill the cavities for the production of the prescribed forging design. The means of lifting the ram determines the name of the hammer.

Steam Drop Hammers. In these, the ram and movable die are actuated by a steam valve which regulates the height of drop and the force of the blow, through the action of a piston rod, operating in a steam cylinder. These hammers are known as double-acting hammers, because the steam is utilized for lifting the die upward, as well as for forcing it downward (Fig. 1). Steam hammers range in capacity from 500 to 50,000 lb and are rated on the basis of the combined falling weight of the ram and piston rod. Because of their great force of impact and rapid operation, steam hammers are generally used for drop forging heavier parts, and also those designs which require numerous hammer blows to complete the various die operations.



1 Anvil
2 R. H. frame
3 L. H. frame
4 Guide
5 Cylinder
6 Bottom cylinder head
7 Top cylinder head
8 Steam valve
10 Steam chest cover
11 Throttle valve
12 Throttle valve head
13 Throttle valve head gland
14 Throttle valve head bushing
15 Throttle valve cover
16 Steam valve rings
17 Steam valve stem gland
18 Steam pipe gland
19 Exhaust pipe gland
20 Bottom spreader
21 Top spreader
22 Tie plate
23 Crossbar
24 Rocker arm
25 Valve crank
26 Ram
27 Rod gland sleeve
28 Piston
29 Piston rod
30 Sow block
31 Sow block key
32 Guide adjusting bolt
33 Motion arm
34 Motion crank
35 Throttle crank
36 Stop spring
37 Cylinder bolt spring
38 Housing bolt spring
39 Throttle control
40 Guide adjusting wedge
43 Lever handle
44 Treadle crank
45 R. H. treadle lever
46 L. H. treadle lever
47 Top guide bolt
49 Bottom guide bolt
51 Guide bolt washer
52 Guide adjusting bolt
53 Stop bolt
54 Stop plunger
55 Top tie bolt
56 Bottom tie bolt
58 Top stop washer
59 Bottom stop washer
60 Steam pipe
61 Exhaust pipe
62 Cylinder bolt
63 Throttle valve stem
64 Lever
65 Steam valve connection
66 Throttle valve connection
67 Lever connection
68 Treadle connection
69 Housing bolt
71 Treadle shaft
72 Treadle shaft bushing
73 Treadle pipe
74 Treadle pipe bolt
75 Treadle spring
76 Piston rings
77 Piston rod gland plate
79 Steam valve stem
80 Steam valve stem jaw
81 Steam valve stem link
83 Rocker arm shaft
84 R. H. frame wedge
87 Frame key
89 L. H. frame wedge

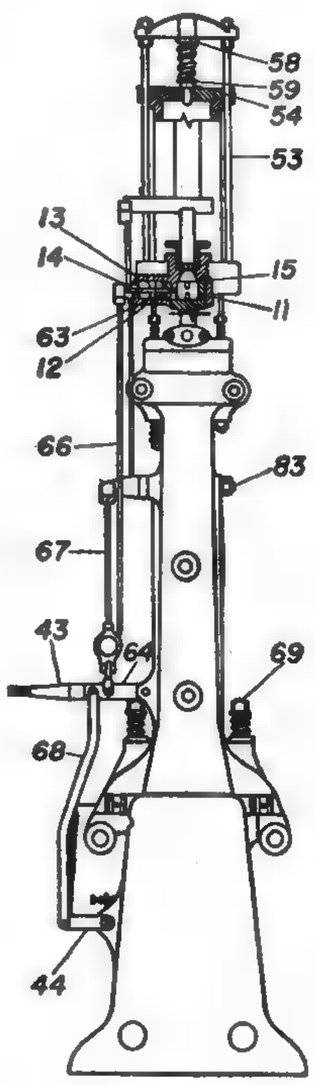


Fig. 1. Basic elements of a steam drop hammer

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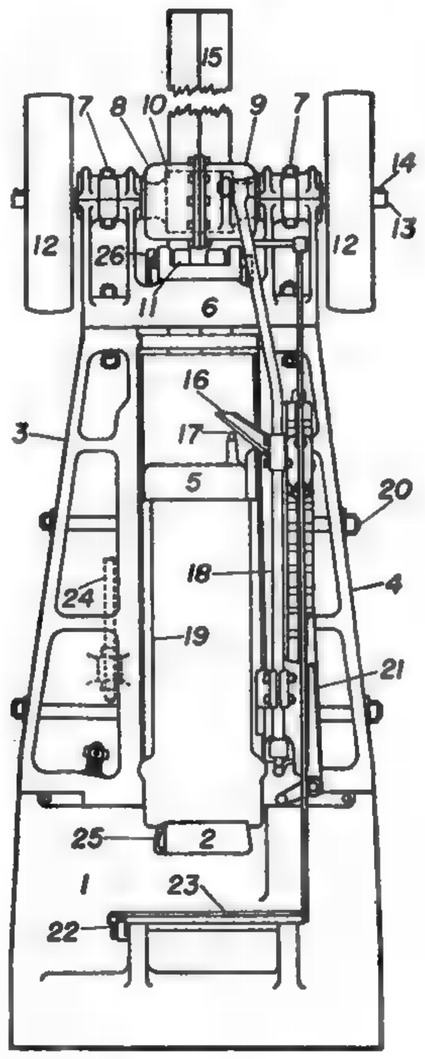
Air Drop Hammers. The construction of these hammers is the same as for steam drop hammers, with the exception of the valve clearances and adjustments. Power derived from compressed air instead of from steam enables equally satisfactory operation. Whether air is more practical than steam for power depends on the relative costs.



1 Anvil
2 Sow block
3 L. H. frame
4 R. H. frame
5 Ram
6 Head piece
7 Caps
8 L. H. front eccentric
9 R. H. front eccentric
10 Roll
11 Clamps
12 Pulleys
13 Roll shaft
14 Pulley key
15 Board
16 Releasing lever
17 Ram pin
18 Front rod
19 Guide
20 Guide bolt
21 Front rod lever
22 L. H. treadle arm
23 Treadle board
24 Board clamp adjusting rod
25 Sow block key
26 Board clamp eccentric

Fig. 2. Basic elements of a board drop hammer

Board Drop Hammers. In a board drop hammer (Fig. 2), the ram is lifted by means of one or more boards keyed to the ram and passing between two rollers at the top of the hammer. The boards are rolled upward and are then mechanically released, permitting the ram to drop when the desired height is reached. The power for this operation is supplied by direct motor drive or by lineshaft and pulleys.

In the board drop hammer, the force of the impact depends on gravity; for this reason it is sometimes known as a "gravity hammer". These hammers, built to standard specifications, have a falling weight or capacity of 400 to 10,000 lb, and are used in the production of the smaller and lighter forged parts.

Dies and Tools. Drop forgings are commercial duplicates of each other and are produced to meet prescribed dimensional tolerances, as well as chemical and physical specifications. A blueprint or sketch of the forging, showing the necessary draft angles, radii, fillets and amount of finish required, is submitted to the die shop as a guide in sinking the dies.

Forging dies are designed to give the required hot mechanical working to the metal, in order to produce a finished forging shape with a minimum of residual stress. These dies are also designed to keep the grain fibers inherent in the rolled bar continuous and unbroken in the forging and, whenever possible, at right angles to the direction of stress or shock in service. The necessary impressions in a die (Fig. 3) for a certain forging, may be described as follows: fuller or swager, edger or roller, blocker, finisher and cutoff. The fuller reduces the size of the section of the material; the edger conforms the material to the area of the sections of the piece to be forged; the blocker gives the forging its general shape; and the finisher completes the forging design. The cutoff tool, used to cut the forging from the bar, may be a part of the die or may be incorporated in the trimming press.

In addition to the impressions used for the various operations of drop forging production, the dies are also provided with a gutter, which is the portion of the die, around the impression, that has been shaped to provide space for the excess stock.

Some die impression forgings, by nature of their design, provide a lock arrangement in the dies, which helps to maintain match or die alignment of top and bottom dies. When a design has no natural lock and when die alignment is difficult to maintain, shifting of the dies may be prevented by the use of lockpins or counterlocks. The dies in Fig. 3 show such locking methods, as well as the tooling used in the production of die impression forgings. Not all these types of tooling or locks are used for every design.

Standard draft angles of 7 deg are generally used in the dies although quite often, in cases where forgings are designed with deep holes, it is desirable to use 10-deg draft for better forging results. The draft or taper in the side walls of the die impressions is necessary for the removal of the forging from the die, and should be taken into consideration when the forging is designed.

Forging dies for small forgings are often designed with multiple impressions, producing several pieces in one flashing. The use of a larger hammer in producing the forgings in multiples is generally thought more economical, providing the quantities to be made are sufficient to justify the extra die expense.

An illustration of a small forging design produced in multiple impression dies is shown in Fig. 4. This is an example of forging three pieces at a time in one flashing.

Die blocks in most general use are made of forged alloy steel and are heat treated to a hardness governed by the size of the block and the design of the forging for which they are to be used. It is common practice to use dies that have been heat treated before sinking. Tables of standard hardness values, which have been devised by die block manufacturers, apply to the surface area of a given size block. Alloy steel dies, heat treated to ■ Brinell hardness of 444 or about 62 scleroscope, are often cut in the die shop and used for the smaller forging designs. For dies requiring a hardness of more than 62 scleroscope, the hardening of the dies is conducted after the die sinking. (*See also* the article "Heat Treatment of Die Blocks and Hot Die Inserts", in the TOOL STEEL SECTION, page 666.)

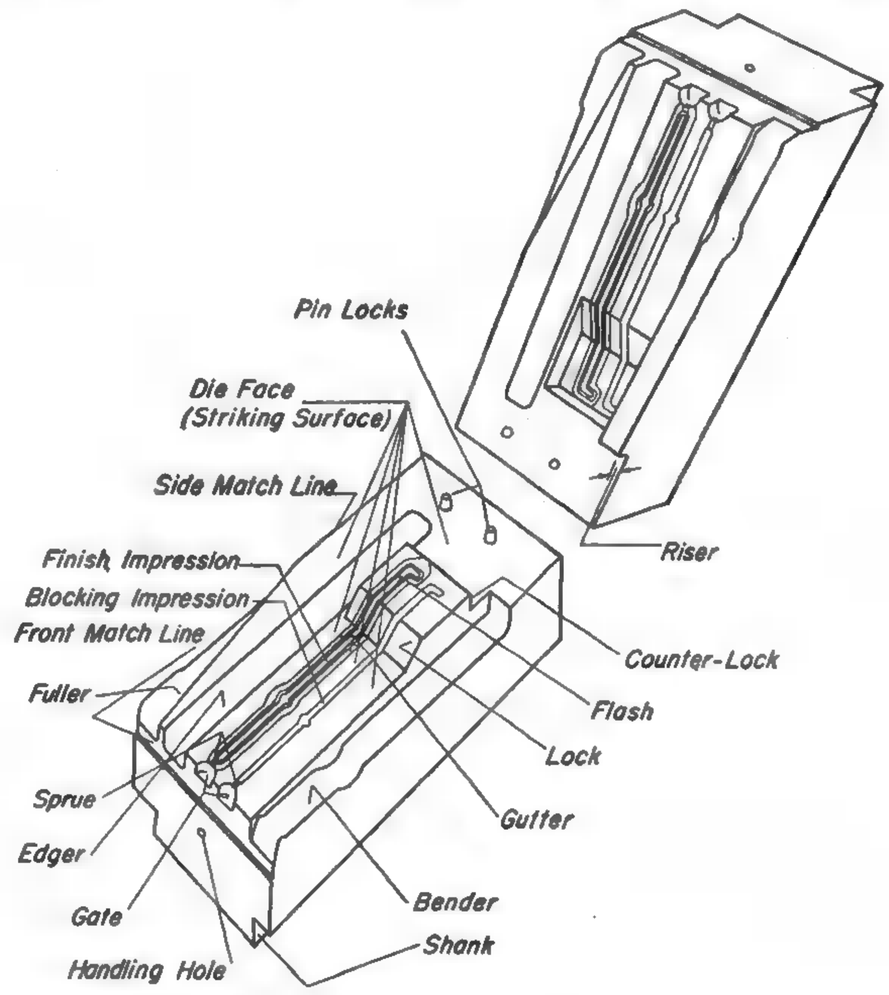


Fig. 3. Drop forging dies showing tool nomenclature

When a set of dies has been completed, the two halves are matched together and a cast of the finishing impression is made by pouring a molten alloy of lead and antimony into the dies. A plasticized sulfur-carbon compound may be used instead, particularly for large impressions, because of its lighter weight. The cast, ■ model of the forging, is measured and checked for die approval before production of forgings in the hammer. All casts are measured with a shrink rule, which compensates for the shrink-

ing of the forging metal. The amount of shrinkage varies with the type of metal forged, as well as with the shape of the forging, but may generally be considered as $\frac{3}{16}$ in. per ft for ferrous forgings.

The flash or excess metal forced out between the dies, in filling the impression to its complete contour, is trimmed from the forging in a mechanical press. Trimming dies are furnished for either hot or cold trimming, depending on the method desired. Hot trimming is done on large forgings and certain alloy steels which would fracture if cold trimmed. This hot trimming is usually performed in a press adjacent to the hammer, at the time of the forging operation. Small forgings are usually trimmed cold. They are trimmed in a press but often in another department.

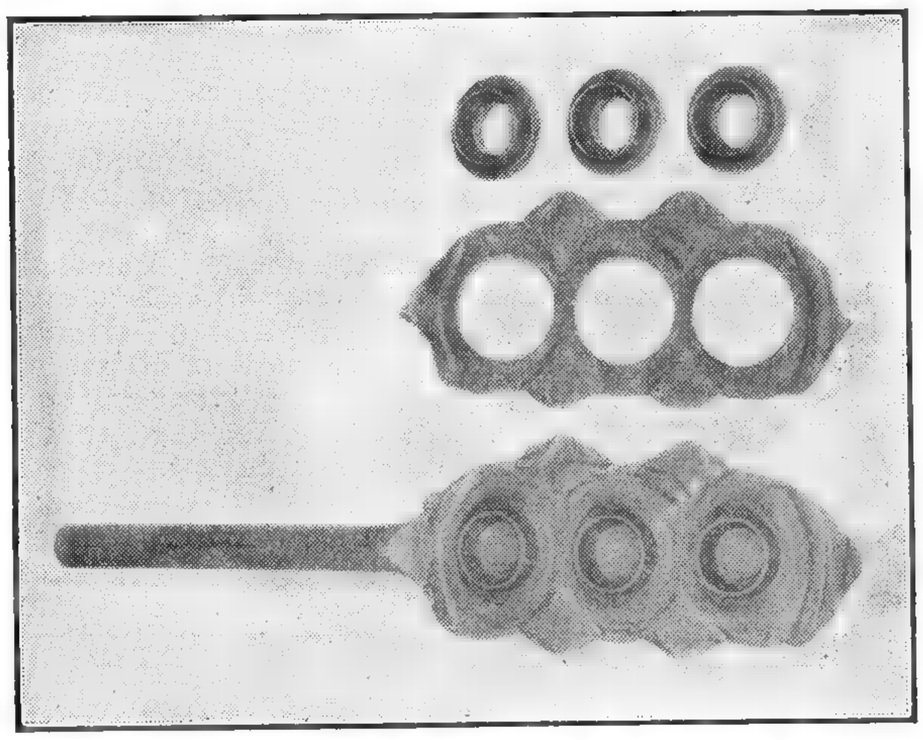


Fig. 4. Example of three pieces produced at one time, showing the trimmed pieces and flashing from the trimmed forging

Trimming dies are made of tool steel and are shaped to fit the outline of the forging at the parting line of the dies. The trimming punch, also of tool steel, is shaped to the contour of the top of the forging to be trimmed. The tools for cold trimming are always quenched and tempered to a hardness that will produce the best wearing and cutting edges for the particular forging design. Hot trimming tools are usually quenched and tempered but are sometimes used in either the annealed or normalized condition. (*See also* "Composition and Heat Treatment of Tools for Hot and Cold Trimming", in the TOOL STEEL SECTION of this Handbook.) A hard facing alloy is often welded to the cutting edge of trimming dies to increase the cutting life. The weld may be applied to the entire cutting edge or localized at points of extreme wear.

The Forging Operation. Drop forging operations are conducted by working from the bar end, cut slug or individual billet. In working from the bar, one or more forgings are made before the end of the bar is reheated. The number of forgings cut off at each heating depends on the size and shape of the forging.

Slugs of the weight necessary for the forging of one piece are cut and forged by the hammer upset method. The slug is placed on end on the die and upset or pancaked to form the forging. This method, affording a particular advantage in the control of grain fibers, is used

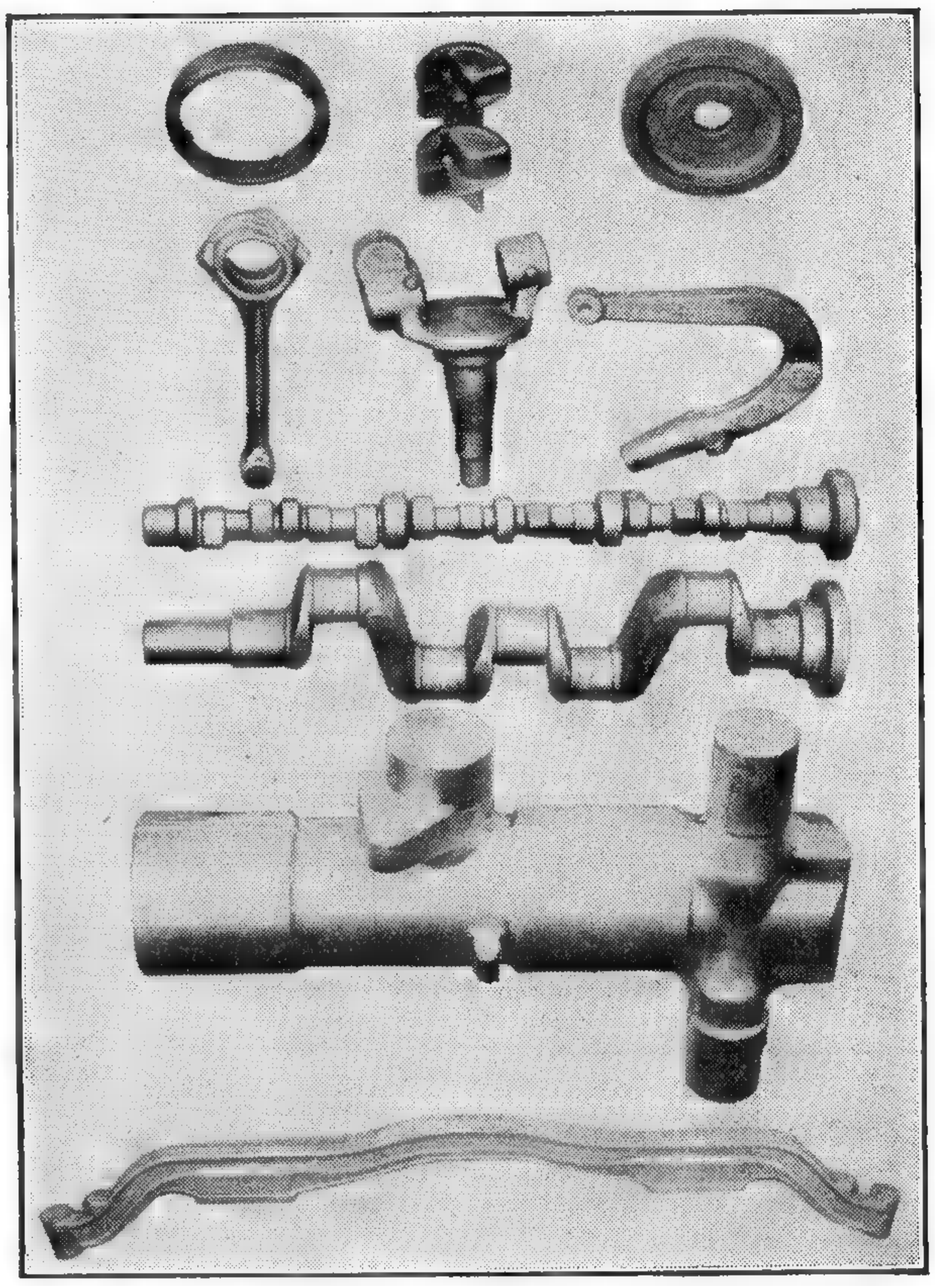


Fig. 5. Miscellaneous drop forgings

generally in the production of gear blanks, hubs, and flange forgings. Figure 5 shows a variety of die impression forgings produced by the drop forging process.

Forgings of medium and larger sizes are made from billets sheared or sawed to the individual length required for the production of one piece. Large and massive forgings often require two or more hammers to effect their completion; each hammer forges progressive steps, with the aid of proper dies and tooling.

While the bar or billet is being forged into a completed drop forging, the metal is further refined into a dense tough fiber structure. This refinement of the forging bar improves the physical properties, increasing the impact, tensile, torsional and compression strength.

Hot Upset Machine Forging

BY W. W. CRILEY*

HOT heading, upset forging or, more broadly, machine forging are terms applied to the hot deformation or plastic flow of steel in forging-machines commonly used for upsetting. Hot upset forging consists primarily of holding a bar of uniform cross section, usually round, between grooved dies and applying pressure on the end in the direction of the axis of the bar by using a heading tool so as to upset or enlarge the end. This method of deformation during compression can be used to forge any of the malleable materials, including wrought iron, alloy steel, copper, bronze, aluminum and others. The forgings thus produced range in weight from a few ounces to several hundred pounds.

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Description of Forging-Machines. Present-day forging-machines, some of which weigh more than 200 tons and are capable of exerting 2000 tons of pressure, are an outgrowth of earlier small machines built mainly for hot

heading bolts. These earlier machines were rated on the basis of the maximum size bolt that they were capable of heading. This method of rating has continued, and has been extended to include even the largest machines.

The machines in general use are mechanically operated from a main shaft, with an eccentric that drives a main or header slide horizontally, and with cams that drive a die slide or grip slide which moves horizontally at right angles to the header slide, usually through a toggle mechanism. Power is supplied to the machine flywheel by an electric motor. A clutch provides for "stop motion" operation, placing the movement of the slide under the control of the operator. (*See* Fig. 1.)

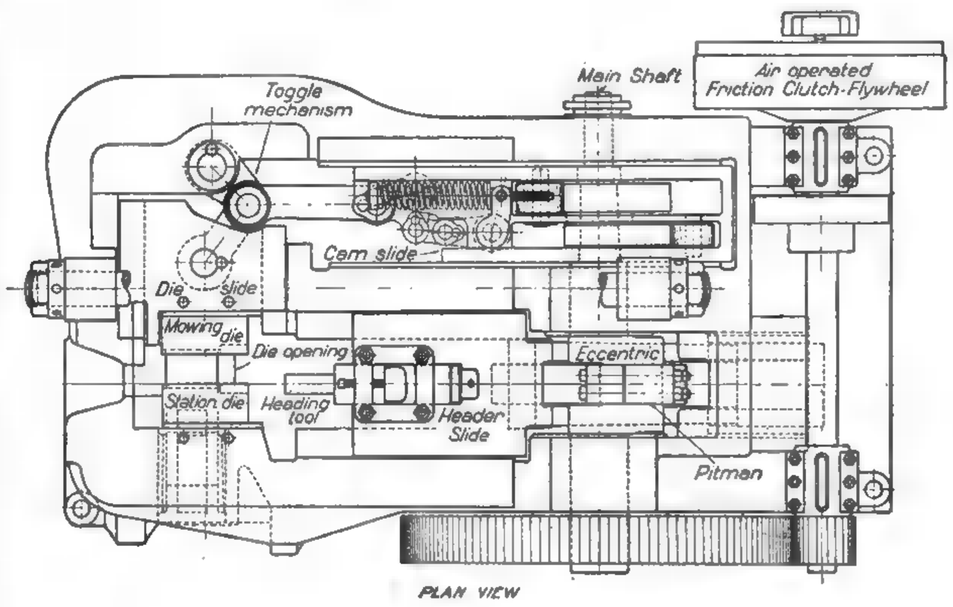


Fig. 1 A plan view of a forging-machine showing arrangement of working parts

Forging takes place in three die elements: two dies or "gripper" dies (one stationary and one moved by the die slide) that have matching faces with horizontal grooves to grip the forging stock and hold it by friction; and "headers" or "heading tools", carried by the header slide in the plane of the die work faces and matching the grooves in the dies. The travel of the moving die is designated as the "die opening", and its timed relation to the movement of the header slide is such that the dies close during the early part of the header-slide stroke. The part of the forward header-slide stroke that takes place after the dies are closed is known as the "stock gather", and the amount that the returning header slide travels before the moving die starts to open is called the "hold on" or simply the "hold".

"Die opening" is the factor determining the maximum diameter of upsets that can be formed on a given machine, transferred between the dies and withdrawn through the throat, without pushing the dies forward and lifting the work piece out over the top. The diameter of the stock, rather than the stock gather, determines the amount of stock that can be upset; however, the stock gather has an important bearing on the depth to which internal displacement can be carried. The height of the die determines the number of progressive operations that can be accommodated in one set of dies.

For forging, the operator places a bar of forging stock heated on the end, in the first groove in the stationary die against a movable stock-gage in order to secure the correct volume of stock in the forging impression. When the clutch is tripped, the moving die closes, grips the stock and holds it, while the heading tool advances and upsets the end of the bar that projects beyond the gripping grooves and is termed "working stock". The operator then transfers the bar to the other die grooves, ordinarily striking it only once in each groove. The number of grooves depends on the steps required in forging.

Forging is not limited to simple gripping and heading operations, since the transverse action of the moving die and the longitudinal action of the heading tool are available for forging in both directions, either separately or simultaneously. In addition to gripping, the die motion can be used for swaging, bending, shearing, slitting, punching and trimming; and in addition to upsetting, the heading tools are used for punching, internal displacement, extrusion, slotting, trimming, bending and other work.

Because the cavities formed by the two dies and the heading tools open in two places at right angles, and because the working stock can frequently be totally confined in these cavities during the forging operation and subjected to a pressure similar to hydrostatic pressure, forcing the stock to fill the impressions completely, a great variety of shapes can be forged and removed from the dies without difficulty, as shown in Fig. 2.

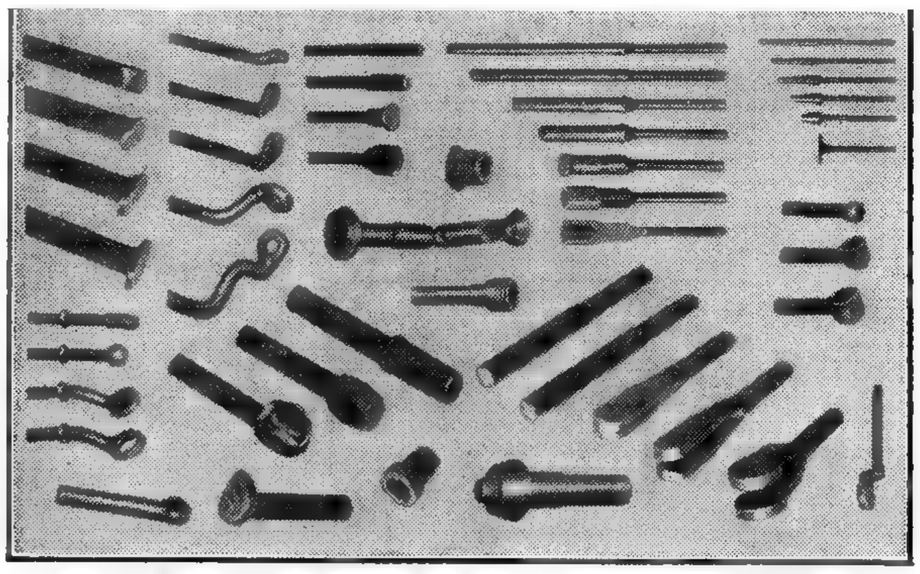


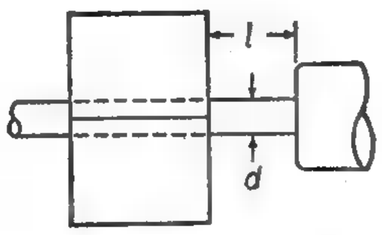
Fig. 2 A group of upset forgings, some of which show the successive forging operations

Forging-Machine Requirements. In order to produce forgings accurately filled out, free from defects and conforming to the close standard tolerances drafted by the Drop Forging Association, February 11, 1937, the modern forging-machine must have the following essentials: (1) a rigid frame with minimum transverse and longitudinal distortion under forging pressure; (2) a powerful die grip to hold the stock securely and to prevent the dies from spreading open with resultant formation of flash; (3) accurate die-slide and header-slide alignment to prevent the mismatching of the impressions of the two dies and heading tools, and to produce deep concentric holes; (4) ample heading power to forge to accurate thickness and to drive the stock into remote parts of the die impressions in order to fill them properly; (5) a fast starting clutch, and operating convenience so that the numerous operations required for producing difficult forgings can be performed before the working stock cools appreciably.

Design and Construction of Dies. Proper dies are also essential to the production of sound forgings so that impressions will retain their correct shapes, particularly at the parting line. The dies should be constructed of suitable grades of die steel for hot work with resistance to heat, pressure, and abrasion, and should be selected with reference to the specific properties required, the speed of forging, and the number of forgings to be produced. (*See* "Heat Treatment of Steels for Hot Forging Machine Tools", in the TOOL STEEL SECTION.) The absence of impact in this method of forging makes it possible to build up dies with inserts, thereby utilizing a variety of high-grade steels without prohibitive cost, in order to meet the needs exactly at different locations in the impressions. The use of inserts gives increased durability and makes the more vulnerable points inexpensively renewable. Inserted dies and tools for upsetting gear blanks are shown in Fig. 5.

Grain Flow. In gear forgings particularly, and other highly stressed parts, an effort is made to secure maximum strength through advantageous internal grain flow, as illustrated in Fig. 5. This flow can be controlled by the shape of the preliminary upsets, and re-entering or sharply folded flow lines can be avoided. Each die should be shaped so as to be easily filled by hydrostatic pressure within the hot metal.

Flash. Flash can be avoided best by locating the parting line between the heading tool and the die at the point of the impression that fills last. Differential heating is also helpful in eliminating flash. When upsetting in a groove in the dies (Rule II, Fig. 3), stock should be hottest at the base of the upset and at the lower forging limit at the end. When upsetting in a recessed tool, the natural heating of the stock gives maximum temperature on the end and lowest temperature at the exposed section, discourag-

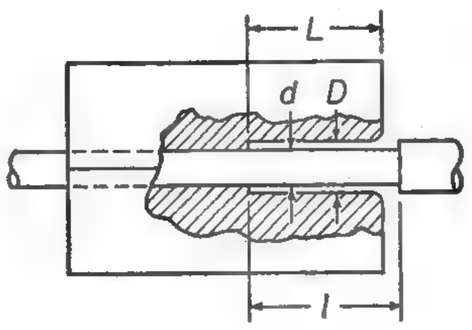


Unsupported Working Stock, One Blow

Rule I. Exposed working stock, up to a maximum length of three diameters, can be upset without support to prevent bending.

Working Recommendation:

$l \leq 2\frac{1}{2}d$



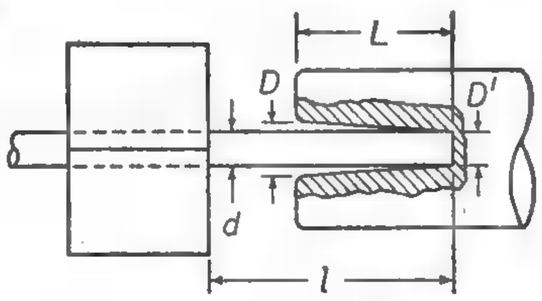
Stock Supported In Die Impression, One Blow

Rule II. Working stock longer than three diameters will be supported against injurious bending, by a die impression of a diameter not greater than 1½ times the diameter of working stock if the length of stock projecting beyond the impression is less than ½ the diameter.

Working Recommendation:

$D \leq 1.4d$

$L > l - \frac{1}{2}d$



Stock Supported In Tool Recess, One Blow

Rule III. Working stock longer than three diameters will be supported against injurious bending, by a heading tool recess of a diameter not greater than 1½ times the diameter of working stock at the mouth and 1⅛ times the diameter of working stock at the bottom and a length of at least two-thirds the length of working stock.

Working Recommendations:

$D \leq 1.4d \quad L \geqq \frac{2}{3}l$

$D' = 1.1d \quad L \geqq l - 2\frac{1}{2}d$

Repeated applications of the second and third rules make possible the upsetting of great lengths of original bar stock. Preference is given to recessed heading tools for stock-gathering because of their durability and because the upsets are free from flash, which tends to form at the die part-line and around the periphery of plungerlike heading tools when upsetting in grooves in the die.

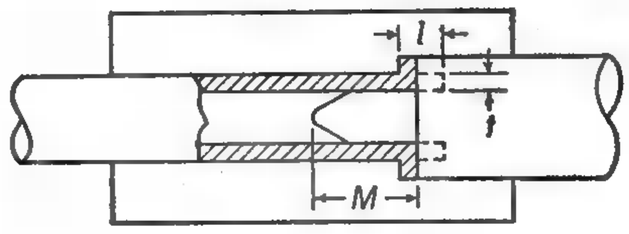
Fig. 3 Rules for upsetting bar stock

ing formation of flash at the parting line between grip dies and header. If flash is unavoidable, it should be located where it can be easily removed by trimming, chipping or grinding.

Factors Governing Upsetting. The number of operations required to produce a forging is determined by the length and diameter of the working stock, the shape of the forging itself, and any special grain flow necessary to produce the desired mechanical properties in the finished forging. Successive upsetting operations should each fill the die cavity completely. Consequently each die cavity in a series should accommodate the same volume of metal, free from defects which would be embedded by subsequent operations. Aside from fins or flash, the most common defects to be avoided are re-entering fiber or internal folds and cold shuts (closed folds in the surface metal).

The rules governing the upsetting or gathering of stock, without injurious bending and resulting cold shuts, are stated in Fig. 3.

Square stock is governed by the same rules as round, using d as the mean of the flat and diagonal dimen-

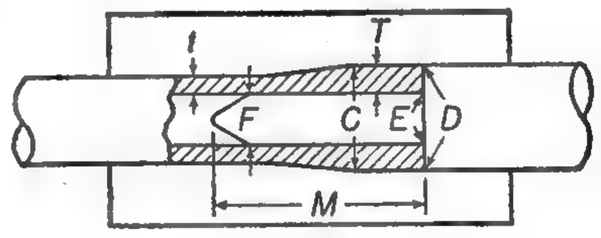


Flanging, One Operation

Rule I. Working stock, up to a maximum length of 2½ times the wall thickness, can be upset in one operation without support to prevent buckling.

Working Recommendation:

$l \leq 2\frac{1}{2}t$



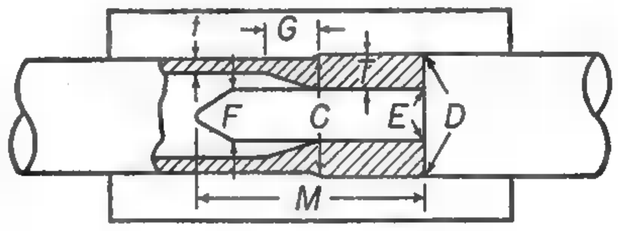
Outside Upsetting, One Operation

Rule II. Wall thickness of working stock can be increased to a maximum of 1½ times its original thickness in one operation, by upsetting to the outside, that is, increasing the outside diameter of the tubing at the upset.

Working Recommendation:

$T \leq 1.4t$

When greater wall thickness is required, successive outside upsets can be made, using the minimum wall thickness of the preceding upset as t in Rule II.



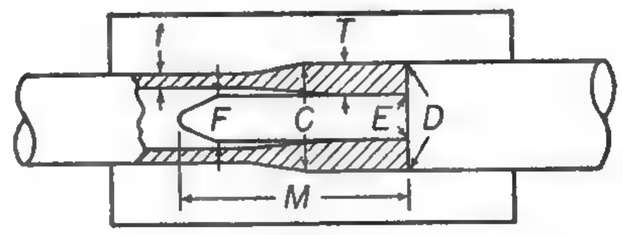
Inside Upsetting, One Operation

Rule III. Wall thickness of working stock can be increased to twice its original thickness, in one operation, by confining the outside diameter and upsetting to the inside, that is, decreasing the inside diameter of the tubing.

Working Recommendation:

$T \leq 2t$

When greater wall thickness is required, successsive upsets can be made, using the minimum wall thickness of the preceding upset as t in Rule III.



Outside and Inside Upsetting

Rule IV. Wall thickness of working stock can be increased up to a maximum of 1½ times its original thickness in one operation, by upsetting to the outside and inside simultaneously, that is, increasing the outside diameter and decreasing the inside diameter in the same operation.

Working Recommendation:

$T \leq 1.4t$

Fig. 4 Rules for upsetting tubing

sions; but rectangular stock bends so easily flatwise that the short rectangular dimension is the one that must be used in the formulas.

Pierced Forgings. Forgings that are internally recessed or deeply pierced are produced most easily by the progressive piercing method, as contrasted with extrusion. In this method, illustrated in Fig. 6, the metal from the interior of the full-length blank is progressively displaced to the outside of the die cavity without excessive pressures or

abrasive flow to cause rapid deterioration of the die elements. The wear on the piercer and the dies is much less than where extrusion or counterflow takes place, as in the piercing operation (*see* article, "Piercing of Steel").

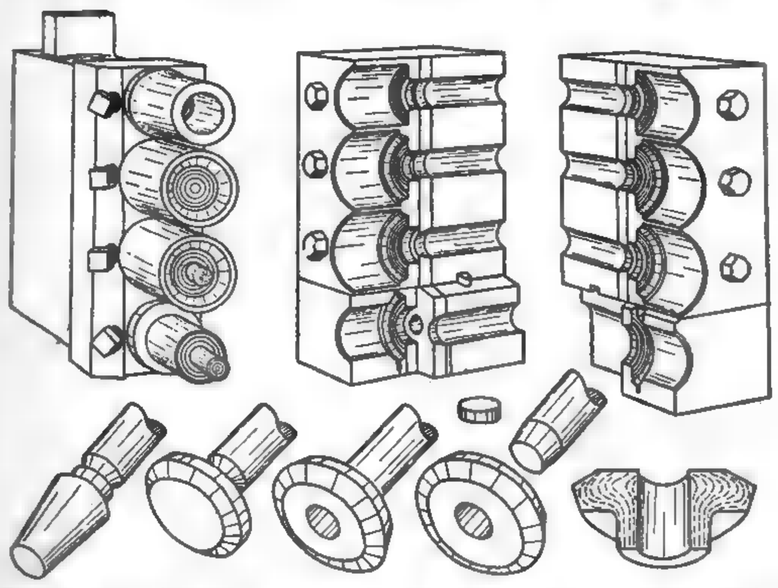


Fig. 5 Inserted dies and tools for upsetting gear blanks with a final combination shearing and punching operation; also the progressive forging steps and a section showing the looping grain flow of the completed forgings

Tubular Upsets. With the extensive use in the oil industry of seamless steel tubing with threaded joints of full body strength, and the use of both seamless and welded tubular structural members where minimum dead weight and maximum strength are required, the upsetting of tubing has assumed importance. Because thin-walled tubing collapses very easily, difficulty is encountered in gripping between the dies to prevent slippage, and the use of a backstop is frequently required. Rapid cooling makes reheating necessary; and the wall thickness limits the extent to which upsetting can be carried in a single operation without injurious folds. Since buckling occurs on the outside, it is possible to gather more wall thickness to the inside, with the outside of the tube closely supported by the walls of the die impression. When it is necessary to upset to the outside, the diameter must be limited so that the walls of the die will keep the amount of buckling short of the point at which wrinkles, folds or cold shuts would be formed. The rules for upsetting tubing are stated in Fig. 4.

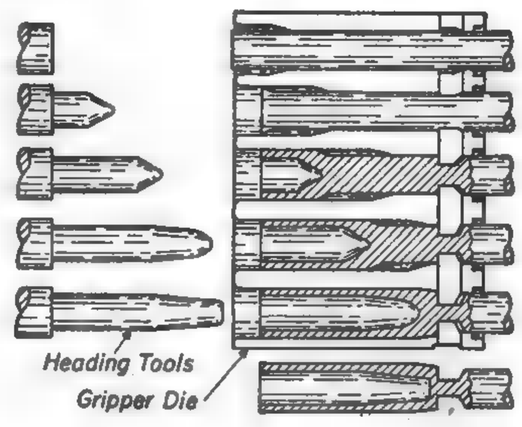


Fig. 6 Progressive steps in deep piercing a shell by internal displacement, showing a cross section of the piercing operation in the die impression, prior to the action of the piercer

When convenient, gaging should be done by a backstop or with the heated portion of the tube projecting as little as possible beyond the mouth of the dies. Mandrel length should be sufficient for the nose to extend beyond the heated portion of the stock. A slight taper on the mandrel and reverse taper in the die cavity beyond the forward position of the tool will facilitate flow of working stock. Highest temperature at the base of the upset, tapering to the lower forging limit at the mouth, decreases resistance of the stock to travel back in the impression, discourages formation of flash around the heading tool, and promotes the filling of the base of the upset.

Mechanical Press Forging

By W. W. Criley*

MECHANICAL forging presses are a distinct type of press designed for forging in impression dies. They are available in capacities up to 6000-tons pressure rating, and are able to produce a wide variety of forgings similar to drop forgings and upset forgings.

Mechanical Requirements. The currently accepted forging presses are upright, driven by a motor and controlled by an air-clutch. They have a full-eccentric type of shaft, imparting constant stroke to a vertically operating ram, carrying the top or moving die with impressions matching those of the bottom or stationary die, which is clamped on the die seat of the main frame. Figure 1 shows a press of about 1600-tons capacity.

To shorten the period of contact between the hot metal and the dies requires great rigidity, reasonably high operating speed and ejectors that act quickly. Good slide alignment is essential, as well as a means for adjusting dies for forging thickness and, because of the positive ram travel, dependable overload protection with facilities for backing off from a stall.

Range of Products. Symmetrical forgings, such as gear blanks, driving flanges and rock drill bits, are produced from blanks of round or round-cornered square stock, sheared to length and placed on end in the die impressions. The number of progressive operations required is governed by the same rules of upsetting as are stated for machine forging, page 40, except that frequently a preliminary operation is introduced for the purpose of breaking off and disposing of scale to avoid trapping it in the die impressions. Ordinarily flash is thrown out at the parting line between the top and bottom dies, as in drop forging; but sometimes flash can be eliminated completely by entering the top die into the bottom impression, with the ejector facilitating removal of the forging.

Automobile valves and cup forgings, like those used in shell case production, can be made by placing a blank in a cylindrical recess in the bottom die and acting upon it with a punch that enters and fits the recess. The stem of the valve is squirted out or extruded, whereas the cup is formed by counterflow up around the punch. In both instances, the metal movement is more rapid than the movement of the punch and slower press speeds are used.

Forging Operations. Forging stock flatwise or transversely is accomplished in die impressions similar to those used in drop forging, with edger or fuller, bender, blocker and finisher impressions, as required. Because of the constant ram stroke, the fuller must have sufficient cross-section to accommodate the original bar stock without flash, in order to avoid folds or cold shuts in subsequent operations. Sometimes when fullering is not required for metal distribution, preliminary flattening is substituted to dispose of scale.

Elimination of scale through induction or controlled-atmosphere heating, hydraulic descaling, or preliminary scale-breaking operations, is of importance since generally the piece is struck only once in each impression. A tong hold is frequently unnecessary, because when the ejectors release the piece from the die impressions, it can be transferred by the flash.

In the absence of variable stroke, the forging press does

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Prepared for the Subcommittee on Forging, with membership as follows: Adam Steever, *Chairman* (Columbia Tool Steel Company), W. W. Criley (The Ajax Manufacturing Co.), A. A. Handler (Deceased), G. R. Houghtaling (Rochester, N. Y.), Waldemar Naujoks (Forging Consultant), William Telfer (University of Michigan) and R. W. Thompson (Transue & Williams Steel Forging Corporation).

not have the ability of the steam drop hammer to draw or fuller blanks with great variation in cross section. For that reason it is desirable to use prerolled blanks or stock that has been previously fullered to the correct shape in trip or steam hammers.

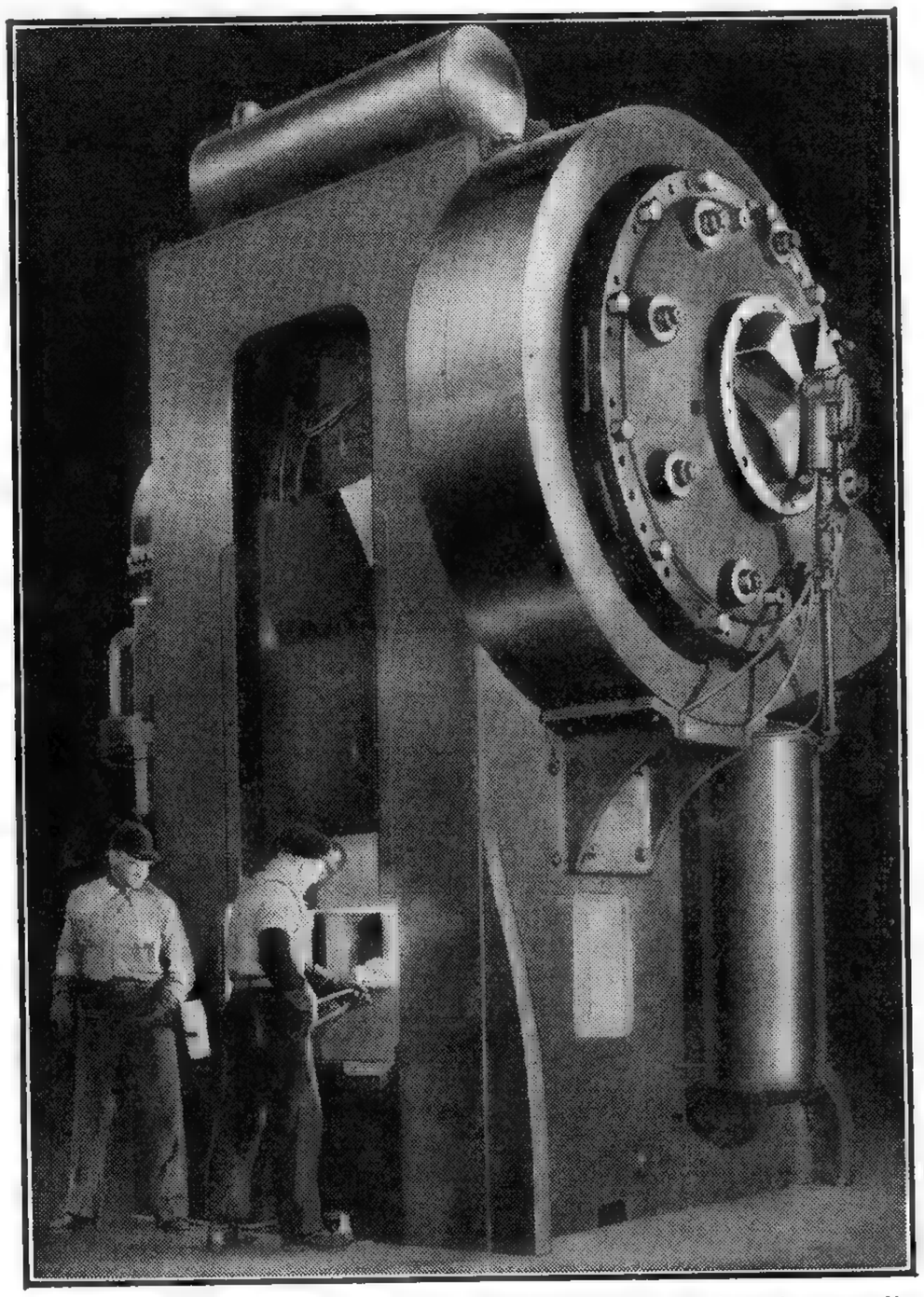

Fig. 1 Mechanical forging press, approximately 1600 tons in capacity

In addition to the usual forging operations, the forging press can be used to hot shear forging blanks of compositions that cannot be sheared cold and to hot trim high-carbon steel forgings that would be damaged by cold trimming.

Die Construction. Although dies can be employed with all impressions sunk in an integral block, identical with those used with drop hammers, the dies need not have the mass called for to absorb impact, since the press displaces the metal by pressure. Consequently, it is preferable and more economical to build up the dies with comparatively small blocks or inserts clamped in holders or bolsters. These can be made of whatever grade of die steel is warranted, and the hardness may be as high as desirable, since there is little danger of cracking from impact.

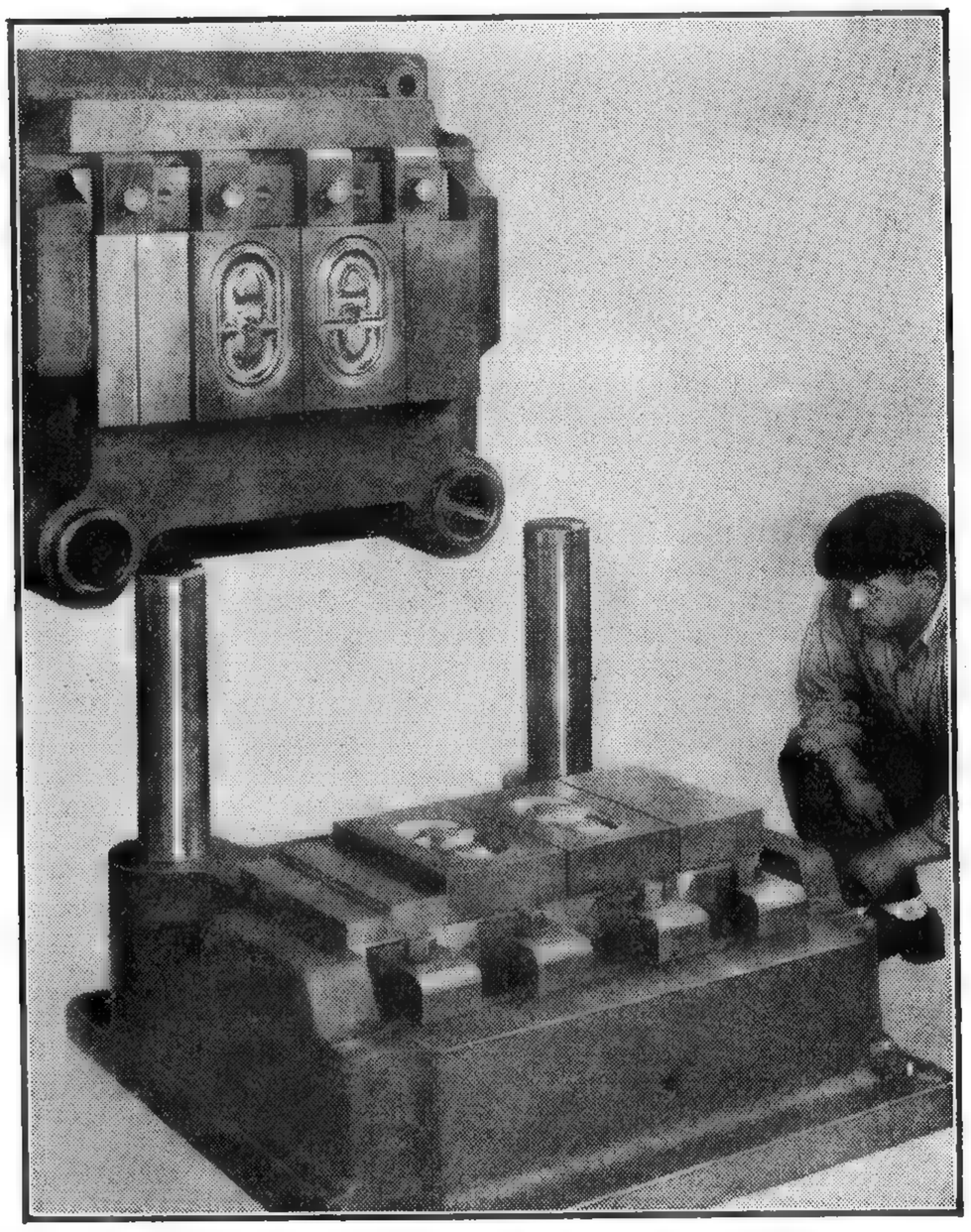

Fig. 2 Bolsters and chain link dies for use in a 2000-ton mechanical forging press

Small rectangular blocks held by toe-clamps are illustrated in Fig. 2.

Coining

By Guy R. Houghtaling*

COINING is a method of cold forming or sizing, by compression, an article of gold, silver, copper, zinc, tin, nickel or other metals. In recent years, iron and steel parts have been subjected to cold sizing for the purpose of imparting smooth finishes and close tolerances, and in numerous instances this coining operation is more economical than the production of a similar finish with cutting tools. A connecting rod for a gasoline engine is an example where coining is used extensively to size the bosses at the ends of crankshafts and wrist pins, within limits of plus or minus 0.001 in. The dies used are ordinarily plain, hardened blocks with stepped parallel surfaces between which the steel forging (about 1/32 in. larger) is squeezed to size.

In coining, it is impossible to suggest a definite percentage of reduction that would be satisfactory for most purposes, since each individual job has its limits, which are usually governed by the ability of the steel in the dies to withstand constant pressure. On work that is confined, a good rule is to use 25% of the ultimate compressive strength of the dies in question. On work that is not confined, 50% of the ultimate compressive strength of the die steel can be used for production runs.

Coining Equipment. *Drop Hammers.* If the pressure is not extreme and if the material will flow readily into the dies, drop hammers can be used to exert instantaneous pressure on the article that is being struck.

Coin Presses. These are usually powerful presses with a slide movement actuated by a toggle between the slides. The toggle is operated by an eccentric or crankshaft.

* Rochester, N. Y. Prepared for the Subcommittee on Forging, with membership as follows: Adam Steever, *Chairman* (Columbia Tool Steel Company), W. W. Criley (The Ajax Manufacturing Co.), A. A. Handler (Deceased), G. R. Houghtaling (Rochester, N. Y.), Waldemar Naujoks (Forging Consultant), William Telfer (University of Michigan) and R. W. Thompson (Transue & Williams Steel Forging Corporation).

Presses of sufficient rigidity may be operated directly by an eccentric.

Screw Presses (percussion). These presses utilize a multiple-thread screw to which is attached a heavy flywheel that stores energy and, on a fast downward movement, exerts a powerful pressure on coin dies.

Hydraulic Presses. These are fast becoming adapted to coining work. The modern, one-unit hydraulic press can be made to operate fast and with high pressures. These presses can be regulated so that only a definite pressure can be exerted on the dies. One distinct advantage is that the action of the hydraulic press permits the metal to take a more definite set because of the length of time in compressive action.

Annealed mild steel, with about 0.20% C, requires approximately 50 tons per sq in. to start plastic flow. This force increases as the article becomes harder and the operation must be stopped before reaching the compressive strength of the die steel.

Hydraulic presses permit using the greatest amount of the operating time cycle in actual squeezing, because the dies can be closed and opened rapidly. Sometimes as much as 3/5 of the time cycle is spent in squeezing, and only 1/5 each in closing and opening the dies.

Coining Dies. These are usually made by sinking a hardened hub into a soft die block. The hub is a faithful reproduction of the article to be coined, and from its impression in the die block comes the article to be manufactured. Most of the details in the actual making of coining dies have resulted from long experience, careful observation and the most painstaking heat treatments. Metals will work harden when squeezed between coining dies; therefore, to get economical production from the dies, it is important to control this condition by annealing.

Coining-Die Steel. The steel selected for the coining dies is largely a matter of personal preference. Carbon steel, formerly selected, is usually shallow hardening, and although it becomes very hard on the surface, it will not withstand intense pressures. Tool steel manufacturers supply a Cr-Ni-Mo drop-forge die block steel that has about 0.65 to 0.70% C and is pack hardened and oil quenched. This steel has a high compressive strength, holds its shape well during heat treatment and, after proper tempering, gives a coining die of long life. Many other steels are suitable, and where simple finishing can be done by machining and grinding, the high-carbon, high-chromium steel is excellent. Modern high production schedules require coining dies to withstand tremendous pressures repeatedly and only steel able to be heat treated for deep hardness is suitable.

Methods of Coining. Usually money is coined in a hardened ring, inside of which are upper and lower dies. Just enough metal is used in the blank to size the coin accurately. Spectacle frames are made from "found blanks" (blanks with proper dimensions and just enough metal to fill the dies). Spectacle parts and jewelry items made of gold-filled metal must come from the coining dies with the surface gold unbroken.

Because of the large amount of flow required on numerous articles that are coined (for example, finger rings), the metal work-hardens before it is possible to fill the die completely. It is then necessary to anneal the blank and sometimes to restrike a number of times, with an anneal before each strike. Since the work-hardened metal requires such enormous pressure to make it flow, the coining dies do not have sufficient compressive strength to resist sinking, so it is most important to anneal the blanks whenever necessary.

It is essential to have clean blanks at the start of the coining operation and perfectly clean blanks after annealing and before restriking. Most copper-base alloys require a red heat to anneal and, unless a protective atmosphere is used during heating, the parts will have to be pickled and washed. Coining dies must be kept clean. Degreasing solvents are recommended as well as frequent use of bristle brushes. Small particles are bound to be removed from blanks during coining and a die can easily be split because of such particles. Another important precaution is to keep even the smallest drop of moisture (water or oil) from entering deep cavities, since metal will not flow into cavities containing moisture.

Numerous pieces of jewelry are made purposely with a surplus of metal called "flash-selvage". These dies are economical to make where it is not necessary to hold thickness to exact dimensions. Therefore, any surplus not needed to fill either upper or lower dies is flowed over the edges of both dies. This surplus or flash must be carefully controlled. Generally, a good rule is to limit the width of the flash to no more than three times its thickness. Where flash must be thicker, flash gutters can be cut in one half of the die, next to the die line.

Coining is usually done by compressing an article into a die. The reverse operation, compressing a soft annealed article onto or around a shaped hardened mandrel or arbor by forcing the article through a compressing die or taper ring, compresses the soft article onto the mandrel or arbor.

The Army Ordnance Department has successfully compressed a machine-gun barrel onto a hardened spiral-fluted mandrel, thereby giving the gun barrel a series of rifled grooves. It had always been considered necessary to machine this spiral groove by cutting tools or broaches.

Numerous difficulties are involved in this external compression of metals, such as unequal cross sections of the part to be compressed and the problem of removing the shaped mandrel after the compressing is done. Plastic molding dies have been made in which a small deep blind hole of irregular shape has been compressed onto ■ hardened mandrel, solving the difficult problems encountered in producing such a blind hole in any other manner.

One method of freeing the mandrel is to force it slightly into the article after the compression die has been removed, which tends to expand the outer member. Another method is to hammer or roll the article externally to expand it enough to free the mandrel. *See also* Novel Methods of M3 Submachine Gun, American Machinist, May 11, 1944, page 109.

Cold Heading

BY THE SUBCOMMITTEE ON BOLTS*

COLD heading consists in forcing metal to flow cold into dies to form thicker sections and more or less intricate shapes. The operation is performed in specialized machines where the metal, in the form of wire or bar stock, may be upset or headed in certain sections to a larger size and, if desired, may be extruded in other sections to a smaller diameter than the stock wire. Although cold heading was developed for the production of bolts, screws, and rivets and is used largely for these parts, the process is applicable to a wide variety of special parts that have somewhat similar form.

* The members of this subcommittee are H. B. Pulsifer, *Chairman* (Deceased), C. L. Harvey (The Lamson & Sessions Co.), H. L. Hopkins (The National Screw & Manufacturing Co.), E. O. Mann (Chevrolet Motor Company) and W. C. Stewart (American Institute of Bolt, Nut and Rivet Manufacturers).

Size and Shape. Because of the high forming pressure necessary and the consequent heavy machinery involved, cold heading is applied only to small and medium-sized parts, generally to those that can be produced from wire no larger than ¾ in. in diam, though facilities are available for upsetting from wire as large as 1 in. in diam.

The extrusion which may accompany cold heading is applied principally to the production of cylindrical sections, less than the stock wire size. This reduction in cross-sectional area may be as much as 30%.

The upsetting or heading by cold forging can be used to produce a great variety of bulbous shapes which are usually

symmetrical about the longitudinal axis but may be offset (Fig. 1). The upset may be at one end of the part or at some intermediate position. The volume limit of such upsetting is expressed in terms of length of stock, in diameters required to fill out the upset. The usual limit of upsetting is a volume of 4½ diam of stock, although there are methods by which larger upsets can be obtained.

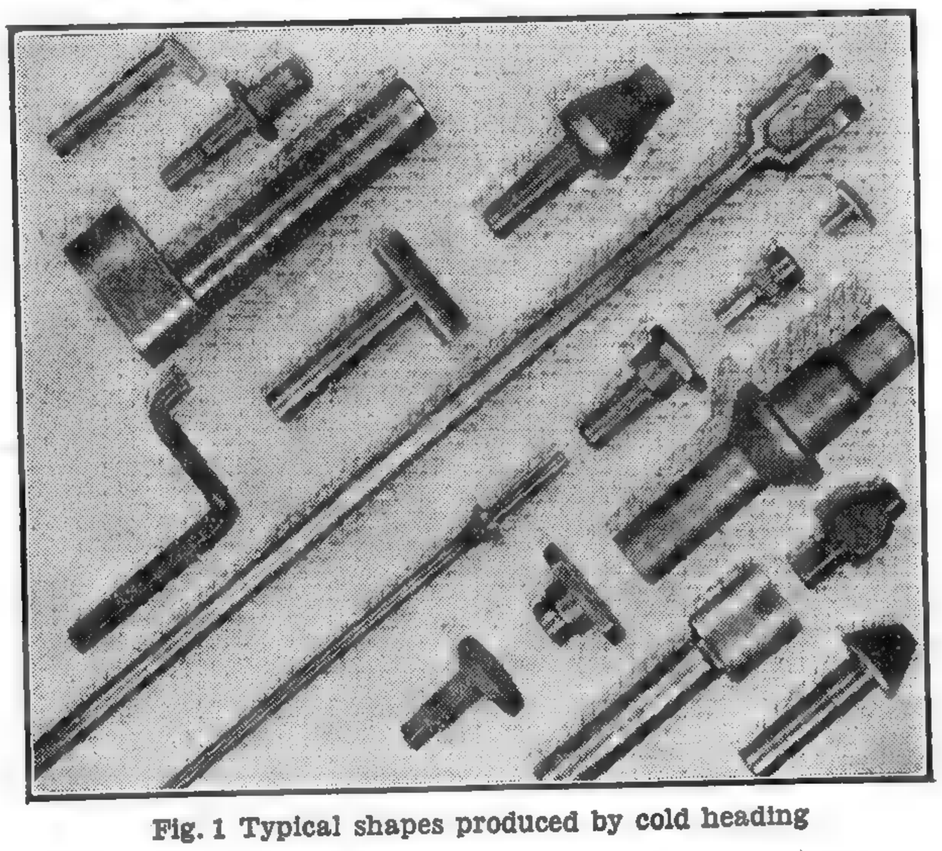

Fig. 1 Typical shapes produced by cold heading

Materials and Treatments. Virtually any material that is malleable when cold can be used for cold heading. Such materials include carbon and alloy steel, stainless steel, copper and its alloys, aluminum and its alloys, monel metal and others, providing a selection of material for almost any service. A little stiffness of material from cold work is desirable in most cold heading stock; otherwise buckling and folding may result. On the other hand, on the hard side, the upper limit may be set by the practical limit of die life, shearing, or bursts from imperfections that would not affect softer stocks. Special-purpose materials, such as screw stocks designed for use in other processes, are not ordinarily cold headed. Similar materials without the free-machining elements, such as high sulfur content in steel, are used with improved properties and reliability.

Although a large proportion of cold headed parts are given no heat treatment, they may be quenched and tempered provided suitable steels are used, thereby enhancing the mechanical properties. Also, in certain low-carbon steels where extreme upsets are made, the parts may be stress relieved at 900 F or higher.

Finish and Secondary Operations. The finish of cold headed parts gives a bright, smooth and burnished appearance where heat treatments are not applied. Also, dimensional tolerances can be held very closely. For these reasons, often cold headed parts can be used in the as-formed condition. However, any of the usual secondary finishing operations, such as machining, grinding, trimming, shaving and drilling, may be applied where unusually close tolerances are desired or where alterations of the cold formed shape are required.

Quality. Cold headed parts have unusually high and reliable quality. In the first place, material of special quality suitable for cold heading is ordinarily used, which has had special care in the steel mill. Then the shaping operation itself is a 100% check, since any serious defects in the material will become apparent visually during the upsetting operation.

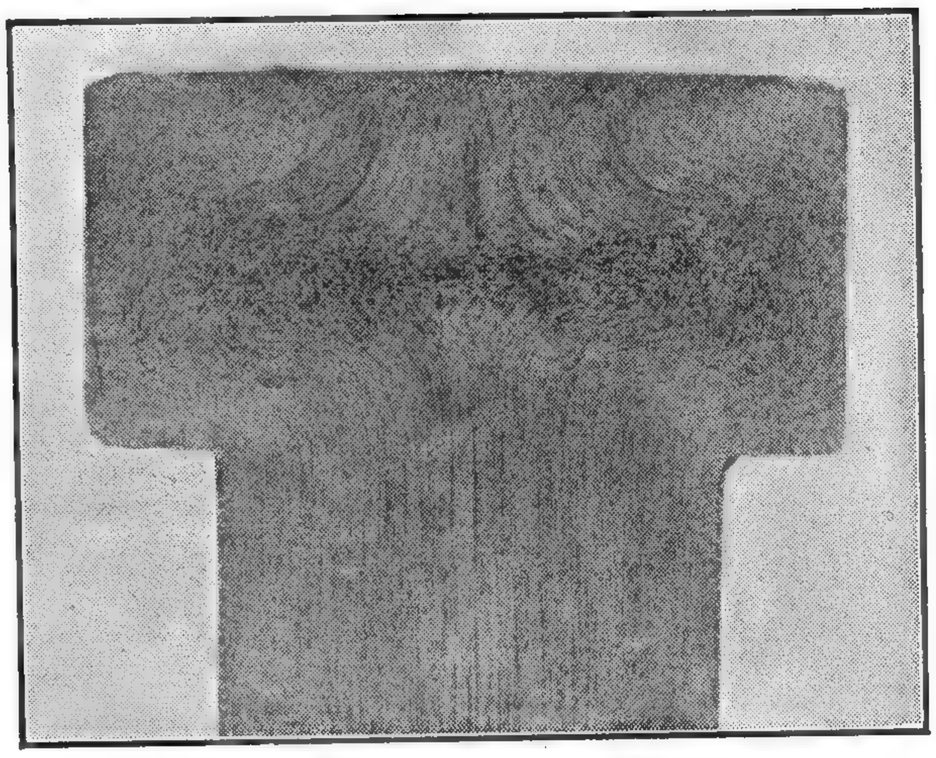

Fig. 2 Flow lines in cold upset bolt head

The strength of cold headed parts is enhanced by the cold working of the metal unless subsequent heat treatments are applied. Even when heat treatments are applied, the cold headed part is superior by reason of the directional flow of the metal. During the upsetting operation the grain flow of the metal conforms to the contour of the part, resulting in the highest degree of reliability and resistance to shock and vibration. This directional flow of the metal can be shown by etching a section of the upset. (*See* Fig. 2.)

Economy. There is little if any waste of material in cold heading. In the as-formed condition waste may be virtually zero compared with the very high losses incident to cutting parts of varying section from the solid. Further, parts are produced at a very high speed—from possibly 50 per minute for large sizes to several hundred per minute in small sizes—all of which tends to make cold heading processes well suited to mass production.

Dies. For information about the heat treatment of cold heading dies, see the TOOL STEEL SECTION, page 672.

Roll Threading and Knurling

BY L. A. WARD*

ROLL threading and knurling are processes for impressing a design into a metal object by means of suitable revolving rolls or dies that are forced against it while it is being rotated. The rolls or dies have a female impression of the desired pattern embossed on their periphery. In roll threading, the design is a helical groove or grooves of the desired contour and pitch. In knurling, the design may be of any desired shape that lends itself to the process.

Little has been published about the history of roll threading and knurling. As early as 1888, socket shells were roll threaded by the Edison Lamp Works; in fact, standard specifications had been formulated there for this work. Knurling was undoubtedly performed some years before this, particularly on solid objects in the lathes that were available. Since knurling is frequently done in combination with spinning, it is probable that knurling hollow objects was also standard practice at an early date.

The advantages of knurling are apparent, particularly as applied to hollow objects where, as compared with machining, there is a considerable saving in cost, because of the reduction in labor, the possible reduction in thickness, and the increased rate of production. The advantages of roll threading are much the same; namely, a reduction in cost, a decrease in time necessary to perform the opera-

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tion, and in addition, improvement of mechanical properties because of the cold working.

Knurling. Since knurling is generally somewhat simpler than roll threading, this will be discussed first. Three different types of equipment are commonly used in knurling: lathes, automatic screw machines, or special machines.

Lathes. Knurling in lathes is ordinarily done only on small runs of work or in combination with spinning operations. It can be performed by using a hand tool of the kind commonly used by a spinner or by using a tool clamped in the tool post and moved against the work in the usual method. The knurling roll or die used in this type of equipment is of any convenient diameter (usually about 2 in.) and is made of hardened steel. In use, the die is pressed against the article to be knurled and sufficient pressure is exerted to produce the desired depth while the article rotates.

Automatic Screw Machines. In automatic screw machines, the knurling tool may be mounted either on the turret, or on one of the cross-feed attachments, or as a swing tool. Detailed description of the tools or cam layouts are available in standard instruction books. The feed and speed will vary with the particular machine and the material being knurled. A table of feeds and speeds would be too long to include here. This information may be obtained from instruction books or by consultation with the machine manufacturers and vendors of the particular material being knurled.

Special Machines. For large-volume production it is frequently more economical to perform the knurling operation in a separate machine specifically designed for the operation. A number of such machines are available for use on either solid or hollow parts. In these special machines the design of the arbor and rolls is extremely important, although somewhat less important for automatic screw machines and simple lathes than for special high-speed machines. In lathe knurling, the operator can readily watch the operation and see that the pattern matches as the work piece revolves; but with an automatic machine this is impossible and the design will be neither uniform nor properly impressed if the size of the roll is incorrect in relation to the work. For hollow parts, an arbor is used to support the work. The arbor and roll are geared together so that they will mate properly at all times. The arbor, embossed with the male impression of the design, is as large as will permit entry and removal from the work. The design embossed on the roll is a female impression of the design to be impressed on the object. In such machines the work material is usually fed into the machine through some device enabling the entire operation to be done automatically. Details should be worked out in consultation with the machine manufacturers.

Roll Threading. Roll threading may be carried on in the three types of equipment listed for knurling; namely, lathes, automatic screw machines and special machines. Roll threading is seldom done in ordinary lathes and then only where it would be either impractical or uneconomical to set up a special machine; for example, where it is desired to roll thread an article that is much longer than would normally be handled in the available automatic equipment.

Lathes. If a rod is to be roll threaded, a roll is fastened in a suitable fixture on the tool post, set at an angle corresponding to the desired pitch, and the feed is set accordingly. A back rest is commonly used to support the rod and it is frequently necessary to go over the thread a number of times to obtain the desired depth.

Automatic Screw Machines. Considerable roll threading is done in automatic screw machines; the tools used are generally similar to those described for knurling. However, instead of ■ design, the roll has a thread cut on the surface in the direction opposite to that to be produced on the work piece. For instance, if it is desired to produce a right-hand thread on the piece, the roll will have a left-hand thread. The diameter of the blank to be threaded is approximately the pitch diameter of the final thread. The outside diameter of the threading roll should be larger than the work piece and is calculated from the following formula taken from the Brown and Sharpe Automatic Screw Machine Handbook.

$$\left.\begin{matrix}\text{Outside}\\ \text{diameter}\end{matrix}\right\} = \left\{\begin{matrix}\text{Pitch}\\ \text{diameter}\\ \text{of piece to}\\ \text{be rolled}\end{matrix}\right\} \text{minus} \left\{\begin{matrix}\text{½ single}\\ \text{depth of}\\ \text{thread}\end{matrix}\right\} \text{times} \left\{\begin{matrix}\text{Multiple}\\ \text{used}\end{matrix}\right.$$

It is impossible to give any fixed multiple which will be suitable for all work, but the threading roll should be made as large as possible. If there are questions concerning the proper multiple, the machine manufacturers should be consulted as well as about the proper feeds and speeds to be used for the particular material being threaded. In many instances, it will be found that the vendors of the metal being threaded can be of material assistance in working out the necessary details.

Special Machines. A number of special machines are used for roll threading a great variety of work; for instance, there are special machines for the roll threading of bolts and screws, as well as machines designed specifically for the roll threading of tubular objects.

In the special machines for roll threading bolts and screws, the operation is carried out by using two suitable dies that have impressions of the thread projected on the work faces. One of these dies is held stationary and the other moves in a plane parallel to the axis of the work material and in a direction normal to that axis. These dies are commonly made of hardened tool steel (*see* the TOOL STEEL SECTION) and the thread is projected on them. The blank used has approximately the same pitch diameter as the bolt or screw being made. This method of threading bolts and screws is probably the most commonly used and is a very rapid, economical one where the volume of production is large enough to warrant the special equipment and tools. The speed used in this type of roll threading ordinarily varies inversely with the size of the bolt being threaded, but common practice is to hold within the range of 30 to 100 pieces per minute.

In the roll threading of sheet metal caps and tubular products, the design of thread is less standard than in bolts, screws and the like. Several different systems of threads are commonly used. Probably the most standard is that used in the manufacture of shells for electric light bulb sockets as well as similar articles; this is called the Uno system. It is difficult to give exact information about the relation of the size of shell to either the outside or pitch diameter of the threaded part. Also there is considerably more variation in this respect than there is with solid objects because of alloy and temper. This results from the wide variation in mechanical properties both between one alloy and another and with variation in temper in any single alloy.

In general, the shell diameter will be slightly larger than the pitch diameter. The arbor size used is as close to the blank diameter as possible, consistent with fitting the shell over the arbor. The roll size is found by subtracting the single depth of thread from the pitch diameter and multiplying by a factor, in a manner similar to that used in calculating roll size for use in automatic screw machines. On special machines for the roll threading of tubular objects, it is found that multiples as high as 12 are occasionally used, but more commonly the multiple is 4. The arbor and roll are mated through gears as for knurling. Depending on the multiple used, the roll will have a single, double, triple or quadruple thread. For instance, when the multiple used is 2, there will be a double thread cut on the roller. In use, the shell or tubular part is ordinarily fed into the machine, the operation is carried out and the threaded shell is discharged automatically. Speeds vary so greatly that it is impossible to give any definite figures.

Although no exact formulas for blank diameters are given for the various types of roll threads, still finding and maintaining the correct one is extremely important. Frequently the success or failure of roll threading of tubular objects hinges on how accurately this size can be maintained. In general, a blank too small produces ■ poorly developed thread which is usually undersize, while a blank too large ordinarily produces an oversize thread which is frequently rough.

Straightening Bars, Shapes and Tubing

By J. D. Armour*

MANY types of straightening devices have been developed for straightening bars, shapes and tubes, from simple hand straightening to very complicated straightening machines. However, the fundamental principle involved in all these straightening methods is the same except in twisting and straightening by stretching. This principle may be explained by referring to Fig. 3. The bar is supported at points *A* and *B* with the convex side of the bow or kink toward point *C*. Sufficient pressure is applied at *C* to cause the bar to become bowed in the opposite direction. The pressure must be sufficient to exceed the elastic limit of the material and to set up just enough strain in the bar to allow it to return to the straight position but no farther, when the pressure is released. The greater the bow in the bar and the higher its elastic limit, the greater the pressure required to produce the correct amount of strain. To straighten a bar by this method, the material must possess the property of resilience, it must be capable of cold deformation, and it must strain harden. In the diagrams of Fig. 2 to 10 inclusive, the arrows show the location of the points corresponding to points *A*, *B* and *C* of Fig 3.

In straightening to remove twist, the bar is twisted in the opposite direction until the elastic limit is exceeded and just enough strain is set up to allow the bar to return to the straight position but no farther.

In straightening by stretching, the bar must be stretched until the elastic limit is exceeded and sufficient strain is set up to prevent the bar from returning to its original position. The bar must be permanently elongated and reduced in cross section to remain straight after the load is removed.

Hand Straightening. Although many mechanical methods have been developed for straightening bars and shapes, the original method of hand straightening is still used extensively on jobs where great accuracy and precision are required or where odd shapes make mechanical straightening impracticable.

For accuracy and precision, surface tables and wooden mallets are used; grooved wooden blocks are used for odd shapes (Fig. 1 and 2). Hand straightening requires great skill on the part of the operator. Sometimes an operator needs several years to develop sufficient skill to do certain jobs of hand straightening.

Punch and Press Straightening. Punch and press straightening are semimechanical methods, the principle of which is illustrated in Fig. 3. The operator usually locates a kink or bow in round bars by holding a piece of chalk close to the surface of the bar and then rotating the bar so that any high spots will be marked by the chalk. The high spot is then brought under the ram of the straightening press and sufficient pressure is applied to take out the kink or bow. In shapes other than rounds, the out-of-straight condition must be detected by eye or with the aid of a straight edge. This type of straightening requires considerable skill on the part of the operator. A straightening press is sometimes referred to as a "gag press" and the straightening operation as "gagging".

Rotary Straightening. In rotary straighteners the bar is rotated while it is being fed into the straightening machine, so this equipment will necessarily straighten only round bars. The simplest form of rotary straightener is illustrated in Fig. 4. The top roll, which can be set at any desired angle, controls the speed of the bar. The top roll can also be adjusted up and down to control the pressure of the bar. Reference to Fig. 4 will show clearly that the same principle of straightening is involved here as for punch or press straightening.

Other popular types of rotary straightening machines are shown diagrammatically in Fig. 5, 6 and 7. Although they are more complicated in design than the simple rotary straightener, in order to obtain such features as speed or polishing effect, these machines involve the same straightening principle, as may be seen in the illustration.

The principle of a straightening machine used for flats, squares and hexagons is illustrated in Fig. 8. It will be seen that, as the bar passes through the machine, it is subjected to a double-straightening action similar to that employed in Fig. 3. In some straighteners for these shapes, both horizontal and vertical rolls are used, making a setup similar to that shown in Fig. 10 for wire.

Wire Straightening. Figure 9 shows the type of straightening machine used for straightening coiled round wire into straight bars. In this process, the wire does not rotate as it feeds through the machine. A cylinder with adjustable dies rotates around the wire and produces the straightening action. Some straightening is provided also by the feed rolls on the entering end, as will be seen from the illustration.

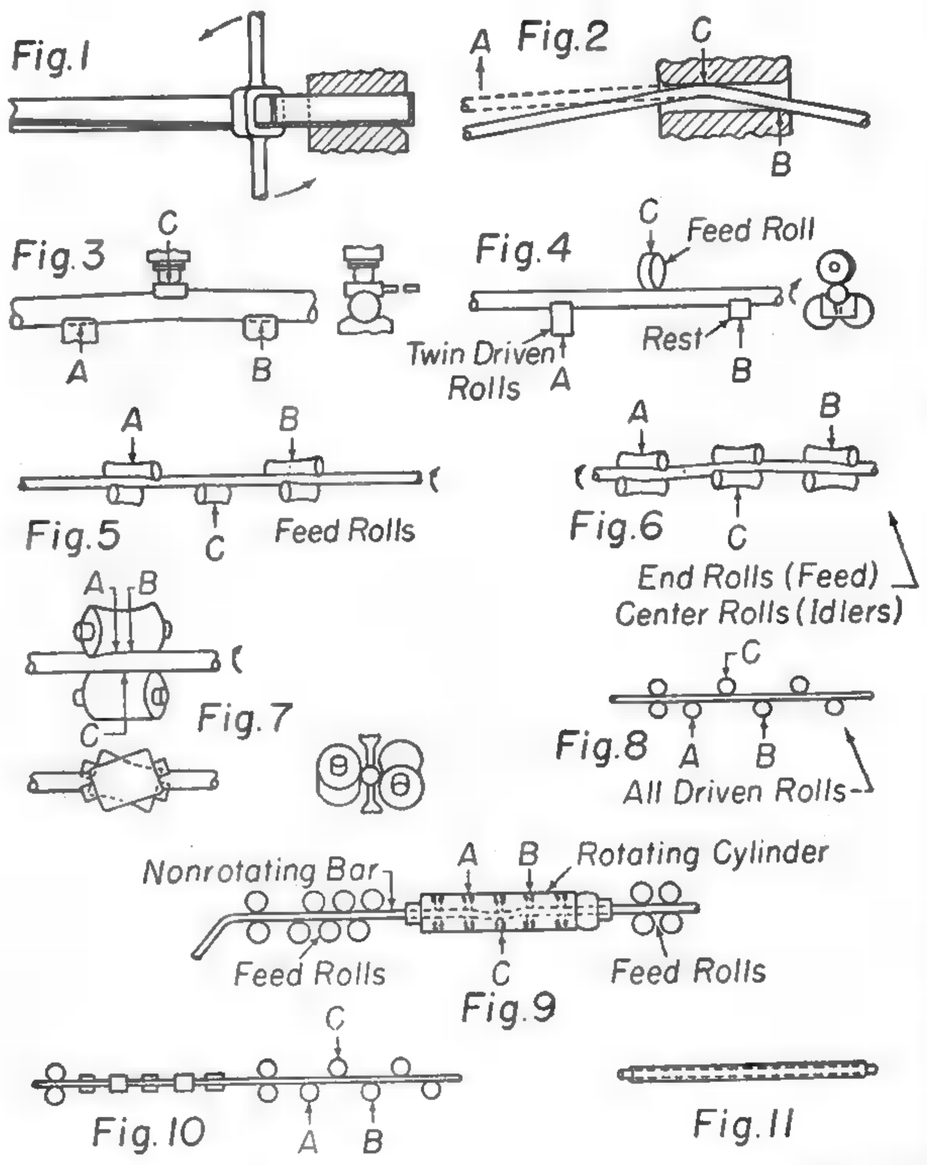

Fig. 1 Hand twist straightener. Fig. 2 Hand straightener. Fig. 3 Punch straightener. Fig. 4 Rotary straightener. Fig. 5 Five-roll rotary-type straightener. Fig. 6 Six-roll rotary-type straightener. Fig. 7 Two-roll rotary-type straightener. Fig. 8 Straightener for flat, square, and hexagonal bars. Fig. 9 Wire straightener. Fig. 10 Horizontal and vertical straightener for flat, square and hexagonal wire and bars. Fig. 11 Straightening by stretching.

Figure 10 illustrates the setup of a wire straightener for shapes other than rounds. It amounts to a double setup similar to Fig. 8, one horizontal and one vertical, so that the wire will be straightened in both directions during a single pass through the machine.

Stretching. Figure 11 shows how a bar must be changed in size to be straightened by stretching. The change in shape is necessarily exaggerated in the illustration. The increase in length and decrease in cross section need actually to be very slight to produce the required effect. This method is well adapted to straightening odd shapes.

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Powder Metallurgy

By C. H. Samans*

POWDER metallurgy is the art of producing metal powders and utilizing them to make serviceable objects. The processes involve the heating (termed "sintering") of a compact formed by compression. No fusion takes place, or, at most, fusion of a minor constituent only. Occasionally either the compression or the sintering may be omitted. These processes may be applied to individual, mixed, or alloyed metal powders, either with or without the inclusion of nonmetallic constituents. The methods of powder metallurgy have permitted the attainment of compositions and properties not possible by the conventional methods of melting or casting.

Typical Products. Powder metallurgical products include:

1 The refractory metals, including tungsten, molybdenum and tantalum, for which the method is a necessary one because of their high melting points and the undesirable coarse grain structure produced by fusion.

2 The superhard materials, including the cemented carbides and diamond-impregnated tools, for which the method is also necessary to produce the structures desired.

3 Bearings and porous metallic parts, in which controlled porosity, the possibility of oil impregnation and the use of nonmetallic additions are required.

4 Electrical and magnetic parts, such as contacts, motor brushes, commutator segments, permanent magnets, and cores for inductance coils, in which characteristics or combinations of materials, impossible to secure by other methods, can be produced.

5 Machine parts, in which the mechanical properties may be somewhat inferior to those of wrought metals, but in which the necessary tolerances and shapes can be attained at a reduced cost, by the elimination of machining operations.

6 Clad and duplexed parts, either all metallic, as in thermostatic bimetal, or both metallic and nonmetallic, as in friction materials.

Typical Processes. The characteristics required in each part are secured by varying certain steps in the manufacturing process. This can be seen from the typical flow sheets shown in Fig. 1.

1 In the manufacture of refractory metals, the powders are pressed into bar form with or without the addition of nonmetallic materials to control grain size or grain shape. Such bars, made from tungsten or molybdenum, are presintered in hydrogen to develop added strength. Tantalum and columbium bars are not preheated. The bars are then heated by their own resistance, by passing an electric current through them, until the core has nearly reached the melting temperature. With tungsten or molybdenum the heating is done in hydrogen; with tantalum or columbium it is done in a vacuum. After this sintering operation, tungsten and molybdenum are worked hot, by swaging or rolling, until they are compacted sufficiently to permit drawing into wire. With tantalum and columbium, working can be carried out at room temperature.

2 In the production of cemented carbides, the refractory carbide powders must be ball-milled with the binder (usually cobalt) for long periods of time, both to produce fineness and to coat the carbide particles thoroughly with the binder. In their final form cemented carbides are difficult to shape, except by grinding or lapping. Hence, they are either pressed to their final form, with proper allowance for shrinkage, or else formed into slabs and given a relatively low presintering heat treatment. In this condition the material can be cut, machined or ground to the desired shape. The final step is a high-temperature sintering operation. Large carbide parts are often hot pressed.

3 Oil impregnation is the unique step in the production of bearings. Blanks are first formed and sintered in such a way as to produce a controlled porosity. After all sizing and machining operations have been completed, the parts are given a special treatment to fill these pores with oil.

4 In the production of porous metal parts, such as filters, the shape and size distribution of the powder particles is all-important, since the parts are sintered from shapes formed either without pressure or with very light pressure.

5 The manufacture of machine parts may involve the use of a re-pressing operation, after sintering, to produce the necessary accuracy in size and to improve mechanical properties. However, parts may be used as-sintered or machining may be the finishing operation.

Advantages and Limitations of Powder Metallurgical Methods. Basically, powder metallurgical methods are used in preference to conventional methods for only two reasons: to secure properties not otherwise obtainable, or to eliminate machining and subsequent operations. As with every industrial process, the economic factors are the determining ones. If specific impurities must be controlled, if chemical composition limits must be held accurately, if certain specific types of shapes or special characteristics must be secured, powder metallurgy offers a convenient method; but the advantages are real only if the alloys, shapes or properties produced cannot be secured as cheaply by other methods. High production rates with close tolerances and a minimum of material waste can be maintained on many parts which, if designed to conventional methods of production, would require numerous machining operations. But these very factors also require that suitable designs be used and that the volume of production be large in order to justify die costs and setup time. As a rule, the smaller the piece, the greater the volume required for an economical run. However, since the real determining factor is the ratio of raw material cost to total processing cost, small pieces can sometimes be run economically by powder metallurgical methods, even though larger pieces of the same shape and characteristics cannot, simply because the raw material cost per pound of powder is usually considerably higher than that of the same material in cast or bar form.

In general, the principal limitations of the process are those imposed by the size and shape of the part, the compacting pressure required, and the materials used. Physical limitations are imposed by the dies required to hold the powders and by the presses available for compacting them sufficiently.

An additional shape limitation results from the necessity of supplying pressures from the top and bottom rather than from the sides. There is almost no lateral flow in the powder mass, so possible shapes are limited by this factor also. Holes parallel to the axis of compression can be readily made by use of a core rod, but holes normal to this axis must be machined after compacting and sintering. Likewise, threaded and other surfaces in which undercutting or re-entrant angles are involved, cannot be molded, but must be formed by machining after the part has been sintered.

Although in time many of these limitations may decrease in importance, the economic balance, which is the determining factor, may still show that costs are too high to compete with conventional methods for many parts.

Metal powders themselves are inherently susceptible to two faults. First, because of their high surface area, they tend to be attacked by and to absorb both air and moisture. Although this can often be minimized by proper storage and pretreatment and by the use of air conditioned press rooms and sintering atmospheres that have a low dew point, costs may thereby become excessive. Second, powders under pressure do not flow like fluids. The problems involved are more nearly those of soil mechanics than those of hydraulics. Powders do not tend to flow, for example, from a region of high compression to one of low compression and, as a consequence, the depth-width ratio is extremely important in the dies used.

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Prepared for the Subcommittee on Powder Metallurgy, with membership as follows: F. N. Rhines, *Chairman* (Carnegie Institute of Technology); C. W. Balke (Fansteel Metallurgical Corporation); J. J. Cordiano (Hardy Metallurgical Company); R. P. Koehring (Moraine Products Division, General Motors Corporation); C. H. Samans; Alexander Squire (Westinghouse Electric Corporation); N. E. Woldman (Upper Montclair, N. J.); F. E. Wormser (Metal Powder Association); L. L. Wyman (General Electric Company).

There is a distinct tendency for the powders to cling to the sides of the die and thereby encourage unequal pressures throughout the mass. For this reason parts compressed from the top tend to have a region of low density at the bottom, whereas those compressed from both top and bottom are usually less dense in the middle. Too little is known concerning the welding and adhesion characteristics of various shaped powders of different metals and alloys. Considerable experimentation is still required in all phases of the art.

Of necessity, additional limitations imposed by the die design influence the shapes which can be made, the tolerances which can be maintained economically, and the dimensional changes resulting both from normal shrinkage and from the unequal heating of the compacted parts during sintering. Shapes that require a weak design must be avoided, because the pressures needed for compacting will result in excessive breakage, both of the dies and of the compact. Because of die wear, lack of cold deformation of the individual particles of many powders, springback after compression, and dimensional changes during sintering, extremely close tolerances can be maintained only by costly individual gaging. However, if the fairly liberal commercial tolerances are allowed, the parts will, usually be sufficiently accurate, particularly when a sizing operation follows the sintering. For example, radial tolerances of 0.003 in. per in. in unsized bearings, 0.001 in. per in. in sized bearings, and axial tolerances of 0.010 in. per in. can be maintained commercially. At an added cost even closer limits are possible.

mented carbides, in which theoretical densities are secured either by hot working or by using very high sintering temperatures. Structural and machine parts made by powder metallurgical methods usually have lower tensile properties than wrought materials of the same or similar compositions. This can be seen from Tables IA and IB. In addition, low ductilities and impact strengths accompany the low tensile strengths. These inferior properties are a direct consequence of the porosity which is unavoidable in the powder method of manufacture. Material of theoretical density can be made, but only by resorting to repressing and resintering, which is rarely feasible, or by using sintering times that are too long to be economical. This is one limitation with which the designing engineer must be thoroughly familiar before specifying machine parts made by powder metallurgical methods.

A final limitation is imposed upon engineers and designers by the relatively small amount of technical information available. Standard tests on metal powders and on finished parts are still not accepted generally, so the ultimate user has no exact method for checking the products used. The widespread interest in and importance of the process, however, indicate that this limitation will probably be of relatively short duration.

Metal Powders. The selection of materials in powder metallurgy is determined by two factors: (1) the alloy required in the finished part and (2) the physical characteristics needed in the powder. Except for the specialized refractory metals and cemented carbides, the most widely used alloys are copper-base or iron-base, and the most

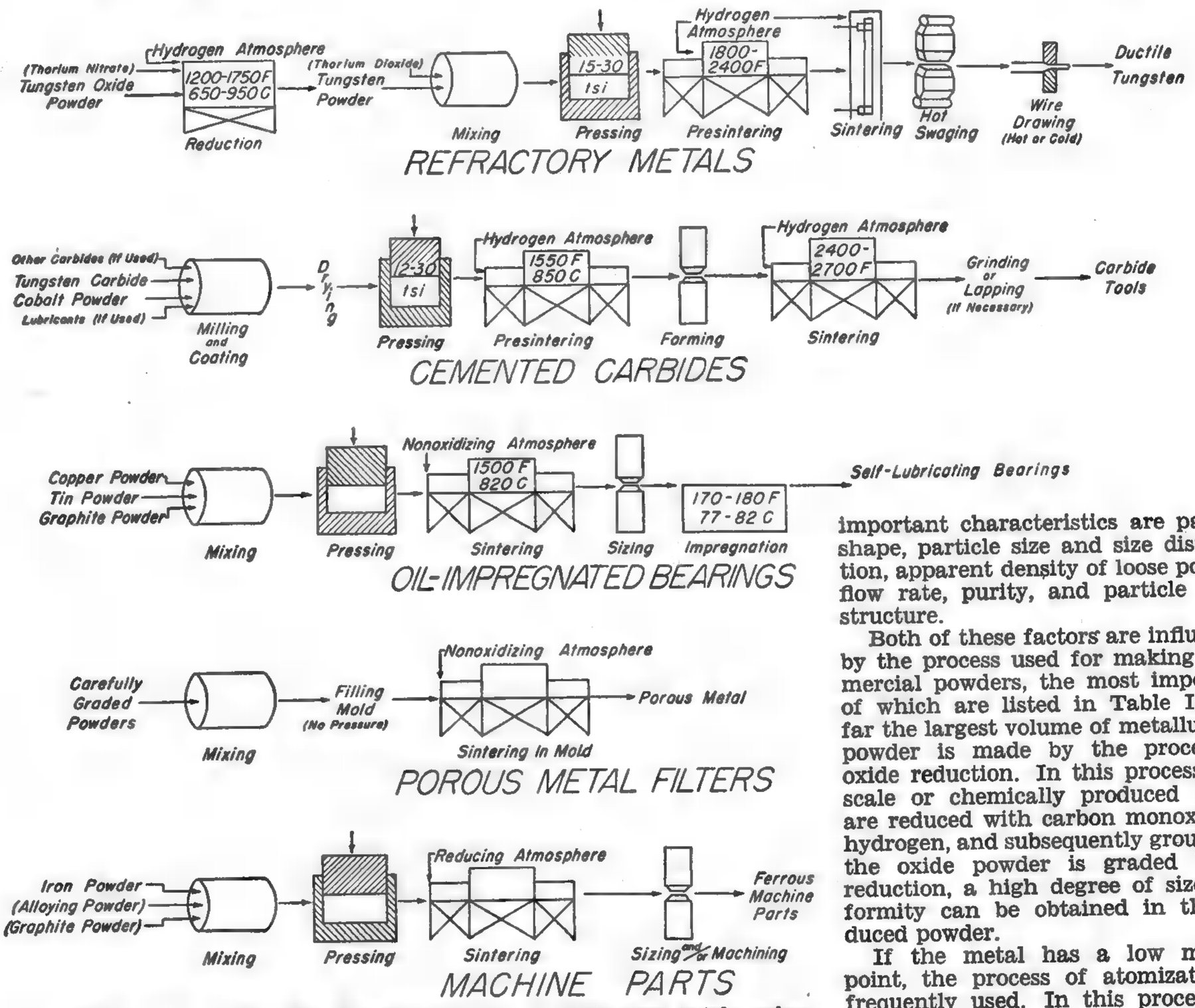

Fig. 1 Typical flow sheets showing steps in the manufacture of articles from metal powders

In structural and machine parts it is desirable to maintain as high mechanical properties as possible. This does not apply to self-lubricating bearings and filters, which are made porous purposely, or to refractory metals and ce-

important characteristics are particle shape, particle size and size distribution, apparent density of loose powder, flow rate, purity, and particle grain structure.

Both of these factors are influenced by the process used for making commercial powders, the most important of which are listed in Table II. By far the largest volume of metallurgical powder is made by the process of oxide reduction. In this process, mill scale or chemically produced oxides are reduced with carbon monoxide or hydrogen, and subsequently ground. If the oxide powder is graded before reduction, a high degree of size uniformity can be obtained in the reduced powder.

If the metal has a low melting point, the process of atomization is frequently used. In this process the molten metal is forced through a small nozzle orifice and broken up by a stream of compressed air, steam or inert gas.

By varying plating conditions properly, either the metal powders can be deposited directly electrolytically, or else a

hard, brittle and easily powdered codeposit of hydrogen and metal can be secured. This can be given a low-temperature bake after it is powdered, to drive off the hydrogen and restore ductility. Electrodeposited powders are frequently dendritic in shape, and may be milled or ground to improve their molding characteristics. They are, relatively, more nearly pure and more expensive than oxide-reduced powders.

Milling by various methods is also used to produce metal powders directly from either friable or malleable metals. The friable metals yield angular, jagged particles of irregular shape. Except with a few special mills, malleable powders tend to produce flakes, provided a lubricant is used to keep the flakes from welding together. The metallic stearates; and any volatilizing agents used to give a desired type of porosity, such as salicylic acid. If segregation occurs, the type of powder, particle size or size distribution, mixing time, or method of mixing must be modified by trial and error to eliminate it. This is likely to be particularly troublesome when powders with fundamentally different specific gravities are involved.

Overmixing may be as bad as undermixing, for it tends to increase the apparent density and to work-harden the particles, and may also decrease the particle size. Overmixing may also result in deterioration of the powder because of air or moisture attack, unless sealed containers are used. Even then, it is becoming common practice in the larger plants to minimize this deterioration factor as much as possible by mixing in atmospheres of controlled humidity. During mixing, reducing gas atmospheres are seldom, if ever, used commercially.

Table IA. Bearing Materials

Material	Tensile Strength, psi	Elongation, per cent	Yield Strength in Compression (0.1% offset), psi	Compressive Strength, psi	Brinell Hardness Number	Porosity, per cent	Density, g per cu cm
90% Cu, 10% Sn, with up to 1½ parts graphite...	12,500	2.0	11,000	70,000	30	25	6.3
5 to 25% Cu, remainder Fe	28,000	0.5	25,000	140,000	50	23	6.0
Iron	12,000	1.0	22,000	130,000	40	25	5.9
99% Fe, 1% C.....	28,000	0.5	22,000	160,000	60	20	5.9

Table IB. Materials for Structural Parts

Material	Yield Strength in Tension, psi	Tensile Strength, psi	Elongation, per cent	Brinell Hardness Number	Density, g per cu cm
Tin bronze with 5 to 10% Sn, remainder Cu (medium density)	12,500	20,000	10	40	7.0
Tin bronze with 5 to 10% Sn, remainder Cu (high density)	20,000	35,000	15	55	8.0
Iron with up to 0.3% C (medium density)	22,000	32,000	6	50	6.6
Iron with up to 0.3% C (high density)	28,000	38,000	8	60	7.0
Fe-Cu alloy with 25% Cu.....	.....	40,000	2	70	7.0

The above table gives the mechanical properties of test pieces pressed and sintered under the same conditions as production items of the same material. Variation in density between the test pieces and standard metal powder parts will invariably produce corresponding differences in the mechanical properties. The mechanical properties of metal powder parts are often not a good criterion of the value of the material, since many metal powder materials find application because of characteristics, such as porosity, which reduce the mechanical properties but impart other properties that can be obtained in no other way. This applies particularly to the first group of materials, Table IA, which are designated as "bearing materials". They are used not only for self-lubricating bearings but also in other applications (gears and cams, for instance) where either self-lubrication is important or the mechanical stresses are low. The figures in the table were derived from the published literature of the manufacturers and are meant only to give an indication of the strength and ductility of average powder material. Much higher values for any of the materials can be obtained by special treatment, but treatments of this type are frequently too costly.

combination of the lubricant and the flake shape makes these powders almost useless in powder metallurgy, but they are readily used in paints and pigments.

Both nickel and iron, under suitable conditions of temperature and pressure, will react with carbon monoxide to form gaseous metal carbonyls. These can be decomposed to yield a metal powder of high purity, but also rather expensive, which has almost spherical particles.

Metal hydride powders are made either for direct addition to other powder mixtures, or for the production of alloy powders by adding the hydride powders to properly mixed and proportioned oxide powders; heating them together under controlled conditions to accomplish reduction and alloying; and subsequently leaching out the inert oxide produced. This rather expensive hydride process is used largely for specialty products.

The ordinary methods of machining, the process of shotting (that is, dropping the molten metal from a small opening through air or an inert atmosphere into water), vapor condensation, chemical precipitation or cementing, and granulation accomplished by stirring rapidly during solidification, are also used but not for high production.

Characteristics of Metal Powders. Characteristics of the various types of metal powders most commonly used commercially are listed in Table II. The data given are intended only as an indication of what might be secured in these materials and should not be used for design or direct manufacturing purposes.

Processing. *Mixing.* Homogeneity of mixing is essential to successful powder metallurgy. This is controlled largely by the particle size and size distribution of the powders and by the duration of mixing. A satisfactory particle size distribution should be secured in advance by proper blending of each major type of powder used. With these blended powders are mixed the alloying powders, either metallic or nonmetallic; lubricants, such as stearic acid or

The time required for mixing may vary from a few minutes to as much as 24 hours, depending entirely on experience and the results desired. In the production of metal carbides, periods of several days are used to coat the carbide powders with the cementing agent, usually cobalt, and to reduce the particle size, rather than merely to mix the two together.

Pressing. Compacting or pressing is the most important operation in powder metallurgy because the practicability of making a given part from metal powder is determined largely by the attainment and maintenance of a satisfactory pressed density.

Pressing is usually done at room temperature, but there are a few applications in which compacts are hot pressed, using much lower pressures. In these, the powders are introduced into a cold graphite die and heated by resistance through the mold and the compact. Many so-called hot pressing operations are actually sintering under pressure.

Although both mechanical and hydraulic presses have been designed for this type of work, the mechanical types are preferred for mass production. Pressure ratings for the mechanical presses may range from 10 tons to as high as 500 tons, for a straight side and knuckle joint single-acting press. Speeds range from 6 to 60 strokes per min, and may be as high as 400 strokes per min for some types of rotary presses. Classification according to depth of die fill is sometimes used, with ratings from 1⅝ to 8 in. Hydraulic presses, as a rule, have higher capacities, as great as 1000 or even 3000 tons. Stroke speeds are much slower, generally less than 20 per min and as slow as 20 per hr for the largest presses, although these speeds can be increased greatly by use of accumulators.

The size of the part that can be made depends to a great extent on the pressure rating of the presses available, since pressures required by powder metallurgical processes usually range from 10 to 50 tons per sq in. and may approach 100 tons per sq in. for some applications.

The usual dies consist of a die body which, for many parts, is filled volumetrically from a hopper; an upper punch, sometimes hollow, but corresponding to the shape of the part to be produced; a lower punch, which forms the bottom of the die body and serves as a stripper to eject the compressed parts; and either a movable or a stationary core rod, which determines the inside diameter.

Dies are usually made of tool steel, machined to a close tolerance, and hardened, ground and lapped to a mirror finish. However, when parts are made from highly abrasive particles, hard carbides may be used for the dies or for liners in them. Replaceable liners, which are discarded when worn, are also used sometimes to reduce the cost of

Table II. Properties of Metal Powders

Metal or Alloy	Type of Powder	Purity of Composition,[a] [b] per cent	Particle Shape or Character	Particle Size Distribution,[b] mesh	Range of Apparent[b] Densities, g per cu cm	Hydrogen Loss, per cent
Aluminum	Atomized	99% Al	Irregular & nodular	— 30 to —325	0.40 to 1.15	Not applicable
Antimony	Milled	99% Sb	Angular	—100 to —200	2.30 to 3.00	Not applicable
Beryllium	Milled	99.5% Be	Irregular	—100 to —200	....	Not applicable
Beryllium alloys	Milled	96,97,98% Cu; 4,3,2% Be	Irregular	— 60 to —200	....	Not applicable
Be-Ni	Hydride	85% Ni; 15% Be	Porous	—100	....	Not applicable
Be-Co	Hydride	90% Co; 10% Be	Porous	—100	....	Not applicable
Bismuth	Milled	99% Bi	Angular	—100	4.40 to 4.60	Not applicable
Brass	Atomized	50 to 90% Cu; 50 to 10% Zn	Spherical	—100	4.10 to 5.10	Not applicable
Brass	Reduced	60 to 90% Cu; 40 to 10% Zn	Porous	—150 to —325	1.90 to 2.80	Not applicable
Bronze	Atomized	90% Cu; 10% Sn	Spherical	— 30 to —100	....	....
Bronze	Reduced	90% Cu; 10% Sn	Porous	—150 to —325	1.90 to 2.80	0.50% (max)
Cadmium	Atomized	99% Cd	Irregular & spherical	—100 to —325	2.30 to 3.00	Not applicable
Chromium	Electrolytic	99% Cr	Irregular	—100 to —325	....	Not applicable
Chromium	Milled	97% Cr	Granular	— 80 to —325	2.20 to 3.60	Not applicable
Chromium	Hydride	30% Cr; 70% Co	Porous	—100	....	Not applicable
Cr-Co	Milled	98% Co	Granular & plate	—100 to —325	2.50 to 3.00	1.00% (max)
Cobalt	Reduced	97.5% Co	Irregular	—100 to —300	....	Not applicable
Columbium	Hydride	95 to 99% Cb	Porous	—100	....	Not applicable
Columbium	Reduced	99.5% Cb		— 50 to —400	3.50 to 4.00	Not applicable
Columbium carbide	....	CbC	Crystalline	—100	....	Not applicable
Columbium hydride	Hydride	95 to 99% CbH	Porous	—100	....	Not applicable
Copper	Atomized	99% Cu	Spherical	— 10 to —150	4.00 to 5.50	0.60% (max)
Copper	Electrolytic	99.5% Cu	Irregular & dendritic	—100 to —325	0.70 to 4.20	0.70% (max)
Copper	Reduced	98.5% Cu	Porous	— 20 to —325	1.70 to 3.10	0.70% (max)
Gold	Electrolytic	99.8% Au	Irregular	—100	....	Not applicable
Iridium	....	99.9% Ir	Porous	—325	....	Not applicable
Iridium	....	99.9% Ir	Crystalline	—325	3.00 to 3.50	Not applicable
Iron	Electrolytic	98.5 to 99.5% Fe	Granular	— 8 to —325	2.00 to 2.60	1.20% (max)
Iron	Reduced	96 to 98.5% Fe	Granular & porous	— 6 to —325	1.80 to 2.85	3.00% (max)
Iron	Carbonyl	98 to 99.9% Fe	Spherical	—180 mesh to —3 microns	1.80 to 3.50	1.80% (max)
Lead	Atomized	99 to 99.5% Pb	Spherical & elongated	—100 to —325	2.50 to 6.00	0.50% (max)
Magnesium	Milled	99% Mg	Irregular	— 6 to —325	0.60 to 0.90	Not applicable
Manganese	Milled	96 to 99.5% Mn	Granular	— 20 to —325	2.60 to 4.00	Not applicable
Molybdenum	Reduced	99.7% Mo	Nodular	— 80 to —325	1.00 to 1.50	0.30% (max)
Nickel	Milled	99% Ni	Granular & plate	— 8 to —325	2.00 to 4.60	1.20% (max)
Platinum	Reduced	99.9% Pt	Porous	—100 to —200	....	Not applicable
Rhodium	....	99.9% Rh	Porous	—325	....	Not applicable
Ruthenium	....	99.9% Ru	Porous	—325	....	Not applicable
Silicon	Milled	96 to 98% Si	Granular	— 20 to —325	0.50 to 1.10	Not applicable
Silver	Electrolytic	99.7% Ag (min)		—100	....	....
Silver	Precipitated	99.9% Ag (min)	Crystalline	—100 to —250	1.20 to 3.60	0.20% (max)
Solder	Atomized	60 to 37% Sn; 40 to 63% Pb	Granular	—150	1.00 to 1.50	Not applicable
Stainless steel	Chemically disintegrated	18% Cr; 8% Ni	Spherical & elongated	— 50 to —325	2.50 to 5.50	0.50% (max)
Tantalum	Hydride	95 to 99% Ta	Irregular	—100	....	Not applicable
Tantalum	Electrolytic	99.7% Ta	Porous	—100	....	Not applicable
Tantalum carbide	....	TaC	Granular	— 80	6.00	Not applicable
Tantalum hydride	Hydride	95 to 99% TaH	Crystalline	—200	....	Not applicable
Thorium	Hydride	98 to 99.5% Th	Porous	—100	....	Not applicable
Thorium	Reduced	97% Th	Porous	—100	....	Not applicable
Tin	Atomized	99% Sn	Irregular	All —100, 90% —325	....	Not applicable
Titanium	Hydride	98 to 99% Ti	Elongated & spherical	— 30 to —325	1.40 to 4.10	0.30% (max)
Titanium hydride	Hydride	98 to 99% TiH_2	Porous	—100	....	Not applicable
Ti-Co	Hydride	30% Ti-Co	Porous	—325	....	Not applicable
Ti-Ni	Hydride	30% Ti-Ni	Porous	—100	....	Not applicable
Tungsten	Reduced	99.8% W	Porous	—100	....	Not applicable
Tungsten carbide	....	WC	Nodular	—200 to —325	2.60 to 3.00	0.20% (max)
Zinc	Condensed	99% Zn	Crystalline	—200	3.00 to 3.50	Not applicable
Zinc	Atomized	99% Zn	Irregular & spherical	—100 to —325	....	....
Zirconium	Hydride	98 to 99.5% Zr	Irregular	— 20 to —150	2.00 to 3.10	....
Zirconium hydride	Hydride	99% ZrH	Porous	—325	....	Not applicable
Zr-Co	Hydride	50% Zr; 50% Co	Porous	—325	....	Not applicable
Zr-Ni	Hydride	50% Zr; 50% Ni	Porous	—100	....	Not applicable
			Porous	—100	....	Not applicable

(a) The purity listed is the total content of the metal, not the metallic or free metal content.

(b) The range of values represents a compilation of the specifications of various manufacturers and not necessarily the specification of any one manufacturer's grades of powder.

die upkeep. It is common practice to maintain initial clearances at 0.0003 to 0.0005 in., although, with use, these will undoubtedly increase. The permissible die clearances depend to a large extent on the part being made and the materials used. If they are too close, either air will be entrapped in the die, leading to poor compacting and excessive porosity, or the die parts may "freeze" together. If they are too loose, powder will tend to be forced between the die body and the punches, forming a flash burr and favoring breakage of the compact during stripping. A slight taper is ordinarily designed in the upper part of the die body to facilitate ejection of the compacted part and to assist the escape of air during the early part of the stroke. Die depth depends on the compression ratio, that is, the ratio of the apparent density and the pressed density of the powder being pressed. It is usually from about 2:1 to 3:1 for iron and copper powders but may be as high as 6:1 or 8:1 for some materials and particle sizes. Information such as this must be determined accurately for each specific part before production is attempted, because only in this way can accurate size tolerances be maintained. With powders of very low density, the greater die depth introduces complications because of uneven pressures and additional friction, both within the powder mass and against the die walls.

The unsintered part is sometimes referred to as a "green compact". Although it is relatively weak, it can be handled safely if ordinary precautions are taken.

Parts in which the axial variations are less than one-fourth their length are ideally suited for compacting. In such parts the compression ratio and the resulting density will be sufficiently uniform without requiring multiple punches. Since the pressure is applied axially, any radial projections or contours that do not require variations in axial length (such as those of gears, cams, and similar parts in which the design of the die body and punch are mated in the desired shape) can be compacted without introducing any additional problems, unless the projections or splines are excessively deep and narrow. When the axial variations of parts are greater than one-fourth their length, as for flanged or winged parts, proper compensation is accomplished most simply by compacting from both the top and the bottom. This may or may not require two compacting movements, depending on the exact shape; but flanged or winged parts always require two movements. The direction of compacting should be chosen in such a way that the cross section perpendicular to the direction of pressing is as simple as possible. If there are several changes of section, like axial projections, multiple punches, which require complicated and expensive die construction, will be necessary.

Sintering. The maintenance of uniform dimensions and a reproducible product require an accurate control of the sintering cycle. Sintering furnaces are frequently of the electric resistance type, but gas or oil heating is often used, particularly when some special atmosphere is needed or when the temperature required does not exceed the limiting temperature for muffles—about 1800 F (1000 C). High temperatures are secured by the use of nickel-chromium alloy elements up to about 2000 F (1100 C), silicon carbide units up to about 2500 F (1370 C), and either molybdenum or tungsten elements operating in hydrogen, or the electrical resistance of the part itself for higher temperatures. High-frequency methods of heating have not proved very satisfactory because of the difficulties of temperature uniformity and control; and molten salts have been tried without much success, largely because of salt impregnation. The residual salt, which cannot be removed after sintering, will cause corrosion.

Most modern sintering furnaces are either continuous or semicontinuous, frequently using mesh-belt or roller-hearth conveyers for temperatures below 2100 F (1150 C). These furnaces are generally constructed with entrance or purging chambers (in which preheating is possible and volatile constituents that are not desired in the main furnace atmosphere can be removed) and with cooling chambers, so that the parts can be cooled to room temperatures before exposure to the outside atmosphere.

The great majority of electrically heated (nickel-chromium alloy, silicon carbide, and molybdenum rod) furnaces do not use a muffle but have the heating elements radiating directly on the work in the heating chamber. Under these conditions the outside steel shell of the furnace must be gas-tight to contain the protective atmosphere. Muffle-type resistance furnaces are also made with a heat-resisting steel or a refractory muffle, unless the operating temperatures exceed about 2100 F (1150 C), in which case silicon carbide muffles must be substituted. Most frequently, heat-resisting steel muffles are used only in gas-heated furnaces; and refractory muffles, only in the molybdenum-wound furnaces, which are becoming obsolete.

Atmospheres* are restricted somewhat because of production difficulties or expense. Tank hydrogen is commonly considered too costly, but some are using it and also hydrogen made by the electrolysis of water. Gas from either of these sources must have the oxygen removed and be dried if "dry" hydrogen is needed.

Drying can usually be effected to a plus 40 F dew point by refrigeration; and, once this is done as a preliminary step, moisture can be further removed to at least a minus 40 F dew point by dryers that use activated alumina. However, some concerns are still using the more complicated treatment of first passing the gas over heated copper turnings to remove oxygen, and then passing it over calcium turnings to remove the water vapor formed.

Commercially, the so-called "hydrogen atmospheres" are usually secured by dissociating ammonia to a mixture of

* For more detailed information concerning protective furnace atmospheres, see the article on page 294 of this Handbook.

Table III. Sintering Conditions for Various Materials

Material	Atmosphere	Temperature, deg Cent	Temperature, deg Fahr	Time, minutes	Remarks
Bronze	Combusted gas	700 to 870	1300 to 1600	10 to 15	
Iron	Combusted gas	800 to 1100	1475 to 2000	45	Atmosphere controlled to prevent decarburization.
Friction materials	Combusted gas	800 to 1100	1475 to 2000	90	Sintered and brazed to backing simultaneously.
Noble metals	Air	1000 to 1200	1825 to 2200	45	
Permanent magnets	Hydrogen	1200 to 1300	2200 to 2375	150	Very dry atmosphere necessary.
Refractory metals	Hydrogen or vacuum	2500 to 3200	4500 to 5800	15	Frequently given low-temperature presintering.
Refractory carbides	Hydrogen	1300 to 1500	2400 to 2700	90	Occasionally sintered in vacuum and sometimes pressed and sintered simultaneously in carbon mold.
Brass	Hydrogen	850 to 900	1550 to 1650	45	Care must be taken to prevent zinc loss by vaporization.
Electrical contacts	Hydrogen	900 to 1200	1650 to 2200	10	Sometimes sintered and solder-backed simultaneously.

The times and temperatures listed are typical but many processes call for appreciable variations from the conditions given. In some applications it is possible to use any protective atmosphere and the final decision concerning which is most desirable may be based entirely on economic considerations. In some instances, dissociated ammonia may be used in place of hydrogen, whereas in others, such as permanent magnets, only the driest form of purified hydrogen is satisfactory. Carboniferous compacts require an atmosphere with the correct ratio of carbon monoxide to carbon dioxide to prevent decarburization; certain other materials must be sintered in a carbon-free atmosphere.

75% H, 25% N. The ammonia has the additional advantages over pure hydrogen of being relatively inexpensive and of being readily produced free from oxygen and water vapor. Generally, it is not dried further. Dissociated ammonia cannot be substituted for hydrogen when the nitrogen will react with either the material being sintered or with the heating elements. Most other commercial sintering atmospheres are produced by the partial combustion of various hydrocarbons. In localities where natural gas is available, it is commonly used for this purpose; otherwise bottled propane is often used in preference to city gas, because of its greater purity. Carbon monoxide atmospheres are secured by heating in a closed container, such as a belt-type furnace, in the presence of a carbonaceous material.

Dry hydrogen is required to secure satisfactory sintering of refractory metals, cemented carbides and alnico magnets. Most iron-base and copper-base alloys are sintered in partially combusted hydrocarbon gas atmospheres, particularly those made with a lean air: gas ratio and refrigerated to a plus 40 F dew point.

However, if decarburization must be avoided in iron-base alloys, a gas must be used that is very low in water vapor and that has a low ratio of carbon dioxide to carbon monoxide. This can be readily secured, either by using a rich air: gas ratio in a generator that is externally heated and contains a special catalyst, or by absorbing carbon dioxide and water vapor from the lean air:gas ratio gas. Vacuum is used with some materials, such as tantalum, which reacts with all the common gases.

The time of sintering depends entirely on the characteristics and homogeneity desired in the sintered part, since intermetallic diffusion, which determines the approach to essential equilibrium, is a rate process. The capacity of a furnace will be dependent on its dimensions and the sintering time required.

An appreciation of the order of magnitude of the three sintering variables—atmosphere, temperature and time—can be secured from the data listed in Table III. These are intended to give a starting point rather than to furnish specific sintering information. The large numbers of sizes, shapes and compositions used commercially make this the only feasible procedure to follow.

Subsequent Operations. Operations following sintering involve sizing, resintering, machining, or impregnation.

It is sometimes necessary to add a few machining operations to take care of shapes that cannot be molded or to maintain extremely close tolerances. Screw threads, undercuts, and holes, grooves or flanges normal to the direction of pressing, are typical examples of the former. With porous bearings the bearing surface is usually not machined, because this tends to close the pores. When impregnation is to follow, the use of a coolant during machining is not advisable. Mechanical properties can often be improved materially by re-pressing, because of the cold deformation so produced; and more accurate dimensional tolerances can be maintained, without the expense of individual gaging, by coining, sizing or re-pressing the finished part in a die of suitable size and shape. These operations are also used sometimes to increase the density of the sintered compact.

Impregnation is the means used to fill the internal pores in the sintered compact. This can be done with oil, as in oil-impregnated bearings, either by a vacuum process or by immersion, for a suitable period of time, in the lubricant held at a temperature of 170 to 180 F (77 to 82 C). Sintered compacts can also be impregnated with alloys that have a low melting point, such as solders, for example, when stiffening or antifriction properties are desired.

Testing Finished Parts. In general only two types of tests are used for powder metallurgical products—density and chemical analysis. Hardness and tensile strength are sometimes determined, but they are useful chiefly for the purpose of comparing the properties of different parts made from similar compositions. Additional special tests have been devised, such as crushing tests for bearings, transverse strength tests for cemented carbides, and various electrical and magnetic tests; but they are used only for special products, depending on the application. Density is commonly determined because other mechanical properties are frequently proportional to it. Standard test procedures have been developed and issued in Army Ordnance Specifications AXS-1396.

In determining the density by this method a modification of the Archimedes method is required, because of the porosity of the sample. The weight of the lubricant-free sample in air is first secured. The sample is next impregnated with oil by a definite procedure, and, after the excess oil is removed, it is again weighed in air. The oil-impregnated specimen is then reweighed while it is immersed in water, and its volume is determined by the usual method. Since two bodies cannot occupy the same space at the same time the water cannot enter the pores because they have previously been impregnated with oil. From these three weights the density can be calculated.

The hardness of a sintered powder metal compact is a much more complex characteristic than that of even a solid metal. Basically, it is a composite of two parts, one resulting from the matrix and one from the porosity. Because of the importance of the porosity factor, hardness values comparable with those of solid metal are seldom produced. Hardness tests are, therefore, usually not suitable for the purpose of specification, except in nonporous materials like cemented carbides, although they are widely used for purposes of production control.

The parts made by powder metallurgical methods are usually of such a size and shape that it would be clearly impossible to cut from them a standard tension test specimen of the type commonly used for solid metals. Tension tests are, therefore, not suitable for specification purposes. In order to determine the strength properties of powder metallurgy materials, small test specimens are compacted and sintered. No standard tension test specimen has been widely accepted thus far, but a flat bar having a test section ¼ in. square is in fairly common use. In any such test, it is advisable to refer specifically to the type of specimen used, in order that better comparisons may result.

The Explosion Hazard of Metal Powders, and Preventive Measures

By Irving Hartmann*

WHEN a layer or pile of dust is ignited, if left undisturbed it usually burns quietly at a rate that depends on ease of oxidation and availability of oxygen. However, if this dust is thrown into suspension in the air, a violent explosion may result.

Thirty years ago it was believed that a dust explosion could occur only if the atmosphere surrounding the dust contained some flammable gas. This view was proved incorrect by tests in the experimental coal mine of the Bureau of Mines and elsewhere. Today it is known that nearly every combustible solid in finely divided form can produce an explosion under the right conditions.

The necessary conditions for an explosion are a dust cloud of sufficient concentration in air or other gas that will support combustion, and a source of ignition sufficiently intense to raise the temperature of a portion of the suspended dust to the ignition point. If, after the initial ignition, the combustion progresses through the dust cloud at such a rate that heat is developed more rapidly than it is dissipated to the surroundings, the phenomenon is termed a dust explosion. When this occurs in a closed or partly closed space, a rapid rise of pressure results. During explosions of many carbonaceous dusts, the pressure results partly from the generation of gaseous combustion products greater in volume than the original air in the space; and partly from the heating and expansion of the gases by the heat of combustion. When dust clouds of metal powders explode in air, the final volume of gas, mostly nitrogen, is usually smaller than the initial volume of air, and the rise in pressure is caused entirely by heating and expansion of the nitrogen.

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Dust explosions in industrial plants have been started by various sources of ignition. These include electric sparks and arcs in motors, fuses, and other equipment; static electrical discharges; frictional or metallic sparks; overheated bearings and other hot surfaces; open lights; glowing particles entering grinding mills and dust collectors; spontaneous ignition of dust; disturbance of burning dust by use of a water hose; chemical reactions between constituents of dust mixtures, as between oxidizing and reducing agents; and other common incendiary agents.

Explosibility Factors. The ignition temperature and the minimum energy required for ignition of a dust cloud have an important bearing on the probability of a dust explosion; however, these two factors appear to have little relation to each other. The ignition temperatures of metal powders range from about 200 to above 1000 C; the minimum energies necessary to ignite metal powders, as determined by experiments with condenser discharge sparks, range from a few millionths of a joule to several joules. The rate of oxidation of several metal powders, including powders of the noble metals, is so small that their suspensions in air are incapable of propagating a dust explosion. While some metal powders can be ignited most readily by direct heat source, other powders, notably atomized aluminum, are ignited more readily by electric sparks.

The nature and violence of a dust explosion are influenced principally by the following factors:

Chemical and Physical Properties of the Dust. Important properties that have a bearing on explosibility include: the ease of oxidation, oxygen requirement for complete combustion, heat of combustion, specific heat, purity, presence of oxide film on surface, shape, size and porosity of particles, and affinity for nitrogen. As might be expected, in general the explosibility increases with decrease in the particle size (increase in surface area) of the dust. For magnesium powders it was found experimentally that stamped or flaked powders are more explosive than milled powders, and these are in turn more explosive than atomized powders.

Concentration and Homogeneity of Dust Cloud. The concentration of dust in the air must be between certain lower and upper limits, in order that ignition of one portion of the cloud should propagate through the mixture and develop into an explosion. Other conditions being equal, the strongest explosions will be produced at concentrations approximating the stoichiometric mixtures.

Composition of Atmosphere. In general, decrease in the oxygen content of the gaseous atmosphere containing a dust reduces the ease of ignition and the violence of a dust explosion. For most dusts there exists a critical oxygen content below which they will not ignite and propagate an explosion.

Ignition Source. The ignition temperature, lower explosive limit, and the violence of explosions produced by dust clouds, are affected in some measure by the type of source initiating the explosion. Generally, a large source is more effective than a point source or a short spark; a source of some duration is more hazardous than an instantaneous one.

Characteristics of Explosion Space. The volume, shape, tightness and construction of the enclosure in which a dust explosion occurs determine to a large degree the damage that may result from it. Of special importance is the presence of vents through which the pressure developed by an explosion might be quickly released to the outside.

Classification of Metal Powders. During the last few years several industrial explosions have occurred, which were caused by dust clouds of magnesium, aluminum, magnesium-aluminum alloys, zirconium, zinc, pure iron powders, and mixtures of metal powders with other dusts. On the basis of this experience and of extensive experimental test data accumulated by the Bureau of Mines,[1] the metal powders currently manufactured can be grouped approximately in the three classes given below. In the experiments the following factors were determined: ignition temperature, lower explosive limit, minimum energy required for ignition, relative flammability, maximum pressures and rates of pressure rise developed by explosions of dust clouds of several concentrations, and limiting oxygen content to prevent ignition and propagation. The three classes of powders are:

1 Powders of High Explosibility. These include zirconium, magnesium, aluminum, titanium, and certain magnesium-aluminum alloys. Dust clouds of these powders can be ignited readily by weak electric sparks and by hot surfaces of comparatively low temperatures (less than 650 C). The lower explosive limits of these powders range from 0.020 to 0.050 oz per cu ft. The powders can all be ignited by spark in an atmosphere of commercial carbon dioxide; and zirconium, magnesium, and some magnesium-aluminum alloys can be ignited by spark in air-nitrogen mixtures containing less than 3% oxygen. Ignition can be prevented by processing the powders in helium. Highest pressures (more than 70 psi) are produced by explosions of magnesium powder dispersions. Zirconium powder can be ignited by weaker electric sparks than can any other dust tested; when it is dispersed into air at ordinary temperatures, the dust clouds ignite under certain conditions without application of any external ignition source, apparently because of static discharge within the cloud.

2 Powders of Moderate Explosibility. The metal powders in this class present almost the same dust explosion hazard as pulverized bituminous coal. They include vanadium, pure iron (carbonyl, hydrogen reduced, electrolytic, sponge), manganese, silicon, tin, zinc, antimony, tellurium, cadmium, ferrovanadium, ferrotitanium, ferrosilicon, and ferrochromium. Ignition temperatures of dust clouds range from about 315 to 850 C, and lower explosive limits from 0.100 to more than 0.500 oz per cu ft. Dust explosions of silicon powder produced higher pressures (over 60 psi) than any of the others in this class. Atmospheres of air-carbon dioxide and of air-nitrogen mixtures, with sufficiently low oxygen content, are effective in preventing explosions of these powders.

3 Powders of Little or No Explosibility. These include lead, chromium, copper, nickel, impure iron, molybdenum, tungsten, cobalt, selenium, and probably all noble metals. (The latter have not been tested.) These powders, having ignition temperatures above 700 C, could not be ignited by the electric sparks used in the tests.

Preventive Measures. The two principal ways to guard against dust explosions are to prevent the formation of dust clouds of explosive concentration and to eliminate all possible sources of ignition in areas where dust is present. The first measure calls for good housekeeping throughout a plant. It requires that dust processing equipment be dust-tight; that suitable dust collectors be installed where necessary; and that dust accumulations on ledges, beams, floors and other exposed surfaces be removed periodically, preferably by vacuum cleaners and soft push brooms. To eliminate the ignition sources, all electrical equipment and wiring should conform to the requirements of the National Electrical Code for hazardous and dusty locations; all open lights and smoking should be prohibited in the affected areas; repair work requiring the use of torches and welding equipment should be performed during shutdowns after removal of all dust; bearings and other moving parts of machinery should be dust-tight and in good working order to prevent overheating; all dust-processing equipment should be properly grounded to prevent accumulation of static charge; if possible, only nonsparking tools should be used, although little is known at present about the incendiary hazards of frictional sparks; and finally, the entrance of foreign matter into grinding mills and fans should be prevented. The heating and ventilating system in the plant should be of a type that will keep the air dry and at fairly even temperature, and will not raise dust into suspension. Where particularly hazardous dust is handled, it is advisable to segregate the dusty operations in separate buildings detached from the main plant. If considered necessary and practicable, inert gas may be provided instead of air in closed equipment. Finally, whenever possible, equipment and rooms in which a potential explosion hazard exists should be provided with relief vents through which the pressure of an incipient dust explosion can be released quickly.[2]

In order to reduce the fire hazard, care should be taken to prevent spontaneous heating of metal powders in storage, particularly shortly after grinding. It should be remembered that some metal powders, including magnesium, aluminum, and zinc, have a tendency to heat in the pres-

ence of moisture. First-aid fire protective equipment, suitable for extinguishing small fires in powdered metals, should be provided and workmen should be trained to use it properly. Small fires in magnesium and aluminum powder can be extinguished by surrounding and gently covering the fire with sand, talc, or other dry inert materials, or by using hard pitch that completely seals the fire.[3] Spray or fog nozzles can be used without danger to control fires in metal powders, although the application may increase the rate of burning of some powders—for example, magnesium. However, streams of water should be used only with great caution in fires where combustible dusts are involved, and the water should never be directed into the burning pile, since this may produce dust clouds and an explosion. Employees and the fire department should be advised of this in advance. Also, water from buckets must never be applied to burning dust.

For further recommendations on the prevention of explosions and fire in metal powder plants, the codes of the National Fire Protection Association[4] for aluminum bronze powder and for magnesium powder plants are important.

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Precision Casting

By F. S. Badger* and A. W. Merrick*

THE application of precision casting to industrial purposes has received a great deal of attention because of its success in wartime production of parts difficult to fabricate by other methods. This process of casting, also known as the "lost wax" or "investment casting" process, is an old one used for many years in the casting of dental inlays, dentures and jewelry. New techniques and materials were devised to make it applicable to high-melting-point alloys used in superchargers and gas turbines.

Process. The process is described below with the major variations used for quantity production of industrial castings. Patterns for the precision casting process must be made of materials such as waxes and plastics that will melt, vaporize or burn completely leaving no residue. These patterns are made by the injection of the pattern material into metal dies. Suitable cast alloy dies are generally used for making wax patterns. The dies are prepared by casting two halves in strong metal shoes around metal master patterns with proper allowance for shrinkage of both wax and metal. The dies may have either single or multiple cavities, according to the size of the patterns and the quantities required.

Machined and hardened steel dies are usually necessary for plastic patterns. These may also be used for wax injection, but they involve more time and much greater expense than cast metal dies, particularly if production is not great, if designs and other details are not definitely established, or if the desired intricate detail is easier to produce in a positive master pattern than in a negative die impression.

The single or multiple patterns are assembled with wax gates and risers for convenient mounting and proper feeding of metal into the mold. In order to produce the fine surface finish desired on precision castings, the pattern assemblies may be dipped or sprayed with a slurry of fine refractory powder. After eventual transfer to the investment mold, this powder serves as a mold-facing material. If very fine investments are used or if the casting surface does not require a high degree of smoothness, the coating step is sometimes omitted.

The coated patterns are attached to a flat plate by molten wax, and a heat-resisting metal flask lined with waterproof paper is sealed to the plate, making a liquid-tight space around the pattern. This space is then filled with an investment slurry of which many types are used. For the casting of nonferrous alloys that have melting points not exceeding approximately 2000 F, plaster of Paris is adequate as the binding medium for silica or other refractory materials. For alloys with higher melting points, silica generally forms the base of the mold and the binding agent is frequently "organic" silica formed by hydrolysis of ethyl silicate.

A number of other types of investment binders are being used industrially, such as phosphoric acid in water or in alcohol, reacting with magnesium oxide or carbonate, or colloidal silica in water. The filled mold assembly is vibrated to pack the solids and remove air bubbles, which may also be eliminated by vacuum treatment.

Complete setup and curing time for the investment molds varies from ½ hr to 24 hr, according to whether plaster is used or a binder with a vehicle of alcohol or water. Time can be saved by early removal of the plate to which the wax patterns and flasks are sealed.

After the mold has been adequately cured, wax patterns are sometimes melted out in a low-temperature oven. The molds, either dewaxed or with pattern material intact, are charged into a mold-heating furnace and heated to temperatures as high as 2000 F, depending on the type of investment and the character of both material and casting. This heat melts and burns wax or vaporizes and burns plastic patterns, leaving clean cavities in the mold. When the mold has been thoroughly soaked at the desired temperature, it is ready to receive the molten metal charge.

The metal charge is melted in small indirect-arc or induction furnaces; every precaution is taken to obtain clean melts and sound castings. Gas melting is often used for alloys that have a low melting point. Castings may be poured statically or centrifugally, either from a ladle, or directly from the melting crucible, or by pressure casting directly from certain patented melting furnaces, using air pressure to insure that all details in the mold are filled Careful attention to details is even more essential in this method of casting than in normal foundry practice, because of the smooth surface required for most of these castings. There are no particular limitations concerning the type of alloys that can be cast, but investments frequently vary according to the characteristics of the alloys to be used. Ordinarily, castings are slowly cooled in the mold, then knocked out and separated from the investment material when cold. Gates may be removed by sawing or by cutting off with abrasive disks. The castings are then cleaned by shot-blasting or sandblasting, and the gated areas are ground to the surface required on the finished castings. The castings are then submitted to whatever inspection is specified for dimensions and quality, such as visual, radiographic, magnetic particle, and fluorescent penetrant inspection.

Applications. The most important use of the precision casting process is in the casting of alloys and shapes that are difficult or impossible to forge and machine. The process is also useful with forgeable and machinable alloys in order to eliminate expensive machining operations. Precision casting may be used to replace die casting where production quantities are relatively low. It is particularly applicable in development work to avoid expensive machine setups or costly forging dies for trial runs, to permit intricate designs and to test various cast alloys for particular parts. The mass production of stationary and moving

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blading for gas turbines has been an outstanding application of precision casting and promises the eventual extensive use of the process in making parts for steam turbines.

Advantages. The precision casting process produces a smooth surface far superior to ordinary cast surfaces. The dimensional accuracy is ordinarily about plus or minus 0.005 in. per in., and is occasionally closer than plus or minus 0.003 in. on small dimensions. Considerable intricacy of design and detail is obtainable, including thin airfoil sections. Difficultly cored holes not obtainable by any other process can usually be cast by this process. There is no parting line in the mold, but there is one in the die for wax or plastic pattern injection. A minimum of finishing operations is necessary. Alloys with improved physical and corrosion properties may be substituted for less desirable alloys at little extra expense, since the metal is seldom the major part of the total cost.

Limitations. Smoothness and accuracy become increasingly difficult to obtain as the size of the casting increases. Small castings weighing less than 1 lb are the most practical to produce, although castings as heavy as 5 lb have been made successfully on a production basis.

Maximum accuracy is usually not obtainable on a part until some production experience has been gained. In general, dimensional tolerances should be left as wide as possible to avoid excessive and unnecessary rejection of castings for dimensional reasons. The precision casting process, while much more accurate than sand casting, does not compete with machining or grinding for accuracy in producing simple shapes.

There are some limitations when complicated internal coring is involved, particularly concerning blind holes and long internal threads. Threads must be chased or finished by grinding where very close fits are required.

Because of the many steps involved, the cost of the process is high and it cannot compete with screw machining or other methods of mass production of readily machinable metals, particularly where large runs absorb high setup costs.

Further information on the precision casting of particular alloys will be found elsewhere in this Handbook.

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Rolls for the Metal Industry

BY THE SUBCOMMITTEE ON ROLLS*

ROLLS are used in the metal industry for reducing the cross section of plastic metal or changing its shape, or both. As a rule two rolls are used, running in opposite directions, as shown in Fig. 1. The metal to be rolled, which will be called the "bar" hereafter regardless of its shape, passes between the rolls and is thereby reduced in cross section. In cross rolling (Fig. 2), used in the making of seamless tubing and straightening rounds, the rolls rotate in the same direction and set a piece of metal in rotation as it passes between them longitudinally.

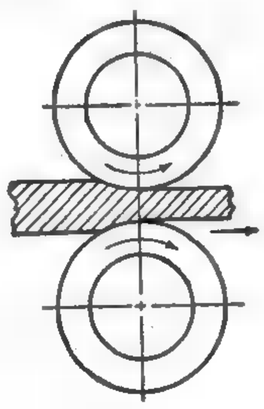

Fig. 1

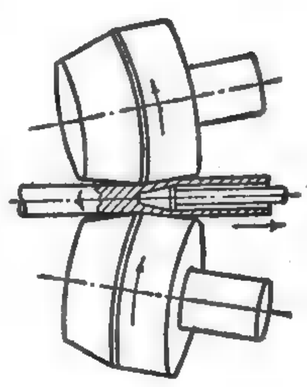

Fig. 2

Fig. 1 Typical rolling process
Fig. 2 Cross rolling

Roll Parts. A plain-bodied roll for rolling flat products is shown in Fig 3. The roll body or roll face is the working part in contact with the bar to be rolled. A grooved roll for rolling shapes is shown in Fig. 4. The metal is reduced by passing it through the grooves or passes. The parts of the roll separating the passes are called the "collars". Some rolls may be combinations of those shown in Fig. 3 and Fig. 4; for example, blooming mill rolls, which may have a portion of the body plain for rolling slabs and another portion grooved for rolling blooms and billets. The roll "neck" is the part that lies in the bearing or journal box. The "wabbler" is the part that receives the torque from the outside source of power. Instead of wabblers, some rolls are equipped with universal joints (Fig. 5), which make contact on surfaces rather than lines or points and thereby minimize wear.

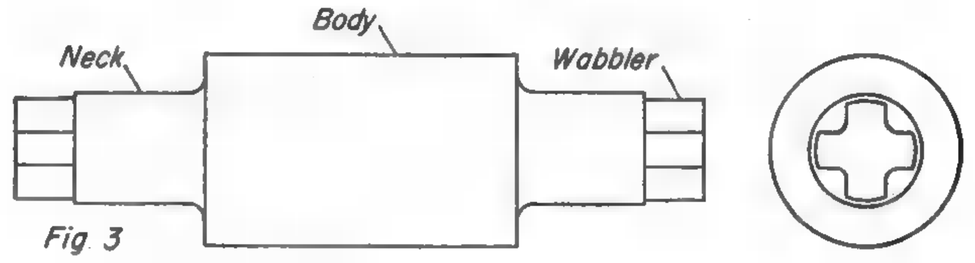

Fig. 3

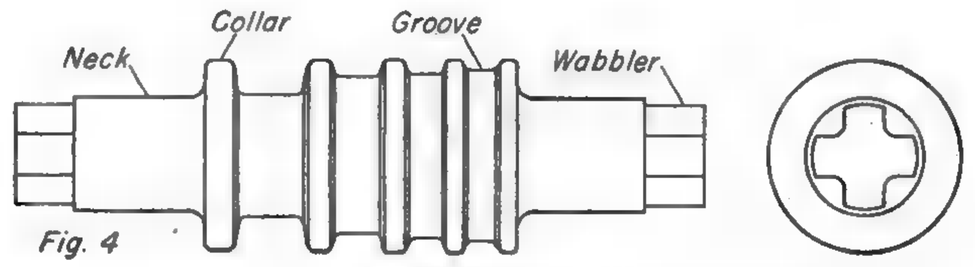

Fig. 4

Fig. 3 Plain roll
Fig. 4 Grooved roll

Roll Types and Arrangement in Roll Housing. "Blooming mill" rolls and "slabbing mill" rolls convert ingots into blooms and slabs.

"Roughing" rolls are used in the early stages of reducing billets and blooms into various shapes.

"Intermediate" rolls (also known as "second roughing", "pony roughing" or "strand" rolls) work on the bar after it comes from the roughing rolls.

"Leader" rolls are those preceding the finishing stand.

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"Finishing" rolls are used to give the bar its final shape. When used for rolling flat products these are sometimes called "planishing" rolls.

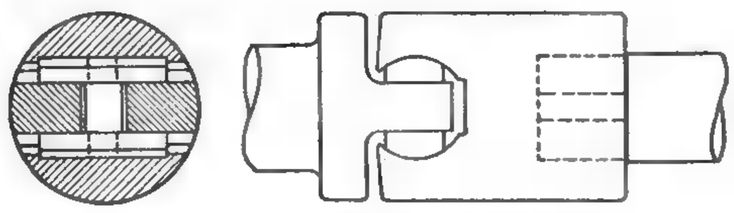

Fig. 5 Universal joint for rolls

If only two rolls are used in a mill, the mill is called a 2-high mill. If three rolls are used (usually on top of one another) the mill is called 3-high, and so on. Not all rolls are in contact with the metal to be deformed. Some rolls act as stiffening or supporting rolls for smaller rolls that are in contact with the work. The smaller rolls are then called "working rolls" and the supporting rolls are called "backing rolls". Figure ■ shows the arrangements of rolls on 3-high, 4-high and cluster mills.

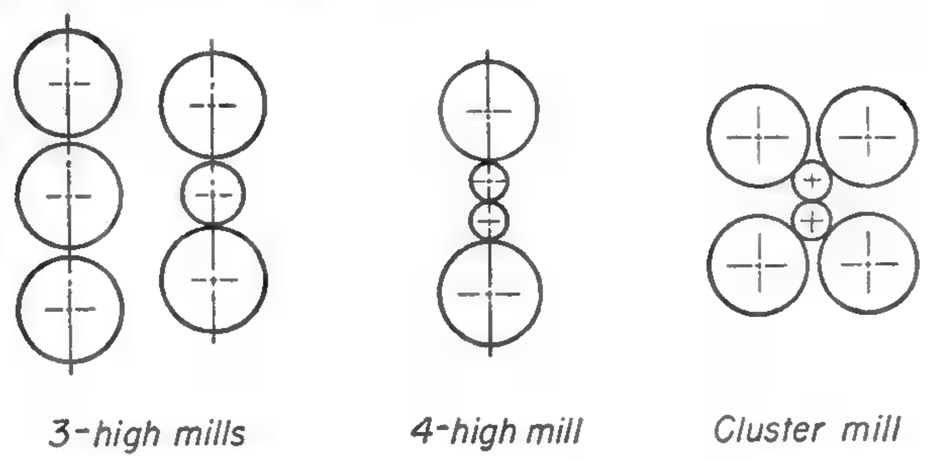

Fig. 6 Arrangement of rolls in 3-high, 4-high, and cluster mills

Roll Requirements. *Resistance to Wear.* This is the first requirement for rolls, since rapid wear impairs the surface or enlarges the section beyond the tolerance that can be used. Wear is caused by the relative motion between the bar and the roll surface. In all rolling there is relative motion between rolls and bar while they are pressed against each other at enormous pressures, which, in severe operations, reach several hundred thousand pounds per square inch. There is no general index for resistance to wear of rolls. For lack of something better, hardness is ordinarily used as an indication. The hardness of the roll is usually determined by the Shore scleroscope because of its portability and because the test involves a minimum marking of roll surfaces. Hardness of a roll is limited by the requirements for strength, since ductility and shock resistance decrease as the hardness increases.

Strength. This property is necessary in the rolls because they must withstand fracture from bending, torsional and shearing stresses to which they are subjected in operation. Sufficient strength for any application depends on the chemical composition of the roll, the heat treatment, and the freedom from residual stress and internal defects. Residual stress is present to some extent in every roll. Size, thermal treatment, design, and casting conditions play an important part in these stresses. Under service conditions, rolls that have unfavorable high residual stresses may rupture easily by uneven or rapid heating on the mill. This is particularly true of chilled iron rolls for flat products. Subsurface strength is necessary to resist spalling, which frequently originates below the surface and progresses outward until the part breaks loose.

Bite. For grabbing the metal and starting it through the roll, bite is necessary, particularly in taking large reductions. Bite depends partly on the roughness of the roll surface. In many blooming or roughing mills, this roughness is artificially increased by ragging or knurling; that is, by cutting longitudinal grooves or welding ridges on the roll surface. Ragging must be done carefully or it will show in the finished bar. Where reductions are small, as in the leader and finishing pass, a smoother roll can be used.

Surface Perfection. The roll surface must be of high quality to obtain a good bar. In that type of cold rolling where a high surface finish is important in the product, the roll surface must be ground to a high finish and must be exceptionally free from defects. Only the highest hardness will preserve such a surface for a sufficiently long commercial operation. In hot rolling, the roll surface is subject to fire cracking, caused by alternate heating and cooling. Fire cracking is greater in the early passes where the hotter metal and larger reductions prevail.

The surface must be metallurgically correct. If the bar material has too great an affinity for the roll metal, it will stick to the roll and "load" it. The solution of this problem is not always easy. A change of roll material helps in some instances; application of a lubricant between roll and bar helps in others; insertion of another metal between roll and bar has become necessary in ■ few instances.

Rigidity. This property in a roll is essential to reduce the deflection or roll spring across the roll length. This is particularly important in rolling flat products, such as plate, sheet or strip. If the rolls spring, the edge of the section is wavy and thinner than the center. For a given diameter, a steel roll is more rigid than a cast-iron roll, but the hardness of the steel roll has no effect on its rigidity since deflections depend solely on the modulus of elasticity, which is the same for hard steel and for soft steel. Leader and finishing rolls are made relatively short for the purpose of reducing roll spring and giving accurate finished dimensions. Crowning the roll, by making the diameter slightly larger at the middle than at the ends, will produce a flatter section, but crowning is a limited remedy since a given crown can be correct for only one thickness, hardness, and width of section.

Size and Design of Rolls. The size of a roll is specified by the diameter and the length in the order named, such as 24 by 48 in. Rolls for shapes are often designated by the nominal roll or pitch diameter, which equals the distance between the centers of the mill-driving pinions. The diameter of the rolls is usually smaller than the pitch diameter because there must be room for the bar to pass between them. Occasionally the roll diameter is larger than the pitch diameter when the rolls are new. Plain rolls used for plate and strip may sometimes be designated by the length of the roll body. Rolls of the smallest possible diameter are used as far as is consistent with strength, bite, and rigidity, because rolls of relatively larger diameter spread the bar, exert greater roll pressure or separating force, and use more power for a given reduction. Rolls are made as long as is consistent with freedom from excessive deflection or breaking by bending. The deeper grooves of grooved rolls are placed as far as possible from the center, in a location where the bending moment is smaller.

For grooved rolls, the safe ratio of body length to diameter depends on the material being rolled and on the temperature of the bar.

Fairly sharp limitations exist as to the largest section that can be rolled on any mill, because on material larger than ■ certain size the rolls do not bite, or they break in bending, the wabblers twist off, the necks overheat, or the mill is stalled.

Table I. Minimum Safe Ratios of Neck Diameter to Body Diameter for Rolls Used on Various Types of Mills

Type of Mill	Ratio of Neck Diameter to Body Diameter
Blooming mills	0.50 to 0.55
Sheet mills and tin mills	0.76 to 0.80
Strip mill, backing rolls	0.55 to 0.65
Strip mill, working rolls	0.60 to 0.65
Merchant bar mill	0.60 to 0.67
Plate mill, middle roll	0.60 to 0.70
Plate mill, top and bottom rolls	0.65 to 0.72
Structural mill	0.57 to 0.65
Continuous bar mill	0.70
Universal mill, vertical rolls	0.57
Cold rolling brass, heavy reduction	0.775
Cold rolling brass, finishing reduction	0.72 to 0.75

The sudden change of diameter from roll body to roll neck intensifies the bending and torsional stress at this location. The neck diameter should not be smaller than a certain safe fraction of the body diameter, which with plain bearings will approximate the ratios given in Table I.

Misuse. Rolls can be broken or damaged easily by misuse. In hot rolling, the entering bar may be too cold or may be heated unevenly. Fire cracking usually occurs if the mill is stopped while the hot metal is between the rolls. If the bar runs between the collars instead of entering the groove, the roll pressure becomes excessive. By accident, strips or bars may wrap around the roll, forming collars and inducing excessive stresses in the rolls. Lubrication may stop in cold rolling. Other mishaps may occur on the mills, overstressing the rolls and contributing to failure some time later. Among the avoidable mistakes are local heating, too rapid heating, too rapid cooling, bruises, and nonuniform cooling. The results of these abuses may not become apparent for a considerable period of time. In the original grinding of rolls, or in regrinding, improper technique can cause serious damage, especially on hardened steel rolls. For precautions in grinding hard steel rolls, see page 59 of this article.

Roll Materials. There are three large classes of roll materials—cast iron, cast steel and forged steel. Cemented carbides have been used for some small rolls.

Cast-Iron Rolls

In American practice, cast-iron rolls are classified as (1) chilled iron rolls, (2) grain rolls, (3) composite rolls, and (4) sand iron rolls.

Chilled Iron Rolls. Chilled iron rolls (scleroscope hardness, 50 to 90) have a definitely formed, clear homogeneous chilled white iron surface on the body, and have a fairly sharp line of demarcation between the chilled surface and the gray iron central portion of the body. The depth of chill is measured as the distance between the finished diameter of the body and the depth at which the first graphitic specks appear. Below this, there is an area consisting of a mixture of white and gray iron known as mottle, which gradually becomes more gray and more graphitic, until it merges with the gray iron structure of the main part of the roll. The mottled area should equal that of the primary chill or be somewhat smaller.

The chilled rolls are subdivided into plain carbon and alloy rolls. Plain carbon rolls, having a hardness of 50 to 72 scleroscope, were the standard rolls in use for both hot and cold rolling until the introduction of the alloy chilled roll. The approximate composition of carbon chilled rolls is as follows:

	C	Si, min	Mn, max	P, max	S, max
Soft	3.00	0.75	0.25	0.50	0.125
Hard	3.50	0.50	0.20	0.50	0.150

The alloy chilled rolls have a hardness range from 60 to 90 scleroscope, controlled by the carbon and alloy content. Their composition is essentially that of the carbon roll plus one or more special alloying elements. The customary maximum percentages of elements used are 1.25% Mo, 1.00% Cr, 5.5% Ni. Many varying combinations produce the properties desired. Rolls of this type, particularly in the harder grades, are used chiefly for rolling flat work, both hot and cold. The softer, machinable grades are used for small shapes and rod mill work.

Grain Rolls. Grain rolls are "indefinite chilled" iron rolls (scleroscope hardness, 40 to 90) .that have an outer chilled face on the body but no definitely formed chilled structure. At the surface there is finely divided graphite, which gradually increases in amount and in flake size, with a corresponding decrease in hardness as the distance from the surface increases. This diminution of properties is gradual and these rolls have high resistance to wear and good finishing qualities to considerable depths. The harder grades are used for hot and cold flat finishing work and the milder grades for deep sections, even with small rolls. The basis of the composition of grain rolls is low-phosphorus pig iron, together with 0.75 to 2.50% Cr. Other alloying elements such as nickel and molybdenum are usually added, singly or in combination, to develop specific properties of hardness and toughness similar to those of chilled iron rolls.

Composite Rolls. Composite rolls (scleroscope hardness: bodies 70 to 90, necks 40 to 50) are rolls in which the body surface is a richly alloyed, hard cast iron, resistant to wear; while the necks, wabblers and body centers are of a different material that is softer and tougher. Both metals are bonded firmly together to form an integral structure that permits the attainment of a wearing surface of high hardness along with a tougher body and neck. Composite rolls are thus better able to withstand impact and thermal stresses. The rolls may be of either the chill or the grain type. The chief application in the rolling of steel has been for work rolls on 4-high hot and cold strip mills and on plate mills; in the rolling of nonferrous metals the chief application has been for the hot breakdown and cold running down of sheet and strip.

Sand Iron Rolls. Sand iron rolls (scleroscope hardness, 35 to 45) are cast in sand molds in contrast with chilled iron rolls and grain rolls, the bodies of which are cast in chilled molds. In sand iron rolls, the metal in the grooves of the body is mildly hardened by the use of cast-iron rings set in the sand mold. Sand iron rolls are used chiefly for intermediate and finishing stands on mills that roll shapes. Since these rolls are comparatively soft, their use is justified only when there is not enough metal being rolled to warrant the use of more expensive rolls.

Manufacture. In the manufacture of chilled iron rolls, pig iron and scrap are used. Low-phosphorus pig iron and grain roll scrap are the basis of grain rolls. Both types are usually melted in a reverberatory or air furnace similar to that used for the melting of iron for malleable castings (*see* "Malleable Iron", page 520); though the chilled type is sometimes made in a cupola.

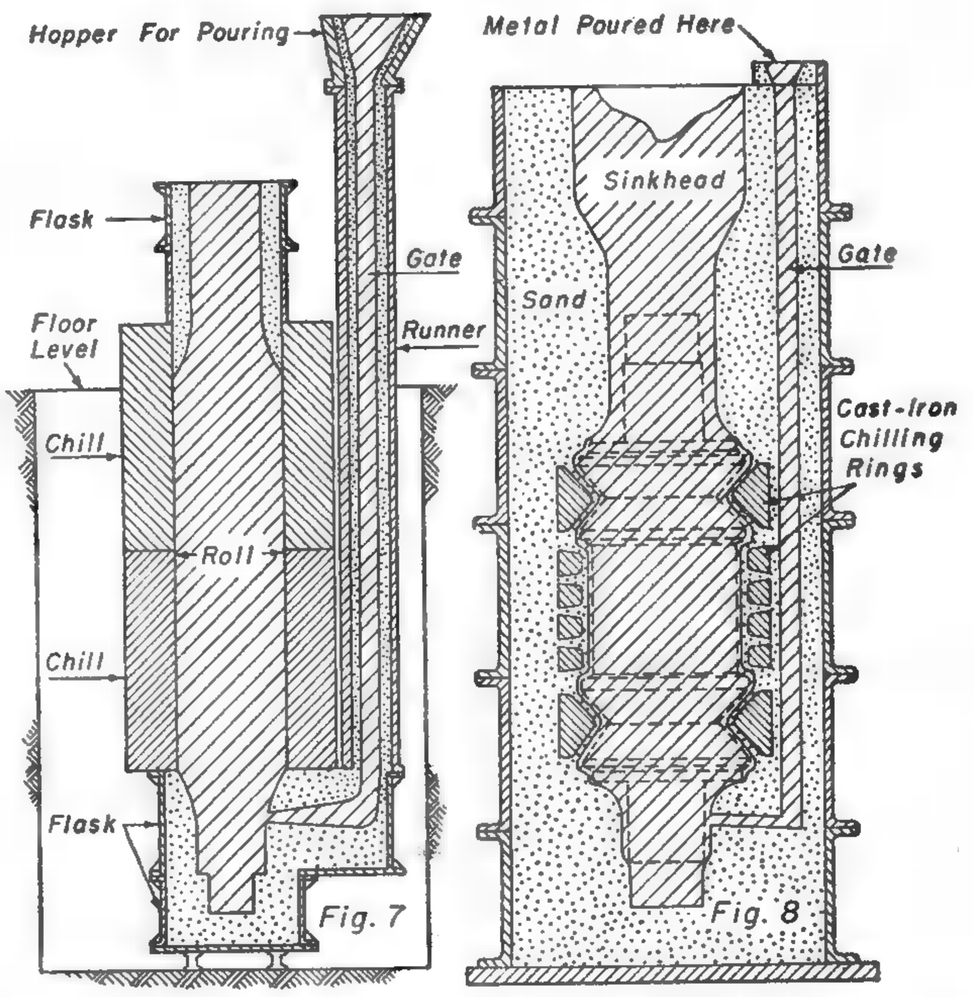

Fig. 7 Typical mold for manufacture of iron roll
Fig. 8 Typical mold for manufacture of alloy steel roll

The mold for casting the roll is erected in a perpendicular position. A typical design of a mold is shown in Fig. 7. When the metal is poured, a rapid centrifugal motion or swirl is produced by the tangentially located gate. The heavy cast-iron cylinder that comprises the body of the mold conducts heat rapidly from the molten metal, causing the formation of a hard white or chilled iron surface layer on the body of the roll. The depth of this chill is controlled by the composition of the iron and is varied to suit the requirements of the roll. The roll casting is allowed to remain in the mold for a period of 12 hr to 6 days, depending on the size. Some special alloy castings are taken from the mold while still quite hot and transferred to an annealing furnace to cool at a controlled rate, or reheated for certain mechanical properties.

Application. The principal use of plain cast-iron rolls is for hot rolling, such as is done on 2-high mills for the rolling of sheet and tin plate. The applications of plain cast-iron rolls, as well as of alloy cast-iron rolls, vary with mill practice and the finish requirements. The applications of these rolls are listed in a general way in Table II.

Table II. Applications of Cast-Iron Rolls

Grade	Hardness, Scleroscope	Application
Definite chill ..... (carbon or molybdenum chill)	50 to 72	Hot and cold rolls for sheet and tin mills, 2-high and 3-high plate mill rolls, jobbing mill rolls, wet and dry work rolls, 4-high hot strip mills, intermediate and finishing stands, rod, merchant, sheet, bar, skelp mills.
Definite chill ..... (alloy iron)	60 to 90	Hot rolls for nonferrous sheet and strip, 2-high and 3-high plate mill rolls, universal mill rolls, work rolls for 4-high hot strip mills, cold rolls for finishing nonferrous and steel sheet.
Definite chill ..... (nickel alloy)	65 to 90	Finishing stands, sheet bar, skelp, strip and merchant mills. Work rolls for 4-high hot strip mills. Cold finishing nonferrous sheet and strip.
Grain ..... (indefinite chill)	40 to 90	*Mild Hard* Light-duty roughing for small merchant and bar mills. *Medium Hard* Intermediate rolls for merchant and bar and large structural mills. *Hard Grade* Finishing rolls for merchant, bar and structural mills, also for flat finishing on sheet bar and skelp mills; sizing, high mill, reeler and welding rolls for tube mills.
Sand iron ..... (no chill)	35 to 45	Mild-duty small mill roughing to large structural finishing.

The harder, richly alloyed chilled rolls are nearly as hard as forged and hardened steel rolls and are competitive with them in the cold finishing of flat work.

Cast Steel Rolls

The differentiation between cast-iron rolls and cast steel rolls cannot be made strictly on the basis of carbon content. Iron rolls are of such compositions that free graphite is apparent in the unchilled portions; steel rolls do not show graphite.

The harder cast alloy steel rolls have hardness equivalent to that of the softer cast-iron rolls, and the superior strength of cast steel rolls often demands their use.

Composition. A few rolls are made from carbon steel, particularly for blooming and billet mills. The carbon range is usually from 0.40 to 0.80% for roughing, and from 0.85 to 1.25% for finishing rolls.

Alloy steel rolls have almost entirely superseded the carbon steel rolls. The majority of alloy steel rolls are within the following range of compositions: 0.40 to 2.60% C; less than 0.12% S, usually 0.06% max; less than 0.12% P, usually 0.06% max; as much as 1.25% Mn; as much as 1.50% Cr; as much as 1.50% Ni; and as much as 0.60% Mo. Lower carbon content gives greater ductility and shock resistance; higher carbon content affords increased hardness and resistance to wear.

A small number of rolls are made with alloy content higher than any indicated above, but these are usually rolls for special purposes.

Manufacture. Steel rolls are generally cast from acid open hearth metal, although basic open hearth steel and electric furnace steel are sometimes used. The steel is cast in a dry sand mold in which suitable metal chills may be placed for more rapid solidification in certain portions of the roll (*see* Fig. 8). The mold is cast in a vertical position and the metal enters the bottom neck at an angle to the circumference, so as to set up a swirling motion. A fairly large head and cope neck are necessary to feed the casting and avoid shrink holes. The cope neck is generally weaker than the drag neck because of the greater segregation at the upper portions of the casting and because of the removal of more of the condensed surface metal in the enlarged area to reach finished size. After casting, the gates and heads are removed from the rolls, which are then annealed or otherwise heat treated, and turned or ground to finished size.

Heat Treatment. According to the service required, the hardness, and the composition, cast steel rolls are generally given one of the following heat treatments:

Single Annealing. This treatment involves heating the steel to just above the A_3 transformation temperature, and then cooling it in the furnace. Single annealing refines the as-cast structure and removes casting strains.

Double Annealing. This treatment involves heating the steel to several hundred degrees above the A_3 transformation temperature, cooling in the furnace to below the A_1 temperature, reheating to slightly above the A_3 temperature, and then cooling in the furnace. The first heating refines the as-cast structure and homogenizes the steel. The resulting coarse structure is refined by reheating.

Normalizing. This treatment involves heating the steel to somewhat above the A_3 transformation temperature in order to refine the structure, and then cooling in air. Normalizing may decrease the ductility of the steel, but the treatment is used under special circumstances to increase hardness and resistance to wear.

Application. Cast steel rolls are graded according to the range of carbon content. The general applications of these rolls are listed in Table III.

Table III. Applications of Cast Steel Rolls

Carbon, percentage	Application
0.50 to 0.65	Where strength is the prime and only requirement
0.70 to 0.85	Blooming mills, jobbing mill, plate mill and sheet mill roughers, muck mills
0.90 to 1.05	Blooming mills, continuous bar mill roughers, backing-up rolls
1.10 to 1.25	Blooming mills where breakage is not great, piercing mills. billet, bar, rail and structural mill roughers
1.35 to 1.55	Intermediate stands for rail mills, structural, continuous billet and continuous bar mills
1.60 to 1.80	Intermediate stands for continuous bar and billet mills, middle rolls for 3-high mills
1.85 to 2.05	Middle rolls for rail and structural mills, finishing mills where housing design is too limited for iron rolls
2.10 to 2.60	Finishing rolls to meet unusual conditions

The applications listed in Table III are not a rigid classification because of the wide variation of conditions from mill to mill. Adjustments in carbon and alloy content are generally made to suit individual conditions.

Forged Steel Rolls

The principal application for forged steel rolls is cold rolling. The forged rolls are generally of a standardized composition. The average composition is, as follows: 0.85% C, 0.30% Si, 0.30% Mn, 2.00% Cr. Nickel, vanadium or molybdenum may be added either singly or in combination. Special types of forged rolls are available for certain special applications.

Manufacture. Forged steel rolls are made from acid open hearth or electric furnace steel, cast in ingot molds of suitable size and shape to afford the required reduction in forging, in order to produce the necessary structure and grain refinement. After being forged, the rolls are put through suitable normalizing and annealing processes and are then rough machined, bored and heat treated. Thereafter the rolls are machined for hardening and are hardened by heating to a suitable temperature and quenching in water or brine. Special fixtures and devices are used in order to insure uniform and extreme hardness on the working face, as well as to prevent or retard hardening of necks, shoulders, fillets and so forth. After the roll has been hardened, it is tempered to relieve stresses and to obtain the desired hardness. The next step is machining and grinding to finished dimensions and desired surface finish. Forged steel rolls are capable of a high surface finish. For special purposes a so-called "mirror finish" may be put on the rolls.

Application. Rolls of this type are used for cold rolling and for the finishing of thin metal where a high-grade

finish is desired. The hardness is varied with the service for which the roll is intended. For extreme hardness and fine finishing of thin metals a hardness greater than 95 scleroscope is commonly used. For soft and thicker metal, and for operations such as running down or semifinishing, a hardness of 80 ot 90 scleroscope may be used. For heavy roughing and special purposes hardnesses less than 80 scleroscope are used.

When forged rolls are used as backing-up rolls in 4-high mills, the scleroscope hardness depends on the size of the roll and character of the mill. For the small strip or band mill, the hardness should be 75 to 90 scleroscope. For the forged backing-up rolls, larger in diameter and used in either hot or cold strip mills, the hardness should be from 55 to 80, in order to insure maximum service. Forged rolls are applied as backing-up rolls when high pressures are used and high strength is required. Forged steel rolls of various hardnesses—such as leveler rolls, pinch rolls, coiling rolls and carrier rolls—are used for many auxiliary purposes around mills.

The extremely hard rolls must be handled with great care, and precautions should be taken to prevent their being subjected to rapid changes in temperature while in use. Before rolls are put into service, they should be preheated to approximately rolling temperature, preferably by means of heated water or low-pressure steam in the bore. Preheating of rolls by means of a gas flame is dangerous and should never be attempted unless the rolls are rotating. Rolls should never be warmed by running them in contact with one another; also, idling the rolls in contact with one another is dangerous. This practice may cause minute surface, or subsurface, fractures that result later in a spall. When not rolling, the rolls should be separated from one another and the cooling water should be turned off immediately whether they are rotating or not. Rapid and excessive heating of roll journals as a result of defective bearings or improper lubrication, causes rapid local expansion or subsequent rapid contraction, and will result in a broken or spalled roll or fire-cracked journal.

Bruises on the faces of rolls frequently bring about spalling. Such bruises often result when the ends of the strip are harder than the rest of the strip. Other factors that account for bruises are badly sheared ends, turned over or broken edges, pinches caused when the shape of the roll is unsuited to the type of rolling or when the mill is set up wrong, nonuniform thickness of strip or sheet, passage of foreign material such as micrometers, and small spalls from back-up rolls. Whenever a roll is bruised it should be ground until no trace of the spall remains after polishing and etching with a solution of ethyl alcohol containing 7% of nitric acid.

Forged steel rolls can be damaged readily by improper grinding. For roughing down and rough grinding, coarse free-cutting wheels are essential. Fineness of grit for finish grinding and polishing depends on the finish required. It is necessary to select a grinding wheel of the proper bond and hardness and to use the correct speeds for roll and wheel; otherwise the face of the roll will be injured. The manufacturers of grinding wheels should be consulted when selecting the wheels for specific shop conditions.

During periods of storage, hardened steel rolls should be well covered with a rust-preventive compound and should be placed in a dry room kept at a reasonably constant temperature. They are best supported on their journals. Manufacturers of forged steel rolls ordinarily furnish instructions for the care and use of their rolls.

Worn or damaged forged rolls can sometimes be rehardened for use in the same mill or can be made into smaller rolls for use in other mills.

Miscellaneous Rolls

Sleeve Rolls. The sleeving of back-up rolls has become a common practice in recent years and, as a result, a definite increase in tonnage and service has been obtained in comparison with that obtained with solid cast back-up rolls. In general, sleeves are manufactured from an oil-quenching grade of forged steel, heat treated to a hardness of 50 to 75 scleroscope, finished and accurately ground on the inside diameter to match a spindle or mandrel, and applied by means of a shrink fit.

The mandrel may be obtained from a solid worn-out cast roll cut down to suit, or from a casting made of alloy steel ground smooth on the outside diameter to fit the sleeve. The shrink fit for this assembly depends on the accuracy and smoothness of the two ground surfaces and is satisfactory only when a minimum is allowed for expansion to avoid possible longitudinal cracking while in service.

The best results obtained from sleeved back-up rolls are in cold reduction mills where the rolling temperatures are held constant, and also in many of the larger hot mills where the surface or frictional heating of the roll can be eliminated.

Carbide Rolls. Since about 1936, small-diameter rolls of sintered tungsten carbide have been used on some small rolling mills for flat work. Rolls 3 in. in diam and 15 in. long are now in use, but they can be made as large as in. in diam and 30 in. long with the present manufacturing equipment.

Carbide rolls impart a better finish to the product than steel rolls and it has been asserted that when steel rolled on carbide rolls is plated, a much better finish is obtained and less plating material is needed to coat the sheets than when the steel sheets have been rolled on steel rolls. At one time it was believed that carbide rolls could be used only on tension mills. However, they have been used on driven mills. Rolls made of tungsten carbide or of tungsten-titanium carbide are used to roll steel for razor blades.

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Cemented or Sintered Carbides

By L. J. Hull* and D. L. Schwartz*

COMMERCIAL cemented carbides are products of powder metallurgy, made of very finely divided carbide particles of the refractory metals, cemented together by a metal or alloy of the iron group, forming a body of great hardness and high compressive strength.

Cemented carbides were first used for wire-drawing dies, from which the application expanded to include all types of drawing dies for round and irregular shapes, and cutting tools for machining all kinds of materials. In addition, cemented carbides have been used for machine and instrument parts and for a wide variety of products where high rigidity and resistance to wear are important.

In general, cemented carbides come under the two broad classifications that follow, depending on their uses.

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1 The straight tungsten carbide with cobalt binder is used in tools for cutting cast iron, nonferrous metals and nonmetallic materials; and in dies for drawing wire, bar, tube and sheet metal, and for blanking; as well as for machine parts where resistance to wear is important.
2 The steel-cutting grades consist largely of tungsten carbide with additions of titanium carbide or tantalum carbide or both, or of columbium carbide. These added constituents produce a material that resists cratering better than the straight tungsten carbide grades. ("Cratering", caused by the hot steel chip, is the formation of a cavity in the top surface of the carbide blank, slightly behind the cutting edge.)

Basically, the process consists of preparing the powder carbides of tungsten, titanium or tantalum; mixing one or more of these carbides with a binder, such as cobalt powder; pressing the blended powder into compacts of desired form; and sintering molded shapes to achieve consolidation.

Preparation of Powders. *Tungsten Carbide.* Of the two tungsten carbides, only the monocarbide is used for manufacturing cemented carbides. Tungsten monocarbide can be prepared by any one of the three methods that follow:

1 Heating a mixture of tungsten powder or tungsten oxide with a calculated amount of carbon powder in a hydrogen atmosphere containing carbon. The carbon powder may be lampblack or sugar carbon; either will give good results if processed properly.
2 Heating tungsten powder or tungsten oxide in a carburizing atmosphere.
3 Forming tungsten carbide by reaction of the constituents in a molten metal that does not form a stable carbide.

Tantalum and Titanium Monocarbides. These carbides can be prepared by the methods mentioned for tungsten monocarbide. To avoid difficulties otherwise likely to occur, the metal powders are usually prepared by heating the oxide with carbon to a high temperature. The carbides may also be prepared in either an inert atmosphere or a vacuum.

Cobalt. The cobalt powder is obtained by reduction of either the oxide or the oxalate in a hydrogen atmosphere, at a temperature not high enough to cause appreciable coarsening of the particles through sintering. Mechanical means may be used to reduce the particle size further.

Milling and Blending. After the carbide has been formed, it is carefully crushed, milled and screened. Compositions of the various commercial grades are prepared by selecting measured quantities of the binder metal and the carbide or carbides and blending the mixture by ball milling, which can be done either wet or dry. There are indications that the hard particles are coated by a film of the binder metals during this blending operation. Where the lining of the mill or the balls used for milling are of the same material as the binder metal, the binder can be obtained from the lining or balls through erosion, by regulation of the time of milling. The duration of ball milling varies from a period of hours to a period of days, depending on the properties required in the final sintered product and on the amount of binder metal.

Compacting and Sintering. The prepared powders are formed into shapes for commercial use by (1) cold pressing, followed by sintering or (2) by hot pressing, during which the pressing and sintering are done simultaneously.

Cold Pressing. For cold pressing, a small quantity of a lubricant, such as paraffin, is added to the powders before they are placed in the mold. This practice facilitates pressing and handling of the compacts.

The material is pressed in either hard steel molds or molds lined with cemented carbides, at pressures that vary between 5 and 30 tons per sq in., depending on the size and shape of the compact. Equipment for pressing is similar to that employed for pressing other kinds of powders—hydraulic machines for the higher pressures, and tablet machines for the lower pressures. The fragile compact may then be given a presintering treatment at a temperature high enough to drive off the lubricant, and to cause partial sintering. After presintering, the material has the consistency of ordinary chalk. In this condition, if extreme care is used in handling, the still-fragile compacts can be ground, turned, bored, faced or otherwise machined into regular or irregular shapes.

Dimensional allowances must be made in the shaping or forming operations to compensate for the shrinkage that takes place during the final sintering operation. This shrinkage may amount to 40% by volume or 15% linearly.

Sintering is performed at a temperature of 1400 to 1500 C from 30 to 60 min either in a protective atmosphere of hydrogen, containing sufficient carbon to prevent decarburization, or in a vacuum. Sintering in a vacuum is often desired for grades that contain titanium and tantalum.

During the sintering operation, the material goes through a plastic stage, as a result of the formation of a eutectic between the cobalt and the carbides at approximately 1350 C. This eutectic becomes the cementing material, wetting the carbide particles that do not dissolve, and the surface tension draws the particles together. The carbide grains are always larger than before sintering, a result of solution and reprecipitation of the carbides on particles that were not dissolved by the cementing material.

After cooling, the sintered compact has its final properties. For a given composition, the physical and mechanical properties can be altered by changing the sintering practice.

Hot Pressing. In the hot press method, the pressing and sintering are combined in a single operation. The prepared powders are placed in a graphite mold, closed at the ends by plungers that transmit pressure during the heating and cooling cycles. The heating can be accomplished by passing the current through the mold assembly, which acts as a resistance, or by placing the assembly in a suitably designed furnace that can be heated electrically by resistance or induction. Also the two methods may be combined.

Sufficient pressure must be applied to fill out the mold completely, and to eliminate gases entrapped during the insertion of the metal powders into the mold, as well as the gases that are generated during the sintering cycle.

Extrusion. The extrusion method of forming cemented carbides is an important development, since by this method, rods, tubes, spiral blanks, twist-drill sections with or without an oil hole, triangular, half-round and many other shapes can be produced in lengths of approximately two feet, or in even greater lengths if warranted.

In this process, the prepared powders are mixed with a suitable plasticizer in controlled amounts. The plastic material is then extruded through an appropriately designed die. Next, the extruded shape is baked at a low temperature, and is finally presintered and sintered, as outlined for the cold pressing method.

From a given composition, the final products obtained by employing any of the various methods of manufacture described above, can have the same qualities, depending on the control of processing. For a given method, raw material and composition, the final sintering practice determines the properties of the product.

Control of Quality. Careful control of the size and shape of the particles and of the distribution of the particle sizes, requires periodic examination during the manufacturing of this material. Variations of grain size and distribution of the particles are detected by metallographic examination. A further guide for the constancy of production operations is provided through determinations of density, hardness and strength.

Density is determined by the usual method, involving displacement of liquid. This test serves as a control of constituents and porosity, against previous standards or theoretical densities.

The measurement of hardness is ordinarily made as a Rockwell-A reading, using a 60-kg load and a diamond brale. It is more common to use a Rockwell-A reading because of the short life of the diamond brale when using the 160-kg load required for Rockwell-C readings. For checking the extremely hard grades, the Superficial Rockwell Tester is occasionally preferred in order to reduce brale failures to a minimum. In addition to the approved procedure for taking Rockwell hardness measurements, extreme care should be taken to support the specimen well.

The cemented carbides show very little permanent deformation or ductility under tension or compression loading. For control of production, the simplest method of estimating the strength of these materials is the transverse rupture test, in which a breaking load is applied to a test bar midway between supports.* The distance between supports should be such that the bar does not fail in shear.

* For additional information concerning such tests, the reader may refer to the article "Bend Tests for Hard and Brittle Metals", page 125.

The fracture test also is utilized for estimating quality. Fractured surface is ordinarily examined at low magnifications for surface skin effects, dark areas that may be graphite flakes or segregation of carbides, bright areas that may be inclusions or lakes of binder metal, voids and other characteristics of the break, which may indicate the toughness and strength.

The technique of applying these tests varies among the various manufacturers of cemented carbides. No standards for conducting the tests have been generally accepted.

Metallographic Examination. Cemented carbides may be readily polished and etched for microscopic examination. Specimens can be cut from large pieces of cemented carbide material by using a diamond cutoff wheel. The surface to be examined is rough ground with a diamond or silicon carbide wheel. The lapping is done with diamond dust on a metal lap. An oil, such as kerosene, may be used as a medium for holding the diamond dust. For rough and intermediate lapping, boron carbide can be substituted for diamond dust; however, it gives less satisfactory results. The three following stages are ordinarily used for lapping:

1 Rough lapping can be accomplished with diamond dust that has particles in the size range of 10 to 30 μ.
2 Intermediate lapping is performed best with diamond dust that has a maximum particle size of 10 μ.
3 Final lapping is performed on a paper lap, glued to a metal polishing wheel, using diamond dust that has a maximum particle size of 1 μ or less.

For estimating porosity and voids in the material, the as-polished surface is usually examined at relatively low magnification. The structural details, grain boundaries and phases are resolved at a magnification of 1000 to 2000 diam, after etching with one of the following solutions, which may be used for either a chemical or an electrolytic etch:

1 One to one mixture of 10% potassium hydroxide and 10% potassium ferricyanide at room temperature
2 A solution of 10% sodium hydroxide for compositions high in titanium carbide (an electrolytic etch)
3 Three parts of 30% hydrofluoric acid and one part of nitric acid
4 Phosphoric acid containing a small amount of nitric acid.

Properties. The combination of high hardness and compressive strength is among the most valuable properties of this material. The effect of temperature on the values of indentation hardness in cemented carbides at elevated temperatures is illustrated in Fig. 1. The abrasive or scratch hardness is also high, in a class with hard substances such as corundum, silicon carbide and boron carbide (*see* Table I). The relative Knoop hardness values of these hard substances are compared in Table II. The combination of high indentation and abrasive hardness in conjunction with high compressive strength, modulus of elasticity and fatigue endurance (comparable with that of hardened tool steel) makes this material versatile for many unique applications. The load that this material will sustain in tension is substantially less than in compression. Before fracture, very little permanent deformation takes place in either tension or compression; nevertheless, indentation by dynamic impact can be produced. Values of physical and mechanical properties are listed in Table III.

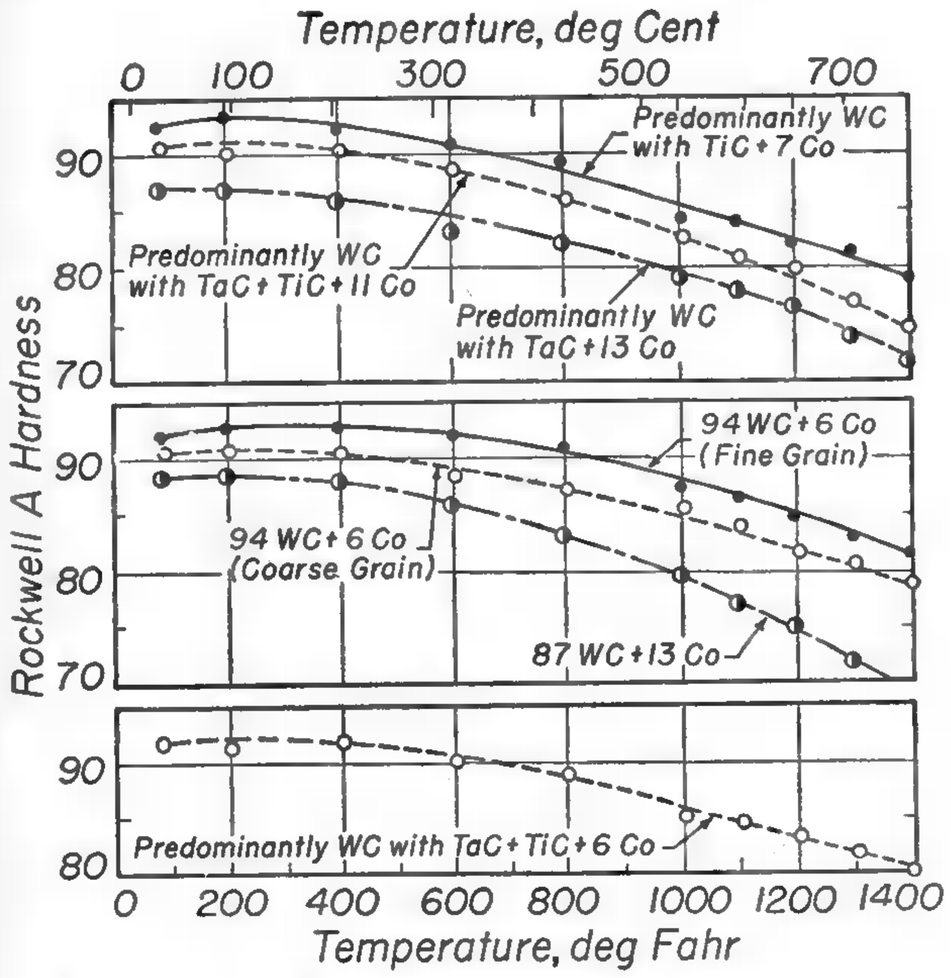

Fig. 1 Rockwell A hardness for commercial compositions of cemented carbide at elevated temperatures. Rockwell A readings (diamond indenter and 60-kg load) were taken on a standard Rockwell machine fitted with extensions for penetrator and anvil, and a heating furnace with hydrogen atmosphere. (Engle[1])

Table I. Relative Abrasive Action of Diamond and Similar Substances on Sintered Carbide[a]

Diamond dust on sintered carbide	1000
Boron carbide on sintered carbide	600
Boron on sintered carbide	480
Silicon carbide on sintered carbide	220
Aluminum oxide on sintered carbide	40

(a) W. Dawihl, K. Schroeter, M. Stackmayer, Z ver deut Ing, **80**, 1001 (1936)

Table II. Knoop Indentation Hardness of Materials Harder Than a Moh's Hardness of 8[a]

Material	Hardness, kg per sq mm
Diamond	6000 to 6500
Sapphire	1600 to 2200
Boron carbide	2250 to 2260
Silicon carbide	2130 to 2140
Aluminum oxide	1635 to 1680
Tungsten carbide plus cobalt binder (cemented carbide)	1050 to 1500
Topaz	1250

(a) Ind Diamond Rev, 5, 103 (May 1945)

Commercial grades of cemented carbides are not considered resistant to chemical corrosion. However, they have been used under corrosive conditions in certain applications, but usually where a material of high abrasive resistance and indentation hardness was required. The carbide constituents of cemented carbides resist acid corrosive attack, but the binder retains most of its basic chemical properties, with the result that corrosion occurs intergranularly between the carbide particles. Many of the alkalies readily attack the carbide particles. Cemented carbides are subject to oxidation at elevated temperatures.

Applications. *Tools.* Grades of commercial cemented carbides are available to meet almost any machining requirement. Ordinarily the work speed used with carbide tools is considerably greater in number of feet per minute than that employed with tools of other materials. This increased speed of cutting results in removing a greater volume of material per minute, for any given depth of cut and feed. The depth of cut and feed per revolution is regulated by the horsepower available, the strength of the work piece and the quality of finish required. For details concerning specific applications, the reader may refer to the tool manuals, which are readily available.

Ordinarily where cemented carbides are used in the construction of tools, a small piece of the carbide material is brazed or fastened mechanically to a steel shank that provides a rigid support under the cutting edge. The three methods commonly used for brazing employ induction heating, an oxyacetylene torch, adjusted to give a nonoxidizing flame, and an electric furnace with a hydrogen atmosphere.

Cemented carbide tools can be ground or sharpened as safely and rapidly as any other type of tool. Silicon carbide and diamond-impregnated grinding wheels are used to grind the carbide, but the grinding of the steel shanks to which the carbide is attached, is done best with an aluminum oxide wheel. The customary procedure is to grind the portion of the steel shank that is not close to the carbide tip, with an aluminum oxide wheel, and then to grind the carbide with the silicon carbide or diamond wheel.

Cemented carbides may be used for cutting operations ranging from light finishing cuts at high speeds and light feeds, to heavy cuts with coarse feeds and slower speeds. Interrupted cuts on steel and other materials are common with tools designed for the purpose.

Cemented carbides are used in the following tools:

Single-point lathe tools	Solid twist drills for nonferrous materials
Reamers	Hi-Brinell drills
Counterbores	Small solid circular saws and large carbide-tipped circular saws
Spot facers	Milling cutters of all shapes, sizes and kinds
Countersinks	Shear blades
Facing tools	Files, flat and rotary
Boring tools	Dental burrs
Turning tools	Planer tools
Threading tools	Bending tools
Fly cutters	Gage contact points
Form tools	Spinning tools
Broaches	Hand scrapers
Core drills	Brinell balls
Boring bars	

Dies. The first commercial application of carbide dies was for the hot drawing of tungsten and molybdenum wire. The usage expanded rapidly and within a few years, carbide dies were generally employed for the cold drawing of wire made of steel, copper, aluminum and other materials. Today a large percentage of wire, rod and tubing smaller than 3½ in. in diam is produced through these dies. In addition, considerable high speed steel wire is drawn hot, using carbide dies.

Besides the application in the wire, bar and tubing field, cemented carbides are employed largely for the cold extrusion and heading of parts such as bolts and nails, and for the cold forming of heavy-walled steel parts, such as the nosing of shell forgings.

Cemented carbides are used extensively in the blanking of steel, aluminum, and like metals and in the cupping, drawing and redrawing of sheet metal parts in sizes from small eyelets to cylinders 10 in. in diam.

Carbide-tipped mandrels for sizing the inside diameter of all types of tubing, produce tubes with a fine finish inside and hold the wall thickness and dimensions of the hole within close tolerances.

Wear. The practical application of cemented carbide for purposes of shaping materials both with and without cutting, is attributed to the properties of high hardness and great compressive strength required of a material to resist wear. During these operations for changing the form of materials, very high pressures are involved, and high temperatures are reached at the mating surfaces between work and tool. At elevated temperatures, cemented carbides retain their indentation hardness better than other metals and alloys. The resistance of this material to abrasion is compared in Table I with the resistance of other known substances of great hardness. After final sintering, the cemented carbides are so hard that they can be shaped only by such operations as grinding, lapping and polishing with the hardest of abrasives, and boring, turning and facing with a diamond tool. Cemented carbides are being used where wear occurs from the loss of dimensions by rubbing, fretting of assembled parts under high stresses without visible motion, and scoring from foreign abrasive particles between mating surfaces.

Although data concerning coefficients of friction for cemented carbides are lacking in the technical literature, information is limited also for many of the other metals and alloys selected by the engineer and designer for parts expected to resist wear. For instance, the coefficient of friction for one shaft and bearing combination can be different from that for another combination, depending on surface finish, irrespective of the many other variables present in every application. As a result, this coefficient cannot be relied on for the selection of a wear-resistant material. However, where the coefficient of friction is low, an improvement in performance is noted. Material for resistance to wear is commonly selected on the basis of two factors—ability to support the load and ability to resist scoring.

Both of these factors are satisfied by the properties of cemented carbides. Shoes for grinding camshafts, centerless grinder rests, and steady rest pads are made to carry heavy loads and resist scoring, even in the presence of abrasive materials and carriers, such as lubricants and coolants that tend to carry the abrasives between the work piece and the rest. Cemented carbides are used also as material for pads inserted in metal forming dies; seals or glands for sump pumps; guides used in the textile industry and in wire fabrication; guides, arbors and the like in spring-forming machines; and various gages for inspection.

The following are additional applications:

Centers for grinders and lathes	Knurling wheel shafts
Steady rest pads and rollers	Spring coiling arbors, pitch tools, guides and the like
Centerless grinder rests	Ways and gibs for machine tools
Gagematic gages	Thread and wire guides
Sizematic machines	

Table III. Physical and Mechanical Properties of Some Commercial Cemented Carbide Compositions[a]

Composition	Density, ■ per cu cm	Rockwell Hardness, A Scale	Transverse Rupture Strength, psi	Compressive Strength, psi[b]	Proportional Limit in Compression, psi[c]	Modulus of Elasticity,[d] psi × 10^{-6}	Poisson's Ratio[e]	Impact Strength, ft-lb[f]	Endurance Limit, psi[g]	Coefficient of Thermal Expansion[h]	Electrical Resistivity at 20 C, microhm-cm
97% WC, 3% Co	15.25	92.4 to 92.9	170,000	815,000	675,000	97.5	....	...	....	.....	21.3
95.5% WC, 4.5% Co	15.05	92.0 to 92.5	200,000	890,000	650,000	90.5	0.214	...	....	.....	...
94% WC, 6% Co	14.85	90 to 92	225,000	750,000	625,000	88	0.212	0.73	95,000	5.0×10^{-6}	...
91% WC, 9% Co	14.60	89.5 to 91.5	275,000	685,000	525,000	83	0.226	...	....	.....	22.3
87% WC, 13% Co	14.15	87.5 to 90	300,000	625,000	375,000	80	0.219	1.10	105,000	5.9×10^{-6}	19.6
80% WC, 20% Co	13.55	85 to 87	350,000	550,000	....	73.5	....	1.75	....	.....	29.2
Predominantly WC, with TaC and 13% Co	13.90	87 to 88	275,000	610,000	375,000	88	....	...	....	7.25×10^{-6}	...
Predominantly WC, with TaC and 6% Co	14.70	91 to 92	220,000	752,000	575,000	91	....	0.65	85,000	.....	...
Predominantly WC, with TiC and 6% Co	11.20	92 to 93	160,000	700,000	....	...	....	0.40	90,000	6.8×10^{-6}	...
Predominantly WC, with less TiC than above, 8% Co	12.80	91.5 to 92.5	250,000	570,000	....	...	....	0.60	90,000	.....	...
Predominantly WC, larger amount of TiC, 7% Co	9.00	92 to 93	150,000	725,000	650,000	88.5	0.226	...	....	7.0×10^{-6}	...
Predominantly WC, with TaC and TiC, 8% Co	11.7	91.5 to 92.5	165,000	720,000	600,000	90.0	....	...	....	6.75×10^{-6}	...
Predominantly WC, with TaC and TiC, 11% Co	11.6	90.5 to 91.5	175,000	680,000	515,000	...	....	0.60	85,000	6.0×10^{-6}	...
Predominantly WC, with TaC and TiC, 15% Co	11.4	89.5 to 90.5	190,000	670,000	....	...	....	0.92	....	7.5×10^{-6}	...

(a) The values given in this table are representative of properties obtained in good production practice for the particular method of manufacture. They are not necessarily the highest values obtainable, nor do they represent the lowest that are of practical use.

(b) Most of the values for compressive strengths are given through the courtesy of P. W. Bridgman of Harvard University.

(c) The proportional limit in compression is the load per unit area at which the increase in strain ceases to be directly proportional to the increase in stress. (Bridgman data)

(d) Many values for the modulus of elasticity were obtained by W. H. Davenport of the Norton Co., who used the musical pitch method.

(e) Calculated from formula $G = \frac{E}{2(1 + \mu)}$ where G and E are determined values for modulus of rigidity and Young's modulus, respectively, and μ is Poisson's ratio.

(f) Impact values are from unnotched specimens in sections approximately ¼ in. sq. A Charpy machine was used.

(g) Values for endurance limits are based on 20,000,000 cycles, for specimens of the R. R. Moore rotating-beam type.

(h) Average coefficient of expansion per deg Cent for the range 20 to 700 C (68 to 1290 F)

Swaging dies
Dies and plungers for molding powders
Collets
Ball mill slugs
Rolls
Balls for ball valves
Spinning and burnishing tools
Liners for brick molds
Chill plates for hardening thin steel
Valve seats

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Cobalt-Chromium-Tungsten-Molybdenum Alloy Tools

By W. A. Wissler*

USEFUL alloys of cobalt and chromium, with tungsten or molybdenum or both, were developed and patented by Elwood Haynes. Alloys of this basic composition are now made by a number of manufacturers, and in a number of grades that cover a considerable range of hardness and other properties. The softer and tougher compositions discussed in the article "Heat-Resistant Castings" (page 570) are used for high-temperature applications, such as cast gas-turbine buckets. The grades that are harder, from 40 to 64 Rockwell C, are used for various tools discussed below.

For tool applications these alloys usually contain from 25 to 35% Cr. The tungsten and molybdenum contents vary from 4 to 25%, or preferably from 6 to 20%, depending on the hardness desired. Carbon, present in amounts from 1 to 3%, exerts a marked hardening effect. The carbon content generally increases as the tungsten content increases. Manganese and silicon are present as deoxidizers, and other elements, such as vanadium, boron, tantalum and columbium, may be added to impart other special properties. Small amounts of iron or nickel are always present, usually as impurities; however, nickel is sometimes added intentionally as a softening and toughening agent.

Although these alloys are highly resistant to corrosion, they are not generally used unless corrosion is accompanied by wear. Outstanding resistance to wear makes them suitable for such applications as machinery parts and metal-cutting tools. The success of their applications results from their ability to stay hard at high temperatures, that is, their "red hardness". High speed steel makes better cutting tools than plain carbon steel because it has a higher hardness at elevated temperatures. Similarly the Co-Cr-W alloys are superior to high speed steel. "Red hardness" also makes these alloys more capable of resisting wear under all conditions where high local surface temperatures are developed. In addition, these alloys have comparatively low coefficients of friction, which means that they develop lower temperatures; thus they remain hard. The Co-Cr-W alloys have certain disadvantages of being appreciably weaker and somewhat more brittle than high speed steels; for these reasons the tools should not be subjected to extreme conditions of stress that might cause breakage.

The metallographic structure of the alloy is complicated. The most noticeable constituent is a large hexagonal carbide crystal that usually appears in an elongated or needle-like form and can be identified as chromium carbide (Cr_7C_3) in which some of the chromium may be replaced by cobalt and tungsten. The matrix consists of various binary and ternary eutectics containing all the constituents of the alloy. The structure is stable at temperatures as high as about 1000 C.

Some of the pertinent properties of these cobalt-base alloys are given in Table I. These properties are influenced by method of manufacture as well as by composition.

Table I

Nominal Compositions and Properties of Co-Cr-W Alloys

	Soft	Medium	Hard
Basic Composition, percentage			
Chromium	30.00	30.00	32.00
Tungsten	4.00	9.00	18.00
Carbon	1.00	1.50	2.50
Manganese	0.50	0.25	0.60
Silicon	0.50	0.75	0.40
Cobalt	Remainder	Remainder	Remainder
Hardness, Rockwell C	40	48	62
Tensile Strength, psi	105,000	76,000	65,000
Elongation, percentage	1	0	0
Melting Point, deg Cent	1275	1250	1270
deg Fahr	2327	2282	2318
Brinell Hardness Number			
At room temperature	375	470	690
At 600 C (1110 F)	280	340	480
At 900 C (1650 F)	100	150	200

Metal-cutting tools are made of the "hard" type listed in Table I. The "medium" grade is used for parts subjected to wear, and the "soft" grade is used for valves, trimming dies and the like. The "soft" grade can be rolled and forged with difficulty.

Melting is usually done in electric furnaces and in small heats. Furnace practices vary with different manufacturers of these products; no descriptions of such procedures have been published.

Since these alloys retain their hardness at high temperatures, forging or rolling of the harder grades is impracticable; therefore they are generally cast to shape and size. These alloys can be ground easily at controlled operating speeds, with wheels especially recommended by the manufacturers; otherwise surface cracking may result.

As stated above, the alloys are usually cast to the desired shape and size. However, some of these alloys,

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furnished as welding rod, can be applied as a hard surface coating over steel and cast-iron parts.*

This method of surface coating is usual for producing such equipment as valves, earth-working machinery and trimming dies. It can also be applied to the production of metal-cutting tools. Such a procedure is not recommended, however, because the cutting quality will be lower than that of a cast bit or blade, but surface coating can be applied in an emergency to produce a form tool that cannot otherwise be readily secured.

Cutting Field. The Co-Cr-W metal-cutting tools are widely used for machining steel, cast and malleable iron, cast steel, stainless steel, brass, bronze and most machinable materials. They are selected for operations requiring speeds faster than high speed steel tools will stand, but not so fast as those at which tungsten carbide tools are generally used. Cast alloy tools are also chosen on the basis of the toughness required for any specific operation. The cast alloy tools are not so tough as high speed steel, but will stand more impact, pressure and vibration than carbide tools. Here again the cast alloys have properties intermediate between high speed steel and tungsten carbide. Careful analysis of specific machining operations is necessary in selecting the proper tool. Important factors include condition of machine tool, hardness of stock to be machined, amount of stock to be removed, finish required and production required per hour or per day. Actual comparative tests are always the best means for putting the proper tool on each job.

Table II. Recommended Speeds and Depths of Cut at 1/32-in. Feed per Revolution

Material Being Machined	Depth of Cut, inch 1/32	1/4	5/8
	Surface Speeds, fpm		
Steel			
Plain Carbon (SAE 1010 to 1040)	250	160	105
Plain Carbon (SAE 1080 to 1095)	150	100	65
Free-Cutting (SAE 11xx and X13xx	300	200	130
Nickel-Chromium (SAE 3115 to 3450)	135	90	58
Molybdenum (SAE 4130 to 4820)	150	100	65
High-Chromium (SAE 52xxx)	125	85	70
Cast Steel			
115 to 140 Brinell	160	125	80
140 to 160 Brinell	150	110	65
Cast Iron			
160 to 180 Brinell	190	155	95
225 to 250 Brinell	150	115	70
Brass	500	333	200
Bronze			
Soft	190	126	75
Hard	150	100	60
Aluminum	1200	870	520
18-8 Stainless Steel	225	170	120

Lathe Tools. One of the most important cutting-tool applications is as single-point lathe bits or tools. One manufacturer recommends these tools for use at surface speeds as great as 100% more than those employed with high speed steel tools, using the same or heavier feeds and depths of cut. Specific recommendations for cutting conditions cannot be made for various operations in different shops; only general data to be used for cutting tests can be given. Typical examples are given in Table II.

Specific instructions, such as size of tool, type of grind and method of grinding, should be obtained from the manufacturer of the tools.

Milling. Another application of these alloys is in milling-cutter blades for large inserted-tooth cutters and in solid cast cutters of the smaller sizes. The general information in Table III indicates normal operating conditions for these cutters.

Table III

Recommended Loads and Speeds for Milling Cutters

Material	Roughing: Chip Load Per Tooth, in.	Roughing: Surface Speed, fpm	Finishing: Chip Load Per Tooth, in.	Finishing: Surface Speed, fpm
Cast or Malleable Iron	0.010 to 0.015	80 to 140	0.005 to 0.010	150 to 300
Cast Steel	0.010 to 0.015	60 to 80	0.005 to 0.010	80 to 100
Bronze	Up to 0.030	175	Up to 0.030	250
Aluminum	Up to 0.030	800	Up to 0.030	1200
Copper	Up to 0.030	400	Up to 0.030	600
Brass	Up to 0.030	400	Up to 0.030	600

Special Tools. Many designs of special tools are available, including spot facers, reamers, form tools and cutoff blades. These tools permit faster cutting speeds than can be obtained with steel tools.

Trimming Dies. Dies can be hard-faced along the cutting edges by the oxyactylene welding process. Such dies usually last many times longer than plain steel dies, and may also be rebuilt, after they have become worn, at only a fraction of their original cost.

Gages. A layer of a hard grade of these Co-Cr-W alloys on the contact surfaces of gages makes them last longer. The coefficient of thermal expansion is very close to that of iron and ordinary steels. Gage blocks of both solid and bimetal construction are now available in one of these alloys.

Burnishing Rollers. Burnishing rollers made of one of these Co-Cr-W alloys are standard in many of the railroad shops for burnishing locomotive driving-axle journals, piston rods, crank pins and other parts that require extremely high finishes and excellent resistance to wear. Such rollers can be run at higher speeds and feeds than steel rollers and also at extremely high pressures. Consequently, one pass with such a roller will give results equal to those obtained by several passes of steel burnishers.

Wear Strips. Pilot bars for boring tools and the like, must resist wear, because the accuracy of the job depends on the wear on such bars. A common procedure is to insert five or six alloy wear strips around the bar.

Agricultural and Earthworking Equipment. Such equipment as plowshares and cultivators for farm use, and dipper-bucket teeth and bucket lips for excavating or dredging are usually hard-faced, and cobalt-base alloys are among the most successful materials for such applications. In general, the life as compared with that of plain steel parts is increased three to six times or more. The wearing parts of crushing and grinding machinery for handling clay, rock, ores and the like are hard-faced with comparable results.

* For additional information, see "Surfacing by Welding", page 722.

Abrasive Wheels for Grinding Metals

By G. T. Rideout*

ALTHOUGH grinding is an essential part of the modern production line it is still an inexact science. A grinding wheel should be selected only after careful consideration of both constant and variable factors. Since many combinations are possible because of differences in these factors, grinding is considered an art. As yet, no mathematical formula can be applied which will result in the correct specification for the grinding wheel. The starting point in choosing a grinding wheel is a table for wheel selection, based on actual experience. Such a table must be used carefully after consideration of the factors involved.

Components of Grinding Wheels. Every grinding wheel has two components—the *abrasive* that does the actual cutting and the *bond* that holds the abrasive grains while they cut. The arrangement of these two components in the abrasive product gives a definite characteristic known as *structure*. These components can be varied by the manufacturer of the wheel to give thousands of combinations.

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Grinding Wheel Markings. In 1944 the Grinding Wheel Manufacturers' Association adopted a standard marking system. It is a standard of markings only and not of grinding action. The abrasives, the bonds and the manufacturing procedures used by different wheelmakers are not identical; therefore, wheels similarly marked but made by different manufacturers may not grind alike.

The markings can be used to explain the characteristics of a grinding wheel and to show the many possible combinations of the components.

The standard marking consists of six parts as shown by this typical marking.

32A 46 – K 5 V BE
1 2 3 4 5 6

1 Abrasive. The letter indicates the kind of abrasive (*A*, aluminum oxide; *C*, silicon carbide) and the figure indicates the particular type of that abrasive.

2 Grain Size. There are 26 standard grain sizes from 10 (coarse) to 600 (very fine). The number indicates the approximate number of meshes per linear inch of a screen through which the grains will pass.

3 Grade of Hardness. The letters designating grade indicate the relative strength (holding power) of the bond that holds the abrasive grains in place. The grade letters range from *A* to *Z* in the order of increasing "hardness".

4 Structure Number. The structure is given a special number determined by the proportion and arrangement of the abrasive and bond. When the abrasive grains are close together relative to their grain size, the wheels have low structure numbers, such as 0, 1, 2, 3, 4, 5. Wider spacing relative to grain size is designated by higher structure numbers, such as 8, 9, 10, 11, 12.

5 Bond. There are six general types of bond—vitrified, silicate, shellac, resinoid, rubber and magnesite.

6 Manufacturer's Record. Many variations are possible in the control of the processes, methods of mixing and molding, and the use of special bonds. The characteristics of the wheel can be varied to meet the requirements of special grinding operations and these differences are revealed by the sixth (final) symbol in the marking.

Work and Operating Conditions. The four constant factors to consider when making the selection of grinding wheel specifications are: (1) material to be ground, (2) amount of stock to be removed, accuracy, finish required and rate of production, (3) area of contact or size of wheel, and (4) type of grinding machine.

In addition, the selection of the grinding wheel is influenced by the five variable factors that are under the control of the user. The variable factors to consider are: (1) wheel speed, (2) work speed (pressure, if off-hand grinding), (3) condition of the grinding machine, (4) skill of the workman, and (5) use of coolant or lubricant.

Selection of the Grinding Wheel. Too often it is wrongly believed that a knowledge of the material to be ground is all that is needed to enable one to select the proper grinding wheel for a given job. An analysis of the steel, if that happens to be the material, will help in the choice of abrasive and, to a certain extent, in the choice of structure number. However, other essential factors must be considered before a dependable selection of wheel can be made.

Factors Affecting the Selection of the Abrasive. The mechanical properties of the material to be ground affect the selection of abrasive. Aluminum oxide is used for materials of high tensile stress, such as carbon, alloy and high speed steels, annealed malleable iron, wrought iron and strong bronzes. Silicon carbide is used for materials of low tensile strength, such as aluminum, copper, brass, soft bronzes, gray iron, chilled iron and cemented carbides.

One form of aluminum oxide may be better than another; for example, heavy cuts on carbon steel may require the regular, tough aluminum oxide abrasive while light cuts on high speed steel will require one of the modified forms of friable aluminum oxide for cooler cutting action.

Factors Affecting the Selection of Abrasive Grain Size.

1 *Amount of material to be removed.* Coarse grit size for fast cutting. (Exception—very hard materials where depth of grain penetration is small.)

2 *Finish desired.* Fine grain for fine finish.

3 *Mechanical properties of material to be ground.* Coarse grain for soft ductile materials and fine grain for hard and brittle materials.

Factors Affecting the Selection of the Grade.

1 *Mechanical properties of material to be ground.* Hard grades for soft materials; soft grades for hard materials.

2 *Area of contact.* The smaller the area of contact, the harder the grade should be.

3 *Wheel speed and work speed.* The higher the wheel speed with relation to work speed, the softer the wheel should be.

4 *Condition of grinding machine.* Presence of vibration or worn master parts usually calls for harder grades.

5 *Skill of workman.* Skillful operators can use softer wheels than unskilled; softer wheels mean faster rate of production and lower grinding costs per piece when total grinding costs are considered, including overhead. The cost of the wheel, one of the smallest items of the total, will give a false cost per piece when it is considered alone.

Factors Affecting the Selection of Structure Number.

1 *Mechanical properties of material to be ground.* Soft, tough, and ductile materials require a wide relative spacing of the abrasive grains designated by high structure numbers such as 8, 9, 10, 11 and 12. Conversely, hard brittle materials usually require a wheel with a low number.

2 *Finish required.* Fine finish requires wheels with close relative spacing of the abrasive grains and designated by low structure numbers, such as 3, 4 and 5.

3 *Kind of grinding.* Operations with flexible application of pressure, such as snagging, require high structure numbers. Surfacing operations call for high structure numbers. Cylindrical, centerless and tool grinding usually work best with medium structure numbers. Heavy pressures, which tend to destroy the form of shaped wheels, call for low structure numbers.

Factors Affecting the Selection of Bond.

1 *Dimensions of wheel.* Thin cutting-off wheels and others subjected to deflection strains require resinoid, shellac or rubber bonds. Wheels more than 42 in. in diam and made in one piece, are usually of silicate bond.

2 *Operating speed.* Vitrified bonds are usually best for speeds slower than 6500 sfpm. Resinoid, shellac or rubber bonds are necessary for speeds greater than 6500 sfpm.

3 *Finish required.* Resinoid, rubber or shellac bonds are generally best for high finish.

4 *Kind of operation.* Vitrified bonds for fast cutting with long service in production or precision grinding. Silicate bonds are suitable for grinding edge tools, cutlery and some machine knives, where heat generated in grinding must be kept at a minimum. Shellac bonds are satisfactory for grinding camshafts and rolls. Resinoid bonds are preferable for high-speed snagging wheels in foundries and billet shops and for cutting-off jobs. Rubber serves best as bonding material for centerless feed wheels and for race grinding, deburring, polishing, cutting-off operations with minimum burning and burr, and snagging operations where finish is important. Magnesite bonds are used for certain types of disk grinding.

Truing and Dressing the Grinding Wheel. *Truing.* A grinding wheel is trued in order to restore its cutting face to accuracy in running, so that it will produce perfectly round (or flat) and smooth work; or to alter the cutting face for grinding special contours.

Dressing. A grinding wheel is dressed in order to improve or to alter its cutting action. Dressing removes the outside layer of dulled abrasive grains or any loading, and may be considered a sharpening operation.

Crush Dressing. A formed crusher applied to the wheel face quickly forms the grinding wheel to the desired shape. Crush dressing permits a more rapid rate of production of formed parts. In addition, it permits grinding of intricate forms that could not be ground with a wheel trued by a diamond. Grinding is cooler and freer than with other methods of dressing. Finish is not quite so good, as determined by measurement.

Coolants, Lubricants and Treatments. The importance of the proper coolant, lubricant or wheel treatment is becoming more apparent each year. Some grinding operations cannot be performed without the correct preparation.

Coolants. The essential purpose is to cool the work and to prevent it from rusting. The use of oils or compounds that are soluble in water will permit faster removal of stock and more pieces per dressing than are possible with dry grinding.

Lubricants. Usually grinding oils have advantages over soluble oils. They allow the wheel to grind in a free-cutting manner with a minimum of wheel breakdown. There is less loading, so the wheel holds its original dressed or trued condition longer and, as a result, stays sharp longer. In fact, the grinding wheel serves four times longer when used with grinding oils instead of soluble oils. In the grinding of some materials even greater benefits are obtained. For these reasons it is advisable to use grinding oils for form grinding or with crush-dressed wheels. The temperature of the work material must be watched in order to permit grinding to the correct size.

Treatments. When dry grinding must be used, especially on nonferrous materials, the grinding wheel becomes loaded quickly. Various materials or treatments are used to impregnate the abrasive wheel for the purpose of improving the grinding action and reducing the tendency to load.

Wheels of Open Structure. In recent years a grinding wheel with especially large pores has been introduced. The special structure gives such wheels a distinctive porous appearance. They are made with vitrified or resinoid bonds and in soft grades are used for broad contact grinding, tool and cutter grinding, surface grinding, and internal grinding of holes that have a large diameter. They are especially useful when grinding tough, ductile, stringy materials.

Causes, Detection and Prevention of Cracking. *Causes.* When cracks appear in ground steel surfaces, grinding is not necessarily the sole cause. Cracks form in hardened steel at spots where stresses exceed the rupture strength of the metal.

Improper grinding procedure may cause cracking from excessive depth of cut, inadequate cooling of the work, improper dressing, or use of too hard a grinding wheel.

Detection. During grinding, if the surface of a piece of hardened steel is found to be cracked and proves to have been burned, then the grinding operation is probably responsible and should be improved. A burned structure may not be visible, since it may have been cleaned off in grinding, but it can be detected by etching the surface in 10% nital or dilute nitric acid, a treatment that makes the burned portion turn dark.

Prevention and Remedies. When retained austenite, untempered martensite or grain-boundary cementite is eliminated by heat treatment, the susceptibility to cracking is greatly decreased. Some of the more common remedies for unsatisfactory grinding are:

Dressing to keep the wheel sharp
A softer grade of grinding wheel
Slower speed of the wheel or increased speed of the work metal
A narrower wheel or area of contact
In wet grinding, a copious supply of coolant on the work
An increase in the rate of traverse
A cooler cutting wheel—"open structure" or porous
In some instances, a beneficial change from wet to dry grinding

Reference

L. P. Tarasov, Detection, Causes and Prevention of Injury in Ground Surfaces, Trans ASM, 36, 389 (1946)

Cutting Fluids for Machining

By O. W. Boston and the Subcommittee on Cutting Fluids*

CUTTING FLUIDS, frequently referred to as lubricants or coolants, consist of those liquids, solids and gases applied to the material being cut and to the tool used in order to facilitate the cutting operation. Lubricants for cutting operations are recommended in this article.

In metal cutting, it is desirable to have high cutting speed, long tool life, low cutting temperature, low consumption of power, the best surface finish, well-broken chips and freedom from corrosion. In different operations these factors vary in importance and usually some are obtained at the expense of others. For instance, in heavy roughing cuts, temperature is of little consequence because minimum distortion and high surface finish are not required. In screw-machine work, however, surface finish, dimensional accuracy as affecting interchangeability, and long tool life are of great importance. For either type of work, desired results are obtained by varying the tool material and shape, the cutting speed, feed, and depth of cut, the structure of material cut, and cutting fluid.

Purpose of Cutting Fluids. A cutting fluid is used for the following purposes: (1) to keep the tool cool, preventing it from becoming heated to a temperature at which the hardness and resistance to abrasion are reduced; (2) to keep the work material cool, thus preventing it from being machined in a warped shape and having consequently inaccurate final dimensions; (3) possibly through lubrication to reduce the power consumption, wear on the tool, and the generation of heat; (4) to provide a good finish on the work; (5) to aid in a satisfactory formation of chips; (6) to wash away the chips (a function particularly desirable in drilling deep holes, hacksawing, milling and grinding); (7) to prevent corrosion of the work piece and machine; (8) to lubricate moving machine parts near the cutting tool.

Classification of Cutting Fluids or Coolants. Cutting fluids and coolants may be divided into the following classes: (1) air used as suction or blast, (2) water, either plain or containing an alkali, (3) emulsions of a soluble oil or paste, (4) oils, such as mineral, fixed, compounded, sulfurized, chlorinated and sulfurchlorinated.

Types of Cutting Fluids and Their Applications. Air is often used as a suction for internal and surface grinding and polishing operations or for grinding and boring operations on gray iron. The main purpose is to remove the small chips or dust from the air, but the temperature is decreased somewhat also. This is referred to as dry cutting.

Water solutions, containing as much as 1 or 2% by weight of an alkali, such as borax, sodium carbonate or trisodium phosphate, have high cooling properties and sufficient corrosion-prevention properties for some jobs. They are inexpensive and are sometimes used for grinding, drilling, sawing, light milling, or turning operations.

Emulsions consist of a soluble emulsifying oil or paste emulsified with water in the ratio of 1 part oil to 10 to 100 parts of water, depending on the type of product and the operation. This inexpensive cutting fluid is used for nearly all types of cutting and grinding in the machining of all types of metals. The richer mixtures of oil and water, such as 1 to 10, are used for broaching, threading, and gear cutting, where an oil is not required in order to secure the desired surface finish or machine lubrication. For most operations a solution of 1 part soluble oil to 20 parts water will be satisfactory for turret lathe work, some screw-machine work, gear hobbing, milling and drilling. Leaner mixtures may be used in simple turning or drilling operations. Lean mixtures, such as 1 to 50 or even 1 to 100, may be used for some drilling and most grinding operations. Often the concentration of the emulsion is determined by the requirements for preventing rust on the metal being machined, or by the requirements for lubricating the machine, and not by the actual machining operation.

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A variety of oils are used for the cutting of metal where machine lubrication is essential, or where a high-grade finish is desirable at low speeds, although superior finishes are obtained sometimes with the emulsions. Oils should have a Saybolt viscosity of 80 to 160 at 100 F. Plain mineral oil, fixed oil, compounded oils are used, or oil with additives—sulfur, chlorine, graphite and such—to improve the properties of the oil or to impart new properties to the oil.

Sulfurized oils are used generally as cutting fluids for rapid production involving good surface finish and close tolerances on metals difficult to machine. These sulfurized oils may be classified in three groups, as follows:

1 Sulfurized mineral oils. These cutting fluids contain as much as 4% active sulfur in straight mineral oil.

2 Sulfurized compounded oils. These oils are combinations of fatty oils, such as lard, rapeseed, degras, sulfur and petroleum oils.

3 Sulfurized-base oils. These are concentrates of fatty oils containing relatively high percentages of sulfur compounds, which the user blends with mineral oil to meet individual requirements.

Sulfurized oils are used extensively in broaching, gear cutting, automatic screw-machine work involving threading and tapping on straight carbon or alloyed steels and hot rolled steels. Sulfurized oils are satisfactory also for machining stainless steel, high-nickel alloys and copper; however, because sulfur stains copper, mineral-lard oil (5 to 10% lard) is more often used.

In addition to the above, various chemicals such as phosphorus and chlorine compounds may be used in cutting fluids. Graphite, mica, white lead and similar solids are sometimes used. Further applications of cutting fluids for copper, aluminum, steel and zinc are discussed below.

Quantity of Cutting Fluid. Best results are obtained when any of the cutting fluids is applied to the work and tool in ample quantity, such as 3 to 5 gal per min for each single-point tool, and at a temperature of 70 to 85 F.

Practical Cutting-Fluid Recommendations

To simplify and to clarify the use of a table of recommendations for the application of cutting fluids to various processes, involving different metals, the metals themselves are first classified in accordance with their machinability ratings when high speed steel tools are used. A wide variety of ferrous and nonferrous metals are rated individually and then arranged in the six classes of Table I.

Table I. The Six Classes of Metals for Which Cutting Fluids Are Recommended

Ferrous metals as compared with AISI B 1112 cold drawn steel	
Class 1	70% or more
Class 2	50% to 65%
Class 3	40% to 50%
Class 4	less than 40%
Nonferrous metals as compared with AISI B 1112 cold drawn steel	
Class 5	100% or more
Class 6	less than 100%

The machinability rating of each metal of the several groups has been given values to the nearest 5%. The various metals have then been grouped into classes, as shown in Table II, to facilitate the drawing up of the cutting-fluid chart. The ratings are based on steels in a cold drawn condition unless otherwise stated. Metals that have been heat treated or processed in any way other than by cold drawing will have different machinability ratings.

It is important to note that because of the favorable difference in price, many users prefer hot rolled steels for numerous purposes. The relative effect of hot rolling may be expressed very briefly as follows:

(*a*) In steels containing 0.30% C or less, cold rolled bars have better machinability than hot rolled bars.

(*b*) In steels containing from 0.30 to 0.40% C, there is little difference in machinability between cold rolled and hot rolled bars.

(*c*) In steels containing more than 0.40% C, the hot rolled material has machinability superior to that of the cold rolled or cold drawn. It is recommended that the carbon steels having 0.40% C or more and alloy steels having 0.30% C or more be annealed for machining; otherwise, lower cutting speeds are necessary. This also applies to paragraph (*b*).

The range of Brinell hardness values for each of the ferrous materials is intended to provide the most desirable limits for normal machinability ratings and, in general, describes the commercial practice in filling steel purchase orders. It is generally accepted that the limiting value of hardness for normal machinability is of the order of 355 Brinell, although many steels are now being machined in mass production at hardnesses of 400 Brinell and higher.

Factors influencing machinability are many. The ratings by tests often show greater variation because of different heats than because of a wide range in composition. Similar steels from different manufacturers may vary greatly in machinability. The relative rating of several materials when cut according to one size and shape of cut with one type of cutting fluid may be quite different if another cut, tool shape, tool material, or cutting fluid is used. The different processes, such as drilling, turning and milling, will yield different orders of ratings for a group of metals. Surface conditions, such as scale and hardness from cold working, may also vary the results. Because there is a lack of specific conditions for almost every variable, it is felt that these ratings are close enough to permit the production man to set up each job, and then from observation, to modify the setup to get best results.

Machining Operations Classified. A similar classification has been given to machining operations, arranging them in the order of severity; for example, the most severe operation (No. I, Table III) is internal broaching, and the easiest (No. 10) is sawing.

Recommendations. Table III indicates the severity of the operation and lists the cutting fluid recommended for each class of metal. Those who use this table may profit by the following general notes on selecting cutting fluids.

The preferred recommendations in **bold face** in Table III are based on general practice and on the results of a survey. The recommendations are intended to serve only as a guide in selection of a cutting fluid. Selection of a suitable fluid should be based on the individual operation; the material being machined; the tool, its material, size and shape; the conditions of operation, such as speed, depth of cut and feed; and the results desired in tool life, chip formation and finish.

The function of this report is to correlate recommendations from general use and practice, together with suggestions for each specific cutting problem. These recommendations represent the average practice of the majority of users of cutting fluids when normal operating conditions are maintained.

It is possible to determine the proper cutting fluid for these normal operating conditions by referring to the table; for example, a normal milling operation, where the operating condition is within the limits specified by the manufacturer of the machine, and the steel of one class as given in the table. However, if a deeper cut, higher cutting speed, heavier feed or the like is desired, it will be necessary for the fabricator to use the table as a guide in placing the operation in the proper classification of severity, indicating the cutting oils recommended for the more severe operation.

In Table III the recommendations for cutting fluids are necessarily types of fluids rather than the specific products of individual companies. This should be remembered in the purchase of such fluids, since two fluids of the same type may be quite different in effectiveness on a given machining operation, because of different manufacturing techniques of the producers.

It is possible to classify these cutting fluids considerably farther and perhaps more specifically. However, such a breakdown of operations, together with the various cutting fluids, feeds, cutting speeds, depth of cut, and the like, makes the analysis bulky and unwieldy. Such a list of recommendations would be difficult to interpret.

Generally, mineral-lard oil and sulfurized oil mixtures that contain low percentages of sulfur are interchangeable.

Table II. Machinability Rating of Ferrous Metals of Four Class Groups and Nonferrous Metals of Two Class Groups*

Class 1. Ferrous (70% and higher)

AISI	Rating, per cent	Brinell
C 1109	85	137 to 166
C 1115	85	143 to 179
C 1117	85	143 to 179
C 1118	80	143 to 179
C 1120	80	143 to 179
C 1132	75	187 to 229
C 1137	70	187 to 229
C 1022	70	159 to 192
C 1016	70	137 to 174
B 1111	95	179 to 229
B 1112	100	179 to 229
B 1113	135	179 to 229
A 4023	70	156 to 207
A 4027*	70	166 to 212
Malleable iron, standard	120	110 to 145
Malleable iron, pearlitic	90	180 to 200
Malleable iron, pearlitic	80	200 to 240
Cast steel (0.35% C)	70	170 to 212
Stainless iron, 12% Cr (Free cutting)	70	163 to 207

* Denotes steel in mill-annealed condition

Class 2. Ferrous (50% to 65%)

AISI	Rating, per cent	Brinell
C 1141	65	183 to 241
C 1020	65	137 to 174
C 1030	65	170 to 212
C 1035	65	174 to 217
C 1040*	60	179 to 229
C 1045*	60	179 to 229
A 2317	55	174 to 217
A 3120	60	163 to 207
A 3130*	55	179 to 217
A 3140*	55	187 to 229
A 3145*	50	187 to 235
A 4032*	65	170 to 229
A 4037*	65	179 to 229
A 4042*	60	183 to 235
A 4047*	55	183 to 235
A 4130*	65	187 to 229
A 4137*	60	187 to 229
A 4145*	55	187 to 229
A 4150*	50	187 to 235
A 4320	55	197 to 228
A 4615	65	174 to 217
A 4640*	55	187 to 235
A 4815	50	187 to 229
A 5120	65	170 to 212
A 5140*	60	174 to 229
A 5150*	55	179 to 235
A 8620 or 8720	60	170 to 217
A 8630* or 8730*	65	179 to 229
A 8640* or 8740*	60	179 to 229
A 8645* or 8745*	55	183 to 235
A 8650* or 8750*	50	183 to 241
A 9420	60	170 to 217
A 9440*	60	187 to 235
Cast iron, soft	80	160 to 193
Cast iron, medium	65	193 to 220
Cast iron, hard	50	220 to 240

* Denotes steel in mill-annealed condition

Class 3, Ferrous (40% to 50%)

AISI	Rating, per cent	Brinell
C 1008	50	126 to 163
C 1010	50	131 to 170
C 1015	50	131 to 170
C 1050*	50	179 to 229
C 1070*	45	183 to 241
A 1320	50	170 to 229
A 1330*	50	179 to 235
A 1335*	50	187 to 241
A 1340*	45	187 to 241
A 2330*	50	179 to 229
A 2340*	45	187 to 241
A 3240*	45	187 to 241
A 4340*	45	187 to 241
NE 9261*	50	179 to 217
A 6120	■	179 to 217
A 6145*	50	179 to 235
A 6150†	45	183 to 241
A 9260*	45	187 to 255
Ingot iron	50	101 to 131
Wrought iron	50	101 to 131
Stainless 18–8 (Free cutting)	45	179 to 212

* Denotes steel in mill-annealed condition. † Spheroidized

Class 4. Ferrous (40% and less)

AISI	Rating, per cent	Brinell
A 2515*	30	170 to 229
E 3310*	40	170 to 229
■ 52100†	30	183 to 229
E 9315	40	179 to 229
Ni-Resist*	30	....
Stainless 18–8 (austenitic)*	25	150 to 160
Manganese oil-hardening steel†	30	....
Tool steel, low-tungsten, chromium and carbon†	30	....
High speed steel†	30	200 to 218
High-carbon, high-chromium tool steel†	25	....

* Denotes steel in mill-annealed condition. † Spheroidized

Class 5. Nonferrous (more than 100%)

Alloy	Rating, per cent	Brinell	Rockwell ■
Magnesium alloys			
Wrought (92.3 Mg, 6.5 Al, 0.2 Mn, 1 Zn)	500 to 2000	■	.....
Cast (90.8 Mg, 6 Al, 0.2 Mn, 3 Zn)	500 to 2000	50	.....
Aluminum			
11 S–T3 (5.5 Cu, 0.5 Pb, 0.5 Bi, 93.5 Al)	500 to 2000	.....	.....
2 S (100 Al) O to H temper	300 to 1500	95 (500 kg)	.....
17 S–T (4 Cu, 0.5 Mn, 0.5 Mg, 95 Al)	300 to 1500	23 to 44 (500 kg)	.....
Brass, leaded FC, CD (62 Cu, 35 Zn, 3 Pb)	200 to 400	100 (500 kg)	58 to 82
Red, leaded (78.5 Cu, 20 Zn, 1.5 Pb)	180	.....	40 to 75
Phosphor bronze, leaded (94 Cu, 1 Pb, 5 Sn)	100	.....	68 to 100
Zinc	200	.....	.....
Silicon bronze (95.60 Cu, 1.0 Mn, 3.0 Si, 0.4 Pb)	120	200	90

Class 6. Nonferrous (less than 100%)

Alloy	Rating, per cent	Brinell	Rockwell B
Aluminum bronze, cast (89.7 Cu, 10 Al, 0.2 Fe, 0.5 Sn)	60	140 to 160	.....
Brass			
Yellow (63 Cu, 37 Zn)	80	.....	.....
Red (80 Cu, 20 Zn)	60	.....	40 to 75
Manganese bronze (59 Cu, 39 Zn, 0.7 Sn, 0.5 Mn, 0.8 Fe)	60	.....	.....
Phosphor bronze (95 Cu, 5 Sn)	40	140	63 to 100
Copper, cast	70	30	.....
Copper, rolled (¼ hard)	60	80	.....
Silicon bronze (95.80 Cu, 1.10 Mn, 3.10 Si)	60	200	90
Gun metal, cast (88 Cu, 10 Sn, 2 Zn)	60	65	.....
Nickel	55	110 to 150	.....
Monel metal			
As Cast	40	175 to 250	.....
Rolled	55	207 to 224	.....
"K" Monel	35	215 to 265	.....
Inconel, temper B, cold drawn (78 Ni, 14 Cr, 6 Fe)	35	130 to 170	.....

Sulfurized oils have a tendency to stain certain nonferrous metals, such as copper and its alloys; therefore mineral-lard oil is more often used on these metals.

Certain materials, such as carbon tetrachloride, chloroform and other volatile solvents, should not be added to cutting fluids, since harmful physiological effects may follow.

In the machining of aluminum, cutting oils are often diluted with kerosene or mineral seal oil with satisfactory results. Kerosene, in amounts as large as 15%, is frequently added to emulsions to improve the surface quality of machined aluminum. For further information, see "Machining Aluminum Alloys".

Magnesium and its alloys are usually machined with mineral seal oil, except where it is desirable to machine dry. A supply of clean cast-iron chips in powdered form, or pitch or graphite should be kept handy to smother a sudden fire. Tools should be kept sharp and heavy feeds should be used. Chips should not be permitted to accumulate on the machine. For more data, see "Machining Magnesium Alloys".

* Each metal is rated to the nearest 5% based on the 100% rating of AISI steel specification B 1112, cold rolled or cold drawn, when machined with a suitable cutting fluid at 180 fpm under normal cutting conditions using high speed steel tools.

Table III. Recommended Cutting Fluids for Various Machining Operations for Each of Six Groups of Metals, Based on Normal Operating Speeds, Tool Life, and Finish

Severity	Type of Operation	Groups of Metals Based on Class of Machinability Ratings: 1 Ferrous (More than 70%)	2 Ferrous (50 to 65%)	3 Ferrous (40 to 50%)	4 Ferrous (Less than 40%)	5 Nonferrous (More than 100%)	6 Nonferrous (Less than 100%)
1 (Greatest)	Broaching, internal	Em **Sulf**[a]	**Sulf**[b] Em	**Sulf** Em	**Sulf** Em	MO Em	Sulf ML
2	Broaching, surface	Em Sulf	Em Sulf	Sulf Em	Sulf Em	MO Em	Sulf ML
3	Tapping, plain	Sulf	Sulf	Sulf	Sulf	Em Dry	Sulf ML
2	Threading, pipe	Sulf	Sulf ML	Sulf	Sulf		Sulf[c]
3	Threading, plain	Sulf	Sulf	Sulf	Sulf	Em Sulf	Sulf
4	Gear shaving	Sulf L	Sulf L	Sulf L	Sulf L		
4	Reaming, plain	ML Sulf	ML Sulf	ML Sulf	ML Sulf	ML MO Em	ML MO Sulf
4	Gear cutting[d]	Sulf ML Em	Sulf	Sulf	Sulf ML		Sulf ML
5	Drilling, deep	Em ML	Sulf Em	Sulf	Sulf	MO ML Em	Sulf ML
6	Milling, plain	Em ML Sulf	Em	Em	Sulf	Em MO Dry	Sulf Em
6	Milling, multiple cutter	ML	Sulf	Sulf	Sulf ML	Em MO Dry	Sulf Em
7	Boring, multiple head	Sulf Em	Sulf Em	Sulf Em	Sulf Em	K Dry Em	Sulf Em
7	Multiple-spindle automatic screw machines	Sulf Em ML	Sulf Em ML	Sulf Em ML	Sulf ML Em	Em Dry ML	Sulf
8	High-speed, light-feed automatic screw machines	Sulf Em ML	Sulf Em ML	Sulf Em ML	Sulf ML Em	Em Dry ML	Sulf
9	Drilling	Em	Em	Em	Em Sulf	Em Dry	Em
9	Planing, shaping	Em Sulf ML	Em Sulf ML	Sulf Em	Em Sulf	Em Dry	Em
9	Turning; single-point tool, form tools	Em Sulf ML	Em Sulf ML	Em Sulf ML	Em Sulf ML	Em Dry ML	Em Sulf
10 (Least)	Sawing, circular, hack	Sulf ML Em	Sulf Em ML	Sulf Em ML	Sulf Em ML	Dry MO Em	Sulf Em ML
	Grinding;						
	Plain	Em	Em	Em	Em	Em	Em
	Form (thread and such)	Sulf	Sulf	Sulf	Sulf	MO Sulf	Sulf

Symbols for Cutting Fluids

K	Kerosene
L	Lard oil
MO	Mineral oils
ML	Mineral-lard oils
Dry	No cutting fluid
Sulf	Sulfurized oils; see note (a)
Em	Soluble or emulsifiable oils and compounds

(a) Oils containing both sulfur and chlorine, when carefully manufactured and sponsored, may be used where sulfurized oils are indicated.
(b) Preferred recommendations are in **bold face** type.
(c) In threading copper, palm oil is frequently used.
(d) It has been reported by several observers that emulsions are usually unsatisfactory on some precision machine tools such as Fellows Gear Shapers and Gleason Gear Generators.

In machining brass, which shows no change in cutting pressures with various cutting fluids, it is advisable to apply a cutting fluid to function as a coolant. Since most free-cutting brass is machined in automatic screw machines, an oil is advisable for lubricating the moving parts of the machine. A paraffin or light mineral oil may suffice, or the mineral oil blended with 10% fatty oil may be used to advantage.

Zinc may be drilled, threaded and turned with common emulsions. The parts should then be worked in an alkaline cleaner, rinsed in hot and cold waters and dried.

In turning monel metal, it has been found that an emulsion permits slightly longer tool life than a sulfurized mineral oil. However, the latter produces broken chips, in many instances desirable. Also see the article entitled "Machining Nickel and Nickel Alloys".

In general, cutting fluids should be applied in large quantities at the highest velocity possible without splashing, directly on the point of the tool where the chip is being formed. From 3 to 5 gal for each single-point tool is most effective. Particularly when carbide tools are used, the cutting fluid should flood the tool before the start of the cut and be applied continuously during the cut. A rapid change in temperature is injurious to most tools.

Cutting fluids should be kept cool, either by sufficient volume or by cooling agents. For satisfactory tool life, the temperature of the cutting fluid should not be permitted to exceed 110 F.

Cutting fluids should be kept clean, and free from suspended chips, bacteria and high acidity.

Oils should be used on complicated machines, where parts such as tool slides must be lubricated. On some types of work, such as milling and drilling, lubrication of the chips in the flutes or chip space is an important factor in removal of the chips.

In high-speed operations, cooling is more important than lubrication, since the speed itself usually provides good surface quality. At low speeds, where the segmental or discontinuous type of chip is formed, the face of the tool may be lubricated periodically; consequently oils are desirable, particularly a sulfurized oil for threading and broaching.

Lubrication for Forming and Wire Drawing

By B. H. McGar*

THIS ARTICLE deals with the lubrication of aluminum, copper and brass, steel, and zinc during forming and wire-drawing processes.

Aluminum. When light-gage aluminum strip is being drawn, a petroleum oil that has a Saybolt viscosity of 100 to 200 at 100 F will give satisfactory lubrication; or a lubricant may be used that is composed of 75% petroleum oil with a Saybolt viscosity of 200 at 100 F, and 25% lard oil with a maximum content of free fatty acid of 3%. On light-gage difficult draws, a lubricant is satisfactory that is composed of 50% high-viscosity petroleum oil and 50% lard oil having a maximum free fatty acid content of 3%. For heavy-gage aluminum a straight oil that is low in content of free fatty acid should be used.

Aluminum wire can be drawn dry by using grease, powdered soap, or a mixture of calcium carbonate and fatty oil, such as lard oil. If a bright, clean finish is desired, it is customary to use either grease or the mixture of fatty oil and calcium carbonate. When wire is to be drawn wet, a light petroleum oil plus a fatty oil is used.

Copper and Brass. A suitable lubricant must be used as an aid in forming and drawing strip copper and brass. For most operations, an aqueous solution (3 to 5% by weight) made from a good grade of soap powder or chips will furnish an excellent lubricant. The solution should be kept slightly warm to prevent it from forming a gel. For

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more intricate operations it is sometimes necessary to use a 3% aqueous solution of a soap-fatty oil compound composed of approximately 50% free fats, 15% soap, and 35% moisture. Compounds of this general character are readily obtainable on the market. Before the drawing operation, the strip of copper or brass can be completely submerged in the lubricant and drained, or the solution can be applied with a swab or, better still, applied by felt rollers that pick up the lubricant and distribute it evenly over the surface of the strip as it is fed into the press. Partly formed or drawn articles are immersed in the solution and are then allowed to drain before being placed in the press again for redrawing. On large-scale production it is feasible to spray a hot (175 F) 6% soap solution on the partially formed articles and dry the soap on the pieces with a blast of hot air. The adherent soap film provides an excellent lubricant for the subsequent operation. Regardless of whether the brass articles are to be left in the as-drawn condition or later annealed, it is good practice to wash them shortly after drawing to prevent red stains. The lubricant can be removed from the articles in a suitable alkaline cleaner, which may be composed of the proper mixture of caustic soda, soda ash, trisodium phosphate and sodium orthosilicate, together with a wetting agent. Usually 3 to 4 oz of cleaner is added to 1 gal of water and used at approximately 185 F. The articles are then thoroughly rinsed in both cold water and hot water and dried.

Copper wire and brass wire are sometimes drawn dry with powdered soap, but ordinarily the wet drawing method is used. A suitable lubricant is obtained by making a water emulsion with a soap-fatty oil compound and controlling the free fat content from 2 to 3%. The solution should be circulated through the machines so that the proper amount of lubricant will fall on the dies and the wire while it is being drawn. It is also essential to control the temperature of the drawing solution, and for that reason a large amount of the solution should be used and cooled in tanks for this purpose, before being recirculated on the machines. It is also common practice in the brass industry to use fermented bran liquor as a lubricant for drawing brass wire. The objection to using such a solution is its offensive odor, but the solution provides adequate lubrication and is inexpensive. The solution is made by adding approximately 1 lb of wheat bran and middlings to 5 gal of water, and allowing them to ferment in a tank for at least one week. The resulting liquor is filtered and used directly in the wire-drawing machines. When a comparatively small reduction is required on brass wire, powdered soap may be used in the die block. Occasionally this soap should be paddled so as to prevent channeling, and the operator should see that the wire comes in contact with the soap before entering the die. Another lubricant used for making small reductions on brass wire is a solution made by adding ¼ lb of powdered soap or chips to 1 gal of water, and the temperature of the bath should be kept at approximately 185 F. The coils of brass wire are completely submerged in this solution, then drained for a short period, and the wire is ready to draw without any additional lubricant other than that which clings to the surface of the wire.

Steel. When forming, drawing, and stamping soft, light-gage steel strip or sheet, a suitable lubricant can be made by adding ¼ lb of deodorized fish-oil soap to 1 gal of water, or by using a light petroleum oil that has a Saybolt viscosity of 100 to 200 at 100 F. Satisfactory results may also be obtained by applying a heavy emulsion composed of 1 part naphthenic-base soap to 4 or 5 parts of water. When a deep or intricate draw is required, a satisfactory emulsion is one made of 1 part of soap-fatty oil compound, consisting of 50% free fats, 15% soap, and 35% moisture, with 3 parts of water. Some operators prefer to use a solution composed of 5 parts of water and 1 part of a filled drawing compound, the latter having a composition of approximately 15% soap, 20% filler (such as talc, fine clay, calcium carbonate, barium sulfate), 30% free fats, and 35% moisture. For light drawing of medium-gage sheet steel, 1 part of filled drawing compound and 2 parts of water is a suitable lubricant. Also, a solution may be used that is made by adding ½ lb of deodorized fish-oil soap to 1 gal of water. When deep drawing the heavier gages it is common practice to use filled compounds composed of 40 to 60% filler and 40 to 60% free fats without dilution. It is also possible to use straight sulfur-base oil for such operations. When selecting a lubricant for any of the above operations, some care and thought should be given to subsequent operations and what type of finish will be applied to the article ultimately, since the cleaning problem might present difficulties.

Steel wire is drawn dry with powdered soap, powdered soap plus lime, aluminum stearate, grease, or grease and lime mixtures. The wire is usually coated with lime before drawing, or covered with a proprietary coating compound. For wet-drawing intermediate gage steel wire, including copper-coated and zinc-coated wire, a water emulsion made from a soap-fatty oil compound makes a satisfactory lubricant, and the free fat content should be controlled at approximately 3%. Fine wire is usually drawn with a soap solution or with an emulsion made from a compound containing a large amount of soap and a small amount of free fat. The emulsion should be controlled so as to have a free fat content of about 1.5% and a pH of 9. The drawing lubricants should be circulated in the machines and cooled in tanks as in the drawing of copper and brass wire. Stainless steel is usually drawn with a petroleum oil plus an extreme pressure additive, or a sulfated base soluble oil containing an extreme pressure additive. The lubricants used for stainless steel will also give satisfactory results for drawing Inconel and Monel wire.

Zinc. Zinc may be drawn successfully in a 3 to 5% aqueous soap solution. Sometimes it has been found beneficial to add to this solution a small portion of lard oil. The lubricant may be applied to the sheet zinc in any of the ways mentioned under copper and brass.

Zinc wire may be drawn in an emulsion made from a compound low in soap content, high in free fat content; the free fat in the lubricant should be controlled between 2 and 3%. Care should be taken to keep the emulsion as nearly neutral as possible to prevent the formation of zinc salts that will render the lubricant useless.

WELDING, BRAZING AND SOLDERING

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Welding Processes

BY THE SUBCOMMITTEE ON WELDING AND CUTTING*

THIS article outlines and discusses the metallurgical aspects of fusion welding and certain allied processes. Recent remarkable advances have given welding a dominant place in the metal industries. It has become common practice to shape and prepare metal parts and then join them by welding to produce engineering structures.

The aim is not to describe at length the equipment and the technique used in applying the various welding processes. Instead, the metallurgical features that affect the satisfactory welding of metals will be analyzed; some methods of inspecting and testing to determine weld quality will be presented; and hazards and safety precautions will be discussed briefly. For more detailed information concerning the application of the various welding processes to particular ferrous and nonferrous metals, the reader may refer to the sections of this Handbook listed at the end of this article.

Since "fusion welding" is defined fundamentally as a group of processes in which metals are joined by bringing them to the molten state at the abutting surfaces, the importance of the effect of heat in all welding operations must be recognized. Welding is usually employed to unite like metals where the joining is required to develop strength and transmit stress.

General Considerations. The metallurgical, chemical, physical, and thermal characteristics of metals greatly influence their weldability. The weld has been defined as "a localized union or consolidation of metals". A number of processes can accomplish such a union, but all processes now in general use have two characteristics in common. First, the union or consolidation is localized; and second, the weld is accomplished in a comparatively short time and frequently in a progressive manner. Thus a small volume in a large mass of cold metal is heated from room temperature to a high temperature and cooled again immediately to a temperature lower than black heat. For ferrous metals, the high temperature is above the transformation range.

In fusion processes the temperature frequently rises considerably higher than the melting point and all temperatures within the indicated range are present at the same time in bordering zones. Throughout the temperature range required by the process, thermal changes such as expansion and contraction must be considered, as well as metallurgical effects such as crystallization and heat treatment; chemical reactions; and changes in physical characteristics, such as strength and ductility.

The simplest phenomenon that occurs in metals during heating is expansion. In the initial stages, expansion is purely a change of volume and in most metals is a completely reversible change regardless of the rate of heating or cooling. At the same time that they are expanding, most metals become increasingly soft, ductile and weak, a fact that is both an advantage and a disadvantage. Consequently stresses become dissipated and advantageously spread over the heated area because the metal can stretch and yield with ease. On the other hand, the low strength at these elevated temperatures makes it necessary to be certain that the piece being welded is free to move so that too great a load will not be placed on the hot metal. Some metals become so weak that it is necessary to support them to prevent buckling or other change of shape.

Particular attention must be paid to the final weld of a closed structure or to the joining of a light section to a heavy section, in order to reduce the residual stress in the structure to a minimum.* Metals that have a high rate of thermal conductivity present a particular problem because the heat is generally spread over a wider area and thus the expansion is greater; also such metals usually undergo a much greater reduction in strength during heating and frequently require support to prevent buckling.

Most common metals react with oxygen of the atmosphere. At higher temperatures the rate of oxidation increases rapidly. Nitrogen from the air also reacts with some metals, forming nitrides, which tend to increase the strength and reduce the ductility. These conditions can be prevented by protecting the molten metal from contact with the atmosphere.

Because weld metal cools rather rapidly, consideration must be given to the effect of gases, either dissolved or entrapped, in the molten weld metal. To ensure sound welds, free from porosity, the molten metal must be free from these gases before it solidifies.

In fusion welding processes metals under the effect of heat are subject to the same thermal, chemical, physical, and metallurgical changes involved in the manufacture of metals. In the welding of steel, for example, the weld is in some respects a steel casting made in a steel mold and the metal of this casting comes either from the steel mold itself or from a combination of the steel mold and the welding rod or electrode. In gas welding, the heat applied to both the mold and the rod is from external sources. In arc welding, the heat results from electrical energy that passes through both the electrode and the mold.

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* The relief of residual stresses in weldments and other structures is discussed in the article on page 237. The reader may refer to that article for a statement of the principles of stress relieving and a summary of certain code requirements for the relief of stresses in welded products. The codes summarized include especially those relating to fusion-welded pressure vessels and pressure piping.

Pressure Welding Processes

Forge Welding. This is the oldest welding process and the only one in which the general practice antedates the twentieth century. It is essentially a process of joining metal pieces that have been heated, within the area of joining, to a condition that approaches plasticity on the surface. As soon as the plastic condition is reached, the parts are quickly superimposed and worked into complete union, either by hammering or by pressure. The hammering is performed either manually or by machine and the force of the hammering or pressure depends largely on the size and mass of the pieces or parts that are being joined.

Oxyacetylene Pressure Welding. There are two methods by which gas welding utilizes pressure to make the weld. In the first, carefully machined and cleaned ends of pieces are butted tightly together under pressure; then the heat is applied. This application of pressure welding is characterized by the fact that the bond is formed by diffusion and recrystallization at a temperature lower than the melting point of the materials being joined. Closed-face pressure welding is the only process effecting the bond completely in the solid phase. The second method involves heating with flames impinging directly on the welding faces, which have been spaced a short distance apart. These faces have previously been made substantially square. When the ends of the pieces have been brought to the fusion point the parts are brought rapidly together under pressure to effect the weld. In both processes an upset is created by the shortening of the parts. No filler metal is added in either process.

In oxyacetylene pressure welding, the strength of the joint can be made equal to that of the base metal. The finished weld is homogeneous and there is no evidence of the juncture except where steels of different alloy content have been joined. Dissimilar metals react differently to an etching reagent and the area of the joint can be detected although no fine line of demarcation exists under microscopic inspection.

Oxyacetylene pressure welding has been applied successfully to the complete range of carbon steels, to both high-alloy and low-alloy steels and to many nonferrous metals. Pressure welding is used for safe-ending boiler tubes, laying cross-country transmission lines for both oil and gas, railroad rails, aircraft landing struts, propeller hubs and 8-in. diam steam forging-hammer rods, to name only a few of the important applications of the process.

The equipment required for oxyacetylene pressure welding is relatively simple compared with other mechanical welding processes. Heating arrangements and a source of pressure are the major equipment. Furthermore, the operating conditions are readily adaptable to complete mechanization and automatic control.

Resistance Welding. In this process, the surfaces to be joined are heated to the plastic condition by the passage of a heavy localized electric current accompanied by mechanical pressure to bring the parts into complete union. To produce the required heavy current at low voltage, alternating current has been found most convenient since, by the use of suitable transformers, almost any desired combination of current and voltage can be obtained. Only in special instances is direct current used for this purpose.

An important factor in all resistance processes is the composition of the electrode, which must possess good thermal and electrical conductivity combined with maximum hardness and sufficient strength. An excellent combination of these requirements has been achieved by the use of a hard copper electrode faced with one of several alloys that have hardness, under welding conditions, much greater than that of copper.

Resistance Butt Welding. In the butt-welding form of the resistance process, pieces are gripped mechanically and pressed together while heat is generated by passing a high electric current through the area of contact. The original upset method is a form of butt welding in which high mechanical pressure is applied and maintained throughout the operation, while the temperature is kept below melting. The extruded metal is upset into a roughly convex form which, if desired, may be molded to a predetermined shape in a die, thus securing a kind of drop forging; or it may be ground off. Today the upset method is generally combined with flashing. The flash method as first developed is a form of butt welding in which, after initial contact and heating, the parts are slightly separated during a brief period, thereby causing intense arcing. The weld is then completed under pressure and at a temperature sufficient to bring to a plastic state a portion of the metal that is partly extruded in the form of a thin burr, which may be ground off. This method is still employed for large pieces, but on smaller pieces the flashing effect that was secured in the original process by separation of the parts, is obtained automatically by successive adjustments of pressure. Because there is no hesitation in the cycle, this form of flash welding is quite rapid.

Resistance Spot Welding. In the spot-welding form of the resistance process, two or more sheets of base metal are held between metal electrodes that pass a large current of fairly low voltage through the sheets. Immediately following this, and with current maintained, the electrodes are forced together with sufficient mechanical pressure to unite the surface of the sheets in a spot approximately the same size as the end of the electrodes. This pressure is maintained until after the current has been cut off.

Resistance Projection Welding. In resistance projection welding, small projections are formed on one or both pieces of base metal to localize the current.

Resistance Seam Welding. The seam-welding form of the resistance process is a series of overlapping welds. Two or more sheets of base metal are usually passed between electrode rollers, which transmit the current and also the mechanical pressure required for producing a welded seam. A current interrupter is used for this type of weld.

Resistance Percussion Welding. The percussive methods differ from the usual forms of resistance welding in that (1) a direct-current supply is essential; (2) there is a sudden discharge of electrical energy at the junction, with an arc, which is extinguished by a percussive blow; and (3) the surfaces united are partially fluid. The energy may be supplied by the discharge of a condenser (electrostatic) or transformed by the collapse of a magnetic field (electromagnetic).

Thermit Pressure Welding. This plastic welding process —used only for joining ferrous metals—differs from the forge and resistance welding processes principally in that the heating to plasticity is obtained from the thermit chemical reaction rather than from fire or electric current.

The chemical reaction that generates the heat required for welding is described later in this article under the heading Thermit Welding. The molten steel and the alumina slag are conducted around the abutting ends to be welded, in such a manner as to localize the heating as near the joint as possible. This requires a suitable mold, ordinarily made of light cast-iron segments, which can be clamped in position and then removed easily after the thermit reaction. This thermit reaction is controlled so that the alumina slag enters the mold first and leaves a coating on it and on the ends being joined, thus protecting these parts from the superheated iron. The passage of the iron through the mold brings the work to welding temperature in a short time, which varies from a few seconds to several minutes, depending on the size. Then a quick application of pressure completes the weld.

Fusion Welding Processes (Nonpressure)

These processes differ from those previously enumerated in that they depart from the union of plastic metals and utilize fusion of metal to effect the desired union. The joining is accomplished by the fusion of metal on or between the surfaces of the parts that are being united. The fused metal is generally obtained by deposit from an external source, although in some instances the abutting edges are merely fused together to form the joint.

Gas Welding. In this process, heat is supplied by the combustion of a suitable fuel gas with atmospheric or pure oxygen. The fuel gas and oxygen are mixed in a suitable torch, regulated to produce an impinging flame that has the desired characteristics. The gases most commonly

used are oxygen and acetylene, although hydrogen and other combustible gases are used to some extent.

Oxyacetylene Welding. In this form of fusion welding the heat required is supplied by the oxyacetylene flame. Usually in fusion welding, a filler metal is added in the form of welding rod to make the welded joint (Fig. 1), although occasionally in oxyacetylene welding, the parts to be joined are merely fused together without the addition of welding rod. To float out impurities or aid in obtaining a satisfactory bond, flux is employed in the welding of some metals, such as cast iron, certain alloy steels, and the nonferrous metals.

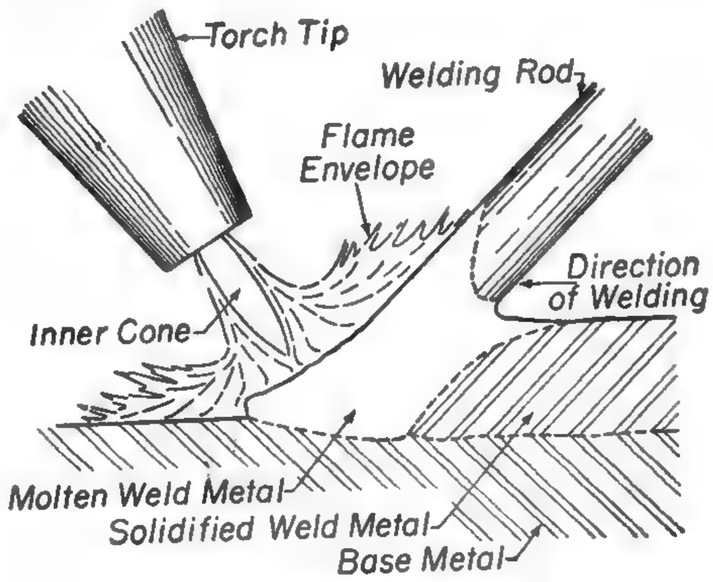

Fig. 1 Oxyacetylene welding

In the combustion of acetylene and oxygen the resulting flame has characteristics that indicate whether it is reducing, oxidizing, or carburizing in character (Fig. 2). If the acetylene and oxygen are in proportion, a neutral flame results. In most gas welding, the neutral flame is recommended; in some welding applications, however, a slightly carburizing or slightly oxidizing flame is considered desirable. Certain of the alloy steels are welded to advantage with a slightly reducing or carburizing flame, and under certain conditions a reducing flame is considered desirable.

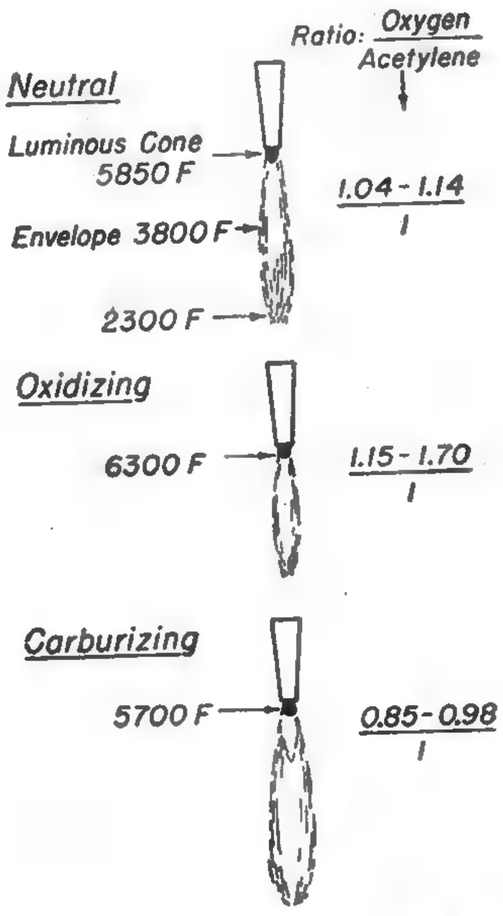

Fig. 2 Characteristics of oxyacetylene welding flame. For complete combustion of acetylene, 1 molecular volume (380 cu ft at 60 F) of acetylene, plus 2½ molecular volumes of oxygen burns to form 2 molecular volumes of carbon dioxide plus 1 molecular volume of water vapor, liberating 542,700 Btu of heat

An important characteristic of the oxyacetylene flame is that the outer envelope of the flame protects the molten metal from atmospheric attack. The oxygen surrounding this envelope of the flame is consumed in the final combustion stage.

Arc Welding. In arc welding, the surfaces to be joined are fused by the heat of an electric arc. Each of the three forms of arc welding derives its name from an identifying feature, such as the electrode material used or the means of transferring heat. These forms are carbon-arc welding, metal-arc welding, and atomic hydrogen arc welding.

Welding current for carbon-arc welding is always direct current. Metal-arc welding utilizes either direct or alternating current. Atomic hydrogen arc welding is ordinarily done with alternating current. Direct current for arc welding is obtained usually from a motor-generator set. The generator may be of either the variable-voltage single-operator type or the specially designed constant-voltage multiple-operator type with suitable controls. Rectifier units are also used for this purpose. For alternating current two methods are used: (1) the static transformer, which is a single-phase unit specially designed for arc welding and which uses various methods of control that are all of the variable-voltage single-operator type; and (2) the alternating-current method of rotating frequency-changer sets, which convert the usual frequency to several times that of the power supply line.

Carbon-Arc Welding. In this process the arc is usually drawn between a carbon or graphite pencil or electrode and the work material to be welded. The heat of the arc causes fusion of the base metal and, if additional metal is required, also fuses a filler rod that is fed into the joint at the desired rate. This process of welding may be accomplished either manually or mechanically. When performed by mechanical methods, this type of welding is commonly called "automatic" carbon-arc welding. The hand process is used only for special applications, largely on account of the erratic nature of such an arc. In the automatic process, the arc is controlled by superimposed magnetic fields.

Unshielded Carbon-Arc Welding. This term is applied when either type of carbon-arc welding is performed without the aid of appreciable amounts of flux. When applied to ferrous materials, unshielded carbon-arc welding is used on relatively unimportant joints only, but with proper procedure it is used to a considerable extent in the welding of deoxidized copper.

Shielded Carbon-Arc Welding. This process utilizes fluxes, in the form of treated paper, powder, paste or gas, or a combination of these. These fluxes have various functions—for example, to envelop the molten metal in a noncontaminating atmosphere to the exclusion of the oxygen and nitrogen of the air; to scavenge impurities from the molten metal; to retard the cooling rate of the weld metal; and to produce weld metal of the desired mechanical properties. This process is applied to most of the important joints to which the carbon arc is suited, generally in automatic form.

Metal-Arc Welding. In this process the arc is struck between a metal electrode and the work piece. The heat of the arc fuses not only the work material but also the electrode, which is in the form of a wire of suitable material. This fused electrode material passes through the arc and unites with the fused base metal to form the welded joint. The process is adaptable to either hand or automatic methods. There are two major classifications of metal-arc welding, *unshielded* and *shielded*. The term "unshielded" is applied when the electrode is either a bare wire (Fig. 3) or is lightly coated with small amounts of flux, sometimes called a "wash-coated" or "dust-coated" electrode.

In shielded metal-arc welding the metallic electrode is covered with a thick layer of fluxing ingredients with or without a fibrous binder (Fig. 4). These flux coverings function in several ways to produce weld metal of high mechanical properties and comparable with the base metal:

1 The flux coverings are usually consumed more slowly than the metal of the electrode, thus forming a cupped end that shields the arc partially from the air.

2 Combustion of the fluxes produces an envelope of gases around the arc, which excludes oxygen and nitrogen of the air from contact with the molten metal of the weld.

3 The fluxing ingredients scavenge impurities from the molten metal of the weld.

4 A protective slag covering is formed that covers the top of the weld and protects the molten metal from contamination by oxygen and nitrogen from the air; it also retards the cooling rate and thus partially heat treats the weld.

5 Alloying elements desired in the weld are sometimes supplied in the heavy flux coverings.

6 Materials are sometimes placed in the coatings to increase the arc stability by virtue of their ease of ionization or greater emission of electrons. Materials may also be added to make the flow of metal across the arc more uniform, by reducing the adhesive force between the molten metal and the end of the electrode, or by changing the surface tension of the molten metal so that globular formation is smaller and more uniform.

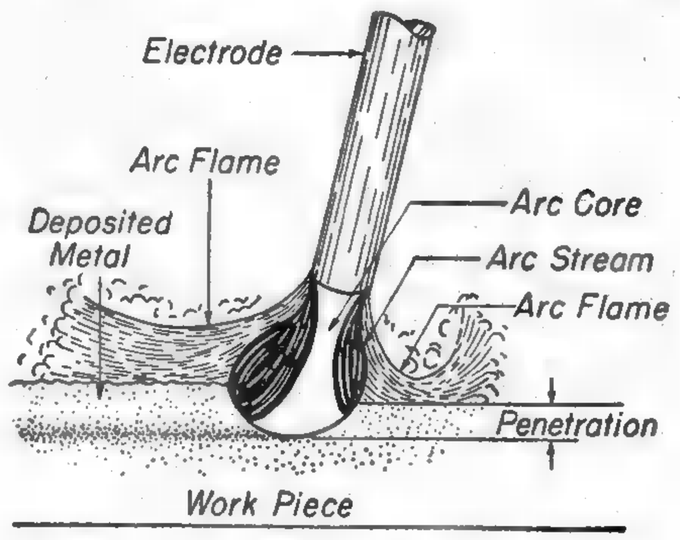

Fig. 3 Arc welding with bare electrode

Shielded-arc welding controls to such an extent the metallurgical processes involved in forming a weld that greater amounts of heat are generally used than without shielding. This results in greater welding speeds and at the same time physical properties in the weld metal equal to those of the base metal, and often superior.

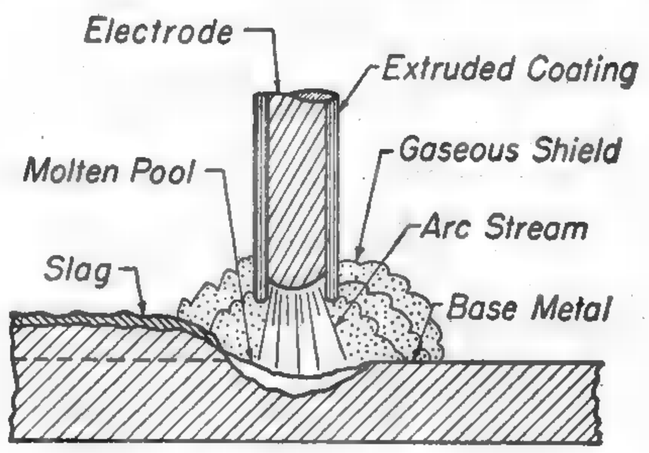

Fig. 4 Arc welding with shielded electrode

The average bare electrode deposit has from 0.11 to 0.15% nitrogen and about 0.3% oxygen (as oxides), while a shielded-arc electrode deposit contains from 0.010 to 0.023% nitrogen and about 0.068% oxygen. A comparison of the physical properties of typical all-weld-metal specimens is as follows:

	Bare Electrode	Shielded-Arc Electrode
Tensile strength, psi	40,000 to 60,000	65,000 to 85,000
Elongation in 2 in., %	5 to 10	20 to 30
Izod impact, ft-lb	5 to 15	50 to 80
Endurance limit, psi	12,000 to 15,000	28,000 to 32,000
Specific gravity	7.5 to 7.7	7.82 to 7.86
Corrosion resistance	poor	better than mild steel
Porosity detected by X-rays	considerable	almost no defects

Atomic Hydrogen Arc Welding. In the atomic hydrogen arc-welding process an alternating-current arc between two tungsten electrodes in a stream of hydrogen gas furnishes the source of heat. The arc column is defined by a thin brilliant line that forms a loop under the influence of its own magnetic field and the streaming gas. In this arc column, which has a temperature between 5500 and 6000 F, the hydrogen molecules are completely broken down into atoms, and during this process a great deal of energy is absorbed. When this atomic hydrogen flame, which is coincidental with the arc column, is placed in contact with the metal parts being welded, the dissociated hydrogen atoms recombine into molecules, giving to the surface the heat that was absorbed during dissociation. The weld metal may be supplied as surplus metal from the parts being welded, or may be added from a filler rod. The atomic hydrogen arc is surrounded by an envelope of hydrogen gas that protects the work material and electrodes from oxidation and reduces existing oxides in the metal. The operator can adjust the size of the atomic hydrogen arc by changing the electrode separation during operation; in this way an arc is obtainable that varies in size from ⅛ in. to more than 1 in. The freedom from oxidation, the intense concentration of heat, the flexibility and ease of operation, combined with freedom from magnetic blowing effects, are features that characterize atomic hydrogen arc welding.

Inert-Gas-Shielded Arc Welding. This is an electric-arc welding process that employs a blanket of monatomic inert gas to shield the weld area. Highly concentrated heat is produced by an arc drawn between a single, virtually nonconsumable tungsten electrode and the work piece. The inert gas (argon or helium) is fed through a nozzle surrounding the electrode in the head of the torch, and flows out to blanket the electrode completely, as well as the arc and weld puddle, for the total exclusion of the oxidizing atmosphere.

The process is used successfully for welding magnesium, aluminum, stainless steel, high-alloy steel, nickel and nickel alloys, brass, silicon bronze, pure silver and other metals. The outstanding characteristic is that all these metals can be welded without the use of flux. Because no flux is needed, corrosion from entrapment of flux in the weld is eliminated.

Among the conspicuous advantages of inert-gas-shielded arc welding are welds free from flux inclusions, slag and spatter. High speeds of welding are practical.

The equipment necessary consists of a torch, used to hold the electrode and to provide a means of getting the helium or argon around the weld; a tungsten electrode; a supply of inert gas, governed by a regulator and measured by a low-pressure flowmeter; and a source of electric current.

Either straight-polarity direct current or alternating current is used. The choice depends somewhat on the alloy and the thickness. Reverse-polarity direct current (electrode positive) has been used for welding magnesium, but many fabricators prefer alternating current because of its greater penetration, speed and range of thickness capacity. Likewise alternating current is almost always used for welding aluminum since straight-polarity direct current will not produce a satisfactory weld. For stainless steel, alloy steels and some copper alloys, either alternating current or direct current may be used. Alternating current is generally preferred for light material because of better arc stability. Direct current is favored for heavier material because of the deeper and narrower weld beads. Standard direct-current and alternating-current welding machines are employed; however, the latter must have a superimposed (low-power) high-frequency current for stabilizing the arc. Successful use has been made of high open-circuit voltage (200 to 300 v) transformers without high frequency for welding aluminum. These applications have been limited mostly to special mechanized operations.

Submerged-Melt Welding Process. This is a method of welding electrically beneath a protective layer of granular and molten mineral material. The process is used for welding virtually all steels, as well as other ferrous and nonferrous metals and alloys. The granular material is usually laid down directly ahead of the welding zone. In the welding zone, the granular material fuses and serves as a medium for conducting the welding current, concentrating the heat produced and protecting the weld from the effects of the atmosphere. Since the atmosphere is excluded from the weld, bare welding wire can be fed directly into the welding zone. There is no flash, glare, or spatter. The molten material also removes impurities from the weld, and as it cools it solidifies, forming a protective cover over the weld. When cool, the fused material cracks off, or can be removed easily. Because of the deep penetration, relatively small amounts of welding rod are required. The welds produced are dense, uniform, and are as strong as the parent metal, or stronger.

The use of the process is limited only by the capacity

of the equipment. With present equipment, material ranging from 22-gage sheet to 3-in. plate can be welded in a single pass. Material of any thickness can be welded by a suitable number of passes.

Speeds of about 200 in. per min can be used on thin material. The currents required vary with the material and are usually about 6 to 10 times those used with the manual electric-arc welding methods. A maximum of about 4000 amp can be applied with the present equipment. This would be approximately the current required to weld plates 3 in. thick in a single pass.

Because of the nature of the process, welds must be made in a horizontal, or nearly horizontal, position. Such welds can be made without special plate-edge preparation in material less than ½ in. thick. Thicker material is usually prepared with a single or double V. Single-pass butt welds are usually backed up by a copper strip or a layer of granular material pressed against the back of the weld. With this process, butt, fillet (positioned and non-positioned), and plug welds can be made.

The process has been widely used in the fabrication of pressure vessels, in shipbuilding, and in all types of steel fabrication where the material can be assembled and positioned suitably for welding. It has also been used in rebuilding worn surfaces or increasing wear resistance.

Thermit Welding. The thermit fusion process, commonly known as thermit welding, originated with a discovery made in Germany, in about 1900, by Dr. Hans Goldschmidt. He found that if a mixture of a metallic oxide and finely divided aluminum were ignited at one spot, the two materials would react exothermically and the reaction would progress throughout the mixture, thereby converting it into two new materials, a superheated mass of the metal itself and a slag composed of molten aluminum oxide (alumina). He found further that the reaction would progress so rapidly that, in the melting of most metals by the thermit process, as much as a ton of material could be converted from a cold mixture in half a minute. Later the most suitable kind of iron oxide (Fe_3O_4), the best size of oxide flakes, and the optimum fineness for use in welding steel were determined, as well as the possibilities resulting from the addition of such elements as chromium, nickel, vanadium, and manganese to a thermit steel mixture.

In the thermit process, the parts to be united are separated by a space, the extent of which depends on their size. The surfaces are thoroughly cleaned by sand blast or otherwise. Usually the space is given the form of a parallel-sided gap cut by means of a gas torch. The slight layer of oxide resulting from the cutting process is apparently beneficial. Around the parts a wax pattern is formed in the shape of the reinforcement desired. A sheet-iron box is placed around this pattern with a space between it and the pattern, and when the wax has hardened, sand is rammed into the space, after provision has been made for the proper number of risers and pouring and heating gates. The wax is then melted by directing a flame into each heating gate, and as the wax flows away, it leaves clear the space to be occupied later by the thermit steel. Heat is continued so as to dry out the sand mold and to bring to a red temperature the parts to be united. If multiple sections are to be welded, a two-part mold and a special wooden pattern may be substituted for the box and the wax.

A proper thermit mixture is then placed in a crucible supported over a pouring gate or gates, and when the work is ready, it is ignited. In about half a minute the reaction is complete, and the thermit steel is then tapped from the bottom of the crucible into the pouring gate. The superheated metal flows around and between the parts to be united, thoroughly combining with their surfaces and welding them into one homogeneous mass, while the molten alumina slag overflows into a basin on top of the mold.

Bronze Welding

The term "bronze welding" is understood by the welding operator to refer to the joining of metals with high melting points, such as cast iron, nickel, and copper, by the use of copper alloy weld metal. Actually, the word "bronze" is not correct, since the alloys are brasses in some instances. For many welding applications, bronze welding offers advantages of speed, economy, and ability to do jobs that might otherwise be difficult or impossible.

Bronze welding is essentially an application of the oxyacetylene process in which the joints produced are not true fusion welds, since the base metal is not melted, although a metallic bond is evidently formed between the deposited metal and the base metal as explained below. Bronze forms a strong bond with metal surfaces that have been heated to the proper temperature and treated with a suitable flux.

The oxyacetylene flame supplies the heat required for the preparation of the edges to be joined and for the melting of the welding rod. Because of the lower melting point of the rods used for bronze welding as compared with that of the material to be joined and the fact that the parts to be joined are required to be heated only to a temperature where tinning and amalgamation with the bronze take place, a much lower welding temperature is required in the bronze welding of steel, for instance, than in the making of a steel fusion weld.

Bronze welding with the electric arc may be accomplished by using a carbon arc and bronze or monel metal filler rod; the arc is directed on the filler metal. Ferrous metals may be welded with bronze or monel metal electrodes by the metal-arc process, although in this process, fusion of the base metal results. It should be noted, however, that the depth of fusion is not great.

Physical Nature of the Bond Between Filler Metal and Base Metal. Investigators have studied the character of the bond between copper alloy and base metal, which produces an adherence of copper alloy to base metal, stronger than the base metal itself when that metal is cast iron. It has been found that three distinct forces act to maintain adherence of the copper alloy to the base metal.

1 Tinning. A clean metal surface will receive a thin film of a molten metal of low surface tension. The bond thus produced depends on the action of atomic forces at the interface between copper alloy and base metal.

2 Alloying. A diffusion of the constituents of the filler metal—copper, zinc, tin, and others—into the base metal, and a corresponding diffusion of base-metal constituents into the filler metal takes place in a narrow zone at the interface between copper alloy and base metal. The base-metal crystals at the interface, when examined under the microscope, show a diffusion of the copper alloy constituents into the crystal grains, and an alloying of the filler metal with the base metal.

3 Intergranular Penetration. The action of the molten copper alloy on the base-metal surface opens the crystal grain structure of the base-metal surface and allows the filler metal to penetrate the base metal along the grain boundaries. This effect of alloying and intergranular penetration accounts for the strength of the bond between copper alloy and base metal, which can be produced without surface fusion of the base metal.

Copper Alloy Welding Rods. The copper alloy welding rod should tin readily when used with a suitable flux. It should be capable of building up a deposited metal that is virtually free from defects that result from slag inclusions, or blowholes. The fumes from zinc or other ingredients of the rod should be kept at a minimum since they may hinder the operator.

In general, the rods have a copper-zinc ratio of 60 to 40 and contain additions of tin, iron, manganese, or silicon, which improve the flowing qualities, deoxidize the weld metal, decrease the tendency to fume, and increase the hardness of the deposited metal for greater wear resistance.

With the arc process, a phosphor bronze or monel electrode may be used. When heavily coated electrodes are used, the coating aids in promoting an easy flow of metal.

Advantages. Bronze welding affords several advantages. Because of the lower temperature at which the filler metal can be added to the base metal, there is an increase in speed of making the joint, and less heat is required than in making a true fusion weld. The copper alloys yield readily while they cool until the temperature is lower than 500 F and there is an appreciable yielding under reasonably low stresses even at atmospheric temperature. This yielding as a single operation does not weaken the deposited metal. Therefore, residual stresses are reduced greatly in bronze welded castings.

Bronze welding should not be used where the finished work is to be subjected to temperatures higher than 500 F. It has also been learned that bronze should not be used where stresses as high as about 15,000 psi may be applied to the finished work with such rapidity as to cause fatigue of the metal. Since iron castings are seldom subject to stresses greater than 5000 psi, this effect can never be an important one in the bronze welding of cast iron. This same comment can be made with regard to bronze welding of malleable iron.

Inspection and Testing

Many products and structures, such as pressure vessels, ships, tanks, buildings and machinery, fabricated by fusion welding, are made under some form of specification that requires inspection by the purchaser. In some welding applications the inspection must conform to some code of construction requirements, and tests are specified to govern the qualification of the welding operator or the quality of the welding performed.

The tests that have been devised include destructive tests and nondestructive tests. Only the destructive tests are definitely quantitative; the nondestructive tests are indicative of quality only, and some of these are indicative only to a limited extent. The destructive tests include tensile, bend, specific gravity, nick-break tests, impact, and hardness tests. The nondestructive tests that have been used on welded joints include the visual, the stethoscopic, X-ray, and gamma ray tests. Electric resistance, magnetic and supersonic inspection methods have also been developed and are being used successfully in many instances. The hydrostatic proof test is a form of nondestructive test that is used for pressure vessels and closed containers.

Visual inspection of fusion welding during the process is also possible, although not generally specified directly. For this inspection the fusion-welded joint offers the peculiar advantage that the inside of the joint may be observed while it is being made. Visual inspection is valuable in studying procedure, but it requires a careful observer, properly trained. The inspector watches the rod or electrode and observes how it melts down, notes the fusion and penetration, and listens to the sound of the arc, or observes the flame adjustment of the torch. All these items properly studied and understood will give a skilled inspector considerable information regarding the quality of the weld under observation.

Mechanical Tests. The application of mechanical tests to weld metal and welded joints is discussed in the article on page 137 of this Handbook. The tests described are: tension, shear, bend (ductility), nick-break, and notched-bar impact.

Nondestructive Tests. *Stethoscope.* The object of the stethoscopic test is to determine by means of the tone that a weld gives off when tapped with a hammer, whether the metal is sound or contains defects, such as lack of fusion or cracks. Just as a sound bell gives a clear ringing note and a cracked bell gives a reedy note, so good weld metal gives a good ringing sound and a poor weld gives a flat sound or note.

In order to identify the sound readily, an ordinary medical stethoscope is used. As a special precaution the end is protected with rubber to avoid any extraneous sounds that would result from scraping the stethoscope on the metal.

The stethoscopic test (Fig. 5) has been applied successfully to pressure vessels, locomotive staybolts and other welded structures, but it is not extensively used today.

X-Ray. Metals can be X-rayed and their internal defects made visible on photographic films. In this way all types of defects can be detected, such as cracks, slag, blowholes, and lack of fusion. Generally the method consists of placing the test piece between the X-ray tube and a film. After an exposure ranging from a fraction of a minute to hours, depending on the power of the tube and the thickness of the metal, the film is developed and examined for defects in the weld. (*See* the article on "Radiography" in this Handbook, page 141.)

This method is used widely in industry and is recognized as the foremost nondestructive test. It is one of the requirements of the ASME Code for paragraph U68 quality welded pressure vessels.

Gamma Ray Tests. Gamma ray tests are similar in method to X-ray tests. The gamma rays emanating from radium penetrate metals rapidly and are more applicable to heavy sections that would require unusually long exposure by X-rays. This type of test has been successfully applied to pipe and to heavy castings such as are used in ship construction. On heavy work pieces overnight exposures are employed.

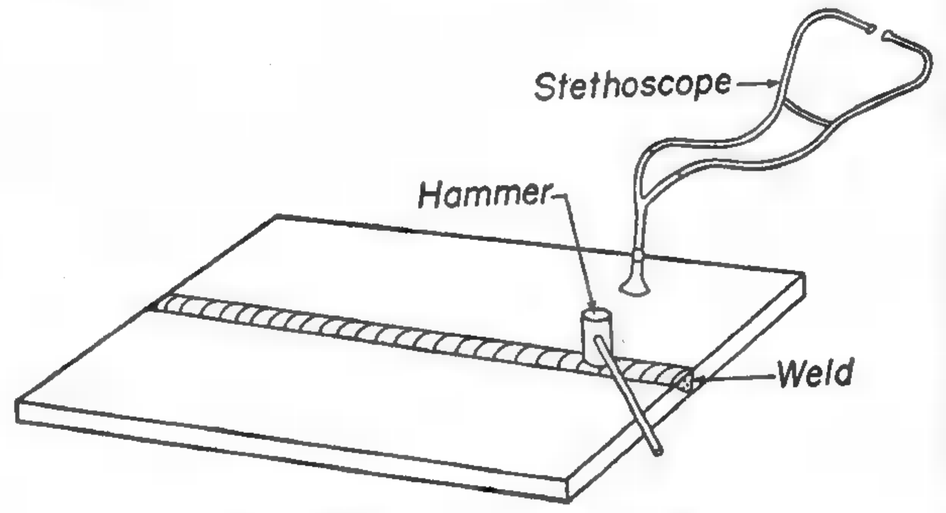

Fig. 5 Stethoscopic testing of welds

Several large castings may be arranged radially around a capsule that contains radium. The films for recording the results are placed on the farthest side of the castings in relation to the radium. Before attempting the use of radium for gamma ray testing, it is essential that the operator be familiar with the properties of radium, and that the necessary precautions be taken to protect persons who are to work with it.

Special Tests. Electric and magnetic tests that depend on variations produced in the flux density by weld flaws, have proved very successful in certain instances. Tests of this type are best adapted for routine inspection work and are frequently used to inspect welds in pipe and tubing.

The supersonic vibration method of testing welds is relatively new but it holds definite promise of becoming an important test method. This and other nondestructive tests are discussed in the section beginning page 141.

Safe Practices in Fusion Welding

The question of safe practices in fusion welding is an important one, since there are inherent hazards in certain applications, no matter what the welding process may be. Special attention will be devoted to the hazards, because it is not the purpose here to enumerate the safety precautions that must be observed in connection with the different welding processes. These precautions have been ably covered by the National Safety Council in Safe Practices Pamphlets No. 23 on Gas Welding and Flame Cutting and No. 105 on Electric Welding. Reference may be made also to American Standards Association War Standard Z49.1, which is now being revised into a peacetime standard, and to the publication of the International Acetylene Association on Safe Practices for Installation and Operation of Oxyacetylene Welding and Cutting Equipment. These pamphlets contain much valuable information concerning the fundamentals of gas welding and cutting, thermit welding, and electric welding, and they should be consulted by everyone who has charge of fusion welding operations.

All operators of welding equipment should be conversant with the safe operating instructions that are furnished with all fusion welding equipment. As a rule, welding equipment is constituted in a way that makes it quite convenient to observe the usual precautions for safety, but in the application of the process involved, there are certain conditions and operations that may endanger the operator if the possibility is not anticipated and avoided. Some of these hazards will be enumerated.

Eye Protection. A serious hazard in welding applications is that of injury to the eyes, from the heat and glare of the flame or arc, and from particles of hot metal that may fly up from the work. Properly colored lenses fitted in goggles

will protect the eyes from the gas flame, but in electric-arc welding, the intensity of the ultraviolet and infrared rays is such that all persons exposed must use shields or helmets that will protect not only the eyes but the skin as well. The lenses of goggles should be selected with considerable care in order to obtain the desired visibility together with adequate protection for the eye; the exterior surfaces of these lenses may be protected from flying sparks by superimposing a clear glass lens over each. The selection of lenses for use with the electric arc must be based on laboratory tests, because the transmission of ultraviolet and infrared radiation cannot be determined by visual inspection; proper protection for the eyes requires more than mere reduction of the glare. Goggle frames should be made of noncombustible material, preferably a nonconductor of heat; if made of metal they should be padded. The frames should have vent holes in the cups to provide ventilation behind the lenses.

Special precautions must be taken to protect other workers or passers-by from the harmful rays given off from arc-welding operations. It is preferable to locate these jobs in special rooms. If this is impracticable, the operations should be screened or enclosed, not only to prevent workers or passers-by from looking directly at the arc, but also to protect them from reflected rays as much as possible. Further protection against reflected rays is frequently provided by applying paint to the screen or enclosure and to other nearby surfaces. Zinc oxide is satisfactory when combined with lamp black to produce a bluish gray color.

Clothing. The welding operator should have some protection from the heat of welding, particularly when working on heavy pieces and for long periods of time. Fire-resisting gauntlets and aprons will serve as a protection against the radiated heat. Woolen clothing is to be preferred to cotton, because it is less readily ignited and it protects the operator from changes in temperature. Operators engaged in arc welding are advised to wear only fireproofed outer clothing.

There have been instances when the operator's clothing has been set on fire by sparks of molten metal that lodge in rolled-up sleeves, and in pockets of clothing. Operators should be warned to keep sleeves buttoned around the wrist and collars buttoned to prevent lodgment of sparks. Some suggest that it is advisable to eliminate pockets from the front of overalls and aprons. A sheet-iron screen in front of the worker's legs will provide further protection against sparks and molten metal in gas cutting.

Electric Installation. When installing and operating electric equipment, the provisions of the National Electrical Safety Code should be followed. The voltage is ordinarily so low that there is little danger of shock from the welding circuit; still the usual precautions should be taken. However, some types of equipment have a high voltage under open-circuit conditions and these should be properly guarded.

Fire Protection. Where welding or cutting must be done in the vicinity of combustible material, special precautions should be taken to make certain that sparks or hot slag from the welding or cutting operations do not reach the combustible material and start a fire.

Cutting or welding work that can be transported should be removed to a safe location in a building that is noncombustible or equipped with sprinklers. If the work cannot be moved, exposed combustible material should be moved a safe distance away, if possible 30 or 40 ft. Also wherever there are floor openings or cracks in the flooring, it is advisable to make certain that no highly combustible materials are stored on the floor below, where they would be exposed to sparks that might drop through the floor.

The sparks and hot slag should be watched to see that they do not come in contact with combustible material, do not lodge in floor cracks, and do not drop through holes to the floor below. Sheet metal guards or asbestos curtains should be used where needed; it is important to make sure that the guards and curtains are adequate. Because hot slag may roll along the floor for a considerable distance, it is important, when using asbestos blankets as a curtain, that no openings exist between the curtain and the floor. The use of tarpaulins should be avoided because experience has shown that they do not provide adequate protection.

Extra men should be stationed nearby with small hose, chemical extinguishers, or fire pails, when the nature of the work requires that blowpipes be used near wooden constructions or in locations where combustible material cannot be removed. In buildings equipped with sprinklers, this protection should be maintained without interruption while cutting blowpipes are being used. A man should be kept at the scene for half an hour after the work is completed, in order to make certain that sparks have not started smoldering fires.

In certain mines, mills, industrial plants, and plants where lacquers and the like are sprayed, dusty and gassy atmospheres require extra precautions to avoid explosions or fires from electric sparks, matches and open fires. Welding or cutting in such treacherous places should be done only when proper precautions have been taken and only after the responsible official in charge has inspected the situation and has given instructions personally to proceed.

Special Precautions. No welding or cutting should be done on used drums, barrels, tanks or other containers until they have been cleaned thoroughly enough to make absolutely certain that no flammable materials are present. Where steam is available, it may be used to remove materials that are easily volatile. Washing with strong caustic soda solution will remove heavier oils. Even after thorough cleansing, the container should be filled with water, if possible, before any welding, cutting, or other hot work is done. Almost always it will be found possible to place the container in such a position that it can be kept filled with water within a few inches of the point where welding or cutting is to be done. It is important to make sure that there is a vent or opening to provide for the release of heated air from inside the container. This can usually be done by opening the bung, hand hole, or other fitting which is above the water level.

Where alterations or repairs are being carried out on large containers that have held flammable substances, periodic examination of the air contents of the vessels should be made from time to time, wherever possible, by means of a gas detector where such an instrument is available. Although the vessel may have been steamed and flushed with soda, there may still be traces of oil or grease under seams, and the heat of the welding or cutting operations may cause such oil or grease to give off flammable vapor, forming an explosive mixture inside the tank. If possible, a supply of carbon dioxide should be kept in the vessels while they are under the process of repair. The use of carbon tetrachloride for this purpose is not recommended because carbon tetrachloride gives off a poisonous vapor when heated.

A jacketed vessel, tank or container should never be welded until after every possible precaution has been taken to vent the confined air sufficiently. A metal part that is suspiciously light is hollow inside, and should be drilled before heating; otherwise it will act like a bomb.

When gas cutting is done, judgment and care should be used in regard to the effect on the structure. No important structural member should be cut while it is under load, except where the removal of the part will not reduce the strength of the whole. Also great caution should be used in cutting holes in structural members or removing portions, unless the design provides for such cutting, without weakening. If gas cutting is used to remove rivets, great care should be taken in removing the head, to avoid reducing the thickness of the base metal at the rivet hole. In cutting away any important or heavy part of a machine or structure, caution should be used to make sure that the severed part will not fall and cause damage to adjacent equipment. If the work part is likely to fall and injure the operator or other workmen, care should be taken to support it properly while it is being cut.

Health Protection. When painted or lead-coated materials are cut or welded, the lead volatilizes and may be breathed into the operator's lungs, causing lead poisoning. In a similar way "zinc chills" may result from breathing the fumes when zinc, brass, bronze, or galvanized metal is being welded.

Under such conditions, protection of the operators depends on ventilation—or better, the operators should be required to wear special gas masks or fresh-air masks.

Special care is required when welding or cutting operations are carried on in confined and poorly ventilated spaces, as in tanks, compartments and holds of vessels.

Artificial ventilation may be necessary to replace the oxygen consumed from the air and the operators should be under close observation by an outside attendant so that help can be rendered immediately in an emergency.

Related Articles in This Handbook. For more specific information concerning the welding of particular ferrous and nonferrous metals, see the articles under the following titles: Welding of Ferrous Metals, Joining Aluminum Alloys, Joining Copper and Copper Alloys, Joining Lead by Soldering and Welding, Joining Magnesium Alloys, Joining Nickel and Nickel Alloys, Working and Joining of Tin, Casting and Production of Zinc Alloys, Joining and Cladding of Precious Metals.

See also the articles: Facing or Surfacing by Welding, Cutting of Metals by Gas and Electric Arc, Relief of Residual Stress, Mechanical Testing of Weld Metal and Welded Joints, and various articles on nondestructive testing and inspection.

Brazing, Silver Brazing, Copper-Hydrogen Brazing and Related Joining Methods

By the Subcommittee on Brazing*

BRAZING is a term commonly applied to a metal-joining process distinguished by two prominent characteristics:

1 Appropriate cementing metals or alloys are used that can be divided into the two general types given here with appropriate ranges of temperature for brazing: (*a*) Silver brazing alloys, containing silver with or without copper, zinc, cadmium, tin, manganese, nickel, and phosphorus, are used between 1175 F (635 C) and 1550 F (843 C) or higher. (*b*) Copper is used with or without zinc, tin, nickel, phosphorus or silver, separately or together, between 1300 F (704 C) and 2150 F (1177 C).

2 In the brazing process there is no melting of the metals or alloys that are being joined. The molten brazing metal or alloy flows between the heated, unfused, adjacent or overlapping surfaces of the joint members by capillary force, or is melted in place between such surfaces.

Brazing, therefore, presupposes the use of a brazing metal that melts and flows at a temperature lower than the temperature of the metals and alloys that are being joined. The "bronze welding" joining process (see page 75) is the same as brazing to the extent that the base metal is not fused, but bronze welding differs from the usual brazing process in that most of the strength of the joint is developed in tension through the bronze deposited in an open V or fillet, rather than in a thin filler that may be in shear between overlapping surfaces or may be in tension or shear or both, between adjacent surfaces.

Metallurgy of Brazing. The metallurgical requirements for successful brazing involve the consideration of the properties of the brazing metal and the metals to be joined.

*Requirements for the Brazing Metal.** Since the brazing metal or alloy must melt and flow freely at a temperature lower than that required for melting the parts being joined, it is necessary to provide a reasonable working differential. Where the temperatures can be controlled accurately, as in dip brazing or in the use of a closely regulated furnace, this temperature differential may be as low as 50 F. Skilled workmen may be successful with this low differential when using a blowpipe or torch, but for commercial work, it is preferable to use a brazing material that flows freely at a temperature at least 200 F below the melting point of the metals or alloys to be joined.

The brazing metal when molten must wet the base metal. The type of film formed on the liquid brazing metal and the character of the surface on the base metal have much to do with the interaction of the brazing metal and the base metal at the brazing temperature. Ordinarily the molten brazing metal should not oxidize too freely, and the oxide that is formed should be readily fluxed; that is, readily dissolved in a flux that is liquid at the brazing temperature. The oxides of copper, silver, zinc, tin and cadmium are readily fluxed. Nickel, silicon, aluminum, chromium and beryllium oxides, in the order named, are increasingly difficult to dissolve in flux. Phosphorus vapor, rising to the surface as a colorless gas at brazing temperatures, reduces copper oxide, thus improving the free-flowing qualities of the brazing metal that contains phosphorus.

The brazing metal must not diffuse too freely into the base metal at the brazing temperature, and it must not dissolve too much of the base metal. These properties affect the penetration of the molten brazing metal when it is introduced into the space between overlapping surfaces. The greater the mutual solubility of the two metals at the brazing temperature, the wider must be the spacing of the overlapping surfaces in order to avoid a situation where the brazing metal becomes spent; that is, alloyed with base metal before it penetrates the desired depth. If, however, the spacing is made too wide between the surfaces to be brazed, the capillary attraction becomes too weak to cause the molten brazing metal to penetrate the desired depth, and gravity comes into play. A compromise must usually be made in spacing the base-metal surfaces.

The brazing metal should not dissolve appreciable amounts of gaseous hydrogen, nitrogen, carbon oxide gases, phosphorous oxide gas or water vapor at the brazing temperature. Silver, copper and their alloys with zinc, tin, nickel or cadmium, singly or in combination, are satisfactory in this respect.

Requirements for the Base Metal. The base metal must have a melting point higher than that of the brazing metal.

The surface must be chemically clean, except for flux, at the start of the brazing operation. Oxides, sulfides, graphite or carbon (from grease broken down by the brazing heat or from the heating gases) are all objectionable.

The surface must be free from oxides at the brazing temperature. Aluminum, chromium and beryllium oxides are difficult to flux. However, the formation of these oxides can be prevented to some extent by fluxing before heating. Also, certain fluoride fluxes can usually dissolve enough of the oxides to permit a braze to be made.

Character of the Brazed Bond. The bond between the brazing metal and the clean base metal is obtained by a slight diffusion of the brazing metal into the hot, solid base metal or by surface alloying of the base metal and the brazing metal.

Effect of Brazing Heat on the Base Metal. If the base metal is in the annealed condition at the time it is brazed, an appropriate brazing temperature will cause no harmful change in physical properties. When the base metal is in the work hardened condition (as for example, cold rolled steel, cold drawn copper line or trolley wire) a certain amount of softening occurs in the metal that reaches the brazing temperature.

However, annealing is a function of both time and temperature and, not infrequently, a part of the work hardness and strength can be retained. This is particularly true when a brazing alloy is used that has a low melting point and the time at temperature is brief, as when the oxyacetylene torch is used or when the dip-brazing method is employed.

When precipitation hardening alloys, such as beryllium copper, chromium copper, and duralumin, or quench hardening steels are to be brazed, all the heating processes—solution, precipitation, and tempering—should be considered. A comparison of the heat treating temperatures with the brazing temperature will indicate whether the braze should be made before or after the solution treatment, or after the complete heat treatment, or between the solution and the

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* The cementing metal, not the base metal. "Brazing brass" is a name often applied to the alpha brass made of 75% Cu plus 25% Zn and so-called because it can be brazed with the 50-50 zinc-copper spelter solder, without being melted itself. It is seldom used as a brazing metal.

precipitation or tempering. For example, (1) steel brazed with copper at 2100 F can be reheated to 1400 F for solution of carbide and quenching. If the same steel were brazed with a silver solder at 1450 F, it is doubtful that the reheating could be accomplished without weakening the joint. (2) Chromium copper or beryllium copper cannot be brazed before the solution heat treatment because if they were, the braze would fall apart at the high temperatures employed.

Applications. The brazing process is used where a ductile joint is desired that will have high strength and resistance to fatigue and corrosion, at a reasonable cost. Such joints may be made singly or in mass production in a continuous furnace or heating setup. They are able to withstand higher service temperatures and higher service stresses than are joints sweated with a soft solder. Steel, copper, brass, bronze, cast iron, cast brass and cast bronze are the metals commonly joined by a brazing process. Aluminum alloys are brazed by a special process at temperatures from 1060 to 1185 F. Frequently, two or more base parts are assembled by pressing, spot welding, staking, pinning, jigging, weighting or clamping and are then fluxed, heated and brazed. Often the various parts of the assembly are made of different metals.

Preparation and Design of the Joint. Clean and properly fitted joints are a prerequisite for satisfactory bonding. All surface scale or oxides should be removed by either chemical or mechanical means. Oil, grease and dirt of any description interfere with good work. If the joints are brazed in an atmosphere rich in hydrogen, the hydrogen at brazing temperature will reduce iron, copper, tin and lead oxides but not oxides of zinc, chromium, aluminum and beryllium. Nor will the hydrogen clean off carbon or dirt.

The allowable clearance between the surfaces to be joined will vary according to the alloy used, the type of joint, the method of heating and the metals joined. With free-flowing brazing alloys, such as copper, silver solder, the spelter solders on steel, or the silver solders on base metals of copper alloy, closely fitted joints will give the best results. The maximum clearance should not exceed a few thousandths of an inch. When bronze welding rods are used, it is common practice to make an open V joint and to fill the joint with successive layers of the brazing alloy. However, the closely overlapping or scarfed joint is often made by means of bronze welding rods.

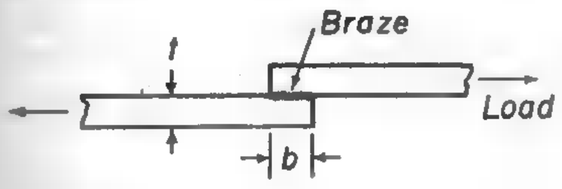

Fig. 1

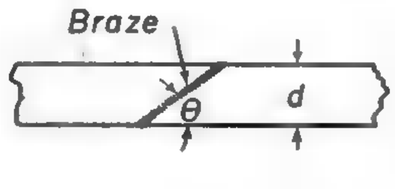

Fig. 2

Fig. 1 A lap braze in sheet metal or flat bars. The dimension *b* is 2 to 3 times *t*

Fig. 2 A scarfed joint in round or flat rods, wire or sheet

When the full strength of sheet metal, or of round or rectangular bars or wires is to be developed by means of a braze in shear, or partly in shear and partly in tension, a common rule is to make the brazed area 2 to 3 times the area of the right section of the base metal (Fig. 1 and 2). In Fig. 2, the brazed area equals right section area/sine θ or for various values of θ the size of the brazed area should be as follows:

θ, degrees	Brazed Area
45	1.4 × Right section area
30	2.0 × Right section area
22½	2.6 × Right section area
19½	3.0 × Right section area

Thus, the angle of the scarfed joint, θ, measured from the axis of the rod, wire or sheet, would be 30 to 19½ deg, if the brazed area is to be made 2 to 3 times the right section area, according to the common rule.

Fluxes. The temperatures required for brazing cause rapid oxidation of the surfaces of the joint and of the brazing metal if these surfaces are exposed to air during the heating. A thin film of oxide will prevent proper bonding of brazing metal to base metal. Hence, the surfaces should be protected with a salt or combination of salts that will help to prevent oxidation and will dissolve or flux any oxides that may form. (A neutral or reducing gas may also be used to forestall oxidation.)

Common borax is a thin fluid at 1400 F and at this temperature it dissolves the oxides of iron, copper, tin, zinc, cadmium, silicon, silver and nickel, but not those of aluminum, chromium and beryllium. It contains approximately 47% water of crystallization, which is driven off when heated, thus causing the flux to "bubble"; therefore, fused borax is generally preferred. If borax is used as a paste, it should be mixed with alcohol, because the fused borax quickly takes up water and becomes common crystalline borax again.

Boric acid is sometimes used alone as a flux, but generally in combination with borax or other salts. Although less active than borax for dissolving oxides of metals, boric acid will spread over the surface at a relatively low temperature and will thus protect the surface from oxidizing during the heating period. Combinations of borax and boric acid are extensively used, particularly with brazing alloys at temperatures higher than 1500 F.

The alkali bifluorides in combination with borax and boric acid are used as fluxes in the joining of metals that have refractory oxides, such as the oxide of chromium on stainless steels, the oxide of silicon on the silicon bronzes, the oxide of aluminum on the aluminum bronzes, or on aluminum or aluminum alloys, and the oxide of beryllium on beryllium copper. The potassium salts are more effective than the sodium salts and, by variation in the proportions of the salts enumerated in this and preceding paragraphs, a wide range of fluxes can be produced to meet the different conditions encountered in brazing.

Many satisfactory prepared fluxes are available, some of which may contain phosphates or halogen salts. Regardless of the particular composition selected, it is most important that the flux be applied in such a manner as to ensure that all oxide films will be removed. Moreover, the flux should be a thin liquid at the brazing temperature, in order to prevent inclusions, which will subsequently give trouble. The surfaces both of the joint and of the brazing alloy should be protected with flux to produce the best results.

The flux may be used dry, in paste form, or in a saturated solution. When used as a paste or as a hot solution, the flux should be brushed over the surfaces before they are heated. Thus a more uniform coating can be obtained and there is less chance for bare spots that will oxidize during the heating. When the brazing alloys are in granular form, it is common practice to mix the flux with the alloy before spreading along the joint. Strip, wire and rods may be coated with flux before they are used, or the end may be dipped into a small can of flux paste just before applying flux to the joint, or the rods may be heated and the dry flux sprinkled on them.

In the process known as "copper-hydrogen brazing", a furnace or blowpipe atmosphere, rich in hydrogen, is used in the absence of a flux. The hot hydrogen has the effect of reducing the less refractory oxides, such as those of iron, copper, tin, nickel and manganese, or of preventing their formation. The refractory oxides of aluminum, beryllium and chromium are more difficult to reduce with hydrogen or to dissolve with flux. Special fluxes, usually with additions of one or more fluorides, are frequently required. Fluxes are also used with brass.

Methods of Heating. There are several different methods of supplying the heat necessary for brazing.

Dip Brazing. In dip brazing, the alloy is melted in a refractory container and covered with flux to prevent oxidation. The parts to be brazed are assembled in a suitable jig to hold them in position and are dipped into the molten alloy. Sometimes a preheat is employed. The size of the bath of metal must be in proper proportion to the work. The bath may be heated by any of the methods used with pot furnaces.

Salt Bath Brazing. Another kind of dip brazing can be done in the salt bath type of furnace. First the parts are assembled and the solder is applied to the joints; then the articles to be brazed are immersed in the bath of molten salt. (*See* page 283.)

Torch (Blowpipe) Brazing. Different types of blowpipes or torches are used, including air-gas, oxygen-gas, oxyacetylene and oxyhydrogen. The high temperature of the oxyacetylene flame allows rapid heating, which is an advantage. A neutral or slightly reducing flame should be used in general, although for some types of bronze welding a slightly oxidizing flame is recommended.

Furnace Brazing. The furnace should be large enough to allow rapid heating, and whenever possible the temperature of the furnace should be considerably higher than the melting point of the brazing alloy. If the assembly consists of many parts, care must be taken to regulate the temperature so that all the joints reach the brazing temperature at approximately the same time.

Electrical Resistance Brazing. The electrical resistance method is used for small parts or for other parts where a thin sheet of the brazing alloy can be inserted into the joint. This method has the advantages of localizing the heat and working quickly. Frequently the principal part of the heat comes from the carbon electrodes, which are in contact with the work material.

Brazing by Induction Heating. In another form of electrical heating, the assembled parts are surrounded with a coil through which a high-frequency current is passed. The currents induced in the parts provide a quick, clean method of heating.

Multiple Gas-Burner Brazing. Rows of gas burners between which the assembled parts may be passed afford another quick and uniform method of heating.

Types of Brazing Alloys. The selection of the best brazing alloy for a given joint depends on many different factors. Since the brazing metal must melt at a temperature lower than the melting point of the base metal or metals to be joined, the melting points of the brazing alloys give a basis for two broad classifications, as mentioned in the early part of this article:

Class I Silver brazing alloys or silver solders
Class II Brass and nickel silver brazing alloys
Copper and copper alloys and brazing rods

A general description of these two groups follows:

*Silver Brazing Alloys.** Ternary alloys of silver, copper and zinc in varying proportions have been used for many years as brazing alloys and are commonly called "silver solders". The addition of silver to binary copper-zinc alloys lowers the melting point; thus a series of alloys can be made that will flow freely at temperatures from 1250 to 1600 F. (*See* CONSTITUTION OF ALLOYS.) Other metals used in making silver brazing alloys are cadmium, tin, nickel, manganese and phosphorus.

Because of their strength, low melting points, free flowing properties and resistance to corrosion, these silver brazing alloys are used extensively on nearly all nonferrous metals and alloys and on steels and iron. The strongest joints are made with small clearances, not more than three or four thousandths of an inch for best results. Such joints withstand severe shock and vibration.

The silver-copper-phosphorus eutectic melts at 1190 F and a self-fluxing alloy containing about 2.5% less phosphorus than the eutectic is used for brazing copper. This alloy, which flows freely at 1300 F, is available as thin-gage sheet, small rods and wire. With brass and other alloys, only a small amount of flux is required. Borax can be used as a flux but special fluxes, more fluid than borax at 1300 F, are preferable.

In general, the use of silver brazing alloys should be considered where the higher temperatures required for other brazing alloys might cause excessive grain growth or damage to the metals to be joined, and where strong ductile joints are necessary. Silver brazing alloys can be obtained in all sizes of wire and gages of sheet, as well as in filings and powders of different sizes, making it possible to apply the most convenient and economical form for the particular use.

Table I gives a list of 15 of the common alloys that are used.

Table I. Silver Brazing Alloys

	Composition, percentage						Melting Point, deg Fahr	Flow Point, deg Fahr
	Ag	Cu	Zn	Cd	P	Sn		
1	10	52	38	....	....	....	1450	1565
2	20	45	35	....	....	....	1430	1500
3	20	45	30	5	....	....	1140	1500
4	45	30	25	nil	....	....	1250	1370
5	50	34	16	nil	....	....	1240	1425
6	65	20	15	nil	....	....	1240	1305
7	70	20	10	nil	....	....	1335	1390
8	80	16	4	nil	....	....	1330	1490
9	50	15.5	16.5	18[a]	....	....	1160	1175
10	15	80	..	....	5[b]	....	1190	1300
11	30	38	32	....	....	....	1370	1410
12	40	36	24	....	....	....	1330	1445
13	60	25	15	....	....	....	1260	1325
14	72	28	..	....	....	....	1435	1435
15	56	22	17	....	....	5[c]	1165	1200

(a) Proprietary alloy, "Easy Flo"
(b) Proprietary alloy, "Sil Fos"
(c) Proprietary alloy, "Ready Flo"

The first eight alloys in Table I are taken from the ASTM Standard Specification for Silver Solders or Silver Brazing Alloys. They represent the range of composition of the old standard silver solders, which were considered to cover ordinary requirements and to eliminate a large number of compositions that really served no useful purpose. The following addenda are given with these specifications, which are still in common use:

The addition, not to exceed 0.50%, of Cd to assist in fabricating the first and second items shall not be considered as harmful impurity.

Items 1, 2 and 3 are suitable for brazing purposes which require a solder that flows more readily than the ordinary copper-zinc brazing solders.

Items 4 and 5 flow freely at a still lower temperature and are recommended for use where strong joints are required and in cases where heating to a sufficiently high temperature to flow items 1, 2 or 3 would be injurious to the article being soldered. Items 6, 7 and 8 are higher grade silver solders and are recommended for special cases where a high degree of malleability and ductility is required.

It is evident that a large number of variations are possible, but except for some special purpose, a selection from

* For additional information concerning the properties of silver brazing alloys, see page 1113, in the PRECIOUS METALS SECTION.

Table II. Brass, Nickel Silver and Copper Brazing Alloys

Brazing Alloy	Melting Range, deg Fahr		Composition, percentage			Remarks
			Copper	Zinc	Others	
ASTM 50–50	1595	1620	50 to 53	Remainder	0.50 Lead, max	Common spelter solders, brass yellow color, in granulated and lump form for general brazing
ASTM 52–48	1600	1620	52 to 53	Remainder	0.50 Lead, max	
Spelter bronze	1575	....	Remainder	45	3 to 5 Tin	Pale yellow in granulated or lump form for special work. Harder than ASTM grades
Black button	1385	1440	Remainder	57 to 65	5 to 9 Tin	Gray to black, granulated, moderate strength. Contains 1% Fe
White spelter solder	....	1600	Remainder	55 to 59	7 to 9 Nickel	White, granulated form, match for nickel silver, cupro-nickel and the like
Phos-copper	1304	1526	93	Remainder	Phosphorus	Rod or strip for self-fluxing brazes on copper. Gray color.
White brazing rod	....	1700	47	42	11 Nickel	High-strength brazing rod
Yellow bronze	1595	1625	Remainder	42	0.5 Tin	General-purpose brazing or bronze-welding rod
Copper	1981	2050	99.9	....	....	Tough-pitch or deoxidized copper in wire, granulated, or electrodeposited on steel for brazing in a hydrogen atmosphere

the above list should be satisfactory. In recent years, the alloys with lower melting points have been widely used; however, the alloys containing lower percentages of silver and having higher melting points are still in common use. In selecting a suitable brazing alloy, it is necessary to consider all factors and then to determine which alloy will give the most economical and satisfactory results. The alloys with lower melting points have the advantage of providing a greater factor of safety, making it less likely that the parts to be joined will be overheated and thus damaged. The use of alloys with lower melting points also shortens the time required for making the joints.

The 72-28 Ag-Cu alloy in the above table is commonly used where the presence of a volatile metal such as zinc or cadmium might be harmful.

Brass and Nickel Silver Brazing Alloys. Brass brazing alloys, generally known as "spelter solders" or "brazing solders", are alloys of copper and zinc in about equal proportions and occasionally contain smaller amounts of tin and nickel. These brazing solders are ordinarily applied in powder or granulated form often mixed with flux, and they are melted by heating the several parts to be brazed, just higher than the melting point of the brazing solder. At this temperature the solder becomes fluid and runs readily between the contacting surfaces, alloying and bonding them together in a manner similar to soft and silver soldering. Dip brazing is also widely used. In this method, the parts to be brazed are first clamped together suitably in the desired positions, are fluxed and sometimes preheated, and are then dipped into a molten bath of the brazing alloy.

From the compositions given in Table II many variations are possible. However, the nine alloys listed are representative. Additional information is given in the article on "Welding Processes" under the heading Bronze Welding.

Brazing solders are supplied in various forms from fine to coarse powders; lump and rod forms are also occasionally used. The lumps are generally melted in a pot for dip brazing, while the rods are more conveniently applied with the oxyacetylene torch.

The ASTM 50-50 copper-zinc spelter solder is the most common of these brazing solders. The white spelter solder is used principally because the color matches that of nickel silver, cupro-nickel or steel.

The black button solder is used where an inexpensive solder of moderate strength and melting range is desired.

The phosphorus-copper alloy is seldom used on any base metal other than copper.

The white and yellow brazing (or bronze-welding) rods are generally used to make a fillet or to fill an open V.

A cupro-nickel alloy is occasionally used instead of pure copper for copper-hydrogen brazing and for the brazing of steel articles that must withstand elevated temperatures.

Fluxes for these alloys are, in general, the same as for silver solders. Fused borax or a mixture of fused borax with boric acid is satisfactory for most purposes. The finer powdered spelter solder is often mixed into a paste with the flux before application to the joint. The paste should be mixed with water-free alcohol or, if it is to be used immediately, with boiling water.

Joints are often brazed in a furnace. If the furnace has an air or burned-gas atmosphere, a flux is necessary on the joint with the brazing alloy. However, electrically heated furnaces with atmospheres rich in hydrogen are in common use. In such furnaces no flux is required, since hydrogen will exclude oxygen and reduce any scale that may be on the metal. Pure copper, in powder, sheet, wire or electroplated form, is most often used. The copper will penetrate long distances between closely overlapping steel surfaces and make a strong, ductile joint.

As with the silver solders, electrical heating by carbon resistor electrodes or induction heating is often preferred.

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Soldering With Soft Solders

By George O. Hiers* and E. E. Schumacher*

THE USE and application of solder alloys, such as lead-tin, lead-tin-cadmium and others, are discussed in this article. Attention is given to varieties of metals that can be soldered, type of fluxes and soldering techniques.

Definition. The alloys mentioned are generally referred to as "soft solders", distinguished from "hard solders" (brazing solders and silver solders), which are described on page 78. The term "soft solders" in this discussion is restricted to alloys that are fusible at temperatures below 700 F, whereas the hard solders are fusible above approximately 1200 F. One of the distinctions between a soldered joint and a welded joint is that in the former, the metals to be joined are not heated to their melting points. Consequently one of the requisites for a solder is that the melting point must be lower than that of the metals being joined.

Materials Soldered. Solders are employed for joining cast or fabricated metals of various compositions. These are principally iron, copper, nickel, lead, tin, zinc, and many of their alloys. Even such materials as glass and porcelain may be joined by soldering, after their surfaces have been coated by metal spraying or other suitable processes.

Solder Compositions. In general, solders are lead-tin alloys with or without the addition of other elements. Table I lists the more common alloys. For many joining operations tin is the major alloying or wetting ingredient. As shown in the phase diagram, melting points are obtainable that are lower than those of either tin or lead. In many cases, the greater the tin content, the more rapid the wetting of the metal to be joined by solder and the more rapid the melting. Within certain limits the useful physical properties are also improved by increased tin content. Where a plastic range under solidifying conditions is required, as in a wiping solder, the selection of alloys is necessarily limited.

Under postwar conditions the use of tin is restricted by various government tin conservation orders. In general, the wartime emergency solders have been satisfactory, although more time and care are required for their application. It has been found difficult to make hermetic seals by using the low-tin solders.

Fundamentals. For good soldering work these rules should be followed:

1 It is essential for a solder to wet or alloy with the metal surfaces on which it is applied.

2 The metal surfaces to be soldered must be clean, free from foreign matter and objectionable grease.

3 The flux should be molten, preferably at temperatures below the solidus point of the solder, in order to insure activity, maintain a continuous film and minimize entrapment in the solder. Gaseous fluxes, such as chlorine or hydrochloric acid gas, have been used to a limited extent to reduce flux inclusions.

4 During soldering, the metal surfaces must attain a

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temperature above the solidus point and preferably above the liquidus point of the solder.

5 All traces of corrosive fluxes should be removed with particular care after the joints have been made.

Selection of a Solder. Most of the solders in Table I will wet all common metals with the exception of aluminum and magnesium. The selection of the particular alloy will depend on permissible temperatures, method of application, physical properties required, economic considerations and governmental restrictions. Table I is a guide.

Preparation for Soldering. Parts should be free from foreign matter and excessive grease. In electrical assemblies copper conductors are often sufficiently clean to permit soldering with rosin flux, without previous treatment. Where tarnish is present, removal by abrasion or chemical means is necessary. Other metallic materials, particularly ferrous parts, require either mechanical abrasion to remove oxides, or cleaning by chemical means. The effectiveness of any soldered joint depends on cleanliness of the surfaces.

Fluxing. For practical purposes, it is generally necessary to use a flux when soft soldering. The chief functions of a flux[1] are to remove mild oxide, to prevent oxidation of the surfaces, to dissolve oxides that may form on these surfaces while they are being heated to the soldering temperature, and to promote the mutual contact between atoms of the solder elements and atoms of the metallic elements to be joined. The flux should be fluid at the temperature of molten solder and should be applied in such a way that by gravity, capillarity or other forces, the solder can displace the flux at the joint.

Mild fluxes, such as rosin, tallow, and stearin particularly, prevent oxidation but are not very effective in removing oxides already present. Zinc chloride, with or without the addition of ammonium chloride, acts both as an oxidation preventive and as a scavenger. Zinc chloride has a melting point of 504 F and the eutectic mixture of zinc chloride with ammonium chloride (71% $ZnCl_2$, 29% NH_4Cl) has a melting point of 354 F, which is slightly below that of many lead-tin solders. Hydrous zinc chloride acts as a flux, thereby permitting soldering below the melting point of the anhydrous chloride. It is generally agreed that the addition of ammonium chloride improves the effectiveness of this flux. A popular paste flux contains about 75% petroleum jelly, 20% $ZnCl_2$, and 5% NH_4Cl with a small amount of water as an emulsifying agent.

In the consideration of new fluxes, attention should be directed to the kind of metals to be joined and to their massiveness. Ordinarily more heat is required for soldering iron or steel than for soldering lead. Whenever a soldering iron is used for large parts, the heating is localized and the heat may be conducted away rapidly; consequently the tool must be exceptionally hot when the article is not preheated. In such situations, the use of rosin as a flux would be unsatisfactory, since this material carbonizes at these higher temperatures, thereby preventing rather than aiding soldering. It is nearly always desirable to tin large metal parts individually before assembling them for soldering together. This preparation facilitates the soldering and makes stronger joints. Preheating is sometimes desirable. Before soldering cast iron, the use of a cold

Table I. Alloys for Soldering and Some of Their Uses[a]

Nominal Compositions, percentage						Melting Range, deg Fahr		
Tin	Lead	Antimony	Bismuth	Silver	Other	Solidus	Liquidus	Uses and Comments
5 to 20	95 to 80	....	....	....	....	570 to 361	595 to 525	For coating and joining metals. For high temperatures and differential soldering.
45	Rem	....	....	....	....	361	439	For automobile radiator cores and hand-soldered electrical connections. Also a sweating solder.
50	Rem	....	....	....	....	361	419	General-purpose solder
38	Rem	....	....	....	0.1 As (max)	361	458	Wiping solder for joining lead pipes and cable sheath
35	Rem	0.5	....	....	....	361	473	General-purpose solder having maximum tin content allowed by order M-43. Also a sweating solder.
60	40	....	....	....	....	361	368	"Fine solder", used where temperature requirements are critical
38 to 40	Rem	....	....	....	....	361	464 to 458	Wiping solder. Also for automobile radiator cores and soldered electrical connections.
23	Rem	....	....	....	9 Cd	294	455	Wiping solder
15 to 35	Rem	....	....	....	....	439 to 361	547 to 473	Low-tin solders. Automobile body solders.
32	Rem	2	....	....	0.1 As (max)	367	466	Emergency wiping solder for joining lead pipes and cable sheath
13	Rem	0.5	23	....	0.1 As (max)	207	415	Wiping solder for joining lead pipes and cable sheath
50	32	....	....	....	18 Cd	294	294	For fusibility and safety devices
16	32	....	52	....	....	203	203	For fusibility, safety and fire prevention devices
13	27	....	50	....	10 Cd	158	158	For fusibility, safety and fire prevention devices
None[b]	Rem	....	....	2.50	....	579	579	Emergency solder. For use where a high melting point is desirable. SAE E07
2 to 5	Rem	....	....	....	....	573 to 518	607 to 594	Dipping or coating metal
4	Rem	3.5	....	....	....	467	554	Automobile body solder
1	Rem	....	....	1.5	....	589	589	For sealing tin cans and for "high"-temperature use
95	....	5	....	....	....	450	464	Sweating copper tubing joints
....	Rem	12	....	....	0.5% As	476	478	For joining ferrous parts. For filling joints in automobile bodies
....	....	....	....	5	95 Cd	639	734	For "high" temperatures
....	....	....	....	....	50 Cd 50 Zn	508	619	For "high" temperatures
....	....	....	....	....	82.5 Cd 17.5 Zn	508	508	For "high" temperatures

(a) The above solders represent typical compositions and uses. The classifications are informative and not complete or restrictive. In the trade, solder designations usually give the tin content first and the lead second; for example, 40:60 means 40% Sn, 60% Pb.

ASTM Tentative Specifications B 32–46T employ a system of designations illustrated by the following example:

"Alloy Grade 40A" refers to nominal 40 Sn, 60 Pb, 0.12 Sb max
"Alloy Grade 40B" refers to nominal 40 Sn, 60 Pb, 0.50 Sb max
"Alloy Grade 40C" refers to nominal 40 Sn, 60 Pb, 2.0 Sb max

(b) This solder is known to be sensitive to corrosion in outdoor environments.

pickling bath of 5% HF is recommended.[2] A more effective method is to use some process wherein the cast-iron surface is first decarburized, then fluxed and soldered.[3]

The selection of fluxes is controlled by the design of the joint, the materials to be joined, and the efficiency with which corrosive fluxes can be removed. In general, ferrous parts cannot be soldered effectively by using mild fluxes, such as rosin, tallow and the like. An active flux is required, such as zinc chloride, zinc chloride–ammonium chloride, or phosphoric acid. Where parts cannot be subjected economically to neutralization of flux or removal of flux after soldering, they should be tinned with the use of corrosive flux, which is neutralized or removed before assembly, thus making the use of a noncorrosive flux possible on final assembly soldering. In the electrical industry, rosin is used ordinarily for fluxing in joining conductors. Some of the other fluxes (for example, tallow) decompose during the soldering operation, giving weak organic acids that ultimately corrode conductors. Stearin, containing 10% oleic acid, is widely used as a flux for lead and many lead alloys. Iron, steel, zinc or galvanized iron general require an active flux for soldering.

Methods of Application. Most common metals and their alloys may be joined readily by means of solder. The method of applying solder to the metals to be joined varies according to the character of the metals, their position, the size of the parts, the speed with which the operation must be completed, and the shape, tensile strength, and appearance required in the finished product. In every instance, the surfaces to be soldered must be brought to the melting temperature of the solder. The necessary heat may be obtained in one of the following ways: by molten solder being poured repeatedly over the surfaces to be joined, as in the wiping method; by the use of a soldering iron; by the use of a torch; by a solder bath; by electric induction heating; by electric resistance heating; or by a stream of hot neutral gas.

Wiping Methods. Wiping is used for joining sections of lead pipe, or lead pipe with brass, bronze or copper fittings; and for joining lead-covered electrical cables, using a lead sleeve. After the cleaning and fluxing procedures, the parts to be joined are heated to the soldering temperature by the careful pouring of molten solder over the joint area. The operator catches the extra solder, which runs off the joint onto a cloth pad, and holds it against the underside of the joint. To effect uniform heating, the solder that is caught is frequently wiped up and around the joint and fresh hot solder is poured over the joint, until it is heated above the solidus temperature of the solder and completely tinned. The plastic, semimolten mass is then manipulated by using wiping cloths to give the joint the desired shape. Old practice required the building of a large mound of solder at the joint. More recent experience in joining lead cable sheath has shown that only a fillet[4] of solder is required for joint tightness.

Stearin in stick form, containing 10% oleic acid, is generally used for fluxing in wiping joints. Plumbers' wiping cloths are sometimes impregnated with tallow or lard oil, which acts as a flux.

Most of the wiping solders used in this country for making joints on pipes or cable sheathing contain 58 to 70% Pb with the remainder tin, although some users prefer the addition of 2% Sb or less. These alloys have a solidification range of about 140 F and contain a considerable quantity of eutectic. The combination of these two factors makes possible the wiping of joints.[5] Other wiping solders are shown in Table I.

Use of a Soldering Tool. A soldering tool is ordinarily referred to as a "soldering iron" and sometimes as a "soldering copper". It is ordinarily made of copper, even when called an "iron". Before the tool can be used efficiently, it must be "tinned" or coated with solder and kept clean.

For making electrical connections, an electrically heated soldering iron is used almost exclusively. Such irons are available in various sizes, with tips made of copper or iron-clad copper. The tool is heated to a temperature high enough to melt the solder quickly, and is drawn at such a rate along the edges to be joined that the momentary high temperature of the edges, together with the rapid melting of the solder, promotes good wetting and aids in the formation of a tight seal. Proper fluxing facilitates transfer of heat in the melting of the solder. Flux-cored solder wires are widely used for efficiency.

The soldering iron serves also in other work where the use of a flame or the pouring of molten solder over the surfaces is prohibitive, because of the fire hazard.

Use of a Torch. Where parts to be joined are too large to be heated by a soldering iron, or are shaped in a way that would make rapid soldering difficult, heating is accomplished by playing the flame of a torch on adjacent surfaces and then applying the solder cold, in bar or wire form of appropriate cross section. Flames should not impinge directly on the fluxed surfaces. The heated surfaces melt the solder and excess solder is removed by wiping before complete solidification. This method is commonly employed by electrical workers for soldering wire joints and sweating on lugs. Plumbers use this procedure with copper water-pipe sleeve couplings.

Solder Bath. Where parts are numerous and can be assembled in a jig, soldering can be accomplished by immersion in a bath of molten solder.

The soldering of automobile radiators is a good illustration of this procedure. The radiator cores, assembled in frames and tightly clamped there, have their tube ends dipped into a solder bath just deep enough to form the required joint. For making up the bath, the solder may be purchased in the form of slabs weighing from 15 to 35 lb. Popular compositions for the bath are 50% Sn, 50% Pb and 40% Sn, 60% Pb, although compositions outside these limits are used.

The soldering of side seams in tin cans is another good example of commercial technique. The cans are carried by a chain belt. The side seams contact a solder-coated roll, picking up some adherent solder that is being carried out of a solder bath in which the roll is partly immersed. In a modern machine 300 cans per minute can be soldered in a single stream or procession.

The leads from the glass envelope of vacuum tubes are joined to the base prongs by immersion in a solder bath.

Induction Heating. Many soldered joints are made by heat supplied by high-frequency inductive means. This method is most effective on ferrous materials but is economical only where equipment is available or production large. Parts should be cleaned, set in a jig and fluxed, and the solder should be placed and adequately shaped for the areas to be joined. Solder wire with flux on the outside may be used. The heating unit consists of copper tubing that is located near the areas to be heated, and situated in such a way as to permit easy arrangement around the work surfaces. In heating sections that require anything more than a minimum power for a short period, water cooling is required in the heating coil. A frequency of 500 kc is often used for these applications.

Resistance Heating. Where small lapped areas are to be soldered, it is sometimes economical to use electric currents to supply the heat. The conditions are similar to those necessary for spot welding, with the current at a considerably lower value. The solder must be placed and some flux used. Shaped carbon blocks serve as electrical contact materials.

Stream of Hot Neutral Gas. In certain delicate soldering operations, a stream of heated nitrogen is used to heat the parts to the soldering temperature. Preplaced solder has been found satisfactory with or without flux, depending on conditions.

Other Methods. In soldering many specialties, the usual soldering methods are often modified or combined, and special tools are devised to fit special conditions. However, no new principles are involved in these special practices.

Neutralization. Where corrosive fluxes are used it is essential, in order to avoid corrosion hazards, to remove the excess flux and flux residues from the parts by any one of a number of methods. Since most corrosive flux and flux residues are soluble in water, thorough rinsing of fluxed parts, preferably in hot running water, is effective. A solution of 5 oz of sodium citrate per gallon of water is effective on nonferrous parts, or only 1 oz of trisodium phosphate per gallon of water on either ferrous or nonferrous parts. These treatments should be followed by a

dip in clean water. The immersion time required will vary with the nature of the joint. Exposed joints will be cleaned in a shorter time than complicated assemblies. The immersion time should be approximately 5 to 20 min. On electrical connections soldered with chloride-bearing flux, extreme care should be used in the elimination of excess flux and residues. Where aqueous solutions are objectionable, as on some electrical parts, alcohol washes may be employed.

Maintenance of Molten Solder Bath. A pot of solder should never be heated beyond the necessary working temperature. On large work, where much heat is required to bring the work to proper temperature for efficient soldering, it is better practice to supply this heat by means of a large volume of solder at about the usual soldering temperature than to raise the temperature of a small pot of the solder unusually high.

As the temperature of the molten solder rises, the surface exposed to the action of the air is oxidized to an increasing degree, unless protected by a reducing material, such as charcoal.

Overheating solder in pots causes considerable dross and should be avoided. Dross may be skimmed off at a moderate temperature. A small amount of ammonium chloride stirred into the dross minimizes solder losses during cleaning.

During solidification of 35:65 or similar solder, the primary crystals of lead sink to the bottom of the melting pot, because of their greater density, and permit the lead-tin eutectic to segregate toward the surface. To insure uniformity of composition, the solder must be kept at a temperature higher than the liquidus temperature of the alloy, and must be thoroughly stirred after melting.

Mechanical Properties. Nightingale's tests[6] show 0.003 in. as a desirable thickness for a solder film on copper, and 0.005 in. on steel. Crow[7] previously indicated that the thinner the solder film, the stronger the joint.

The National Bureau of Standards[8] has investigated seams for copper sheeting. It was decided there that lap seams should be at least ¾ in. wide. For such a seam the maximum safe load was placed at approximately 350 lb per sq in. of seam area. The corresponding load for ½ in. previously tinned, flat lock seams was 375 lb per sq in. of seam area. A 50:50 solder was used for the tests.

For automobile radiator cores of the honeycomb type 40% Sn, 60% Pb solders are favored because of their supposedly greater resistance to vibration fatigue. Data for endurance limits are not available.

A 5% Sn, 95% Pb alloy has become fairly popular for use in joints maintained at 250 F under stress, as shown in Table II. The alloy containing 1.5% Ag, 1% Sn, 97.5% Pb is excellent for this application.

Table II. Shear Strength of Soldered Copper Sleeve Joints

Nominal Composition of Solder						Strength at 85 F (Quick Test)	Maximum Allowable Prolonged Stress		
Pb	Sn	Ag	Cd	Zn	Sb	psi	85 F psi	250 F psi	325 F psi
95	5	..	..	..	..	3000	590	215	160
60	39	..	..	..	1	5700	260	90	...
95.3	..	4.7	..	..	..	2900	800	220	105
97.2	..	2.8	..	..	..	2900	800	220	105
85.4	..	..	14.3	0.3	..	6000	740	...	90
■	..	..	17.5	0.5	..	6000	740	...	90
50	50	..	..	..	..	5500	235	80	...
..	95	..	..	..	5	6200	1200	380	275

The National Bureau of Standards has also studied the strength of soft-soldered copper-tube sleeve joints.[9,18] The data in Table II are illustrative of the strength of soldered joints in general. By enlarging the dimensions, soldered joints may be designed to have greater strength than the parts that are united. The studies conducted by investigators at the Bureau indicate that solders containing quantities of tin should not be used on copper joints maintained at temperatures higher than 250 F.

Since solder is frequently used to join metals stronger than itself, seams must be reinforced by crimping, interlocking, riveting, or bolting before soldering,[10] in order to insure high strength. Thus a joint can be made stronger by relieving the solder of the load and making the major function of the solder the hermetic sealing of the seam. Soldering frequently helps in making efficient, electrically conductive joints.

Miscellaneous Notes. Aluminum may be soldered with alloys rich in tin that contain also considerable zinc. One method is to rub the aluminum surface beneath molten solder, thereby piercing the oxide film and permitting the solder to alloy with the aluminum.[11,12,17] Brazing or welding aluminum is usually preferred to soldering.

When soldering stainless steel, ample time should be allowed for the flux to act properly before the solder is applied. For this purpose either zinc chloride–ammonium chloride flux containing hydrochloric acid, or orthophosphoric acid flux is satisfactory.

For soldering zinc or galvanized iron, the presence of antimony in the solder is undesirable, because with zinc, antimony forms a compound difficult to fuse, thereby interfering with the flow of the solder unless the soldering is done rapidly. A similar reaction occurs when high-antimony solders are used on copper.

Some pastes and powders on the market are composed of pulverized tin or solder mixed with flux. Tubular solder wire is quite popular, with one or more cores containing rosin or other flux. A new variety is soft solder wire containing flux in grooves in the outer surface.[13] Adequate amounts of solder should be used in joints, but economy suggests using no more than enough. To aid the consumer in the economical use of soldering materials, manufacturers offer suitable forms and dimensions of solder. Some of the forms obtainable are tinner's bar, triangular bar, meter bar, ingot, wire in spools or in segments, drops, capping bar, slabs, powder, tape, ribbon and miscellaneous forms.

The time required to make a good soldered joint may preferably and actually be extremely short. Prolonging the period of time in which the solder in a joint is molten may increase the amount of alloying, but the effect is not generally considered beneficial. For soldering copper, it is advisable to use a temperature lower than 752 F, in order to reduce the formation of brittle copper-tin compounds that tend to decrease the strength of a joint.

Related Articles in This Handbook. For more specific information concerning the soldering of nonferrous metals, see the following articles: Joining Aluminum Alloys, Joining Copper and Copper Alloys, Joining Lead, Joining Magnesium Alloys, Joining Nickel and Nickel Alloys, Joining and Cladding of Precious Metals.

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MECHANICAL TESTING

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Mechanical Property Tests of Metal Products

BY R. L. TEMPLIN*

THE mechanical property tests most commonly used in evaluating the quality of metal products include the tension, hardness, torsion, notched-bar impact, and some type of bend test. Other types of tests may be used, depending on the particular product or its intended application. Generally, the values obtained from such tests pertain specifically to the samples selected. It is essential, therefore, to select samples properly if the test data are to be closely representative of a metal product.

Uses of Data From Mechanical Property Tests. One of the primary purposes, in making mechanical property tests of metal products, is to determine conformance or nonconformance with specifications. The data may thus serve as an index to the quality of a product in comparison with similar products obtained previously or from other sources. Such data may also be used for comparison of a given material with other materials and, in conjunction with other factors, may assist in satisfactory replacement or improvement of a material. Manufacturers of metal products frequently use such data for control of manufacturing methods as well as for guidance in the development of new materials. Finally, one of the major uses of mechanical property values is to furnish a basis for the selection of values for engineering design.

Sampling. Metal products often exhibit variations in their mechanical properties, caused by unavoidable variations in the details of the commercial processes used in the manufacturing of the products. Although knowledge of the scope of these variations may be of considerable interest to both the producer and the user of the products, yet in most specifications for metal products, the primary purpose of the mechanical property tests specified is to furnish evidence that the piece of product sampled and tested has as good quality as similar pieces previously furnished. It is assumed that the piece selected for testing represents adequately the other pieces in a given lot. On this basis, specifications for products frequently indicate quite definitely from exactly what location in the product, as well as from how many pieces, specimens are to be taken for mechanical property tests.

Not all tests of mechanical properties require that pieces or coupons be taken from the sample selected. For example, most of the hardness tests can be performed on the sample selected, without destroying the sample or preventing its subsequent use in service. With such nondestructive types of mechanical property tests, it is possible to test every piece in a lot of material. However, mechanical property tests such as the tension, compression, bending and notched-bar types, require taking of samples, and it is important to select the method of sampling that will furnish the desired information.

For metal castings three sampling procedures are avail-

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Prepared for the Subcommittee on Mechanical Testing.

able: test coupons may be cut from sample castings, separately cast or attached test coupons may be used, or sample castings may be tested as a whole. Data concerning the mechanical properties of test coupons that have been cut from a given location in a casting may give a reliable indication of the mechanical properties of the casting in that particular location but, in general, these data will not represent the properties at other locations in the casting. Likewise, separately cast or attached test coupons cannot be expected to represent closely the properties throughout a casting, particularly if there is a marked difference between the dimensions of the casting and those of the coupon. The separately cast and attached test coupons, however, do serve in many instances as a satisfactory index of the quality of the casting they represent. Proof tests or maximum load tests of selected sample castings, wherein the method of testing as well as the amount of load can be agreed upon, often furnish satisfactory data for use as a basis of acceptance or rejection of the product. For further information about the method of sampling to be used for metal castings, the reader is referred to the article "Mechanical Testing of Castings", page 136.

In general, the sampling of wrought metal products involves fewer difficulties than the sampling of castings. This is particularly so for sheet, plate, bar, wire and tubular products. However, variations in the mechanical properties of sheet and plate may be expected, depending on whether the specimens are taken parallel or normal to the direction of rolling, as well as whether coupons are taken from the center, near the edge, or near one end or the other of large pieces. Large forgings often present problems in sampling similar to those found in the testing of castings. Product specifications intended to insure the quality of such products should, therefore, indicate the type and location of test specimen in sufficient detail to be used in determining the acceptability of the product.

If the purpose of the mechanical property tests to be made is to assist in the selection of a new material, or in the development of new manufacturing processes or changes in present processes, the sampling should be extensive enough to explore adequately the variations occurring in the material or product. In such instances, it is usually not necessary to save the sample item being tested, and the tests called for in standard specifications pertinent to the product are supplemented by those additional tests necessary to explore the sample thoroughly.

Test Specimens. Specimens for mechanical property tests are prepared from test coupons or samples and ordinarily have empirical dimensions for size and shape which, by general consent, have come to be recognized as standard. Because changes in size and shape affect some of the mechanical property values appreciably, it has been found necessary to put mandatory requirements for specimen dimensions into specifications for metal products. Compliance with these requirements is essential if the test data are to be mutually satisfactory to producer and user, and if a comparison is to be made with data from similar items.

Since variations in the methods used in preparing test specimens may have considerable effect on the test data, it is essential that careful and uniform procedures be followed in machining and finishing test specimens. Procedures should be used that will not cause temperature changes or distortions which, in turn, would affect appreciably the mechanical property values.

Mechanical Testing Apparatus. Most apparatus for testing mechanical properties consists essentially of a machine for applying a force or load to a specimen in a prescribed manner, a means whereby the force or load applied can be measured within acceptable limits, and a means for measuring deformation of the specimen. In all such equipment the errors involved in the indicated values for force, load or deformation should be within specified limits, generally given in specifications for standard testing methods. To insure the continued maintenance of such equipment, standard methods of calibration of apparatus have been developed and accepted, such as those found in specifications of the American Society for Testing Materials.

The Preparation of Test Specimens

By R. L. Templin*

THE proper preparation of test specimens from samples of metal products requires careful attention to the details of the procedures involved, if satisfactory test data are expected. Given a sample of a metal product, the problem presented is to prepare from the sample the desired size and shape of test specimen in the most economical manner and without appreciably affecting the mechanical properties of the material of the sample. If the sample or specimen coupon has been cut from the product by means of the cutting torch or by shearing, the metal adjacent to the cut edges, which has been affected by the cutting heat or cold working, must not be included in the portion of the test specimen that directly governs the test data to be determined. The amount of metal to be removed adjacent to heated or cold worked edges will depend on a number of factors, but primarily on the size of the article from which the coupon is taken and the kind of metal. The kind and size of cutting torch that is used may also be important. In the preparation of coupons sheared from sheet or plate, an approximate safe rule to follow is to remove an amount of metal equal to the thickness of the sheared material; that is, if the coupon was sheared from plate ¼ in. thick, ¼ in. of metal adjacent to the sheared edge should be removed between the sheared edge and the edge of the reduced section of a tensile specimen.

Care must be used in trepanning specimen coupons so as not to induce objectionable stresses in them. When this is unavoidable, provision is sometimes made for stress-relieving procedures that depend on the material and on agreement between supplier and purchaser.

Tensile Specimens. The most widely used types of tension test specimens for sheet, plate, strip, and thin-wall tubular metal products with large diameter are those shown in Fig. 1 and 2. The smaller type of specimen has more detail dimensions specified than the larger type, because experience has shown that the additional details indicated are necessary for satisfactory results in testing thin metal products. Symmetry about the principal axes of tensile specimens is one of the essential requisites towards obtaining axial and uniform stressing during testing.

Tensile specimens of these two types should not be prepared by blanking or shearing to the finished dimensions specified, because of the cold working effects, the distortion of the specimen edges, and the roughness of the sheared surfaces. All these factors affect the test results to a varying degree, depending on the composition, the temper and the thickness of the metal, as well as on the details of the blanking or shearing tools and their lubrication. It is satisfactory, however, in testing some thin metal products, to blank or shear tensile specimen blanks, which are then finished to final size in the reduced section by filing, shaping, milling or grinding. This practice is particularly satisfactory in the preparation of specimens wherein half the difference in width between the ends and the reduced section of the specimen is equal to or greater than the thickness of the specimen.

Theoretically, it is desirable to use a tension test specimen with uniform cross section throughout the length of its reduced section. Practically, this is difficult to obtain in the two types of specimens being discussed, because of the variations in thickness of the metal products from

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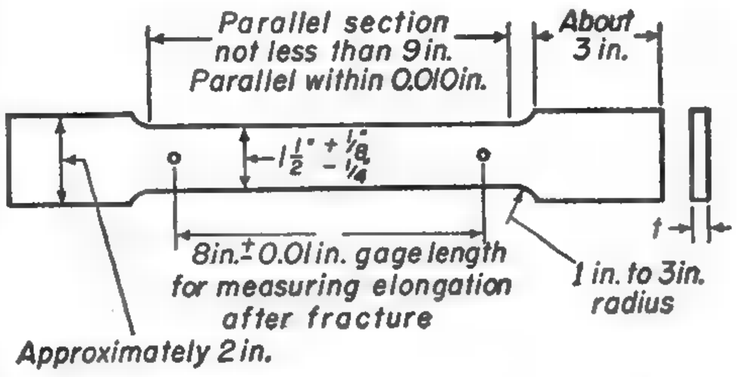
Prepared for the Subcommittee on Mechanical Testing.

which they are taken, and because of the difficulties frequently experienced in machining the specimens. To overcome these troubles and to compensate for the effects of the gage marks usually put on the specimens, it has been found desirable to relieve the width of the reduced section of the specimens at the center. This relief is accomplished preferably by gradually tapering the width (or the diameter of round specimens) of the reduced section from the fillets to the center, as shown by the dimensions specified for the specimen in Fig. 2.



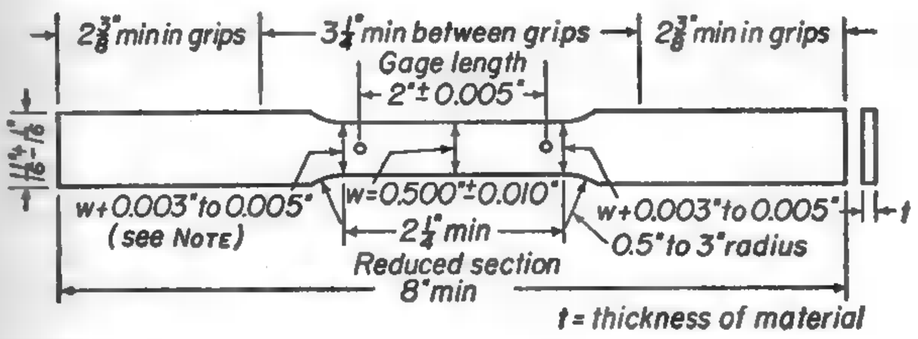
Note 1. When necessary, it is permissible to use a narrower specimen, but in such a case the reduced portion shall be not less than 1 in. in width.

Note 2. Punch marks for measuring elongation after fracture shall be made on the flat or on the edge of the specimen and within the parallel section; either a set of nine punch marks 1 in. apart, or one or more sets of 8-in. punch marks may be used.

Note 3. The dimension "t" is the thickness of the test specimen as provided for in the applicable material specifications.

Fig. 1 Standard rectangular tension test specimen for plate material ranging from ⅛ to 1½ in. thick. For plate more than 1½ in. thick the specimen may be machined to not less than ¾ in. in thickness, or a standard round tension test specimen may be used. (ASTM)

When they are to be prepared in considerable numbers, the smaller, rectangular-shaped tensile specimens can be machined easily to the desired dimensions and quite economically by transverse milling, using a suitable vise for holding a pack of specimen blanks, and a set of suitable milling cutters.[1] When only a few specimens are to be prepared, the machining can be done by filing, shaping, longitudinal milling or grinding, or combinations of these. Irrespective of the procedure used, the final dimensions specified should be met and undercutting of specimen width, at the ends of the reduced section particularly, should be avoided. The final machine finish for tensile specimens is particularly important and should be of high quality. The surfaces should be smooth and all corners sharp but free from burrs or other undesirable irregularities.



Note: Gradual taper from ends of reduced section to middle. All machining dimensions are shown below and testing dimensions above specimen. The ends shall be symmetrical within 0.01 in.

Fig. 2 Standard rectangular tension test specimen for sheet metals ranging in thickness from 0.005 in. to, but not including, ½ in. (ASTM)

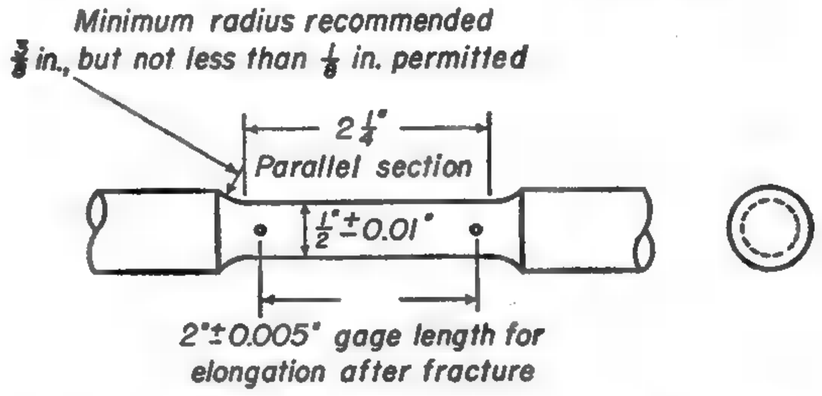
Commercial milling machines of specialized design are available for finishing the larger type of rectangular tensile specimen. These machines mill both edges of the reduced section simultaneously in a longitudinal direction. They were developed primarily for use in preparing specimens of mild steel plate.

Milling or other cutters used in machining test specimens should be sharp, maintained in good condition, and used in accordance with best practice for the material being machined. The rate of removing metal during the machining operation should be consistent with conditions insuring a good finish, desired dimensions and minimum effects on the metal by cold working or overheating.

Throughout the preparation and handling of the specimens, care should be taken to avoid damage, such as nicks, scratches, dents, kinks, bends and improper marking previous to testing. The proper marking for identification of thin sheet-metal tensile specimens often presents a serious problem. The use of steel stencils generally distorts the ends of the specimens enough that subsequently they cannot be held properly by any testing-machine grips. The thinner the specimens, the more serious the marking troubles. The use of sharp scribers, suitable inks, crayons or electric pencils is generally more satisfactory than steel dies or stencils.

The lengths of ends of the sheet and plate type of tensile specimens as specified are minimum lengths. In many instances, appreciably more reliable test results will be obtained by the use of longer specimen ends.

Where round tensile specimens can be used, they offer a number of advantages in comparison with the rectangular type. In general, they are easier to prepare, require less material and give more consistent data. Specimens of this type can be used satisfactorily throughout a considerable size range and give directly comparable test data if proper similitude in their dimensions is maintained.



Note: The gage length, parallel section, and fillets shall be as shown, but the ends may be of any shape to fit the holders of the testing machine in such a way that the load may be axial.

Fig. 3 Standard round tension test specimen for general use in testing metals (ASTM)

The basic size of round tensile specimen long used in this country is shown in Fig. 3. Some proportional sizes of similar smaller specimens are shown in Fig. 4. Irrespective of the size of these specimens, three types of ends are recognized and used, depending on the desire of the user or the testing equipment available. The details of the various types of specimen ends are not usually specified, but those shown in Fig. 4, 5, and 10 have proved satisfactory for many metal products. These specimens have plain round ends for use in wedge grips of the V type, shouldered round ends for use in special fixtures, and threaded ends to fit threaded adapters. In all instances, best results will be obtained if the grips, fixtures or adapters are loaded through suitable tension members that are spherically seated.

Round tensile specimens, when prepared from readily machinable metals, are generally turned on the engine lathe. If a relatively large number of specimens is to be made, special tooling can be used to decrease substantially both preparation time and cost. Forming tools, turret tool posts, combination center-drill and end-facing tools, automatic limit stops, special chucks, special lathe dogs, and automatic die heads for threaded-end specimens are some of the items that can be used in decreasing the time and cost of machining. In some instances, the turret lathe or automatic screw machine can be used to advantage. Round specimens of the light metals can be finished rapidly and economically by the use of a special forming tool on the cross slide of the engine lathe. Such a device uses a skiving cutter that has the same profile as the reduced section of the tensile specimen, including both the fillets and the taper in the specimen.

For round tensile specimens of metals that are not readily machined with the usual cutting tools or the tungsten-carbide tools, grinding probably offers the best method of finishing. To avoid grinding cracks in specimens of such materials, care should be taken to use suitable shape, grade

and bond in the wheel selected, together with proper speeds, feeds and coolants. If it is permissible, turning to size or slightly oversize, before hardening, is quite desirable, but if the hardening process causes warpage, provision should be made for correction to the desired dimensions by final grinding. The provision of suitable centers before hardening of the specimens usually facilitates the final grinding. Sometimes it is necessary to grind the centers before finish grinding the rest of the specimen, in order to obtain the desired final dimensions of the specimens. For some hardened metal specimens, suitable centers can be provided by soldering or brazing pieces of soft metal onto the ends of the specimens.

For best test results it is essential that the threads on the ends of threaded specimens be concentric with the axis of the specimen; that the inner or loading surfaces of shouldered-end specimens be plane and normal to the axis of the specimen; and that the ends of plain round specimens be symmetrical to and concentric with the axis of the specimen. Furthermore, for each of these types, the grips or fixtures into which the ends of the specimen fit should be so made and in such condition that the specimen will be stressed uniformly and axially, if satisfactory results are desired.

Tension specimens from tubular metal products that have outside diameters of 1½ in. or less are usually prepared from samples having full cross section and are provided with closely fitting bullet-shaped metal plugs, as shown in Fig. 6. If the capacity of the available testing machine is adequate, such specimens may be used for products as large as 2 in. OD. The thinner the wall thickness of such specimens, the closer the tolerances that should be used in fitting the end plugs. In general the plugs should be machined so that they require a light push or drive fit, preferably with no lubricant. The usual commercial tolerances for inside diameter of tubular products are greater than those giving satisfactory results in fitting plugs into tensile specimens. When numerous tension tests of tubular specimens are involved, it is economical to provide many pairs of plugs of various sizes which can be stored in suitable racks and machined to the desired sizes as needed, by light cuts or filing in a lathe. New plugs of the larger sizes are added as needed.

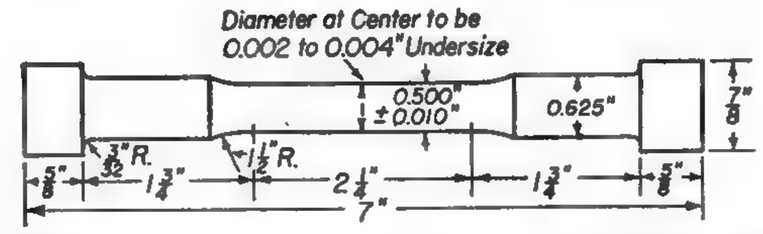


Fig. 5 Shouldered-end tension test specimen particularly adapted to hard steels and brittle materials

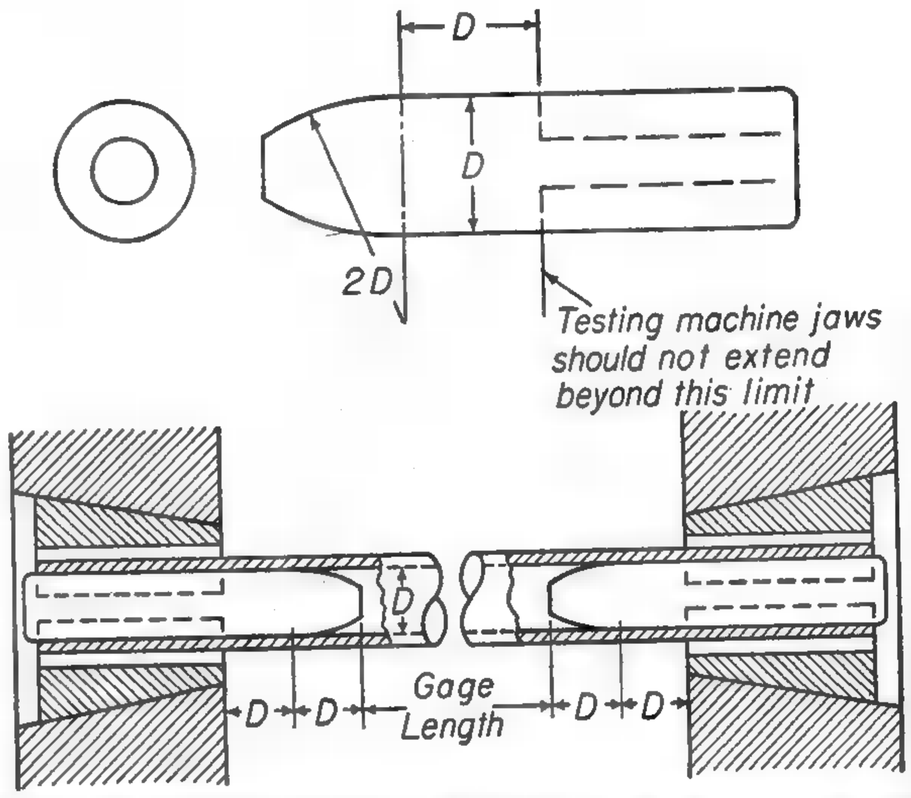


Fig. 6 Standard tension specimen for metal tubing ranging to as much as 2 in. OD but particularly for sizes 1½ in. OD and less (ASTM)

In the preparation of the plugs, leaving a narrow shoulder at their butt ends is very helpful in locating the plugs properly in the ends of the specimens. Obviously the height of these shoulders should always be less than the thickness of the specimen wall. The length of the parallel portion of the plugs is not specified, but a minimum value in terms of the specimen diameter is about two diameters for the larger specimens. For the smaller sizes of specimens, the lengths of the plugs are usually governed by the length of the V-wedge grips used, together with the length of plug required to extend beyond the ends of the grips. For discussion of tests for tubular products, see page 132.

After the plugged specimens have been tested, the plugs can be removed readily without damage to them, by expanding the specimen until they fall or are readily pulled out. This is done by hammering the plugged ends of the specimens on a suitable metal anvil or, still more easily, in a special hardened V block which has longitudinal stepped teeth ($\frac{1}{16}$-in. to ⅛-in. pitch) machined in the sides of the 90-deg V groove. When a wide range of specimen diameters is involved, the block is generally provided with two to four sizes of V grooves. Various sizes of hammers should be used, depending on the size of specimens.

In some instances the smaller sizes of tubular metal products, ½-in. OD and less, can be plugged with a low-melting alloy such as Wood's metal, and satisfactorily tested. Removal of plugs of this kind is accomplished by

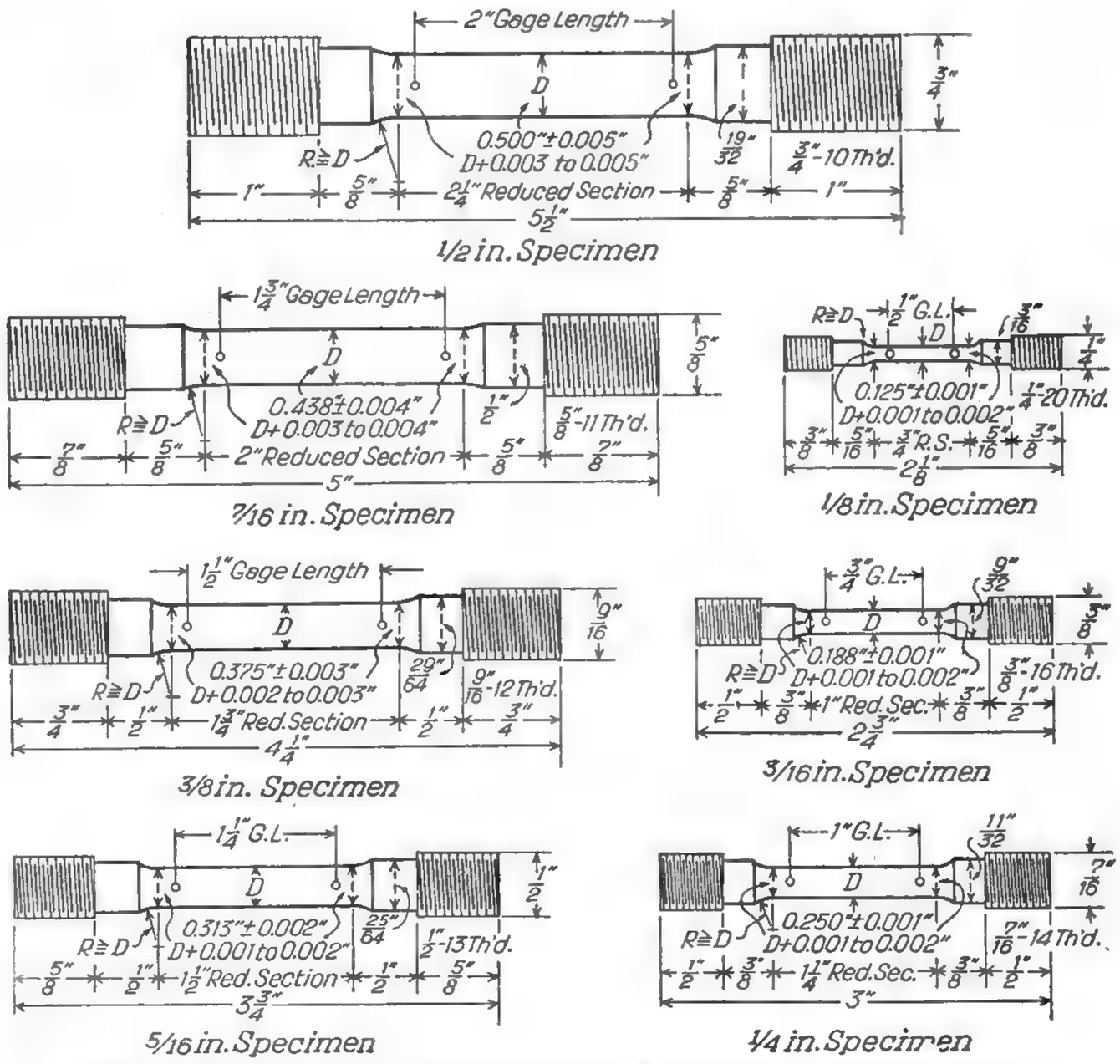
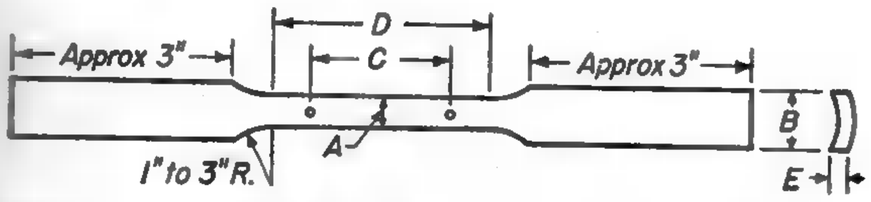


Fig. 4 Proportionate sizes of threaded-end round tension test specimens for metals

dipping in hot water so that the alloy is saved for subsequent use. Other low-melting alloys can be used for plugs in tubular specimens, but somewhat higher temperatures are required in removing these plugs after use. Some tubular products are tested by flattening the ends and testing with flat wedge grips.



Specimen	Dimensions, in. A	B	C	D min	E
No. 1	½ ± 0.010	1/16 ± 1/16	2	2¼	thickness
No. 2	¾ ± 0.010	1 ± 1/16	2 4	2¼ 4½	thickness
No. 3	1 ± 0.01	1½ ± 1/16	2 4	2¼ 4½	thickness
No. 4	1½ ± 0.01	2 ± 1/16	8	9	thickness

Cross-sectional area may be taken as the product of A and E

Fig. 7 Longitudinal tension test specimen for ferrous tubular products of large diameter (ASTM)

Tubular metal products larger than 1½ in. or 2 in. OD, with wall thicknesses less than ½ in., are generally tested for tensile properties by using the smaller rectangular specimen previously described (Fig. 2), or the one shown in Fig. 7. For the products having wall thicknesses ½ in. or greater, subsize round tensile specimens usually give best results. The testing-machine grips used with the rectangular type of specimens may have curved faces to fit the curved ends of the specimens, or the ends of the specimens

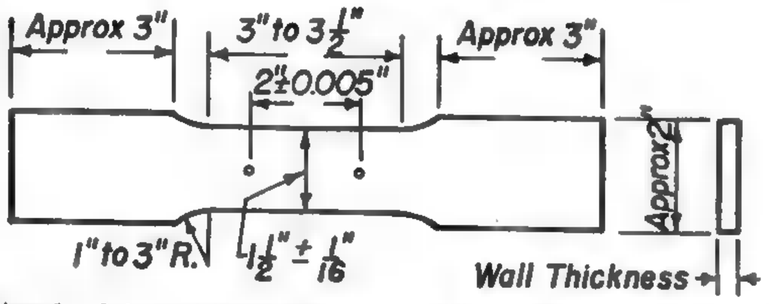


Fig. 8 Standard transverse tension test specimen machined from ring cut from tubular ferrous products (ASTM)

may be flattened so that they can be tested with flat-faced wedge grips. Difficulties with suitable end flattening procedures sometimes outweigh the slight additional cost of preparing the round type of tensile specimens. Transverse tensile specimens of the size shown in Fig. 8 are used for some ferrous tubular products. The location of such specimens is shown in Fig. 9. It may be pointed out that the elongation values obtained from tension tests of metal products vary inversely as the gage length and as some function of the cross-sectional area of the specimen.

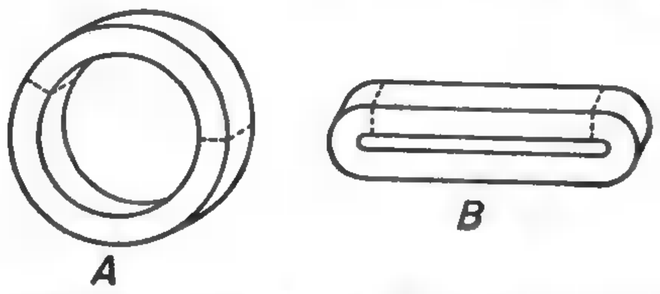


Fig. 9 Location of transverse tension test specimen in ring cut from tubular ferrous products (ASTM)

This makes direct comparison of elongation values difficult when using different sizes of specimens and a constant gage length. The tensile and yield strength values, on the contrary, show little if any variations within the range of specimen sizes generally used, if the specimens are uniformly and axially stressed.

Tension specimens for malleable iron and for cast iron are shown in Fig. 10 and 11.

Compression Specimens. Compression specimens for metals are not at the present time as standardized as the tensile specimens. Tentatively, however, three types are recognized as being suitable for metals. The short specimen is used for compression tests of bearing metals, the specimen of medium length for determining the general compressive strength properties, and the long specimen for determining the modulus of elasticity of metals. The dimensions suggested for general use are as follows:

Specimen	Diameter, in.	Length, in.
Short	1⅛[a] ± 0.01	1 ± 0.05
Medium length	0.798 ± 0.01	2⅜ ± ⅛
	1 ± 0.01	3 ± ⅛
	1⅛ ± 0.01	3⅜ ± ⅛
Long	0.798 ± 0.01	6⅜ ± ⅛
	1¼ ± 0.01	12½ min

(a) Area of cross section approximately 1 sq in.

Compression tests are appreciably more difficult to make, with satisfactory results, using the ordinary type of universal testing machine, than are the tension tests.

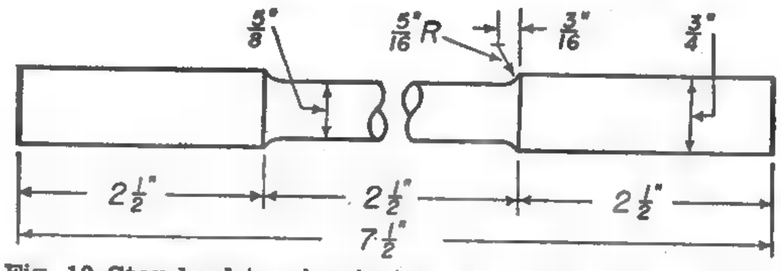
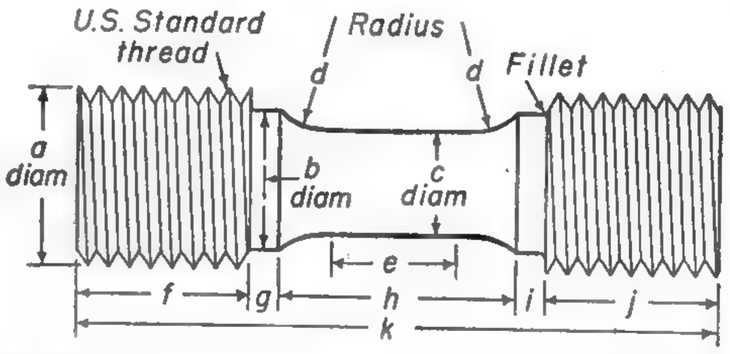


Fig. 10 Standard tension test specimen for malleable iron (not machined) (ASTM)

The reason for this greater difficulty is that in the compression tests eccentricities in loading tend to increase as the load on the specimen is increased, whereas in the tension tests, the eccentricities tend to decrease under increasing load. This is true especially for loads in the plastic range. In spite of these difficulties, compression tests can be carried out successfully if proper attention is given to details of apparatus and procedure.



Dimension (in inches)	Specimen A	Specimen B	Specimen C
a	¾	1⅛	1⅞
b	⅝	15/16	1 7/16
c	0.505	0.750	1.25
d	1.00	1.00	2.00
e[a]	Shall be equal to or greater than c (diameter)		
f	1.00	1.00	1¾
g	0.25	0.25	5/16
h, min	1.25	1.50	2¼
i	0.25	0.25	5/16
j	1.00	1.00	1¾
k, min	3.75	4.00	6⅜

(a) Length of parallel

Fig. 11 Standard tension test specimen for cast iron (ASTM)

It is very necessary that the ends of compression specimens be flat and mutually parallel. In addition, the end surfaces should be normal to the axis of the specimen within very close limits. As in the case of tensile specimens, compression specimens should be machined so as to have a surface finish of high quality. The corners of the specimens should be sharp and free from burrs, nicks, scratches and any other irregularities that would produce stress concentrations during testing. A final requisite, frequently neglected, is that both the ends of the specimen and the bearing surfaces with which they come in contact during testing should be clean and dry before assembly for testing. Cleaning can be accomplished by the use of suitable solvents, such as acetone, and is essential for the purpose of obtaining a symmetrical distribution of stress intensity on the ends of the specimen.

Suitable devices that assist in obtaining uniform stress

distribution on the ends of compression specimens during testing include spherical compression bearing blocks, properly designed and made; suitable adjustable bearing blocks for correcting out-of-parallelism of testing machine platens; and suitable compression tools or subpresses for insuring axial application of load during testing. Additional devices are necessary when making compression tests of thin specimens of sheet metal or long cylindrical specimens having low lateral stability.

Shear Specimens. Although a variety of shear tests are made on metal products, no generally recognized standard methods or specimens have been adopted. One type of shear test is the torsional, in which either a solid or tubular specimen is used. Solid specimens are often tested full size, but for more accurate results they may be reduced in lateral dimensions, as in the tensile specimens. The tubular or hollow specimens that have a thin wall are more suitable for obtaining shearing strength values for metals, largely because the cross section of the specimen has more nearly uniform stress than is found in the solid specimen. For ultimate shear strength determinations, the hollow specimens should have short reduced sections of about ½ diam, and a diameter-to-thickness ratio of from 10 to 12. For determination of shear modulus and yield strength values, a hollow specimen is to be preferred that has a length of at least 10 diam and a ratio of diameter to wall thickness of not over 10, for its reduced section. The actual dimensions of the specimen used may well be chosen to suit both the size and type of testing machine available, as well as the product to be tested.

Shear tests of sheet or plate are made by suitable punches and dies either fitted directly into a testing machine or into a subpress which can be used in a testing machine, so that the load required to shear a specimen of a given size can be measured. The punches and dies are usually circular and the specimen is of suitable size and shape to allow a complete disk to be punched from it and yet have a minimum margin beyond the shearing surface equal to or greater than about twice the thickness of the specimen. Another form of shear test (Amsler) is made by using three ringlike dies with either round or square holes through their axes, so that a specimen of the same shape can be inserted through the three dies; the outer dies are supported and the middle die is displaced laterally so as to shear a short section from the specimen by using a suitable fixture in a testing machine. From such a double shear test, the shearing strength is readily obtained. In such tests the shearing tools should be kept sharp and free from burred or nicked edges, and should be used under constant conditions of lubrication and speed.

Notched-Bar Impact Specimens. Tentative standard methods are now in use for making single-blow notched-bar tests of metals. The types and sizes of specimens recommended by the ASTM are shown in the article on page 112. Unnotched specimens ¼-in. sq have been extensively used for checking nonferrous die-cast metals.

Experiments have been made using many types of notched-bar tests, and numerous sizes and shapes of specimens have been studied in attempting to develop a satisfactory, so-called "shock resistance" test. This investigational work is still in progress, but so far no one type of test or specimen appears to suffice for all metals; consequently there are many differences in commercial testing practices. In some applications the notched-bar test has shown considerable merit, but in others even the best results obtained have been of dubious value.

Other forms of the "impact" test include repeated impact and torsion-impact tests, each requiring different sizes of specimens, depending on the testing machine used.

Preparation of specimens for the notched-bar test requires the same kind of care as that used in preparing tension or compression specimens. Particular attention must be given to the machining of the notches. When the specimens are of the type in which the notch can be made by drilling or by drilling and reaming, the direction of the machining scratches will be such as to have a minimum effect on the test results. Notches which must be milled transversely can usually be improved by polishing with a wire held in an electric drill using a suitable abrasive compound, or by other methods that will remove the tool marks that would be parallel to the axis of the notch. Furthermore, to insure consistent results the specimens should be square within close limits. The care necessary in finishing specimens will depend on the material tested.

Hardness Specimens. Hardness tests require no special size or shape of specimen but there are other limitations covered in the article "Hardness Tests", page 93.

Bend Specimens. A standard method of bend testing for determining the ductility of metals is now in use (ASTM E 16 – 39). The method was developed primarily for the testing of welds and was not intended to be substituted for the simpler and wholly adequate bend test requirements commonly specified for many wrought metal products. The test specimens required in the method just referred to, include both a rectangular and a round specimen. The rectangular type is usually the preferred form, with a width at least three times the thickness. The edges of the specimen should be smooth and the corners should have a radius not greater than ⅛ the thickness of the specimen. The length of the specimens is generally varied with the thickness, but this is considered unimportant provided sufficient length is allowed for performing the bending operation. When the round type of specimen is used, the results obtained should be considered as comparative only, since for most metals the elongation of the outer fiber has been found to vary with the diameter of the test specimen.

The gage length over which the elongation is to be measured is specified as 0.3 for plate from ¼ to ½ in. in thickness and 1 in. for all plates over ½ in. in thickness. The gage length should be located at the section of maximum bending, and in the center third of the width of the specimen. The detailed procedure for carrying out the bend tests using these types of specimens is given in the standard methods of the ASTM.

Other types of cold bend tests are used for different types of metal products. In general, such tests are made by bending a strip or piece of the metal around a mandrel or die of specified dimensions, by steady application of load, or by hammering until rupture occurs or until an angle of either 90 deg or 180 deg is attained. Many forms of cold bend attachments are available for commercial testing machines; also machines are available that are intended solely for the purpose of making bend tests. Although the cold bend test is one of the oldest tests and apparently one of the simplest, yet the results obtained are frequently affected by the procedure and apparatus used.

The well-known transverse flexure test as applied to brittle materials, such as cast iron, is sometimes considered a form of bend test. Three sizes of specimens have been standardized for use in making the transverse test on gray iron castings. These have the following as-cast or skin-machined dimensions:

Transverse Test Bar	Dimensions		Distance between Supports in Transverse Test, in.
	Diameter, in.	Length, in.	
A	0.875	15	12
B	1.20	21	18
C	2.00	27	24

Such tests give both breaking load and deflection data.

Fatigue Specimens. See "Fatigue Tests", page 118.

Cupping Specimens. Cupping tests of sheet metals are used as an index of the ductility and, in some instances, of the drawability of the material. Although these tests have been used for many years, at the present time no standard conditions of test have been generally accepted; the result is that the values from different types of machines are not concordant. The specimens used in these tests are usually in the form of disks, squares or strips of suitable dimensions (about 3 in. in diam or width) to fit into the testing machine, and of the same thickness as the sheet metal which they represent.

References

1 R. L. Templin, Methods for Determining the Tensile Properties of Thin Sheet Metals, Proc ASTM, 27, Part II, 235-250 (1927)

2 Tentative Methods of Impact Testing of Metallic Materials (E23—41T), ASTM Standards, 1946

The Calibration of Testing Equipment

By Bruce L. Wilson*

ERRORS of the testing equipment used to determine the mechanical properties of materials result in errors in the test values obtained. Such errors may lead to disagreement between different laboratories or, if the errors are large, to failure of parts of machines or structures in service. If such errors are to be avoided, adequate calibration of all mechanical testing equipment is necessary.

The mechanical properties commonly used in specifications are defined in other sections of this book. Some of these properties can be determined with one piece of testing equipment; others require the use of several different instruments and machines. For instance, the breaking strength of a wire can be determined with one machine, a tension-testing machine, but the modulus of elasticity requires the use of equipment for determining the cross-sectional area of the specimen, a testing machine for applying loads, and a strainometer for measuring the strains under load. Since the error in any value determined by a mechanical property test is influenced by the errors of each instrument or machine used in its determination, the calibration of each piece of equipment is necessary to insure that the error in the result is no more than allowed.

Adequate calibration of mechanical testing equipment involves the determination of both the accuracy and the sensitivity of the equipment, and it is important that these two properties should not be confused. A sensitive instrument or machine is not necessarily accurate, but the accuracy is, in general, limited by the sensitivity.

The instruments used in calibrating mechanical testing equipment must be calibrated. Errors of instruments used for calibrating other equipment should be small compared with the errors to be determined. In general, the errors of instruments used for calibrating mechanical testing equipment should not exceed one fifth, or preferably one tenth, of the allowable errors of the equipment being calibrated.

Calibration of Testing Machines. The calibration of a testing machine which indicates the magnitude of the forces applied to specimens, usually consists of the calibration of the load-weighing mechanism of the testing machine. In such a calibration, the loads indicated by the testing machine and the loads indicated by the calibrating device are determined for several different loads. For each indicated load, the error is computed by subtracting the correct value of the load (determined with the calibrating device) from the load indicated by the testing machine. The loading range of a testing machine is then determined as the range of indicated loads for which the testing machine gives results within the permissible variation, which is usually expressed in per cent. The most generally recognized permissible error for testing machines is plus or minus 1%, the value given in the ASTM Standard Methods of Verification of Testing Machines.[1]

Four methods of calibration are given in the ASTM specification. These include calibration by standard weights, calibration by proving levers, calibration by elastic calibration device, and calibration by comparison.

In the calibration of testing machines the loads are usually applied in ascending order, since machines are most commonly used in this way. For some types of machines, particularly those in which the load is measured by measuring the pressure in a hydraulic jack, the errors for increasing and decreasing loads will not agree; therefore, it is important to calibrate a testing machine in the way in which it is used.

It is customary to calibrate a testing machine for ten or more test loads in each loading range. It is advisable to repeat some of the test loads several times to determine whether the testing machine gives reproducible results.

Specimens are usually loaded in testing machines in such a way as to make the resultant force coincident with the axis of the machine. For this reason the loading range of a testing machine is usually determined by applying the calibration loads so that the resultant load will be as nearly along the axis of the testing machine as possible. If a machine is to be used for measuring eccentric loads, the errors of the machine should be determined by applying calibration loads in such a way that the resultant load is applied at definite distances from the machine axis.

The errors of testing machines for rapid rates of loading may differ from the errors for slow rates of loading, and frequently may be considerably greater. These additional errors should not be neglected when determining the rates of loading to be used in testing.[2]

It is usually recommended that testing machines, when in constant use, be verified at intervals of 6 months, and when used intermittently, at intervals of 2 or 3 yr. However, it is important that a testing machine be calibrated immediately after repairs or adjustments have been made to the weighing mechanism, or after the machine has been moved, unless it is a self-contained portable machine. The character of the calibration graph, showing the errors of the machine as a function of the machine reading, is often valuable in locating sources of trouble in a testing machine.

Calibration by Standard Weights. Small vertical testing machines, with weighing mechanisms attached to their lower compression platens, can be calibrated to capacity by loading the machines with standardized weights. Standard metal weights are placed directly on the weighing platen of the testing machine, or upon trays or other supports suspended from the weighing platen. For axial loading, the weights are distributed symmetrically in relation to the weighing platen. The applied load and the indicated load are recorded for each test load, and the error is calculated from these values. This method of calibration can be used only on certain types of vertical testing machines and is seldom used for test loads greater than 2000 lb.

Calibration by Proving Levers. Vertical testing machines can be calibrated by means of standardized proving levers and standard weights. Proving levers are simple levers that have a ratio of about 10 to 1. Proving levers have been used for loads up to 200,000 lb but the capacity load of proving levers usually does not exceed 20,000 lb. Methods of standardizing and using proving levers are given in the ASTM Method.[1] Horizontal testing machines may be calibrated by means of bell crank levers. Methods of standardizing bell crank levers have been described.[3]

The chief disadvantages of proving levers are that the equipment is not portable and that the method is limited to relatively small loads, making it impossible to calibrate most testing machines to capacity by this method.

Calibration by Elastic Calibration Device. Usually testing machines are calibrated by means of elastic calibration devices. By far the most common of these devices is the proving ring developed at the Bureau of Standards about twenty years ago. Amsler boxes, and loops fitted with dial micrometers are also used. Because of the errors of the dial micrometers, it is usually recommended that devices fitted with dial micrometers be used only at the loads for which they have been calibrated, unless the calibration of the dial micrometers shows that the errors in this portion of the device would not, upon the interpolation of the values, result in load errors outside the tolerances for the calibrating device. Proving rings and Amsler boxes, which are equipped with micrometer screws, are used within their loading ranges to measure loads other than those for which they have been calibrated.

A proving ring is an elastic ring in which the deflection, when the ring is loaded along the diameter, is measured by means of a micrometer screw and a vibrating reed mounted diametrically in the ring. Compression proving rings that have capacities from 300 to 300,000 lb are commercially available. Tension proving rings are available in capacities as great as 100,000 lb. All proving rings submitted to the National Bureau of Standards are calibrated for compliance with the National Bureau of Standards Specification for Proving Rings.[4] This specification contains the requirements which have been found necessary

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to insure that proving rings will be satisfactory, reliable instruments for calibrating testing machines.

Amsler boxes are essentially hollow cylinders equipped with a micrometer screw for measuring changes in volume with load. A plunger attached to the micrometer screw projects into the interior of the hollow cylinder, which is filled with mercury. By means of the micrometer screw, the mercury column in the glass capillary tube connected to the reservoir, is adjusted to an index mark.

It is essential that any type of elastic calibration device be calibrated by determining its readings under accurately known loads. For this purpose two dead weight testing machines have been installed at the National Bureau of Standards.[5] In one, loads from 200 to 10,100 lb may be applied by 100-lb increments in either tension or compression. In the other, loads from 2000 to 111,000 lb may be applied by 1000-lb increments. The weights of these machines were adjusted to within less than 0.02% of their nominal values.

For calibrating elastic devices in compression, with loads exceeding 111,000 lb, the loads applied to the device being calibrated are measured by means of three calibrated proving rings.

The ASTM Methods require that, for loads not exceeding 100,000 lb, an elastic device be calibrated by applying dead weights known to be accurate within 0.02%. For loads exceeding 100,000 lb, an elastic device may be calibrated by another elastic calibration device, by a combination of several elastic calibration devices, or by proving levers and dead weights, provided that the applied load is known to be accurate to within 0.1%. The use of the lever system of a compound-lever testing machine or of a platform scale is not allowed.

To minimize errors caused by temperature it is important that the elastic device and the testing machine be at nearly the same temperature during a calibration.

When a testing machine is being calibrated with an elastic device, the device should be preloaded, since this practice is followed in calibrating such devices. In preloading an elastic device, care should be taken not to exceed the capacity load of device or testing machine.

For some types of elastic calibration devices it is necessary to follow a fixed time schedule of loading in order to avoid errors resulting from small temperature effects caused by stress. These effects are less pronounced for devices subjected to bending than for devices subjected to direct tension or compression, as has been pointed out by Tuckerman.[6]

For ordinary purposes the ASTM Methods permit the use of elastic devices with errors not exceeding plus or minus 0.2%. The National Bureau of Standards Specification for Proving Rings requires an accuracy of plus or minus 0.5% at 10% of capacity load and plus or minus 0.1% at capacity load. The errors of most rings certified at the National Bureau of Standards comply with the ASTM tolerance of plus or minus 0.2% for loads from 10% of capacity load to capacity load.

Calibration by Comparison Method. In calibrating a testing machine by the comparison method, the tensile strengths of two groups of specimens taken from the same bar are determined with the machine being calibrated and with a testing machine which has been calibrated by one of the three methods described above. This method, which is described in detail in the ASTM Standards, is less accurate than the other methods.

Calibration of Torsion-Testing Machines. Known torques may be applied to the weighing mechanism of a torsion-testing machine, by applying known forces to a lever arm of known length. Forces may be applied either by means of dead weights or by means of an elastic calibration device and a jack.

Calibration of Hardness-Testing Machines. Two general methods, one direct and one indirect, are used in calibrating hardness-testing machines.

For indentation hardness-testing machines, such as the Brinell, the direct calibration involves a determination of the shape of the indenter, the errors of the applied loads, the rate and time of application of load, and the errors of the equipment used to measure the indentations. This method is applicable to Vickers and Tukon machines.

For some machines it is not practicable to carry out a direct calibration, because of a lack of the necessary equipment or because the shapes of the indenters and the constants of the machines have not been defined in terms of the fundamental units of length, mass and time. For such machines an indirect calibration is made by determining the hardness readings of standard test blocks, standardized and supplied by manufacturers of hardness-testing machines. Rockwell and Scleroscope machines are usually calibrated by means of test blocks.

Calibration of Impact-Testing Machines. Direct calibration of an impact-testing machine would involve a measurement of the decrease in the rotational velocity of the pendulum, the calculation of the corresponding difference in kinetic energy, and a comparison of the result with the value indicated by the machine. Because this direct method of calibration is very difficult to carry out, a simpler method is ordinarily used.

If frictional, vibrational and other losses are neglected, the kinetic energy of the pendulum at the instant of impact with the specimen is equal to the potential energy possessed by the pendulum before release; and the kinetic energy of the pendulum immediately after breaking the specimen is equal to the potential energy of the pendulum at the maximum elevation to which it swings after breaking the specimen. The energy absorbed by the specimen, neglecting losses, is the difference in the energy of the pendulum in its initial position and in the highest position that it attains after breaking the specimen. This energy may be calculated by multiplying the total weight of the pendulum by the change in elevation of the center of gravity.

The center of gravity of the pendulum is a point on the interior of the pendulum. Therefore it is more convenient to determine experimentally the product of the total weight of the pendulum and the elevation of the center of gravity, by a method described in detail in an ASTM Method.[7] This method involves the determination of the calibration weight of the pendulum by measuring the vertical force necessary at the center of the striking edge in order to support the pendulum in a horizontal position. The energy of the blow with which the specimen is struck is the product of the calibration weight and the change in elevation of the center of the striking edge, when the pendulum is raised from the point of impact with the specimen to the position from which it is released. The errors of the scale may be determined by a comparison of the indicated readings and the values may be calculated by multiplying the calibration weight by corresponding elevations of the striking edge above the impact position. Calibration should also include determination of corrections for friction and windage, determination of the location of the center of percussion and of the striking velocity, as outlined in the ASTM Method.

Calibration of Strainometers. The calibration of a strainometer, such as an extensometer, a compressometer or a strain gage, usually involves the determination of the calibration factor of the instrument and determination of the strainometer error for different instrument readings.

The calibration factor of an instrument is the factor by which the change in the instrument reading must be multiplied to obtain the equivalent strain. That is, the calibration factor equals the ratio of the change in length to the product of the gage length and the corresponding change in strainometer reading. For direct-reading strainometers, the calibration factor is unity. It is customary to determine the error of a strainometer for several different instrument readings by means of a suitable calibrating device.

A device for calibrating strainometers usually consists of a rigid frame, suitable coaxial spindles or other fixtures to which the strainometers may be attached, a mechanism for moving one spindle or fixture axially in relation to the other, and a means of measuring accurately the change in length so produced. It is important that the mechanism for moving one spindle with respect to the other should permit sensitive adjustments. The changes in length may be measured by means of an interferometer, a micrometer screw, or standard gage blocks and an indicator. If standard gage blocks and an indicator, or a micrometer screw

are used, they should be calibrated. The errors of the calibration device should not exceed one fifth of the permissible error of the strainometer.

A calibrating device with which the changes in length may be measured, either by means of standard gage blocks and an indicator, or by means of the interferometer method, has been described by A. H. Stang and L. R. Sweetman.[8] A calibrating device that makes use of a calibrated differential screw has been described by R. L. Templin.[9]

For some strainometers, the position during calibration, the mounting pressure, the material and hardness of the spindles of the calibrating device, and the temperature—all have been found to influence the readings. The effects of some of these variables on Huggenberger tensometers and Tuckerman strain gages have been described by Vose[10] and Wilson.[11] Care should be taken to eliminate errors caused by these variables, both during calibration and during the use of the instruments.

The calibration factor of the instrument may be obtained either graphically or algebraically from the strainometer readings and the ratios of the changes in length of the calibration device to the strainometer gage length.

The allowable error for a strainometer depends on the mechanical property being determined. Strainometers having errors which do not exceed 0.00005 or 0.00001 in. per in. are often used for determining values of the modulus of elasticity or elastic limits. The allowable error is usually greater for strainometers used for determining yield strengths.

Wire strain gages cannot be calibrated by means of the usual type of calibrating device. Selected gages are calibrated by attaching them to beams, or to tension or compression specimens, and loading the specimens to produce the desired strains as indicated by sensitive calibrated mechanical or optical strain gages. If careful control is maintained over the manufacture of gages, the calibration factors of the gages selected for calibration can be kept sufficiently constant to insure that the factors of the gages not calibrated will not differ by more than about 1 or 2% from the factors furnished for the gages. W. R. Campbell has given information concerning the performance of wire strain gages in tension and compression, and the errors from prestraining, temperature changes and weathering.[12–16]

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Hardness Tests

BY THE SUBCOMMITTEE ON HARDNESS TESTING*

HARDNESS, as the term is commonly used in metallurgy, is a measure of the resistance of a material to indentation by an indenter of fixed geometry, under a static load. A hardness test of this type is known as an "indentation hardness test".

Considerable information can be derived from a hardness test, but intelligent appraisal of a hardness number requires knowledge of the composition and condition of the metal at the time of the test, as well as understanding of the factors that influence the accuracy of the test.

Applications of Hardness Testing

Inspection and Control. For optimum performance in a particular use, a metal is conditioned by heat treatment or cold work, or sometimes both. Such treatments are usually accompanied by a change in hardness of the material; thus, when the hardness resulting from treating a given material by a given process is established, it affords a nondestructive, rapid and simple means of inspection and control for the particular material and process.

Estimation of Other Properties of a Metal. For many practical purposes, the tensile strength of heat treated carbon steel and low-alloy steel may be estimated from the hardness of the steel, when the hardness is in the range from 200 to 500 Bhn. According to reported data,[1,2] multiplying the Brinell hardness number by 500 gives the approximate tensile strength. There seems to be no generally useful relationship between hardness and tensile strength for nonferrous materials. A hardness test is no substitute for the tensile test and provides no information concerning ductility, unless all factors determining mechanical properties are known to be controlled.

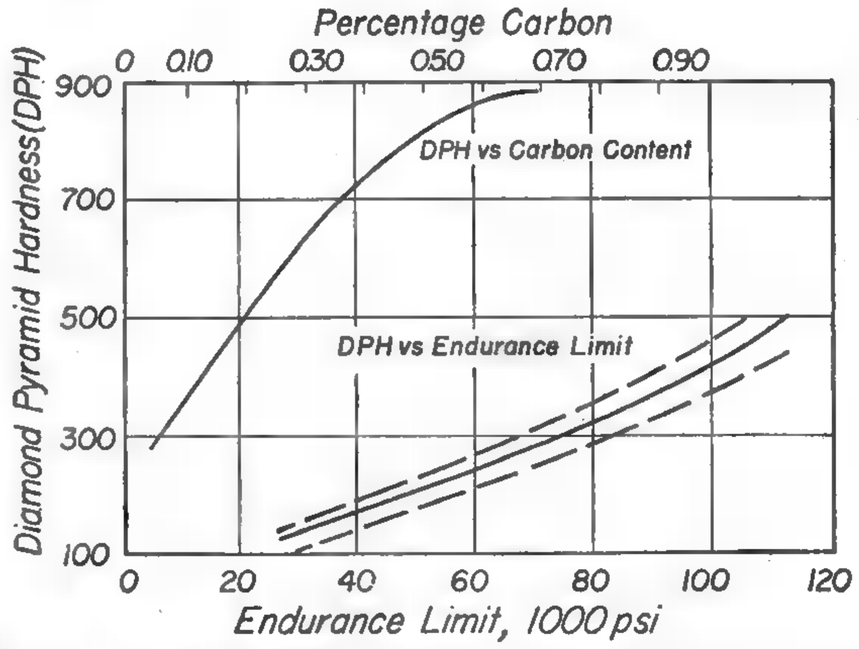

Fig. 1 Relationship between hardness and carbon content of ferrous materials, and between hardness and endurance limit. Hardness versus carbon content is based on hardness tests of material in the martensitic condition.

Figure 1[2] shows that with ferrous alloys there is an approximate correlation between hardness and endurance limit; nevertheless, care should be used in interpreting curves of hardness versus fatigue strength, since the relationship may be altered by heterogeneity of the metal, by surface finish and by residual stresses. This relationship applies to high-quality hot worked steels when prop-

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erties are varied by tempering temperature or carbon content chiefly, and when the steels are fully hardened to the martensitic condition before tempering.

Other Applications. Shallow-penetration hardness tests permit the investigation of surface conditions, such as depth of the decarburization resulting from heat treatment, and depth of case in carburizing and cyaniding.

Since precipitation hardening is reflected in hardness changes, it is often studied with the aid of hardness tests.

The suitability of a specific composition of steel for an intended use is frequently governed by the hardenability, the evaluation of which requires the use of hardness tests. *See* "Hardenability Tests", in this Handbook.

A rather interesting application of the hardness test is for estimating the approximate carbon content of a steel from the measured hardness of the steel in the martensitic condition. Data of Burns, Moore and Archer,[4] converted to diamond pyramid hardness (DPH), and presented in Fig. 1, indicate the trend of this relationship for steels that contain between 0.10 and 0.60% C.

Principles of Indentation Hardness Testing. Since the hardness test yields much useful information, and because no one combination of test load and indenter size has been satisfactory for testing specimens of all sizes and all degrees of hardness, it has been necessary to devise many hardness scales. Regardless of which indentation hardness scale is selected, the test is usually performed by impressing into the specimen, which is resting on a rigid platform, an indenter of fixed and known geometry, under a known static load applied either directly or by means of a lever system. Depending on the type of test, the hardness is expressed by a number that is either proportional to depth of indentation for a specified load and indenter, or proportional to a mean load over the area of the indentation. Indentation area is measured either as contact area or as projected area. (The projected area is bounded by the outline of the indentation lying in the plane of the specimen surface.) Because an indentation is measured after either partial or complete removal of the test load, thus permitting elastic recovery, such a measurement does not represent the actual size of the indentation under load, but is a measurement of the recovered indentation.

Table I. Specifications for Hardness Indenters

	Brinell	Rockwell		Vickers	Knoop	Monotron
Material of which indenter is made	Hardened Steel or Tungsten Carbide	Diamond	Hardened Steel	Diamond	Diamond	Diamond
Shape of indenter	Sphere	Cone	Sphere	Square-Based Pyramid	Rhomb-Based Pyramid	Hemisphere
Dimensions of indenter	D = 10mm	θ = 120°	D = 1/16 in., 1/8 in., 1/4 in., 1/2 in.	θ = 136°	a = 130°, θ = 172°30′	D = 0.75mm

Five types of indenter in common use are listed in Table I. For hard metals, diamond indenters are preferable because they deform less than those made of steel. Hardness numbers determined by using cone and pyramid indenters are virtually independent of the test load, whereas those determined by using a ball indenter are not. This means that, for a given specimen, a hardness number based on the relationship between load and indented area, will vary with a change in load on a ball indenter, but will remain constant with a pyramid indenter; this characteristic of a ball test necessitates a change in ball diameter with change in load (as described under the Brinell Test) in order to use the same scale for measuring the hardness.

Common Methods of Making Indentation Hardness Tests

Brinell Hardness Test. The Brinell hardness tester usually consists of a hand-operated vertical hydraulic press, designed to force a ball indenter into the test specimen. The load applied by the instrument can be varied over a considerable range.

Standard procedure requires that the test be made with a ball of 10 mm ± 0.0025-mm diam under a load of 3000 kg for ferrous metals, or 500 kg for nonferrous metals. For ferrous metals the loaded ball is pressed into the test specimen for at least 10 sec; for nonferrous metals the time is 30 sec. The diameter of the impression thus produced is measured by means of a microscope containing an ocular scale, usually graduated in tenths of a millimeter, permitting estimates to the nearest 0.05 mm. At high hardness levels, when greater precision is desirable in the measurement of the diameter of the impression, a micrometer-slide comparator type of Brinell microscope measuring to ± 0.01 mm is recommended.

The Brinell Hardness Number (Bhn) is the ratio of the load in kilograms to the impressed area in square millimeters, and is calculated from the following formula:

$$\text{Bhn} = \frac{P}{\frac{\pi D}{2}\left(D - \sqrt{D^2 - d^2}\right)}$$

where P = Test load in kilograms,
D = Diameter of ball in millimeters,
d = Diameter of impression in millimeters.

Ordinarily calculation is unnecessary because tables are available for converting the observed diameter of impression to the Brinell hardness number.

The use of two loads (3000 kg for ferrous metals and 500 kg for nonferrous metals) and one size of penetrator, limits this test to relatively large specimens. For testing a smaller specimen, a lighter load and ball of smaller diameter may be used if the ratio of the load to the square of the ball diameter is the same as that in the test with a heavier load. Table II[5] shows the various combinations of diameter of the indenter and the load to be applied in order to maintain the correct value for each of four different ratios.

Rockwell Hardness Tests. A Rockwell test is made by slowly elevating a specimen against the indenter until a minor load has been applied, as indicated by an index hand on a dial gage. A major load is then applied by releasing a loaded lever system; the speed of descent of the lever is controlled by an adjustable oil dashpot. At the completion of the descent of the lever, the major load is removed and, with the minor load still acting, the Rockwell hardness number is read on the dial gage. This number is based on the depth of indentation less the elastic recovery following removal of the major load, less the penetration resulting from the minor load. Because of the reversal of the order of the numbers on the dial gage, a high number is associated with a shallow impression made in hard material, and a low number with a deep impression in soft material.

Table II. Combinations of Diameter of Indenter and Load for Brinell Test

Metal	Ratio[a] L/D^2	Load (kg) for Indicated Diameter (D) of Ball Indenter D = 1 mm	D = 2 mm	D = 5 mm	D = 10 mm
Steel and materials of similar hardness	30	30	120	750	3000
Copper alloys and materials of similar hardness	10	10	40	250	1000
Copper and materials of similar hardness	5	5	20	125	500
Lead, tin and materials of similar hardness	1	1	4	25	100

(a) L = test load. D = diameter of ball indenter. It is recommended that a designation such as "Bhn (10/3000/30)" be used to indicate ball diameter (mm), test load (kg), and duration of load application (sec).

Several different Rockwell scales, each associated with a particular combination of load and indenter, are necessary to cover the range of hardness encountered in metals. There are also two machines, the normal Rockwell tester for relatively thick sections, and the Rockwell superficial tester for materials too thin to be tested with the normal tester. Indenters include steel balls of diameters 1/16, 1/8, 1/4 and 1/2 in. and a 120-deg spheroconical diamond ("Brale") with a spherical apex of 0.2-mm radius. Major loads are 60, 100 and 150 kg on the normal tester and 15, 30 and 45 kg on the superficial tester. Both machines are capable of making precise measurements of depth; one scale division on the dial gage measures a vertical displacement of the indenter of 0.002 mm with the normal tester and 0.001 mm with the superficial tester.

The original, and most commonly used, Rockwell scales are B (1/16-in. ball indenter and 100-kg load) and C (spheroconical indenter and 150-kg load), both obtained with the normal tester. Because of the multiplicity of Rockwell scales, the hardness number must be designated according to the scale used; for example, as Rockwell B (R_B), Rockwell C (R_0) and so on. The various Rockwell scales are defined in Tables III and IV.

To obtain the best possible performance from a Rockwell tester, the following procedure is recommended:

1 The tester should be placed so that vibration does not seriously affect the readings of the dial gage.
2 For the minor load to be properly applied, the large needle on the dial gage should be at "set" within plus or minus five scale divisions. If the elevating operation results in the needle stopping within this range, but not on "set", no further adjustment should be made by means of the elevating screw, but the dial should be rotated to bring "set" under the needle.
3 On the normal tester, the dashpot, which controls the speed of application of the major load, should be adjusted so that the operating crank completes its travel in 5 sec with no specimen on the machine, but with the machine set up to apply a major load of 100 kg. In a similar manner the superficial tester is set for 7 sec with a major load of 30 kg.
4 The machine should apply the major load, that is, the operator should avoid any manual pressure on the crank after releasing the lever system. The major load is allowed to act until either the pointer on the dial gage suddenly slows down or the weight arm is completely free from control of the dashpot; the latter is preferred, because it is a clean-cut end point.* Within 2 sec after either of these points is reached, the operating crank should be returned gently to its starting position; snapping the crank to the starting position may cause an error of several points in the dial indication.
5 The performance of the machine should be checked frequently against standard test blocks supplied by the manufacturer. If the hardness value obtained differs from that inscribed on the test block, the machine should be adjusted according to the instructions supplied by the manufacturer.
6 Because the accuracy of the hardness determination depends on an accurate measurement of the depth of penetration, particular care must be taken to seat the indenter and anvil firmly. Any vertical movement at these points results in additional depth being registered on the gage and, therefore, means a false number.

Vickers Hardness Test. This test employs a square-based diamond pyramid indenter with an included angle of 136 deg between opposite faces; loads usually range from 5 to 100 kg. To make a test, the specimen is elevated to within about 1 mm of the indenter, and the lever loading system is set in starting position by means of a foot lever acting on a weight-and-cam mechanism that furnishes the motive power for the test. With release of the weight-and-cam mechanism, the indenter descends under the load, indents the specimen, and then returns to the starting position. The rate of descent of the indenter and the time the indenter is on the specimen are controlled by an oil dashpot, usually adjusted for a time cycle in the range of 10 to 20 sec. A buzzer system warns the operator if the specimen is not supporting the full load because of being too far from the indenter or not held rigidly enough for the size of the applied load.

* With the enclosed models, this end point virtually coincides with the completion of the travel of the crank.

Table III. Hardness Scales for Normal Rockwell Tester

The minor load is 10 kg; one scale division on the dial measures 0.002 mm vertical displacement of the indenter.

Scale Symbol	Indenter	Major Load, kg	Dial Scale	Application of Scale
B	1/16-in. Ball	100	Red	Materials of B 0 to B 100 hardness
C	Diamond	150	Black	Materials of C 20 to C 70 hardness
A	Diamond	60	Black	Extremely hard materials, such as tungsten carbide, which might chip indenter at higher load; also for hard sheet too thin for heavy loads.
D	Diamond	100	Black	Sometimes used on case hardened material
E	1/8-in. Ball	100	Red	For testing very soft materials such as bearing metals
F	1/16-in. Ball	60	Red	Substitute for the E scale(a)
G	1/16-in. Ball	150	Red	Phosphor bronze

(a) The E scale and the following scales may be more suitable for soft material in which, because of inhomogeneities, it is preferable to use a larger ball, making an impression of greater area and thus obtaining more of an average hardness. In such tests the smallest ball should be used that can satisfy the conditions, because of the loss of sensitivity as the size of the indenter increases.

Scale symbol	H	K	L	M	P	R	S	V
Ball diameter, in.	1/8	1/8	1/4	1/4	1/4	1/2	1/2	1/2
Load, kg	60	150	60	100	150	60	100	150

The red dial is used with all these scales.

The impression is measured through a microscope fitted with an ocular micrometer that contains movable knife edges; the distance between the knife edges is indicated on a counter calibrated in microns. The impression appears as a dark square on a light background. The length of the diagonal of the square is measured and used to compute the diamond pyramid hardness number (DPH), which is the load (kg) divided by the impressed area (sq mm). Although tables are supplied to convert the measurement of length to DPH, the following formula may be used:

$$\text{DPH} = \frac{1.8544L}{d^2}$$

L = Load in kilograms
d* = Length of diagonal of impression in millimeters

For ordinary testing, the range of loads is 5 to 100 kg; in this range a load of 10, 30, or 50 kg is usually employed. Theoretically, in this test the hardness number is independent of the load, but some slight discrepancies in this relationship have been observed; hence, it is advisable to report the load used.

Failure of the machine to check a standard block may be caused by:

1 Sticking of the plunger carrying the indenter
2 Sticking of the reciprocating bar that raises and lowers the loading lever
3 Too great lowering of the oil level in the dashpot
4 Zero position of the ocular micrometer being out of adjustment

The above description applies to the Vickers-Armstrong machine. Another machine designed specifically for the diamond pyramid hardness test is the Amsler-Vickers tester, which includes the main features of the Vickers test; namely, automatic application and removal of the load, the 136-deg square-based diamond pyramid indenter, and measurement of the impression with a microscope equipped with an adjustable ocular micrometer.

* For the Vickers-Armstrong tester, d is obtained from the ocular reading r, from the following relation:
$d = 0.002r$ or $0.001r$ (for 2/3-in. objective), and
$d = 0.005r$ or $0.0025r$ (for 1½-in. objective), depending on the constants of the ocular micrometer.

Table IV. Hardness Scales for Rockwell Superficial Tester

The minor load is 3 kg; dial has only one scale; one division on dial scale measures 0.001-mm vertical displacement of the indenter.

Scale symbol	15-N	30-N	45-N	15-T	30-T	45-T
Indenter	Diamond	Diamond	Diamond	1/16-in. Ball	1/16-in. Ball	1/16-in. Ball
Load, kg	15	30	45	15	30	45

N scales are used for material of such hardness that it would be tested with the C scale if of sufficient thickness.
T scales are used for material of such hardness that it would be tested with the B scale if of sufficient thickness.

Eberbach Tester. The Eberbach tester is a relatively recent development in the use of the DPH scale for testing "microhardness". The indenting unit employs a 136-deg diamond pyramid indenter loaded by springs and is readily substituted for the objective of any microscope. For making a test, a field is selected through the microscope; the indenting unit is then substituted for the objective of the microscope, and an indentation is made by bringing the specimen and indenter into contact by means of the focusing adjustment of the microscope. The microscope objective is then replaced and the indentation is measured through a micrometer eyepiece. The range of available loads is approximately 7.5 to 550 g. At present such testing appears to be qualitative rather than quantitative, but is a valuable tool for determining the relative hardness of microstructural constituents.

The Tukon Tester. The Tukon tester applies loads from 25 g to 50 kg and uses either the "Knoop" type of diamond indenter or the conventional square-based diamond pyramid indenter (Vickers) described under the Vickers Hardness Tester. The Knoop indenter is of pyramidal form having an included longitudinal angle of 172 deg, 30 min and included transverse angle of 130 deg, 0 min.

The Tukon tester is fully automatic, under electronic control in a synchronous cycle. The specimen to be tested is placed on a special micrometer stage that has two-way adjustment in a horizontal plane. The indentation is made by elevating the specimen against the indenter until the specimen resists further indentation, at which time electronically actuated contacts are opened, elevation of the specimen ceases, and the load remains on the specimen for a fixed period of time, after which the specimen is automatically lowered to clear the indenter, and then moved under a micrometer measuring microscope. Under the microscope, the Knoop impression appears rhombic in shape, with a ratio of long diagonal to short diagonal of 7.11 to 1. The long diagonal is measured and the Knoop hardness number is computed from the following formula:

$$I = \frac{L}{A_p} = \frac{L}{l^2 C_p}$$

where I = Knoop hardness number
L = Load (kg) applied to indenter
A_p = Projected area (sq mm) of indentation
l = Length of long diagonal (mm)
C_p = Constant for each indenter, supplied by manufacturer.

The hardness number, corresponding to a measured length l, for a given load, may be determined from a table supplied along with the tester.

When the square-based diamond pyramid indenter is used, the DPH formula is employed for calculating the hardness number.

Monotron Test. The Monotron test consists of measuring the load required for pressing a diamond indenter of 0.75-mm diam into the test specimen to a depth of 0.045 mm. Depth of penetration is measured under load by means of a compensated depth micrometer gage; a pressure gage indicates the load in kilograms applied to the indenter. The loading range is from 0 to 160 kg. The Monotron hardness is the load indicated on the dial gage when the 0.75-mm diam indenter is employed. Other Monotron scales are as follows:

Scale	*Indenter*
M-2	1-mm diamond ball
M-3	$\frac{1}{8}$-in. tungsten carbide ball
M-4	2.5-mm tungsten carbide ball

For testing materials of high hardness, such as tungsten carbide, it is customary to penetrate only 0.015 mm deep in order to avoid damage to the diamond; the load indicated is then multiplied by three to obtain the hardness number at a penetration depth of 0.045 mm. Such a procedure is possible because of the linear relationship between load and depth of penetration.

Bierbaum Microcharacter. This is a form of scratch hardness test rather than indentation. The apparatus consists of a diamond cutting-point in the form of a corner of a cube, a means of drawing the test surface under the diamond point, and a microscope with an adjustable ocular micrometer to measure the width of the cut. The load on the diamond is 3 g. The hardness number is expressed by the formula, $K = 10^4/\lambda^2$ where K is the hardness number and λ is the width of the cut measured in microns. This instrument is better suited for research work than for commercial testing.

Automatic Testers. This type of tester, either wholly or partly motor-driven, is used in production work.

Brinell Test. One adaptation[7] of the Brinell test is entirely power-driven. A 3000-kg load is used, one-half of which is applied as a preload to "set" the specimen and minimize the effects of surface conditions such as scale. As the remainder of the load is applied, a dial gage records penetration beyond the preload point. The dial numbers are not intended to be Brinell hardness numbers, but ■ position on the dial is empirically determined that corresponds to the Brinell hardness number of a satisfactory part. This is done by preparing a test surface properly on a representative product and obtaining the Brinell hardness number in the conventional manner, using the automatic machine to indent the specimen. A test is then made with the machine, on an unprepared surface of the specimen. The dial reading is assumed to correspond to the conventional Brinell hardness number with surface conditions taken into consideration automatically. Obviously, surface conditions must be fairly constant. Since this is only a comparative test, the results should never be construed as true Brinell hardness numbers.

Rockwell Test. In this version of the tester an electric motor, driving a cam, lowers and raises the lever, thus applying and withdrawing the major load. The time required for a complete cycle can be either 4 or 1¼ sec; the high speed is for hard specimens, the low speed for soft. It is questionable whether this tester gives true Rockwell readings. As in the conventional test, the minor load is applied by manual control. The dial gage indicates the hardness.

Portable Hardness Testers. *Brinell Meter.* This tester is constructed in such a manner that a small portion of a 10-mm steel ball projects through the base of the instrument, and within the instrument a bar of known Brinell hardness number backs up the ball. To obtain a hardness number, the tester is held in such a manner that the ball is between the test specimen and standard bar; the head of the instrument is struck a sharp blow with a hammer; then the diameters of the indentations in the specimen and bar are measured. With the aid of a table, the ratio of these diameters is used to determine the Brinell hardness number of the specimen.

The King Portable Brinell Machine. This machine is capable of making a standard Brinell test with either 500 or 3000-kg load on a 10-mm ball. The design provides a clamping device that enables the machine to be used in any position; the test head can be removed from the frame for mounting on a large planer or boring mill. The complete tester weighs 26 lb.

Scleroscope. This instrument measures the rebound hardness of a material by allowing a diamond-tipped tup to fall by its own weight and to rebound from the test specimen. The height to which the tup rebounds is taken as a measure of the hardness of the material. The tup operates within a vertical glass tube on which is inscribed a scale for measuring the height of rebound. A dial gage can be used for measuring and recording this height.

This test is used especially for measuring the hardness of smooth surfaces that must not be marked by an indentation. A rough surface will cause low readings.

File Hardness Test.* In defining the term "file hard", one should specify the hardening procedure used on the test block that the file cannot "touch". The surface of the steel article being tested is rubbed slowly but firmly with the sharp teeth of the file until the operator has determined whether or not the file will "bite", that is, whether or not the material is "file hard".

The test is, for the most part, limited to untempered hardened parts, and comparative testing within a given

* Condensed from E. T. Morton's "File Hardness Test", which appeared in the 1939 edition of this Handbook.

shop. The information derived from it is influenced by the following factors:

1 *Size and Shape of File.* These should be standardized as: (*a*) 6-in. Pillar Testing File No. 0 and No. 1 to be used on flat, oblong, and square test pieces; file No. 0 is suitable for hardened steel, file No. 1 for tempered steel. (*b*) 8-in. Pillar Narrow Testing File for hardened steel. (*c*) 6-in. Three Square Testing File No. 1, for testing an object of irregular shape in which there are crevices and grooves.
2 *Hardness of File.* As long as a file will cut a master test specimen, it is suitable for testing purposes.
3 *Speed of Filing.* The slower the speed, the more accurate the test.
4 *Pressure.* This will vary among operators, but should be kept as firm and as nearly constant as possible.
5 *Angle of Contact.* This should be kept as nearly constant as possible.
6 *Composition and Heat Treatment.* With steels of Rockwell C 60 or more, differences in composition and heat treatment are associated with apparent anomalies, such as the relative hardness of two materials being reversed with the file test as compared with an indentation hardness test.

Factors Influencing the Accuracy of an Indentation Hardness Test

Accuracy of Load Applied. Any tester supplied by a reputable manufacturer should apply loads in a stated range with negligible error, but wear and accumulation of dirt, which result in excessive friction, may impair the accuracy of the loading mechanism; therefore, it is advisable to service the machine regularly. It should be remembered that loads beyond the recommended range of a machine are not to be relied on for accurate testing.

Impact Loading. In addition to causing inaccurate hardness numbers, impact loading may damage diamond indenters. Such loading can be avoided by smooth and steady operation of the loading mechanism, when it is under manual control. When the load is applied under the control of an oil dashpot, the oil should be kept at the recommended level. A slow speed of applying the load is preferable to a fast one, since there is less danger of serious impact effects.

Duration of Load Application. Some metals exhibit high rates of flow under the test load;[8] consequently, to obtain consistent hardness results, it is necessary to control the duration of load application.

Condition of the Indenter. Flattening of a steel ball indenter results in error in the hardness numbers; the ball should be checked often for permanent deformation and discarded when such deformation occurs. Diamond indenters must be accurately ground and polished; chipping of such indenters causes inaccurate tests.

Condition of the Anvil. The anvil on which the test specimen rests must be clean and smooth; care should be taken not to bring the anvil against the indenter. When testing thin material, the hardness range of which is unknown, it is best to start with a light load in order to minimize the possibility of the indenter punching through the specimen and indenting the anvil.

Method of Measuring the Impression. When measurement of the diameter of the impression is required, the sensitivity of the ocular micrometer must be suitable for the size of impression. For most shop applications, Brinell impressions made with 3000 and 500-kg loads, are measured with sufficient precision at ×10 and ×20 magnification, with a millimeter scale the smallest division of which is 0.1 mm; for high-precision Brinell testing at hardness levels higher than about 480 Bhn, ■ carbide indenter should be used and the diameter of the indentation should be measured to ± 0.01 mm at ■ magnification of ×40 with a Brinell microscope of the micrometer slide comparator type. For the smaller impressions of the DPH test, using loads of 5 to 100 kg, an optical method that measures to plus or minus one micron is desirable; furthermore, with optical methods of measuring, in order to obtain a sharp image of the impression, the magnification should not be so great as to sacrifice good resolution of the image. Adjustable ocular micrometers should be checked against a standard length of stage micrometer.

The measurement of the depth of the impression is subject to error if there is any binding in the mechanism of the dial gage; furthermore, such a measurement requires a high degree of sensitivity in the dial gage because of the shallow depth of indentation.

Thickness of Specimen. The specimen should be thick enough so that no bulge or other marking appears on the surface opposite that of indentation. The recommended thickness of the specimen is at least ten times the depth of the impression. With Rockwell tests, the depth of penetration can be obtained from the dial gage; with a DPH test, the penetration depth is 0.143 of the diagonal length of the impression. Data in Table V should aid in the selection of a suitable hardness scale that will maintain the recommended relationship between specimen thickness and depth of penetration; the values of Table V are ten times the depth of impression as measured directly by the Rockwell tester and as calculated from measurements of diameter in other tests, assuming that the impression has the same contour as the indenter.

Surface Condition of the Specimen. The surface of the specimen on which the indentation is made should be flat and representative of sound metal; decarburized metal, pits, scale and grease should be removed. To obtain such a surface usually requires a filing, grinding or cutting operation. These operations result in a layer of disturbed metal, the hardness of which is not necessarily representative of the underlying metal; furthermore, the depth of the layer depends on the severity of the operation. This is particularly noticeable on metals of high strain-hardening capacity, as shown by Hull and Welton[9] who found that as the depth of finishing cut in machining increased, the depth of work hardening increased. Another possible effect of grinding and cutting is overheating the specimen to such an extent that the material for some distance below the surface is no longer representative. These surface effects result in erratic hardness numbers and so must be reduced by finer polishing until they represent only a small portion of the depth of indentation; the amount of reduction is controlled largely by the depth of indentation, which varies with load, size of

Table V. Minimum Thickness of Specimen (in inches) for Accurate Hardness Number with Indicated Test*

Hardness of Material, DPH	DPH Test				Rockwell Normal				Rockwell Superficial			Brinell, 10-mm ball	
	5 kg	10 kg	30 kg	50 kg	A	C	B	E	15-N	45-N	30-T	3000 kg	500 kg
1000	0.0054	0.0076	0.0133	0.017	0.013	0.025	....	.....	0.003	0.011	.....	....	....
900	0.0057	0.0081	0.0140	0.018	0.014	0.027	....	.....	0.003	0.012	.....	0.046	....
800	0.0060	0.0086	0.0149	0.019	0.015	0.030	....	.....	0.004	0.014	.....	0.052	....
700	0.0065	0.0092	0.0159	0.020	0.017	0.033	....	.....	0.005	0.016	.....	0.060	....
600	0.0070	0.0100	0.0171	0.022	0.020	0.038	....	.....	0.006	0.019	.....	0.071	....
500	0.0076	0.0110	0.0188	0.024	0.023	0.044	....	.....	0.007	0.022	.....	0.085	....
400	0.0086	0.0120	0.0210	0.027	0.027	0.050	....	.....	0.009	0.026	0.0046	0.102	....
350	0.0092	0.0130	0.0224	0.029	....	0.055	....	.....	....	....	0.0055	0.114	0.025
300	0.0099	0.0140	0.0242	0.031	0.033	0.059	0.020	.....	0.012	0.032	0.0066	0.134	0.028
250	0.0108	0.0155	0.0266	0.034	....	0.066	0.025	.....	....	....	0.0079	0.162	0.032
200	0.0121	0.0170	0.0297	0.038	0.041	0.072	0.032	0.0185	0.015	0.040	0.0101	0.197	0.037
150	0.0140	0.0198	0.0343	0.044	....	....	0.045	0.0242	....	....	0.0141	0.275	0.050
100	0.0171	0.0248	0.0419	0.054	....	....	0.071	0.0370	....	....	0.0213	0.400	0.074
75	0.0198	0.0280	0.0485	....	....	....	0.108	0.0506	....	....	0.0288	0.500	0.100
50	0.0242	0.0343	.....	....	....	....	....	0.0836	....	....	0.0440	....	0.130
25	0.0343	0.0485	.....	....	....	....	....	.....	....	....	.....	....	0.248

* Data from Westinghouse Electric Corporation

indenter, and hardness. However, if the size of the indentation is to be measured with a microscope, the surface finish must be capable of giving a well-defined impression, and may require continuing with a finer polishing procedure. There seems to be no established optimum degree of surface preparation for an accurate test; however, a few check tests on specimens of uniform material, but with different degrees of surface preparation, will usually determine the finish necessary to eliminate variation in hardness caused by these effects. A shallow indentation is more affected than a deep one. For many practical purposes, the 3000 and 500-kg Brinell tests are sufficiently accurate on a surface prepared by filing, followed by sufficient polishing on abrasive paper to obtain a good image of the impression in the microscope. With the lighter loads used in normal Rockwell and DPH testing, the surface finish should be at least the equivalent of 320-grit abrasive paper; and for 5 and 10-kg DPH tests and Rockwell superficial tests, the surface should

Table VI. Hardness Conversion Numbers for Steel

Brinell Hardness Number				Rockwell Hardness Number			Rockwell Superficial Hardness Number					
Diamond Pyramid Hardness Number	10-mm Standard Ball, 3000-kg Load	10-mm Hultgren Ball, 3000-kg Load	10-mm Carbide Ball, 3000-kg Load	C Scale 150-kg Load, Brale Penetrator	A Scale, 60-kg Load, Brale Penetrator	D-Scale, 100-kg Load, Brale Penetrator	15-N Scale, 15-kg Load, Superficial Brale Penetrator	30-N Scale, 30-kg Load, Superficial Brale Penetrator	45-N Scale, 45-kg Load, Superficial Brale Penetrator	Scleroscope Hardness Number	Approx Tensile Strength, 1000 psi	Diamond Pyramid Hardness Number
940	*	...	...	68.0	85.6	76.9	93.2	84.4	75.4	97	...	940
920	*	...	...	67.5	85.3	76.5	93.0	84.0	74.8	96	...	920
900	*	...	...	67.0	85.0	76.1	92.9	83.6	74.2	95	...	900
880	*	...	...	66.4	84.7	75.7	92.7	83.1	73.6	93	...	880
860	*	...	...	65.9	84.4	75.3	92.5	82.7	73.1	92	...	860
840	*	...	745	65.3	84.1	74.8	92.3	82.2	72.2	91	...	840
820	*	...	733	64.7	83.8	74.3	92.1	81.7	71.8	90	...	820
800	*	...	722	64.0	83.4	73.8	91.8	81.1	71.0	88	...	800
780	*	...	710	63.3	83.0	73.3	91.5	80.4	70.2	87	...	780
760	*	...	698	62.5	82.6	72.6	91.2	79.7	69.4	86	...	760
740	*	...	684	61.8	82.2	72.1	91.0	79.1	68.6	84	...	740
720	*	...	670	61.0	81.8	71.5	90.7	78.4	67.7	83	...	720
700	*	615	656	60.1	81.3	70.8	90.3	77.6	66.7	81	...	700
690	*	610	647	59.7	81.1	70.5	90.1	77.2	66.2	..	...	690
680	*	603	638	59.2	80.8	70.1	89.8	76.8	65.7	80	329	680
670	*	597	630	58.8	80.6	69.8	89.7	76.4	65.3	..	324	670
660	*	590	620	58.3	80.3	69.4	89.5	75.9	64.7	79	319	660
650	*	585	611	57.8	80.0	69.0	89.2	75.5	64.1	..	314	650
640	*	578	601	57.3	79.8	68.7	89.0	75.1	63.5	77	309	640
630	*	571	591	56.8	79.5	68.3	88.8	74.6	63.0	..	304	630
620	*	564	582	56.3	79.2	67.9	88.5	74.2	62.4	75	299	620
610	*	557	573	55.7	78.9	67.5	88.2	73.6	61.7	..	294	610
600	*	550	564	55.2	78.6	67.0	88.0	73.2	61.2	74	289	600
590	*	542	554	54.7	78.4	66.7	87.8	72.7	60.5	..	284	590
580	*	535	545	54.1	78.0	66.2	87.5	72.1	59.9	72	279	580
570	*	527	535	53.6	77.8	65.8	87.2	71.7	59.3	..	274	570
560	*	519	525	53.0	77.4	65.4	86.9	71.2	58.6	71	269	560
550	505	512	517	52.3	77.0	64.8	86.6	70.5	57.8	..	264	550
540	496	503	507	51.7	76.7	64.4	86.3	70.0	57.0	69	260	540
530	488	495	497	51.1	76.4	63.9	86.0	69.5	56.2	..	254	530
520	480	487	488	50.5	76.1	63.5	85.7	69.0	55.6	67	250	520
510	473	479	479	49.8	75.7	62.9	85.4	68.3	54.7	..	244	510
500	465	471	471	49.1	75.3	62.2	85.0	67.7	53.9	66	240	500
490	456	460	460	48.4	74.9	61.6	84.7	67.1	53.1	..	234	490
480	448	452	452	47.7	74.5	61.3	84.3	66.4	52.2	64	230	480
470	441	442	442	46.9	74.1	60.7	83.9	65.7	51.3	..	224	470
460	433	433	433	46.1	73.6	60.1	83.6	64.9	50.4	62	220	460
450	425	425	425	45.3	73.3	59.4	83.2	64.3	49.4	..	214	450
440	415	415	415	44.5	72.8	58.8	82.8	63.5	48.4	59	210	440
430	405	405	405	43.6	72.3	58.2	82.3	62.7	47.4	..	204	430
420	397	397	397	42.7	71.8	57.5	81.8	61.9	46.4	57	200	420
410	388	388	388	41.8	71.4	56.8	81.4	61.1	45.3	..	195	410
400	379	379	379	40.8	70.8	56.0	80.0	60.2	44.1	55	190	400
390	369	369	369	39.8	70.3	55.2	80.3	59.3	42.9	..	185	390
380	360	360	360	38.8	69.8	54.4	79.8	58.4	41.7	■	180	380
370	350	350	350	37.7	69.2	53.6	79.2	57.4	40.4	..	175	370
360	341	341	341	36.6	68.7	52.8	78.6	56.4	39.1	50	170	360
350	331	331	331	35.5	68.1	51.9	78.0	55.4	37.8	..	166	350
340	322	322	322	34.4	67.6	51.1	77.4	54.4	36.5	47	161	340
330	313	313	313	33.3	67.0	50.2	76.8	53.6	35.2	..	156	330
320	303	303	303	32.2	66.4	49.4	76.2	52.3	33.9	45	151	320
310	294	294	294	31.0	65.8	48.4	75.6	51.3	32.5	..	146	310
300	284	284	284	29.8	65.2	47.5	74.9	50.2	31.1	42	141	300
295	280	280	280	29.2	64.8	47.1	74.6	49.7	30.4	..	139	295
290	275	275	275	28.5	64.5	46.5	74.2	49.0	29.5	41	136	290
285	270	270	270	27.8	64.2	46.0	73.8	48.4	28.7	..	134	285
280	265	265	265	27.1	63.8	45.3	73.4	47.8	27.9	40	131	280
275	261	261	261	26.4	63.5	44.9	73.0	47.2	27.1	..	129	275
270	256	256	256	25.6	63.1	44.3	72.6	46.4	26.2	38	126	270
265	252	252	252	24.8	62.7	43.7	72.1	45.7	25.2	..	124	265
260	247	247	247	24.0	62.4	43.1	71.6	45.0	24.3	37	121	260
255	243	243	243	23.1	62.0	42.2	71.1	44.2	23.2	..	119	255
250	238	238	238	22.2	61.6	41.7	70.6	43.4	22.2	36	116	250
245	233	233	233	21.3	61.2	41.1	70.1	42.5	21.1	..	114	245
240	228	228	228	20.3	60.7	40.3	69.6	41.7	19.9	34	111	240

*For the 10-mm standard steel ball, no values of Brinell hardness are given higher than 500 Bhn. This is in conformance with the limitations established by the Standard Method of Test for Brinell Hardness of Metallic Materials (ASTM Designation E 10).

The values of scleroscope hardness number and approximate tensile strength are from the 1946 SAE Handbook. All other values are from ASTM Standard E 48-43T.

be as smooth as possible. For tests using light loads, such as Tukon tests, the best procedure requires a metallographic polish, after sufficient metal has been removed to get below the disturbed metal from previous operations that might have caused serious work hardening.[9]

The surface of the specimen adjacent to the anvil of the tester requires attention when a dial-gage measurement of the impression is to be used. Since scale, paint, grease and deep grinding marks result in sinking of the specimen when the test load is applied, such movement is recorded as added depth, thus giving a false hardness reading. Sinking of the specimen during a test that involves measurement of the diameter of impression, is not objectionable if the amount is not too great for the full test load to be applied to the specimen.

Shape of Specimen. For the greatest accuracy in any indentation hardness test, the test surface of the specimen should be flat and should be normal to the vertical axis of the indenter. A specimen that extends beyond the edge of the anvil must be supported so that it does not tip.

When a cylindrical shape is to be tested, a flat test surface should be prepared if possible, and a V-notch anvil should be used to support the specimen. If it is necessary to make a test on a curved surface, a hardness value based on measurement of depth is likely to be more in error than one determined by the measurement of the long and short diagonals of a DPH impression, taking the average hardness. Ingerson[10] has published correction factors that may help in determining the hardness of a curved surface.

For testing a tube, some form of internal support is necessary to ensure accuracy in hardness tests.

Locations of Indentations. The placing of an impression in relation to the edge of the specimen or to another impression, affects the accuracy of the result. According to O'Neill,[11] impressions should be at least 2½ diam from the edge of the specimen, and the distance between impressions should be 5 diam for ball tests and 2½ diam for cone and pyramid tests. Small cracks should be avoided, since they result in low hardness numbers as well as in damage to diamond indenters.

Uniformity of Material. If the impression area is not large enough, numerous impressions should be made in order to account for variations in the hardness number that are associated with structural inhomogeneity of the mate-

Table VII. Hardness Conversion Numbers for Steel

Brinell Hardness Number				Rockwell Hardness Number		Rockwell Superficial Hardness Number					
Rockwell C Hardness Number	Diamond Pyramid Hardness Number	10-mm Standard Ball, 3000-kg Load	10-mm Hultgren Ball, 3000-kg Load	10-mm Carbide Ball, 3000-kg Load	A Scale, 60-kg Load, Brale Penetrator	D Scale, 100-kg Load, Brale Penetrator	15-N Scale, 15-kg Load, Superficial Brale Penetrator	30-N Scale, 30-kg Load, Superficial Brale Penetrator	45-N Scale, 45-kg Load, Superficial Brale Penetrator	Scleroscope Hardness Number	Approx Tensile Strength, 1000 psi	Rockwell C Hardness Number
68	940	*	...	...	85.6	76.9	93.2	84.4	75.4	97	...	68
67	900	*	...	...	85.0	76.1	92.9	83.6	74.2	95	...	67
66	865	*	...	...	84.5	75.4	92.5	82.8	73.3	92	...	66
65	832	*	...	739	83.9	74.5	92 2	81.9	72.0	91	...	[illegible]
64	800	*	...	722	83.4	73.8	91.8	81.1	71.0	88	...	[illegible]
63	772	*	...	705	82.8	73.0	91.4	80.1	69.9	87	...	63
62	746	*	...	688	82.3	72.2	91.1	79.3	68.8	85	...	62
61	720	*	...	670	81.8	71.5	90.7	78.4	67.7	83	...	61
60	697	*	613	654	81.2	70.7	90.2	77.5	66.6	81	...	60
59	674	*	599	634	80.7	69.9	89.8	76.6	65.5	80	326	59
58	653	*	587	615	80.1	69.2	89.3	75.7	64.3	78	315	[illegible]
57	633	*	575	595	79.6	68.5	88.9	74.8	63.2	76	305	57
56	613	*	561	577	79.0	67.7	88.3	73.9	62.0	75	295	56
55	595	*	546	560	78.5	66.9	87.9	73.0	60.9	74	287	55
54	577	*	534	543	78.0	66.1	87.4	72.0	59.8	72	278	54
53	560	*	519	525	77.4	65.4	86.9	71.2	58.6	71	269	53
52	544	500	508	512	76.8	64.6	86.4	70.2	57.4	69	262	52
51	528	487	494	496	76.3	63.8	85.9	69.4	56.1	68	253	51
50	513	475	481	481	75.9	63.1	85.5	68.5	55.0	67	245	50
49	498	464	469	469	75.2	62.1	85.0	67.6	53.8	66	239	49
48	484	451	455	455	74.7	61.4	84.5	66.7	52.5	64	232	48
47	471	442	443	443	74.1	60.8	83.9	65.8	51.4	63	225	47
46	458	432	432	432	73.6	60.0	83.5	64.8	50.3	62	219	46
45	446	421	421	421	73.1	59.2	83.0	64.0	49.0	60	212	45
44	434	409	409	409	72.5	58.5	82.5	63.1	47.8	58	206	44
43	423	400	400	400	72.0	57.7	82.0	62.2	46.7	57	201	43
42	412	390	390	390	71.5	56.9	81.5	61.3	45.5	56	196	42
41	402	381	381	381	70.9	56.2	80.9	60.4	44.3	55	191	41
40	392	371	371	371	70.4	55.4	80.4	59.5	43.1	54	186	40
39	382	362	362	362	69.9	54.6	79.9	58.6	41.9	52	181	39
38	372	353	353	353	69.4	53.8	79.4	57.7	40.8	51	176	[illegible]
37	363	344	344	344	68.9	53.1	78.8	56.8	39.6	50	172	37
36	354	336	336	336	68.4	52.3	78.3	55.9	38.4	49	168	36
35	345	327	327	327	67.9	51.5	77.7	55.0	37.2	48	163	35
34	336	319	319	319	67.4	50.8	77.2	54.2	36.1	47	159	34
33	327	311	311	311	66.8	50.0	76.6	53.3	34.9	46	154	33
32	318	301	301	301	66.3	49.2	76.1	52.1	33.7	44	150	32
31	310	294	294	294	65.8	48.4	75.6	51.3	32.5	43	146	31
30	302	286	286	286	65.3	47.7	75.0	50.4	31.3	42	142	30
29	294	279	279	279	64.7	47.0	74.5	49.5	30.1	41	138	29
28	286	271	271	271	64.3	46.1	73.9	48.6	28.9	41	134	28
27	279	264	264	264	63.8	45.2	73.3	47.7	27.8	40	131	27
26	272	258	258	258	63.3	44.6	72.8	46.8	26.7	38	127	26
25	266	253	253	253	62.8	43.8	72.2	45.9	25.5	38	124	25
24	260	247	247	247	62.4	43.1	71.6	45.0	24.3	37	121	24
23	254	243	243	243	62.0	42.1	71.0	44.0	23.1	36	118	[illegible]
22	248	237	237	237	61.5	41.6	70.5	43.2	22.0	35	115	22
21	243	231	231	231	61.0	40.9	69.9	42.3	20.7	35	113	21
20	238	226	226	226	60.5	40.1	69.4	41.5	19.6	34	110	20

* For the 10-mm standard steel ball, no values of Brinell hardness are given higher than 500 Bhn. This is in conformance with the limitations established by the Standard Method of Test for Brinell Hardness of Metallic Materials (ASTM Designation E 10).

The values of scleroscope hardness number and approximate tensile strength are from the 1946 SAE Handbook. All other values are from ASTM Standard E 48-43T.

rial. Testing a material by making a large number of small impressions affords a method for establishing the degree of inhomogeneity of the material.

Advantages and Disadvantages of Different Types of Tests

The selection of a hardness test is usually determined by ease of performance and degree of accuracy desired.

The Brinell test is an old, established test that provides a means of studying the work hardening of metals, a property of considerable importance in relationships based on hardness, and on hardness versus tensile strength.[8,12] Because of the standard practice of using a 10-mm ball and 3000 or 500-kg loads, this test is limited to large specimens; however, the large indentation is an advantage when the material tested is not uniform; also, the surface does not need to be so smooth as that for smaller impressions. To make the Brinell test useful on small specimens requires changing the size of the load and ball in order to keep the hardness numbers on the same scale. Perhaps this is not a disadvantage, since other widely used tests change the indenter and load without keeping the same hardness scale. Because it is related to the diameter of the impression, the Brinell hardness number is less subject to errors of unrecovered vertical motion of the specimen than is a dial-gage hardness; however, using a microscope to measure the impression is less convenient than reading a dial gage. The standard practice of employing a steel ball makes hardness testing inaccurate above 479 Bhn (510 DPH) because of deformation of the ball—a disadvantage that can be overcome to some extent by the use of a tungsten carbide ball.

Table VIII. Hardness Conversion Numbers for Steel

Brinell Hardness Number					Rockwell Hardness Number			Rockwell Superficial Hardness Number					
Brinell Indentation Diameter, mm	10-mm Standard Ball, 3000-kg Load	10-mm Hultgren Ball, 3000-kg Load	10-mm Carbide Ball, 3000-kg Load	Diamond Pyramid Hardness Number	C Scale, 150-kg Load, Brale Penetrator	A Scale, 60-kg Load, Brale Penetrator	D Scale, 100-kg Load, Brale Penetrator	15-N Scale, 15-kg Load, Superficial Brale Penetrator	30-N Scale, 30-kg Load, Superficial Brale Penetrator	45-N Scale, 45-kg Load, Superficial Brale Penetrator	Scleroscope Hardness Number	Approx Tensile Strength, 1000 psi	Brinell Indentation Diameter, mm
2.35	*	...	682	737	61.7	82.2	72.0	91.0	79.0	68.5	84	...	2.35
2.40	*	...	653	697	60.0	81.2	70.7	90.2	77.5	66.5	81	...	2.40
2.45	*	...	627	667	58.7	80.5	69.7	89.6	76.3	65.1	79	323	2.45
2.50	*	...	...	...	....	....	....	....	....	....	..	....	2.50
	...	601	...	677	59.1	80.7	70.0	89.8	76.8	65.7	..	318	
	...	...	601	640	57.3	79.8	68.7	89.0	75.1	63.5	77	309	
2.55	*	...	...	...	....	....	....	....	....	....	..	....	2.55
	...	578	...	640	57.3	79.8	68.7	89.0	75.1	63.5	..	309	
	...	...	578	615	56.0	79.1	67.7	88.4	73.9	62.1	75	297	
2.60	*	...	...	...	....	....	....	....	....	....	..	....	2.60
	...	555	...	607	55.6	78.8	67.4	88.1	73.5	61.6	..	293	
	...	...	555	591	54.7	78.4	66.7	87.8	72.7	60.6	73	285	
2.65	*	...	...	...	....	....	....	....	....	....	..	....	2.65
	...	534	...	579	54.0	78.0	66.1	87.5	72.0	59.8	..	279	
	...	...	534	569	53.5	77.8	65.8	87.2	71.6	59.2	71	274	
2.70	*	...	...	...	....	....	....	....	....	....	..	....	2.70
	...	514	...	553	52.5	77.1	65.0	86.7	70.7	58.0	..	266	
	...	...	514	547	52.1	76.9	64.7	86.5	70.3	57.6	70	263	
2.75	495	...	...	539	51.6	76.7	64.3	86.3	69.9	56.9	..	259	2.75
	...	495	...	530	51.1	76.4	63.9	86.0	69.5	56.2	..	254	
	...	...	495	528	51.0	76.3	63.8	85.9	69.4	56.1	68	253	
2.80	477	...	...	516	50.3	75.9	63.2	85.6	68.7	55.2	..	247	2.80
	...	477	...	508	49.6	75.6	62.7	85.3	68.2	54.5	..	243	
	...	...	477	508	49.6	75.6	62.7	85.3	68.2	54.5	66	243	
2.85	461	...	...	495	48.8	75.1	61.9	84.9	67.4	53.5	..	237	2.85
	...	461	...	491	48.5	74.9	61.7	84.7	67.2	53.2	..	235	
	...	...	461	491	48.5	74.9	61.7	84.7	67.2	53.2	65	235	
2.90	444	...	...	474	47.2	74.3	61.0	84.1	66.0	51.7	..	226	2.90
	...	444	...	472	47.1	74.2	60.8	84.0	65.8	51.5	..	225	
	...	...	444	472	47.1	74.2	60.8	84.0	65.8	51.5	63	225	
2.95	429	429	429	455	45.7	73.4	59.7	83.4	64.6	49.9	61	217	2.95
3.00	415	415	415	440	44.5	72.8	58.8	82.8	63.5	48.4	59	210	3.00
3.05	401	401	401	425	43.1	72.0	57.8	82.0	62.3	46.9	58	202	3.05
3.10	388	388	388	410	41.8	71.4	56.8	81.4	61.1	45.3	56	195	3.10
3.15	375	375	375	396	40.4	70.6	55.7	80.6	59.9	43.6	54	188	3.15
3.20	363	363	363	383	39.1	70.0	54.6	80.0	58.7	42.0	52	182	3.20
3.25	352	352	352	372	37.9	69.3	53.8	79.3	57.6	40.5	51	176	3.25
3.30	341	341	341	360	36.6	68.7	52.8	78.6	56.4	39.1	50	170	3.30
3.35	331	331	331	350	35.5	68.1	51.9	78.0	55.4	37.8	48	166	3.35
3.40	321	321	321	339	34.3	67.5	51.0	77.3	54.3	36.4	47	160	3.40
3.45	311	311	311	328	33.1	66.9	50.0	76.7	53.3	34.4	46	155	3.45
3.50	302	302	302	319	32.1	66.3	49.3	76.1	52.2	33.8	45	150	3.50
3.55	293	293	293	309	30.9	65.7	48.3	75.5	51.2	32.4	43	145	3.55
3.60	285	285	285	301	29.9	65.3	47.6	75.0	50.3	31.2	..	141	3.60
3.65	277	277	277	292	28.8	64.6	46.7	74.4	49.3	29.9	41	137	3.65
3.70	269	269	269	284	27.6	64.1	45.9	73.7	48.3	28.5	40	133	3.70
3.75	262	262	262	276	26.6	63.6	45.0	73.1	47.3	27.3	39	129	3.75
3.80	255	255	255	269	25.4	63.0	44.2	72.5	46.2	26.0	38	126	3.80
3.85	248	248	248	261	24.2	62.5	43.2	71.7	45.1	24.5	37	122	3.85
3.90	241	241	241	253	22.8	61.8	42.0	70.9	43.9	22.8	36	118	3.90
3.95	235	235	235	247	21.7	61.4	41.4	70.3	42.9	21.5	35	115	3.95
4.00	229	229	229	241	20.5	60.8	40.5	69.7	41.9	20.1	34	111	4.00

* For the 10-mm standard steel ball, no values of Brinell hardness are given higher than 500 Bhn. This is in conformance with the limitations established by the Standard Method of Test for Brinell Hardness of Metallic Materials (ASTM Designation E 10).

The values of scleroscope hardness number and approximate tensile strength are from the 1946 SAE Handbook. All other values are from ASTM Standard E 48-43T.

The Rockwell test, rapid and simple in operation, provides a means of measuring the hardness of small specimens. The hardest as well as the softest materials can be tested, since different scales of hardness may be applied, some of which are related empirically to one another with conversion tables. The hardness number is easily read on a dial gage, but it is subject to error if there is any unrecovered vertical motion of the specimen during the test.

The diamond pyramid hardness test is a relatively recent development when compared with the Brinell and Rockwell tests. Because of the constant angle of penetration, the DPH is theoretically independent of load and thus all hardness numbers are on the same scale; actually, this is true for loads of 5 to 100 kg. Furthermore, the diamond indenter is well suited for testing the softest as well as the hardest materials. Like the Bhn, the DPH is related to the diagonal of the impression and does not suffer from errors of unrecovered vertical motion of the specimen. The automatic loading feature of the machines designed for this test, eliminates errors from variation in rate and duration of loading and impact loading. Since the image of the impression is a square, it can be read more accurately than a Brinell impression, but it requires a better surface because of the small size of the impression. The optical measurement might be considered too time-consuming but, for production work, the Vickers microscope is equipped with an adjustable shutter that can be set for the desired hardness limits, thus eliminating adjustment of the ocular micrometer for each impression; an Amsler tester is available that projects the image of the impression on a ground glass for measuring purposes. Because of the shallow impressions, this test is well suited for measuring the hardness of thin as well as thick materials (*see* Table V). Some vertical motion of the specimen does not result in error—a feature that makes this test ideal for small sections that have odd shapes, since such specimens can be mounted in bakelite or in clamps for testing.

The Tukon tester, a recent development, is a precision machine used in testing surface conditions and specimens too thin to be tested with the machines that employ heavy loads. The Tukon tester is also well suited for testing the hardness of small parts such as are found in watches since, as in the Vickers test, specimens can be tested while mounted. With this test a new hardness scale has been introduced (Knoop hardness); its relationship to other scales has not yet been determined. Since the Tukon tester uses a pyramidal form of indenter, hardness numbers should be independent of load, but this does not appear to be true. When this machine is employed, the hardness of microconstituents can be investigated with either the Knoop

Table IX. Hardness Conversion Numbers for Metals Softer than 240 Bhn

(Wilson Mechanical Instrument Company Chart No. 38)

Rockwell Hardness Scales*									Bhn	
B	F	G	15-T	30-T	45-T	E	K	A	500-kg Load *	3000-kg Load *
100	....	82.5	93.0	82.0	72.0	....	....	61.5	201	240
99	....	81.0	92.5	81.5	71.0	....	....	61.0	195	234
98	....	79.0	....	81.0	70.0	....	....	60.0	189	228
97	....	77.5	92.0	80.5	69.0	....	....	59.5	184	222
96	....	76.0	....	80.0	68.0	....	....	59.0	179	216
95	....	74.0	91.5	79.0	67.0	....	....	58.0	175	210
94	....	72.5	....	78.5	66.0	....	....	57.5	171	205
93	....	71.0	91.0	78.0	65.5	....	....	57.0	167	200
92	....	69.0	90.5	77.5	64.5	....	100	56.5	163	195
91	....	67.5	....	77.0	63.5	....	99.5	56.0	160	190
90	....	66.0	90.0	76.0	62.5	....	98.5	55.5	157	185
89	....	64.0	89.5	75.5	61.5	....	98.0	55.0	154	180
88	....	62.5	....	75.0	60.5	....	97.0	54.0	151	176
87	....	61.0	89.0	74.5	59.5	....	96.5	53.5	148	172
86	....	59.0	88.5	74.0	58.5	....	95.5	53.0	145	169
85	....	57.5	....	73.5	58.0	....	94.5	52.5	142	165
84	....	56.0	88.0	73.0	57.0	....	94.0	52.0	140	162
83	....	54.0	87.5	72.0	56.0	....	93.0	51.0	137	159
82	....	52.5	....	71.5	55.0	....	92.0	50.5	135	156
81	....	51.0	87.0	71.0	54.0	....	91.0	50.0	133	153
80	....	49.0	86.5	70.0	53.0	....	90.5	49.5	130	150
79	....	47.5	....	69.5	52.0	....	89.5	49.0	128	147
78	....	46.0	86.0	69.0	51.0	....	88.5	48.5	126	144
77	....	44.0	85.5	68.0	50.0	....	88.0	48.0	124	141
76	....	42.5	....	67.5	49.0	....	87.0	47.0	122	139
75	99.5	41.0	85.0	67.0	48.5	....	86.0	46.5	120	137
74	99.0	39.0	....	66.0	47.5	....	85.0	46.0	118	135
73	98.5	37.5	84.5	65.5	46.5	....	84.5	45.5	116	132
72	98.0	36.0	84.0	65.0	45.5	....	83.5	45.0	114	130
71	97.5	34.5	....	64.0	44.5	100	82.5	44.5	112	127
70	97.0	32.5	83.5	63.5	43.5	99.5	81.5	44.0	110	125
69	96.0	31.0	83.0	62.5	42.5	99.0	81.0	43.5	109	123
68	95.5	29.5	....	62.0	41.5	98.0	80.0	43.0	107	121
67	95.0	28.0	82.5	61.5	40.5	97.5	79.0	42.5	106	119
66	94.5	26.5	82.0	60.5	39.5	97.0	78.0	42.0	104	117
65	94.0	25.0	....	60.0	38.5	96.0	77.5	....	102	116
64	93.5	23.5	81.5	59.5	37.5	95.5	76.5	41.5	101	114
63	93.0	22.0	81.0	58.5	36.5	95.0	75.5	41.0	99	112
62	92.0	20.5	....	58.0	35.5	94.5	74.5	40.5	98	110
61	91.5	19.0	80.5	57.0	34.5	93.5	74.0	40.0	96	108
60	91.0	17.5	....	56.5	33.5	93.0	73.0	39.5	95	107
59	90.5	16.0	80.0	56.0	32.0	92.5	72.0	39.0	94	106
58	90.0	14.5	79.5	55.0	31.0	92.0	71.0	38.5	92	104
57	89.5	13.0	....	54.5	30.0	91.0	70.5	38.0	91	103
56	89.0	11.5	79.0	54.0	29.0	90.5	69.5	....	90	101
55	88.0	10.0	78.5	53.0	28.0	90.0	68.5	37.5	89	100
54	87.5	8.5	....	52.5	27.0	89.5	68.0	37.0	87	...
53	87.0	7.0	78.0	51.5	26.0	89.0	67.0	36.5	86	...
52	86.5	5.5	77.5	51.0	25.0	88.0	66.0	36.0	85	...
51	86.0	4.0	....	50.5	24.0	87.5	65.0	35.5	84	...
50	85.5	2.5	77.0	49.5	23.0	87.0	64.5	35.0	83	...

Rockwell Hardness Scales*									Bhn
B	F	15-T	30-T	45-T	E	H	K	A	500-kg Load *
50	85.5	77.0	49.5	23.0	87.0	....	64.5	35.0	83
49	85.0	76.5	49.0	22.0	86.5	....	63.5	....	82
48	84.5	....	48.5	20.5	85.5	....	62.5	34.5	81
47	84.0	76.0	47.5	19.5	85.0	....	61.5	34.0	80
46	83.0	75.5	47.0	18.5	84.5	....	61.0	33.5	..
45	82.5	....	46.0	17.5	84.0	....	60.0	33.0	79
44	82.0	75.0	45.5	16.5	83.5	....	59.0	32.5	78
43	81.5	74.5	45.0	15.5	82.5	....	58.0	32.0	77
42	81.0	....	44.0	14.5	82.0	....	57.5	31.5	76
41	80.5	74.0	43.5	13.5	81.5	....	56.5	31.0	75
40	79.5	73.5	43.0	12.5	81.0	....	55.5	....	..
39	79.0	....	42.0	11.0	80.0	....	54.5	30.5	74
38	78.5	73.0	41.5	10.0	79.5	....	54.0	30.0	73
37	78.0	72.5	40.5	9.0	79.0	....	53.0	29.5	72
36	77.5	....	40.0	8.0	78.5	100	52.0	29.0	..
35	77.0	72.0	39.5	7.0	78.0	99.5	51.5	28.5	71
34	76.5	71.5	38.5	6.0	77.0	99.0	50.5	28.0	70
33	75.5	....	38.0	5.0	76.5	....	49.5	....	69
32	75.0	71.0	37.5	4.0	76.0	98.5	48.5	27.5	..
31	74.5	....	36.5	3.0	75.5	98.0	48.0	27.0	68
30	74.0	70.5	36.0	2.0	75.0	....	47.0	26.5	67
29	73.5	70.0	35.5	1.0	74.0	97.5	46.0	26.0	..
28	73.0	....	34.5	....	73.5	97.0	45.0	25.5	66
27	72.5	69.5	34.0	....	73.0	96.5	44.5	25.0	..
26	72.0	69.0	33.0	....	72.5	....	43.5	24.5	65
25	71.0	....	32.5	....	72.0	96.0	42.5	....	64
24	70.5	68.5	32.0	....	71.0	95.5	41.5	24.0	..
23	70.0	68.0	31.0	....	70.5	....	41.0	23.5	63
22	69.5	....	30.5	....	70.0	95.0	40.0	23.0	..
21	69.0	67.5	29.5	....	69.5	94.5	39.0	22.5	62
20	68.5	....	29.0	....	68.5	....	38.0	22.0	..
19	68.0	67.0	28.5	....	68.0	94.0	37.5	21.5	61
18	67.0	66.5	27.5	....	67.5	93.5	36.5	....	..
17	66.5	....	27.0	....	67.0	93.0	35.5	21.0	60
16	66.0	66.0	26.0	....	66.5	....	35.0	20.5	..
15	65.5	65.5	25.5	....	65.5	92.5	34.0	20.0	59
14	65.0	....	25.0	....	65.0	92.0	33.0	....	..
13	64.5	65.0	24.0	....	64.5	....	32.0	....	58
12	64.0	64.5	23.5	....	64.0	91.5	31.5	....	..
11	63.5	....	23.0	....	63.5	91.0	30.5	....	..
10	63.0	64.0	22.0	....	62.5	90.5	29.5	....	57
9	62.0	....	21.5	....	62.0	....	29.0	....	..
8	61.5	63.5	20.5	....	61.5	90.0	28.0	....	..
7	61.0	63.0	20.0	....	61.0	89.5	27.0	....	56
6	60.5	....	19.5	....	60.5	....	26.0	....	..
5	60.0	62.5	18.5	....	60.0	89.0	25.5	....	55
4	59.5	62.0	18.0	....	59.0	88.5	24.5	....	..
3	59.0	....	17.0	....	58.5	88.0	23.5	....	..
2	58.0	61.5	16.5	....	58.0	....	23.0	....	54
1	57.5	61.0	16.0	....	57.5	87.5	22.0	....	..
0	57.0	....	15.0	....	57.0	87.0	21.0	....	53

* The 15-T, 30-T, and 45-T scales are for Rockwell Superficial Tests. See Table III for other scale designations

* 10-mm standard steel ball

or DPH indenter; extremely brittle materials, such as glass and minerals that crack or shatter under other types of indenters, can be tested with the Knoop indenter. Knoop, Peters and Emerson[6,13] have found the following relationship between Knoop hardness and Mohs' scale of hardness.

Mohs' Scale of Hardness		Knoop Hardness Number	
1	Talc	....	
2	Gypsum	32	
3	Calcite	135	
4	Fluorite	163	
5	Apatite	360	parallel to axis, 430 perpendicular to axis
6	Orthoclase	560	
7	Quartz	710	parallel to axis, 790 perpendicular to axis
8	Topaz	1250	
9	Sapphire	....	
10	Diamond	5500 to 6950	

Hardness Testing at Elevated Temperatures

Both dynamic and static tests have been employed to measure hardness by indentation at elevated temperatures, but dynamic testing appears to have received more attention. In static testing, the load on the penetrator is applied slowly; in the dynamic test, loading is accomplished by one of the following: a falling weight, a released spring, or a blow from a hammer or pendulum.

Experimental difficulties are encountered with either type of test, as follows:

1 The surface of the test specimen must be protected from oxidation during heating. Protection may be obtained at relatively low temperatures with water, oil, or salt baths; at higher temperatures an electric furnace with a controlled atmosphere (such as purified nitrogen) may be used or the equipment may be designed to operate under reduced pressure (vacuum).

2 Because of the general tendency of metals to exhibit continuous flow under stress at elevated temperatures, it is necessary to maintain a constant time interval of indentation in static testing; otherwise, tests of different materials are not comparable. This effect of time is believed to be insignificant in a dynamic test, because of the instantaneous nature of the impact loading.

3 The dynamic test is subject to error from energy losses caused by rebound of the falling weight, friction along guides, and vibration of the machine and test specimen.

4 Because of the appreciable period of contact between the indenter and the specimen in the static test, it is desirable that the indenter and specimen be at the same temperature, since a cold indenter chills the specimen during the test. This limitation is not encountered in a dynamic test because of the very short duration of contact. Consequently, a steel indenter is suitable for dynamic testing but not for static testing, because the indenter will soften at the test temperature; hence, for a static test, a diamond indenter is preferred, although the sintered carbide ball may be satisfactory. The useful life of the diamond indenter at elevated temperature is a serious problem. According to Lysaght * the ordinary setting material of the diamond deteriorates at high temperature, but special setting material permits the repeated use of the diamond at 1200 F and short exposure to temperature up to 1500 F (total heating and cooling cycle, 5 hr, including 1 hr at temperature) in an atmosphere diluted with nitrogen. Under these conditions, the service life of the indenter is unpredictable.

The type of test to select depends on the application of the tested part in service. For instance, if plastic flow is considerable, a static test might produce more useful information. A dynamic test might be preferred where rapid deformation is encountered in service. Another consideration is the temperature of test desired; dynamic tests are possible up to 2200 F, whereas, at present 1500 F appears to be the limit imposed by the indenter on the static test.

Dynamic Test. Fetz[14] has published results of original experimental work and an extensive survey of technical literature that concerns this type of test. The method of Fetz appears to be typical of the dynamic test and consists of a drop hammer, operated by a foot release, sliding vertically along two polished steel front guides. A steel ball 10 mm in diam is fastened to the lower end of the hammer. After the sample has reached temperature, it is removed from the furnace, held on an anvil with tongs and indented by the ball attached to the falling hammer. The time interval between removing the sample from the furnace and striking it with the hammer does not exceed 1.5 sec and is usually less than 1 sec.

The hardness number has been expressed in different ways by different investigators, generally by one of the following relationships:

$$H = \frac{E_1}{V} \quad \text{or} \quad H = \frac{E_1 - E_2}{V}$$

where H = Dynamic hardness number
E_1 = Impact energy in mm-kg
E_2 = Rebound energy in mm-kg
V = Volume (cu mm) of indentation based on diameter measurement made at room temperature.

The dynamic hardness is sometimes expressed as a Brinell number obtained from correlation experiments conducted by the investigator. Because of variations in testing technique, such correlations do not permit quantitative comparison of hardness data obtained by different investigators, although qualitatively the same trends may be observed.

In order to have similar test conditions, it is recommended that the weight of the specimen and the impact energy be standardized. Also, the specimen should be of such a size that its heat capacity will minimize loss of heat during the time interval required for the test.

Static Test. Bishop and Cohen[15] have used the Rockwell tester and diamond Brale indenter up to 1100 F in a purified nitrogen atmosphere, without evidence of deterioration of the indenter. The furnace is designed to rest on the elevating stage of the tester and the specimen can be observed during heating and testing. A flow of purified nitrogen is used to prevent scaling. The indenter is heated to the temperature of the specimen. The furnace contains an anvil for supporting the specimen, and an extension member places the indenter within the furnace. An oil-trough seal is provided that allows either vertical or horizontal displacement of the specimen relative to the indenter, without affecting the protective atmosphere. Water flowing through copper coils cools the apparatus at the necessary points.

To make an indentation, the furnace and specimen are elevated with the Rockwell mechanism until the minor load has been applied; then the major load is applied and removed in the usual manner. The hardness number is read on the Rockwell C scale and is reproducible to plus or minus 0.5 of a number.

The Vickers hardness tester has recently been adapted to hardness testing[16] at temperatures up to 1700 F by the use of a vacuum furnace and an extension member added to the indenter piston for placing the indenter within the furnace. A standard Vickers diamond is employed and the impression is made in the usual manner after the furnace, specimen and indenter have come to equilibrium at the test temperature. The specimen is then cooled and the indentation is measured at room temperature. Means are provided for moving the specimen while at temperature in order to make several indentations on it.

Another method of static testing, employed by Harder and Grove,[17] is that of mutual indentation produced on two cylindrical specimens of the material being tested, under selected loads. This method appears to give satisfactory results up to 1475 F, but has the disadvantage of requiring specimens of a special shape.

Hardness Conversion Tables

Each of the instruments used customarily to measure the hardness of metals by the indentation method is best adapted to certain types of work. Brinell tests are especially suited to cast iron and to most pieces of medium to heavy section, but cannot be used for measuring the hardness of sheet metals. The Tukon tester has a field of application in very thin sheets, small parts, and measurement of microhardness; in this field the Rockwell instruments and most others are inoperable. Rockwell tests are indispensable for rapid production testing and are used on a wide range of materials.

Indentation hardness testers determine not a single fundamental property but a combination of properties; the contribution of each of these properties to the hardness number varies with the type of test. That is why no absolute conversions have been made from one hardness scale

* Communication from V. E. Lysaght, Wilson Mechanical Instrument Co.

to another. It is necessary to base hardness conversions on comparative tests of materials that have very similar mechanical properties. Many of the conversions now in use include a wide range of materials; consequently, the conversions may be inaccurate for specific applications.

Conversions based on a single class of materials have been developed for heat treated steels, nickel alloys, magnesium alloys, brass, aluminum alloys, and probably many others. However, conversions for steel and brass are the only ones that have been recognized by the technical societies. Others should be reviewed and published for general use if they are found reliable.

The reliability of hardness conversions is no greater than that of the original test values. Each type of hardness test is subject to certain errors. If the precautions cited above are carefully observed, the reliability of hardness readings made on instruments of the indentation type will be found comparable. Differences in sensitivity within the range of a given hardness scale (for example, Rockwell B) may be greater than between two different scales or types of instruments. When more than one range of load is available for a given instrument, the largest load should be used that is consistent with the dimensions and nature of the specimen and with the maximum allowable size of impression for the indenter. That is, use of superficial hardness scales, such as Rockwell 15-N and 10-kg DPH, should be confined to applications where higher loadings are not applicable—such as Rockwell A or C or 50-kg DPH. The scleroscope has been found less reliable than tests of the indentation type, and conversions to other scales are correspondingly uncertain.[18]

Tests have proved that even the most reliable data cannot be fitted to a single conversion relationship for all metals. The differences in physical or mechanical properties that influence the hardness values in this manner have not been fully determined. However, two factors have been found to contribute greatly to this behavior, namely, the modulus of elasticity and the capacity for work hardening. The modulus of elasticity has been shown to influence conversions at high hardness levels,[19] and there is reason to believe that at low hardness levels, conversions between hardness scales measuring depth and those measuring diameter, are likewise influenced by differences in the modulus of elasticity. Furthermore, work hardening has a very potent effect in most soft metals,[8,12] making it difficult to isolate the various factors that affect the conversion relationships.

Table X. Hardness Conversions for Aluminum Alloys and Copper in the Cold Worked Condition

Rockwell B	Rockwell F	Rockwell —Superficial Hardness— 45-T	30-T	15-T	Bhn 500-kg Load *	DPH	Rockwell B
70	98.2	46.4	65.2	84.7	118.0	127.5	70
68	97.2	45.0	64.3	84.2	115.0	124.0	68
66	96.2	43.5	63.4	83.8	112.0	121.5	66
64	95.3	42.0	62.5	83.4	109.0	118.0	64
62	94.4	40.5	61.6	83.0	106.5	115.5	62
60	93.5	39.0	60.8	82.7	104.0	112.5	60
■	92.6	37.5	60.0	82.3	102.0	110.0	58
56	91.7	36.0	59.1	81.9	100.0	108.0	56
54	90.8	34.6	58.2	81.5	98.0	106.0	54
52	89.9	33.1	57.4	81.1	96.0	104.0	■
50	89.0	31.6	56.5	80.7	94.0	102.0	50
48	88.1	30.1	55.6	80.3	92.5	100.0	48
46	87.2	28.7	54.7	79.9	90.5	98.0	46
44	86.3	27.2	53.8	79.6	89.0	96.0	44
42	85.4	25.8	53.0	79.2	88.0	94.5	42
40	84.5	24.3	52.1	78.8	86.0	92.5	40
38	83.6	22.8	51.2	78.4	84.5	91.0	38
36	82.7	21.4	50.3	78.0	83.5	89.5	36
34	81.8	20.0	49.5	77.6	82.0	88.0	34
32	80.9	18.5	48.6	77.2	81.0	86.5	32
30	80.0	16.1	47.8	76.8	79.5	85.5	30
28	79.1	15.6	46.9	76.4	78.5	84.0	28
26	78.2	14.1	46.0	76.0	77.0	82.5	26
24	77.4	12.7	45.1	75.6	76.0	81.0	24
22	76.5	11.2	44.2	75.2	75.0	80.0	22
20	75.6	9.7	43.4	74.8	74.0	79.0	20
18	74.7	8.2	42.5	74.4	73.0	78.0	18
16	73.8	6.7	41.7	74.0	71.5	76.5	16
14	72.9	5.2	40.8	73.7	70.5	75.5	14
12	72.0	3.8	39.9	73.3	69.5	74.5	12
10	71.1	2.3	39.0	72.9	68.5	73.5	10
8	70.2	0.8	38.2	72.5	67.5	72.5	8
6	69.3	....	37.4	72.1	66.5	71.5	6
4	68.4	....	36.5	71.8	66.0	71.0	4
■	67.6	....	35.6	71.4	65.0	70.0	2
0	66.7	....	34.8	71.0	64.0	69.5	0

* 10-mm standard steel ball

Table XI. Hardness Conversions for Flat Rolled 18% Cr–8% Ni Type Stainless Steel

Rockwell B	Rockwell F	Rockwell —Superficial Hardness— 45-T	30-T	15-T	DPH	Rockwell B
100	113.0	68	80.0	90.5	250	100
98	111.9	66	78.5	89.8	235	98
96	110.7	64	77.1	89.1	222	96
94	109.6	62	75.6	88.5	211	94
92	108.4	60	74.1	87.8	200	92
90	107.3	58	72.6	87.1	190	90
88	106.1	56	71.2	86.5	181	88
86	105.0	54	69.7	85.8	173	86
84	103.9	52	68.2	85.1	165	84
82	102.8	50	66.8	84.5	158	82
80	101.6	48	65.3	83.8	151	80
78	100.5	46	63.9	83.1	145	78
76	99.4	44	62.4	82.5	140	76
74	98.2	42	60.9	81.8	135	74
72	97.1	40	59.5	81.1	130	72
70	96.0	38	58.0	80.5	125	70

Conversions for Steels Harder than 220 Brinell. Conversion Tables VI, VII and VIII, which were prepared jointly by the Society of Automotive Engineers, American Society for Metals, and American Society for Testing Materials, are based on extensive tests of carbon and alloy steels, mostly in the heat treated condition. They have been found reliable on virtually all alloy constructional steels and tool steels in the as-forged, annealed, normalized, and quenched and tempered conditions, provided the steels are homogeneous. Such materials as high-manganese steel, 18% Cr–8% Ni steel, other austenitic steels, and nickel-base alloys, as well as alloy constructional steels and tool steels in the cold worked condition, may not conform to these relationships with the same degree of accuracy as the steels for which they are intended. The values for scleroscope hardness number and approximate tensile strength are from the SAE Handbook and are not included in the original tables approved jointly by the three societies.

Precautions in Using Conversion Tables for Steels.

1 The values given are recommended for use in converting the results of one form of hardness test to another, only with respect to flat surfaces, and only when the foregoing test procedures and precautions are observed.

2 Attention is called to the limitation of use of the standard steel ball to hardnesses less than 500 Brinell. The Rockwell superficial hardness and diamond pyramid hardness tests require especially smooth surfaces for accurate results. In all tests, the specimen should be approximately ten times as thick as the depth of the indentation, to avoid anvil effect. (*See* Table V.)

3 It is very important that conversions from Brinell hardness to shallow-impression tests, such as Rockwell superficial and diamond pyramid hardness tests, be made only on materials that are of uniform hardness to a depth at least ten times that of the indentation. Such hardness conversions should not be made on surface-hardened, coated or decarburized surfaces.

4 Although the Rockwell hardness and Rockwell superficial hardness values in the tables are given to tenths of a point, in order to maintain exact relationships between the various scales, it is customary to report these values to the nearest point only.

5 In Table VIII, rows 3 and 4, the reader may note that a Brinell number of 627, determined with a carbide ball, corresponds to a lower DPH value than a Brinell number of 601 obtained with a Hultgren ball, because of the elastic flattening of the Hultgren ball. Therefore the DPH and Rockwell values in these rows are not inverted.

6 Experience has shown that, even under carefully controlled conditions, some deviations from the conversion relationships will occur.

Conversions for Metals Softer than 240 Brinell. For ferrous and nonferrous metals softer than 240 Brinell, a single set of conversion relationships inevitably introduces large errors because of the wide difference that may exist in the amount of cold working before testing, as well as the amount that occurs during the test itself.

The dependence of hardness conversions on the amount of strain hardening of the sample before testing, has been demonstrated by means of Brinell, DPH, Rockwell, and Rockwell superficial tests on a variety of ferrous and nonferrous alloys in the annealed and strain hardened conditions. As an example, annealed ingot iron and a cold rolled aluminum alloy each had a Brinell hardness of 66. The annealed iron had a Rockwell B hardness of 31 compared with 7 for the strain-hardened aluminum alloy. Thus a conversion relationship that is correct for iron would be 24 points Rockwell too high for the aluminum alloy. On the other hand, if materials have Brinell or Rockwell hardness values that are equal in the annealed state as well as after heavy cold deformation, these materials will have similar hardness conversion relationships for all degrees of strain hardening. This is true of yellow brasses and low-carbon steels and irons. The Wilson Chart No. 38,* part of which is reproduced in Table IX, is based largely on tests of these materials. It is for this reason that the following statement is published as a part of the Wilson Chart 38.

> "The indentation hardness values measured on the various scales depend on the work hardening behavior of the material during the test, and this in turn depends on the degree of previous cold working of the material. The B-scale relationships in the table are based largely on annealed metals for the low values and cold worked metals for the higher values. Therefore, annealed metals of high B-scale hardness, such as austenitic stainless steels, nickel and high-nickel alloys, do not conform closely to these general tables. Neither do cold worked metals of low B-scale hardness, such as aluminum and the softer alloys. Special correlations are needed for more exact relationships in these cases."

When the hardness level of a material is considerably different from that of yellow brass, as in aluminum and aluminum alloys, it is necessary to use specially prepared conversion relationships. Table X, based on tests of aluminum alloys and copper, and Table XI for flat rolled stainless steels of the 18% Cr–8% Ni type, are examples of conversions for alloys that have hardness ranges lower and higher, respectively, than the range for yellow brass. These tables are based on a limited number of data compared with Wilson Chart No. 38 (Table IX), and are included primarily to demonstrate experimental deviation from this widely used conversion table. For example, in Table X the 500-kg Brinell value of 66 corresponds to a hardness of 4 Rockwell B compared with 28 Rockwell B in the Wilson Chart (Table IX).

The dependence of hardness conversion relationships on strain-hardening characteristics can be demonstrated further by the Rockwell scales 15-T, 30-T, 45-T, F, and B, in which loads ranging from 15 to 100 kg are applied on a $\frac{1}{16}$-in. diam ball indenter.[12] (Fig. 2.) As higher loads are used, the increased strain raises the hardness by an amount that depends on the pretest capacity of the metal for strain hardening. An annealed metal of high capacity for strain hardening will harden much more in the test than will a cold worked metal. If both have the same hardness in a Rockwell 15-T test using a 15-kg load, the annealed metal will develop higher hardness in a Rockwell B test under a 100-kg load. In Fig. 2, an annealed iron and a cold rolled aluminum alloy have Rockwell 15-T hardness of 71 and 72 respectively. The Rockwell B hardnesses are 31 for the soft annealed iron and 7 for the strain hardened aluminum alloy.

In Fig. 2, lines representing the data from Tables X and XI are compared with the Wilson Chart line for the relationship between Rockwell B and Rockwell 30-T scales. In all other instances, lines have been drawn through the points for soft annealed metals (at the left) and strain hardened metals (at the right), disregarding chemical composition. Specialized hardness conversions more accurate than the generalized conversions now used for soft metals are suggested by these charts. Two approaches are, as follows: (1) By material classifications suggested by the Rockwell B versus Rockwell 30-T relationships of Fig. 2. (2) By strain hardening classification determined by the indentation contour as indicated in Fig. 2.

Method 1 requires organization of test data into specialized tables for specific classes of materials, and selection of the proper table based on knowledge of the class of material being tested.

Method 2 depends on knowledge of the state of strain hardening of the test piece. The limiting conditions can usually be identified by the appearance of the hardness in-

* Supplied by Wilson Mechanical Instrument Co., producers of Rockwell hardness-testing machines

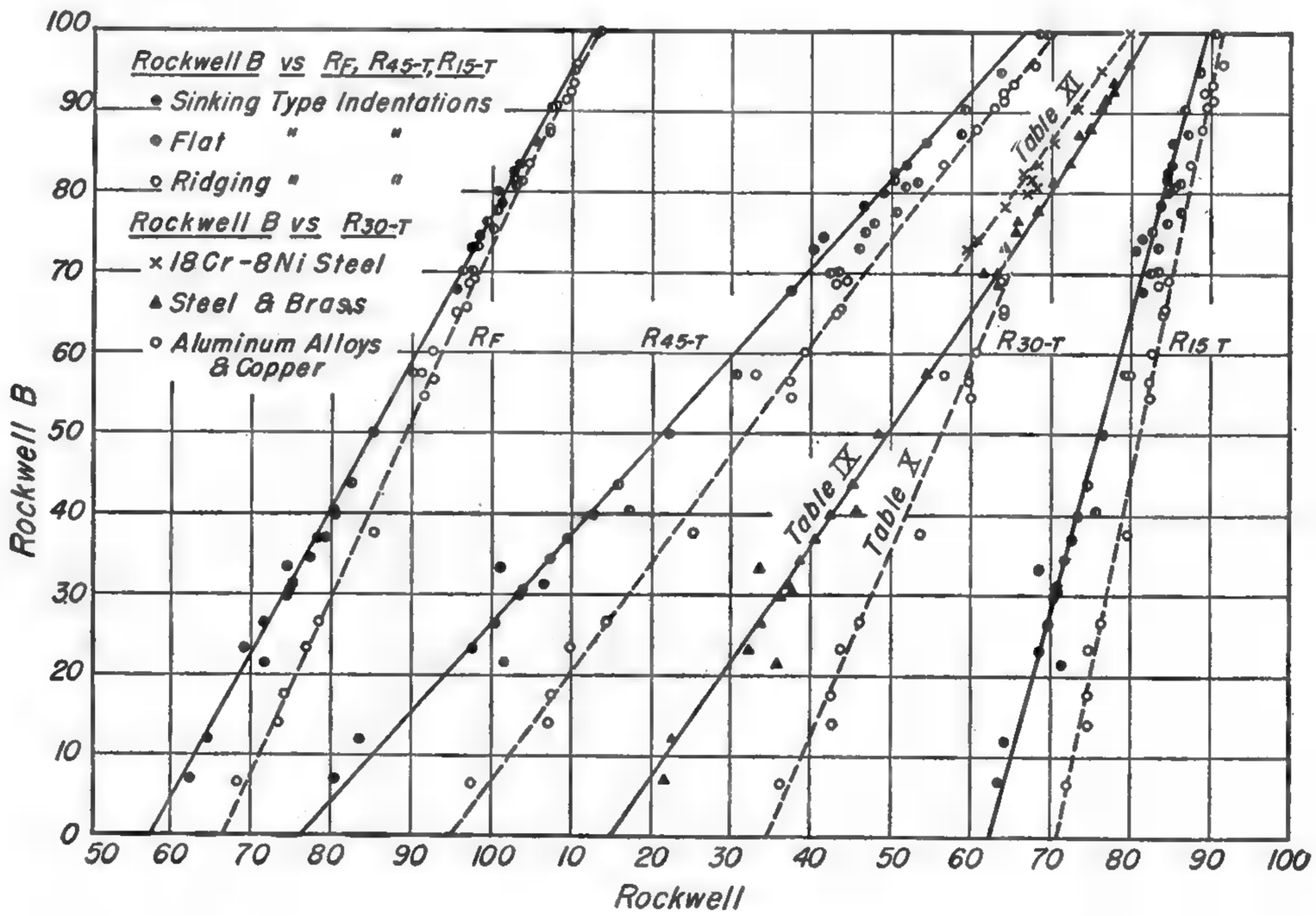

Fig. 2 Experimentally determined comparisons of Rockwell hardness tests

dentations themselves. Soft annealed metals have characteristic "sinking" type indentation contours when indenters of the ball type are used. On the other hand, heavily cold worked metals have sharp "ridging" type indentations. While annealed metals are being progressively cold worked, the indentation contours pass through a "flat" stage in which the lip of the indentation is neither rounded nor sharply ridged. The diameter of the indentation should approach 50% of the ball diameter in order to develop these characteristics in easily recognized form. A low-power magnifier is useful in observing Rockwell indentations.

The Meyer hardness test has been used to give a quantitative measure of the capacity for work hardening, thereby facilitating the selection of the proper conversion relationship in Method 2.[8,12] The Meyer constant n, representing the capacity for work hardening, is determined from the following relationship between load L and impression diameter d:

$$L = ad^n$$

The impression diameter is measured for two or more loads and the constants a and n are obtained, usually by a graphical method in which the variables are plotted on logarithmic graph paper.[20] Although 10-mm Brinell ball indentations are preferred, the $\frac{1}{16}$-in. and ⅛-in. Rockwell balls can be used.

The Meyer n constant has been found to vary from about 2.50 for dead soft annealed metals to slightly less than 2.00 for cold worked metals. The Meyer a constant is a measure of hardness level and is not related to work-hardening capacity. While it would be possible to establish conversions based on the constant n, the labor required in the determination of such conversions would not ordinarily be justified for hardness conversions alone.

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The Tension Test

By Maxwell Gensamer*

THERE are only two methods of mechanical testing in which it is possible to keep the strains uniformly distributed throughout the specimen over a considerable range of strains; these are the tension test and the compression test. For materials that are even slightly ductile, the compression test provides no measure of ductility. Ductile materials do not fracture in compression, except through the action of parasitic tensile stresses developed in the skin after "barreling" has developed. The tension test provides tests for ductility, and through the circumstance that the load in the test goes slowly through a maximum, this test provides an easy and reproducible measure of strength, little affected by the testing conditions. Advantage can be taken of the uniformity of strain before "necking-down" begins, in order to obtain precise measurements of the relations between stress and strain, relations that can be used to calculate with fair precision similar relations for all other kinds of loading or straining. The tension test is relatively easy to adapt to high and low temperatures and high rates of straining.

The test is carried out in machines which vary widely in detail, but all consist of two essential members: (1) a device for straining the specimen, and (2) a device for measuring the resistance of the specimen to this straining.[1] When the stress-strain curve is desired, the circumstance that the strain is uniformly distributed over only a part of the specimen requires the use of a third member, (3) a strain gage, usually known as an extensometer, designed to measure the strain over only that part of the specimen in which strain is substantially uniform. After necking-down begins, with localization of the strain, the extensometer is useful only to indicate the final over-all elongation.

The devices for straining the specimen are usually of either of two types—mechanical screw or hydraulic. Screw machines are of two types—either rotating nut with translating screw, or rotating screw with translating nut. In both, the translating member is one of the crossheads, the so-called "moving crosshead". The stationary crosshead actuates the system for weighing loads. It is important, especially in compression testing, that these crossheads remain parallel throughout the travel of the moving crosshead, especially under load. Hydraulic straining devices are of two types—the packed-ram type and the lapped-ram type. In the packed-ram type, oil leakage is greatly reduced, but the friction of the packing prevents using the pressure in the cylinder as a measure of the load on the specimen. In the lapped-ram type, the pressure may be used as a measure of load, but provision must be made for recirculating the oil which is intentionally permitted to leak, so that friction may be reduced to a minimum. When the pressure in the cylinder is used to indicate the load on the specimen, it is important that effective aligning devices be employed to prevent misalignment of the piston in the cylinder; otherwise frictional errors will occur. The rate of motion of the moving crosshead can be varied easily and continuously over a wide range when hydraulic machines are used, but it is more difficult to reproduce a particular rate of motion than with mechanical machines.

Devices for measuring loads usually employ mechanical levers or hydraulic systems. In the mechanical machines, the moving poise system is losing favor, and the pendulum type is gaining in popularity. Although it sacrifices some sensitivity, the pendulum type gives a continuous indication of load. Numerous hydraulic systems have been devised; the most common of these are the Bourdon tube, the piston and pendulum, and the Bourdon tube combined with a calibrated helical spring. All of these can be quite accurate and sensitive; the Bourdon tube alone is more difficult to use in conjunction with recording devices. To avoid the frictional errors involved in measuring directly the pressure in the strain cylinder, a hydraulic capsule is fre-

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Prepared for the Subcommittee on Mechanical Testing.

quently used, which makes the straining system and the weighing system independent. Hydraulic capsules may be employed with many types of straining devices, including the screw types.

Devices for measuring strain are too numerous to discuss in detail; they may be mechanical, optical or electrical. The most common mechanical devices are the dial gage, lever and pointer combinations, and wedge or cone types. Wedge or cone devices are used for instruments that have wide range and low sensitivity; the dial gage, for intermediate sensitivity; and the lever and pointer instruments, for high sensitivity. The optical and electrical instruments exceed the mechanical in sensitivity. The most popular optical system is Tuckerman's autocollimating modification of Marten's mirror system. The most popular and most adaptable electrical gage is the wire resistance strain gage; the magnetic gap extensometer is also in wide use.

The tension test may be arranged for great precision, in order to obtain data for the design of structures to operate within the elastic range; high precision is usually profitable only for relatively small strains, seldom greater than one per cent. For large strains, where forming characteristics or the capacity of a structure for absorbing energy are being considered, high precision is sacrificed for wide range and ease of observation. In the range of small strains, the data are greatly affected by the care with which the test is conducted. Observations along a single gage-line on the surface of the specimen will vary greatly around the specimen, unless care is taken to eliminate bending moments applied to the specimen by eccentric or oblique loading.[2, 3] The effect of these moments on modulus of elasticity measurements can be avoided by averaging the extension on opposite sides of a symmetrical specimen, but such averaging cannot prevent errors in the observation of the limit of elastic action. The stress at which small departures from ideal elastic action occur will appear to be lower if such deviations from ideal tensile loading are obtained. The stress-strain curve will be the more affected, the smaller the strain; at large strains, the specimen has become fairly well aligned. The tensile strength and ductility of ductile materials are seldom affected appreciably, even by considerable misalignment of the specimen, except when the specimens are thin sheet.

Misalignment is avoided by applying the load to a *straight* specimen at points on its centroid. So-called "self-aligning grips" seldom provide more than good first approximations to alignment, although these grips are adequate for tensile strength and ductility and, unless misused, generally satisfactory for determinations of yield strength when the yield strength is defined in terms of relatively large strains—for example, 0.1 or 0.2%. For stress-strain relations at small strains, means must be provided for centering the specimen in the grips until, upon loading, the strain can be shown by measurement to be uniformly distributed, within the degree of precision required by the application of the results. This measurement is accomplished by making simultaneous observations with at least three extensometers, located 120 degrees apart around a cylindrical specimen, or with four extensometers, one on each face, for rectangular specimens. When sheet specimens are being tested, misalignment may be so great that the stress-strain curve can be affected to several per cent extension; extensometers should be mounted on the *edges* of a sheet specimen to check the alignment for precise work at low strains.

Analysis of Tension Test Data for Small Strains.[4, 5] For strains measuring less than several per cent it is customary and satisfactory to plot the load per unit of original area, known as "stress", against the extension per unit of original gage length, known as "strain"; correction for the changing area and changing gage length is unimportant until large strains are reached. Such uncorrected curves have been plotted in Fig. 1, on the left, over a limited range of strains, for a typical alloy which exhibits no yield point, and on the right all the way to fracture for steel, which alone among alloys is usually characterized by a yield point. (Single crystals exhibit a sharp break in the stress-strain curve; fine-grained nonferrous alloys do not.

The *modulus of elasticity* is the slope of the stress-strain curve in the elastic range, at small stresses, where the curve is a straight line within experimental error. The *tangent modulus* is the slope of the curve at a particular stress or strain. The *secant modulus* is some particular stress divided by the corresponding total strain. The values of the tangent modulus and the secant modulus apply only to the stress and strain to which they refer.

The *elastic limit* is the stress beyond which inelastic action is obtained. In metals it coincides with the *proportional limit,* which is the stress at the point of departure from a straight line. These limits can be only approximated, for their values depend on the sensitivity of the strain gage used. The *yield strength* is much more useful, and is defined as the stress required to produce a given amount of permanent strain. It is tedious and unnecessary to determine the yield strength by measuring

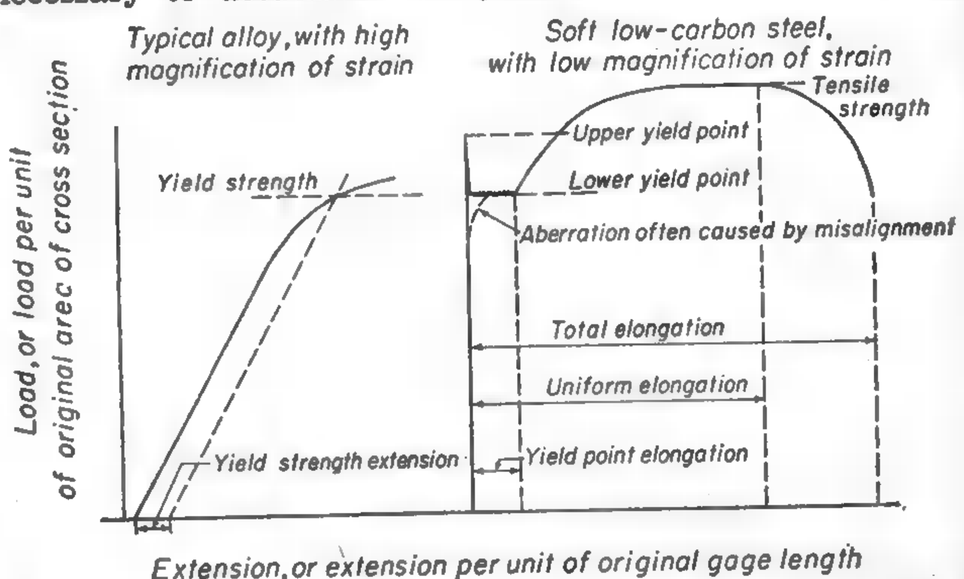

Fig. 1 Load-extension diagrams in tension. The load is usually load per unit of original area of cross section and the extension is usually extension per unit of original gage length. These have the same dimensions as stress and strain, with which they are often confused.

the permanent strain or set after removing the load. With all alloys, upon release of the load, the curve is a straight line from the point of release to zero stress (except for minute departures, unimportant in engineering work). This property makes it possible to use the "offset" method for determining the yield strength. Starting at the intersection of the stress-strain curve with the strain axis, the procedure is to set off on the strain axis a distance corresponding to the strain used in the definition of the yield strength (most frequently 0.2%, but often a smaller strain, and in every instance specified). If, from the point so obtained, a straight line is drawn parallel to the stress-strain curve at low stresses, the intersection of this line with the stress-strain curve is the yield strength. Johnson's apparent elastic limit was formerly popular but has now been superseded by the yield strength as measured by the offset method; Johnson's limit is the stress at the point on the stress-strain curve where the slope is two-thirds the modulus of elasticity. Sometimes it is specified that the extension for a given stress, known as the *proof stress,* is not to exceed a certain amount.

The yielding characteristics of steels which exhibit a definite yield point are described in terms of the upper yield point, the lower yield point, and the yield point elongation. The *upper yield point* is the stress reached before the sudden drop in stress. Up to this point the behavior is usually almost ideally elastic. The sudden drop in stress results in a sudden drop of the beam when a lever-and-poise type of testing machine is used. This pronounced drop, an easily detected departure from elastic action, is used to determine the "yield point by the drop of the beam". It measures the upper yield point, which is very sensitive to nonuniform loading; slight bending can eliminate the upper yield point, causing the curve to take the shape of the dashed line in the right half of Fig. 1. Even though it is widely used in the specification of ferrous products, there is no evidence that yield point by the drop of the beam is of any value as a material constant. The *lower yield point* is a material constant much less affected by the testing conditions, although it is rather sensitive to the speed and temperature of testing (much more so than are tensile strength and measures of ductility). Because the load varies considerably during yielding, it is necessary to take an average value; this introduces some uncertainty,

but not enough to be important. The value taken as the lower yield point is usually the mean stress during yielding immediately after the initial drop.

In dropping from the upper to the lower yield point, the steepness of the curve is determined entirely by a characteristic of the testing machine called the "spring constant" for the machine. It is impossible to observe a diminution of load with extension when the rate of diminution at constant rate of straining is *more* than the spring constant of the machine. A certain amount of motion of the crossheads is necessary to relax the load, and the ratio of the diminution of load to the motion of the crossheads required to produce it is called the "spring constant". A "soft" machine is one with a small spring constant; a "rigid" machine has a high spring constant. A "rigid" machine permits the observation of a steep drop in the load extension diagram, whereas a "soft" machine limits the observable slope under decreasing loads. The spring constant has no effect on the curve during an increase in load.

The *yield point elongation* is the percentage of increase in length to the point of resumption of rising load with increasing strain. At this point the specimen begins to strain uniformly, in contrast with the very nonuniform distribution of strain during yielding, observable through strain markings called "Lüders lines" or the "Piobert effect".

Analysis of Tension Test Data for Large Strains.[4,5,6] As the load increases, the deformation continues to be uniformly distributed until necking-down begins (except for the disturbances introduced by inhomogeneity of the specimen, and the "end effects" caused by the restraint of deformation in the vicinity of the grips or enlarged ends of the specimen). Necking-down occurs at that point on the stress-strain curve where the continuously diminishing slope of the curve reaches a critical value equal to the rate at which the stress would be increased by straining at constant load, because of the diminishing area. This critical value always occurs in direct loading when the strain reaches the value of the strain hardening exponent described below. During necking-down the load diminishes, although the true average stress (load divided by area at the point of least area) continues to increase. The maximum load that is reached divided by the original area of the cross section is the *tensile strength*. It is sometimes observed that the upper yield point is higher than the tensile strength. The point of necking-down, which fixes the tensile strength, is not the maximum stress that may be withstood without fracture. The *fracture stress* is the breaking load (lower than the load corresponding to the tensile strength, unless fracture occurs prior to necking) divided by the final area at the point of fracture.

As measures of ductility, the *reduction of area* at fracture and the *elongation* to fracture are used as percentage reduction of the original area and percentage increase of the original gage length. The percentage reduction of area at fracture is only slightly affected by the shape of the tensile test specimen. As long as the ratio of the width to the thickness does not exceed about 5 to 1, for rectangular cross sections,[7] the reduction of area remains the same as for circular cross sections. Rectangular cross sections diminish in thickness more in the center of the boundary surfaces than at the corners, so that the cross section after fracture is a figure bounded by curved lines; it is necessary to measure the greatest and the least dimensions in both directions and from these to calculate the area at fracture. Simple formulas are available for the calculation of areas from these data.[8] Reduction of area is unaffected by the length of the specimen except for end effects, if the specimen is short enough. The usual specimen (0.505-in. diam and 2-in. gage length, with the customary enlarged ends) is a little short of the length beyond which further increase in length has no effect on the tensile reduction of area at fracture; shorter bars may show less reduction of area.

Elongation to fracture is usually measured by fitting the broken specimen back together and measuring the distance between punch or scribe marks. When measured in this way, it is often referred to as "bench elongation". Elongation may also be taken from an autographic record of the load-extension diagram; the two should agree. Elongation is so much affected by the gage length over which it is measured that the gage length must always be specified unless it is very long.[9] Except for end effects, it can be shown that the elongation may be considered as made up of two parts—the *uniform elongation,* which the whole specimen suffers, up to the time when necking-down begins; and *local elongation,* which is a maximum at the center of the necked-down region and diminishes away from that point, gradually approaching a negligible value at a distance from the point of maximum elongation equal to several times the diameter. In long bars there are usually several points where necking-down begins almost simultaneously, so that finding a region of uniform elongation may be difficult. The elongation is always less near the ends of the bar. The standard specimen is not quite long enough to avoid this end effect, even at the middle of the gage length. The infinite-gage-length elongation refers to the uniform elongation; the zero-gage-length or infinitesimal-gage-length elongation refers to the elongation calculated from the reduction of area at fracture.

Reduction of area is usually measured with micrometer calipers, having anvils which have been ground to "points". These should have minute flat areas at the points, small enough to introduce no serious error when applied to the concavely curved surface of the broken specimen when the halves are fitted back together; or spherical points if the radius is sufficiently large. It is advisable to have some vise-like arrangement to hold the broken parts together during gaging. Elongation is usually measured with dividers, applied to punch or scribe marks. Generally these marks may be quite deep without affecting the results, but brittle materials and thin sheets occasionally break at deep marks with less than usual elongation. A gridwork of lines, applied by the photoengraving technique, obviates this effect and may be used to study the distribution of elongation over the specimen. Variation in ductility from specimen to specimen and from point to point, and variation with direction in the same specimen are often considerable, and are almost always greater than the variation of the other tensile properties. Tests taken transverse to the direction of greatest elongation in working are generally inferior in ductility, often considerably so.

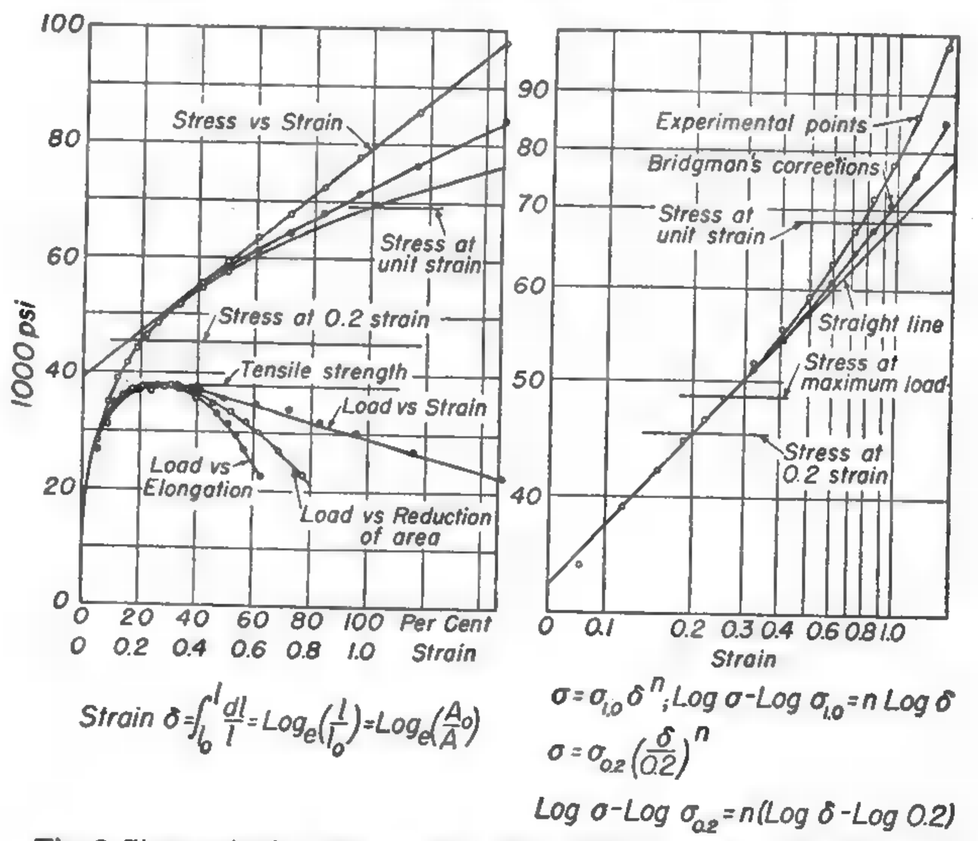

Fig. 2 Stress-strain curves variously plotted. To the left, load-extension, load–reduction of area, load–true strain, average stress—average strain, corrected stress (Bridgman correction)—true strain, and extrapolated true stress—true strain curves are shown plotted directly. To the right, the last three are shown plotted logarithmically. The slope of the log-log plot is the strain-hardening exponent; the stress for a strain of 0.2 has been called the flow strength, in this article.

Stress-strain curves in the plastic range require a treatment somewhat different from that used where the strains are only a few per cent. In Fig. 2 the data are for an iron alloy, and for plastic strains only. To the left, the data are plotted in several ways—stress against strain or load against strain. To the right is a plot of the logarithm of the stress against the logarithm of the strain. Experience has demonstrated that the part of the stress-strain curve in which confidence may readily be placed, is a straight

line when plotted logarithmically. Beyond the point where necking-down begins, there are departures from the straight-line plot for which quantitative corrections cannot yet be made. These departures result from the circumstance that simple tension no longer exists after necking-down begins, and also from the increase in speed of deformation, localized by this necking-down. It is probably fair to assume that the curve would be straight to the point of fracture if necking-down could be avoided, while maintaining the same speed and temperature of testing throughout.

It may be helpful to follow the plotting of a point on the final logarithmic curve, all the way from the original data to the final straight-line plot. If it were not for necking-down, which begins at the maximum load (or maximum in load divided by original area, which is what is plotted here) it would be possible to go from a load or nominal stress versus extension curve to a load versus reduction of area curve, by calculation. Until necking-down begins, the one curve can be calculated from the other, by using the fact that the volume or density of a metal is unchanged by plastic deformation, requiring constancy of the product of length by area. But after necking-down, this calculation is not possible, for the over-all extension depends on the *distribution* of deformation.

To obtain a true stress-strain curve the area must be *measured, after* necking-down begins. For each point then the *diameter* must be measured at the point where it is least, at the center of the necked-down region. From the *area* the *strain* may be calculated, using always the logarithmic strain when the strains are large. The logarithmic strain takes into account the fact that the gage length is changing throughout the test, and it may be regarded as the true strain; it is simply the integral of dl/l, instead of $\Delta l/l_0$, the conventional strain.[10]

Dividing the load by the actual area gives the apparent true stress. However, this needs correction because there are lateral tensile stresses in the necked-down region, which lead to higher average stress than would exist if simple tension prevailed; and, unless the test is run very slowly, the rate of straining may be high. Bridgman[11] has attempted to calculate the correction required by the presence of lateral tensile stresses, but his correction is apparently not sufficient; the corrected points still lie a little above the straight line in the log-log plot of stress versus true or logarithmic strain.

The fact that the log-log plot is a straight line means that all tensile curves are general parabolas, fitting equations of the form $\sigma = \sigma_{1.0}\,\delta^n$, where σ is the true stress, $\sigma_{1.0}$ is the true stress at unit strain ($\delta = 1.0$), δ is the true strain $(\ln \frac{l}{l_0})$, and n may be called the strain hardening exponent; n is the slope of the log-log plot. It is interesting to note that the rate of strain hardening, $d\sigma/d\delta$ obtained by differentiation of the above equation, is equal $\frac{\sigma}{\delta}n$, that is, the ratio of the stress to the strain multiplied by n; the greater n, the greater the rate of strain hardening. The constants which describe *completely* the whole course of the *corrected* plastic stress-strain curve are then $\sigma_{1.0}$ and n.

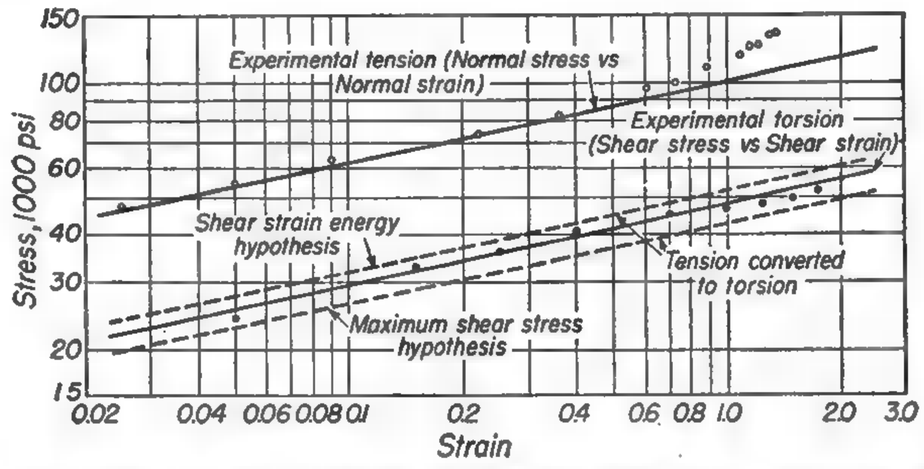

Fig. 4 Comparison of tension and torsion data. The dashed lines are the tension data converted by calculation for comparison with the torsion data. Within narrow limits the agreement between data taken in tension and in torsion is quite good if tension data beyond the point of necking-down are neglected.

It is advisable to discuss not $\sigma_{1.0}$, but the stress for a strain of 0.2, or $\sigma_{0.2}$. The reason for this is that the $\sigma_{1.0}$ value is influenced too much by how the line is drawn through the experimental points; the only reliable experimental points for steel center around $\delta = 0.2$. Below $\delta = 0.1$, the points are quite reliable *if* the specimen is aligned very carefully before starting the test, *and* if a correction is made for the elastic strain. But above $\delta = 0.3$, necking introduces uncertainties. Extrapolation from $\delta = 0.3$ to $\delta = 1.0$ is unreliable. On the other hand, the stress at $\delta = 0.2$ is extremely reliable and independent of the slope n of the line drawn through the points. The equation for the curve can just as well be written $\log \sigma - \log \sigma_{0.2} = n$ ($\log \delta - \log 0.2$), which is $\sigma = \sigma_{0.2}(\delta/0.2)^n$. Observe that the stress at the maximum load, which would be the tensile strength if the original area had been used instead of the actual area, is a point of no particular significance, since it does not come at a particular value of strain. The stress at $\delta = 0.2$ is the stress at the strain which is nearly average for the strain at maximum load—in iron about 20%, but varying from 10 to 30%. This stress at 0.2 strain may be called the flow strength, in the same way that it has been agreed to call the stress at a strain of 0.2% or 0.002 the yield strength.

The general applicability of tensile data is illustrated by Fig. 3, comparing stress-strain curves obtained in simple compression, simple tension, and two kinds of biaxial stretching: (1) balanced, when the strains in a sheet are the same in all directions, and (2) unbalanced, with a ratio of the strains of about 0.7 to 1, as determined in hydraulic bulge tests. The data have been converted to the stress invariant by use of the von Mises function, and to the strain invariant required to satisfy the law of constancy of volume and the assumption that the metal flows in the same way that a viscous fluid flows when acted upon by combined stresses. Neither of these methods of arriving at the stress and strain invariants is exact, but they do yield values almost

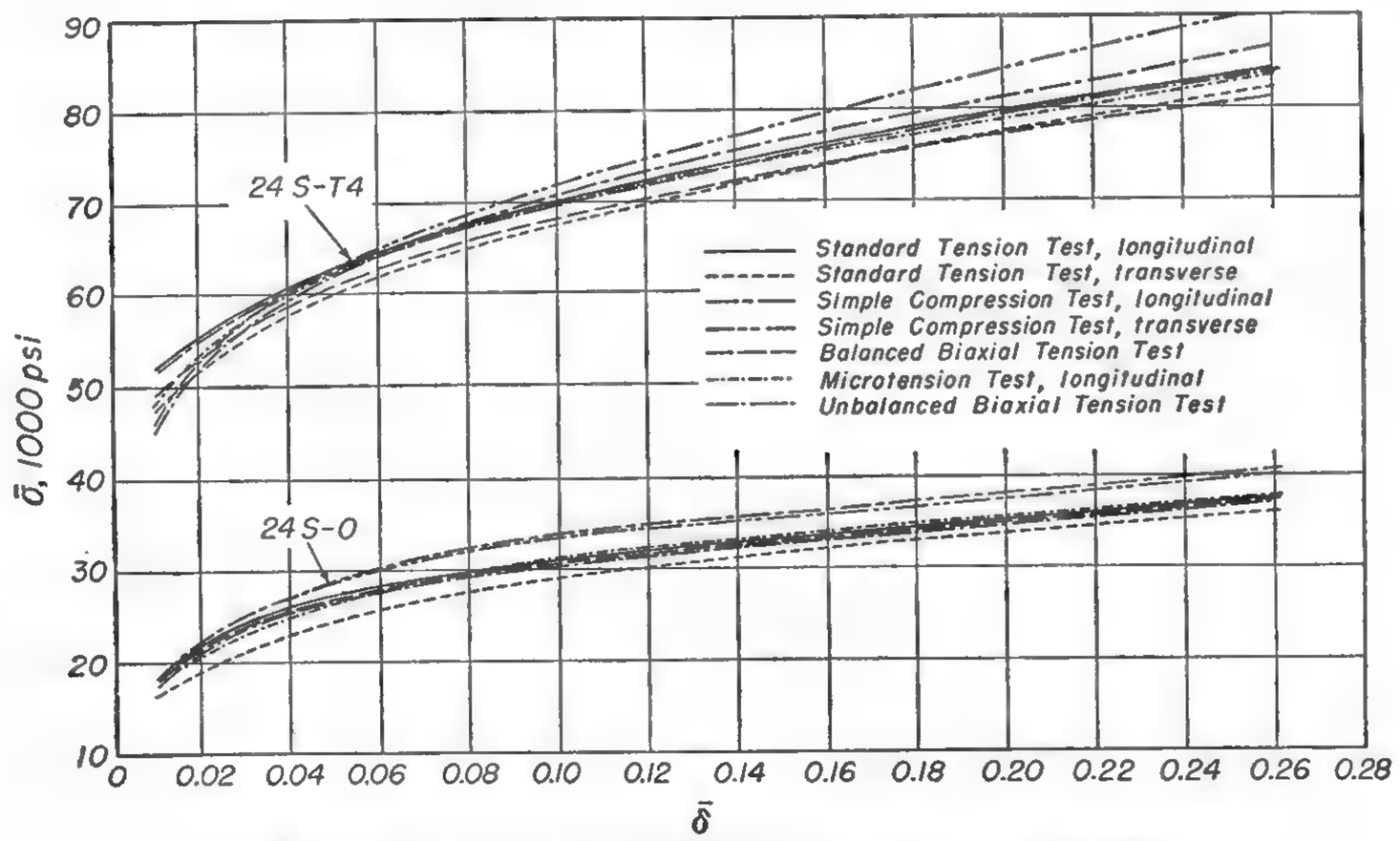

Fig. 3 Significant stress-strain curves for various methods of loading.

within the limits of experimental accuracy. It is nearly impossible to be sure that the curves of Fig. 3 do not coincide; hence, for practical purposes, we may use the tension curve to calculate the curves for other loading conditions, where the *average* values of the three principal stresses are not too different. It would not do to calculate in this way a stress-strain curve with superimposed high hydrostatic pressure.

The tension curve may even be used to calculate the stress-strain curve in torsion, when the properly corrected curve is used. This is shown in Fig. 4, taken from the work of Hollomon and Zener. The line through the tensile data, above, has been transferred by the von Mises or shear-strain-energy calculation, and again by the hypothesis of simple maximum shear stress in order to compare it with experimental data obtained in torsion, or twisting. It should be observed that if the *uncorrected* points obtained after necking in tension are ignored and if it is assumed that the data obtained in tension before serious necking apply to larger strains, there is good agreement between the tension data and the torsion data. In all ranges of strain, general experience shows that the torsion points fall between the values to be expected from the tension points by the application of the shear-strain-energy hypothesis and the maximum-shear-stress hypothesis. The spread between the two extremes is only 15%.

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Compression Tests

By M. F. Sayre*

WITH metals, compression tests are much less commonly used than tension tests. In fact, only one of the many ASTM metals specifications calls specifically for compression tests as a requirement for acceptance of the material. It is usually tacitly assumed that metals are equally strong in tension and compression, or that if any difference exists, the compressive strength is the greater of the two. Tests for determining tensile strength are considered to give satisfactory indications of the quality of the material and of the allowable stresses to be used in compression as well as in tension.

In many instances this assumption is correct; in others it is not. In recent years there has been an increasing realization that, if valid design stresses are to be chosen, compression tests may be necessary, with the load acting in the direction in which the stress is to act in service. Consequently there has been a considerable increase in the number of compression tests being made, particularly on thin sheet material.

Compared with tension tests, compression tests have this disadvantage—they give somewhat less information. Under increasing compressive loads, specimens made of ductile materials tend to shorten in length and increase in diameter to an indefinite extent, so that no values equivalent to percentage elongation and percentage reduction of area can be determined, and ultimate strength has no particular meaning. A second disadvantage of the compression test is that, in order to obtain satisfactory results, somewhat greater care must be used in preparation of specimens, and the testing machine must be in somewhat better condition than is necessary for obtaining equally satisfactory results in tension testing. With present-day machine tools for preparation of specimens and with present-day testing machines, these requirements can be fulfilled without too much difficulty, so that compression testing can be carried on rapidly and in a routine manner.

The basic requirements for a satisfactory compression test are discussed below.

Alignment of Machine. The movable crosshead of the machine in which the test is to be made should move in a straight line at right angles to the stationary crosshead, without appreciable lateral motion and without wobbling. If the crossheads of the testing machine do not meet this requirement, it may be desirable to carry on the actual test in a subpress placed between the crossheads.

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Prepared for the Subcommittee on Mechanical Testing.

A subpress as recommended in ASTM Method B9–47T is shown in Fig. 1. The hollow plunger in this subpress is guided by a rigid frame, so that it moves in a vertical direction. The load is applied through a central rod within this plunger. The side play of the rod is sufficient to allow

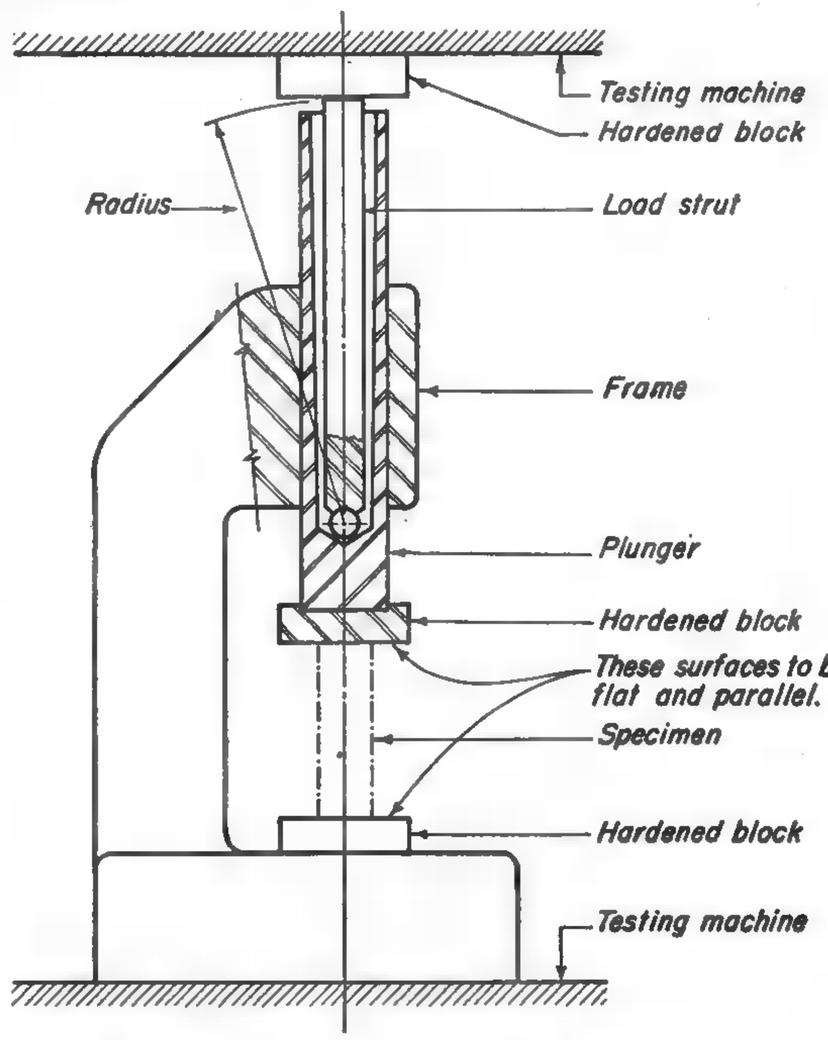

Fig. 1 Subpress recommended in ASTM Method B 9–46T

for any lateral movement or wobble in the upper crosshead of the testing machine, thus preventing jamming action between the plunger and its guide because of lateral forces. Since the load does not reach the plunger until it is below the guide, the plunger does not tend to increase in diameter and so does not stick in the guide, as a result of Poisson's ratio effect, while the load is applied. In testing machines where the movable crosshead is freely suspended from a ball-and-socket joint at the top of the machine, additional

side play is undesirable, and a modified subpress, with the load applied directly to the head of the plunger, may give better results.

Alignment of Specimens. The specimens used should have end faces machined plane and parallel, within very close limits. Details concerning dimensions of standard specimens for materials other than sheet are given on page 86, in the article entitled "Preparation of Test Specimens". Where reliable values for the properties of the material are desired, the test specimen should be at least

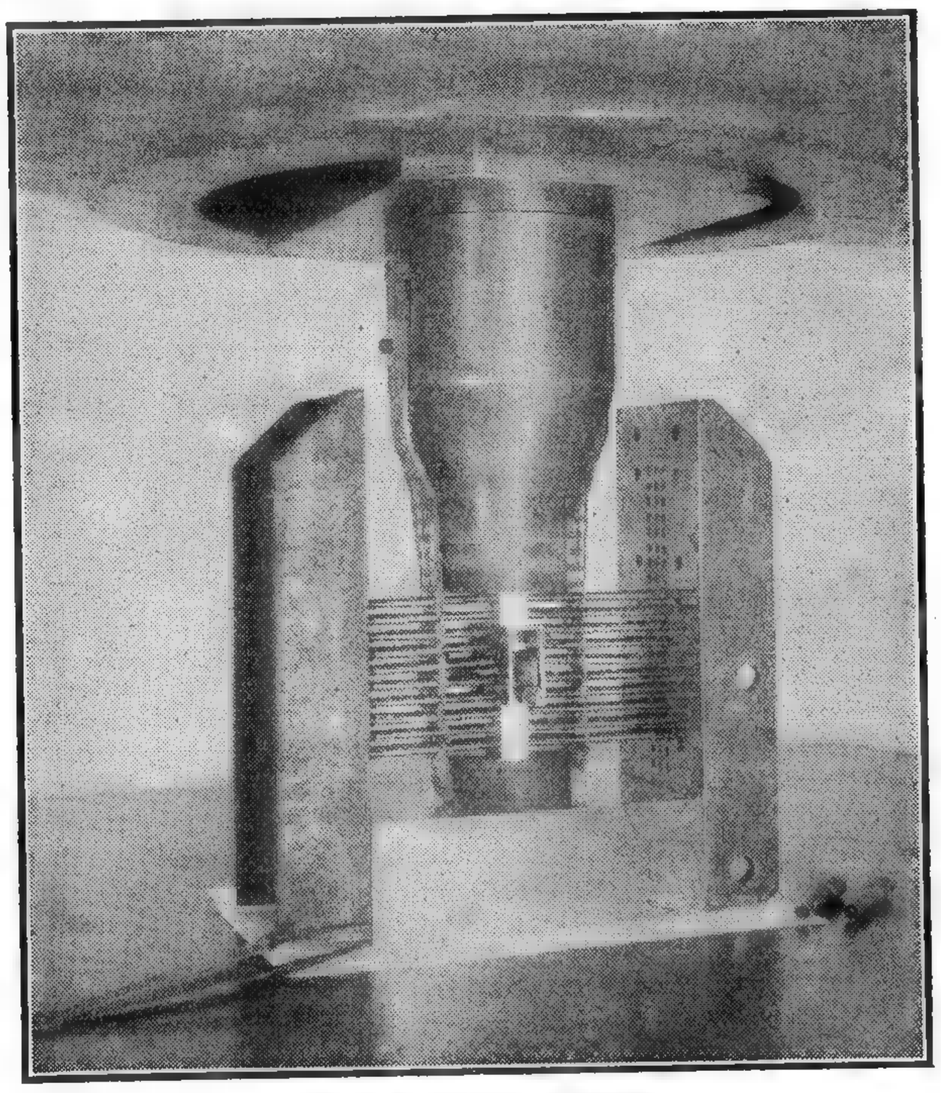

Fig. 2 Pack ready for test

three times as long as the diameter. Occasionally, where the dimensions of the stock from which the specimen is to be cut do not permit greater lengths (for instance, in compression tests of plate stock with the load applied at right angles to the face) short specimens may be used, with length about equal to the diameter. This procedure is followed in ASTM Specification B22–46T, for Bronze Castings for Turntables and Bearing and Expansion Plates for Bridges, which calls for cylinders 1⅛ in. in diam and 1 in. long. Results obtained from specimens of this shape will be comparable with one another but, because of the effect of end restraints, these results will show strength values higher than in tests of longer specimens.

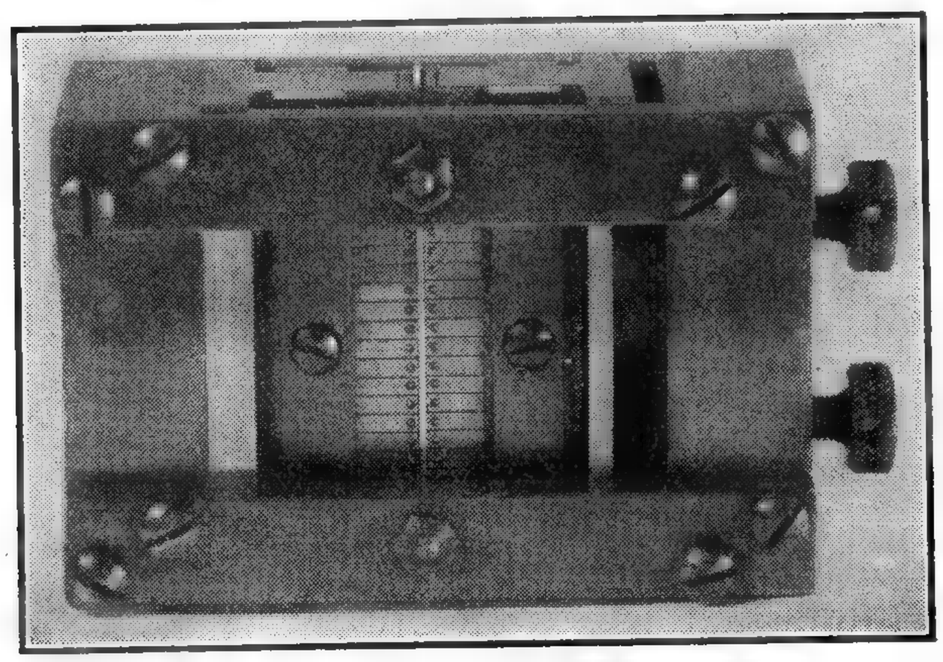

Fig. 3 Specimen in Montgomery-Templin fixture

Recently several different techniques have been developed by which satisfactory compression tests can be conducted on thin sheet specimens. In tests on thin sheet material, the specimens are supported laterally, either continuously or at close enough intervals to prevent buckling. The first methods used called for rows of very carefully adjusted steel pins, as shown in Fig. 2, or for rollers, as shown in Fig. 3, on each side of the specimen. It soon became evident that less elaborate methods were feasible. The problem is to provide adequate lateral support without introducing an undesirable amount of longitudinal friction, both initially and after the specimen has decreased somewhat in length and increased proportionately in thickness under load. The specimen must extend beyond the guides at the ends far enough to allow for this decrease in length but not enough to encourage the metal to buckle, and should extend at the sides far enough to support extensometers.

A fixture developed at the National Bureau of Standards is shown in Fig. 4. The tool steel guides shown are 0.46 in. wide by 2.20 in. long, and are held together by four bolts, which are intentionally made long and of small diameter so as to give a certain amount of elasticity. For sheet materials thicker than 0.020 in. the test specimen is made 0.50 in. wide by 2.25 in. long. With thinner materials (down to 0.006 in.) the overhang at the sides and ends is made

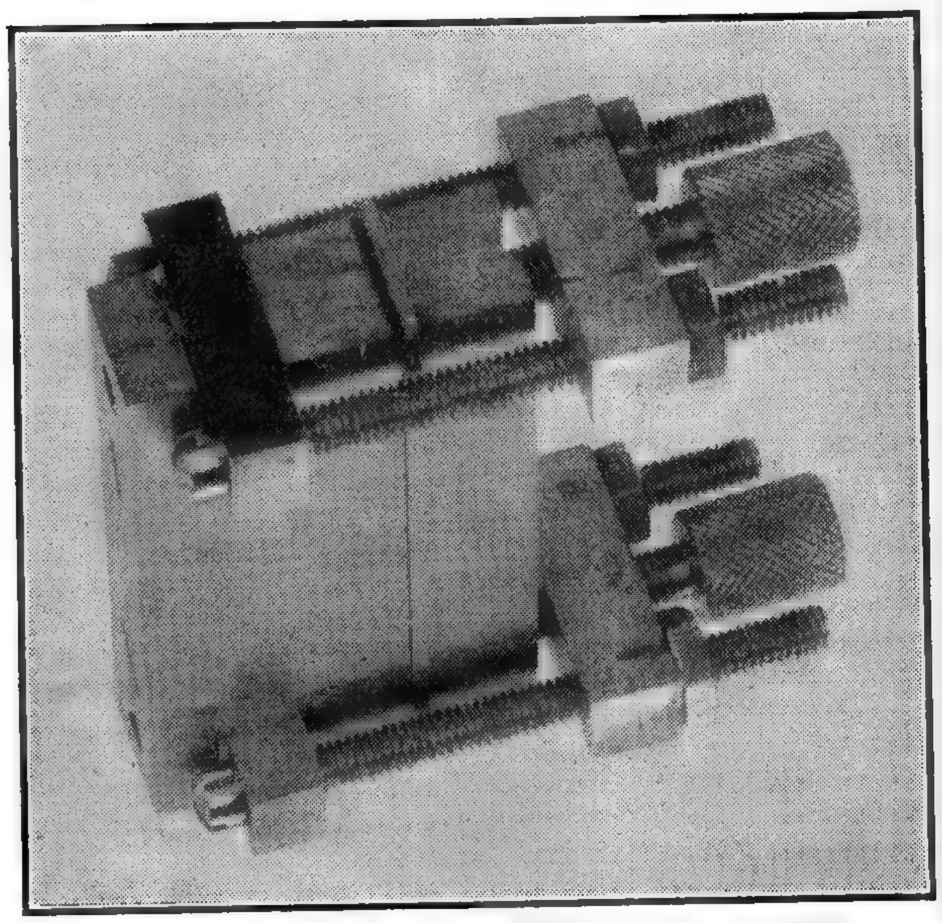

Fig. 4 Specimen between NBS lubricated steel guides

somewhat less. A thin film of heavy-duty lubricant for automobile wheel bearings is spread on the specimen. Then the specimen is placed between the guides and the bolts are tightened by trial until the guides will not slide down on the specimen under their own weight, but will slide smoothly if an additional force of not more than one pound is applied. Strains can be measured by using gages mounted on the projecting edges of the specimen. This fixture is intended primarily for use with a subpress, but good results have also been obtained by using it directly between the crossheads of a testing machine.

Alignment of Bearing Blocks. The bearing blocks used should have hardened steel faces that are plane and bear evenly on the end faces of the specimen. When the upper bearing block is made with a spherical seat, having the center of the sphere at the midpoint of the face of the bearing block, theoretically the block can be adjusted so as to bear evenly on the top face of the specimen, although the lower bearing block may be very slightly out of horizontal alignment, and the two faces of the specimen slightly out of parallel alignment. In practice this adjustment is not always easy to achieve. If the block is allowed to rest on the top face of the specimen while the crossheads are being moved together, the upper face of the bearing block may not line up exactly with its spherical

seat, and skew forces will be developed as the block moves laterally to seat itself. If the block is supported by springs so that it is held in contact with the spherical seat, swiveling the block while load is being applied, to the exact position that will give an even bearing on the specimen, will be difficult. In both instances, care should be used to make sure that the top face of the specimen centers accurately on the bearing block, and to avoid a tendency for the block to swivel as the load is being applied. However, the friction in the spherical seat is usually great enough so that the bearing block cannot be relied on to adjust automatically to the face of the test specimen as the load is being applied, and so that the bearing block will swivel jerkily if the specimen yields. This friction can be reduced by applying a forced oil feed to the bearing, but the practice is expensive and has not often been used.

Instead of employing the bearing with spherical seat, better results can be obtained by using test specimens with accurately parallel ends, and by adjusting the bearing blocks themselves so that their faces are parallel. This parallelism of the blocks can be checked with inside micrometers or dial gages, or by bringing the two faces lightly in contact with each other with no specimen between and by checking with feelers or by using Prussian blue for even contact. One method of making adjustment for lack of parallelism is to loosen the upper bearing block slightly so that it can rest evenly on the lower block, and then to grout the space between the upper block and the crosshead with plaster of Paris. While this is being done, the blocks should be under a moderate load in order to take up any slack elsewhere in the mechanism. An alternative method, developed at the laboratories of the Aluminum Company of America, uses a lower bearing block made of two hardened steel disks. Each of these disks is made with a very slight taper in thickness, so that when one is placed upon the other, with the thickest dimension of one opposite the thinnest of the other, the over-all thickness of the two is constant. As one of the tapered disks is rotated on the other, the assembly as a whole becomes a tapered disk. The rims of both disks are graduated to indicate the amount of taper produced and the direction of this taper. With these disks in zero position, the spacing between bearing blocks is measured at various points, and the disks are then rotated by known amounts until this spacing is made uniform. A single adjustment of this fixture will suffice for a whole series of compression tests.

As load is applied, the lateral dimensions of compression specimens increase because of Poisson's ratio effect below the elastic limit, and because of plastic yield beyond it. Near both end faces, this swelling tends to be restrained by friction between the specimen and the bearing blocks. If any lubrication is present—even residual oil from machining operations—the result is likely to be imperfect restraint and consequent variation among different specimens. To obtain consistent results, it is desirable to clean all bearing surfaces with a solvent, such as acetone, before testing, thus producing essentially complete restraint.

Speed of Testing. As in tension testing, speed of testing should logically be stated in terms of rate of increase of unit strain along the gage length of the specimen. For practical purposes this is not an easy unit to use, so the rate of increase of unit stress is used in its place for hydraulic testing machines and the free-running speed of the crosshead is used for machines of the screw type. Most of the compression tests made on metals are for research or investigational purposes rather than in connection with acceptance tests, and no standards of speed have been established, beyond an old ruling that the free-running speed of the crosshead should not exceed 0.05 in. per min. For short specimens this speed is likely to be too high. To obtain consistent stress-strain curves, it is desirable that about the same speed be used with successive specimens, and that the halts made for taking gage readings be brief and reasonably uniform in duration. Otherwise the short-time creep which occurs, once the elastic limit has been passed, may result in an irregular stress-strain curve.

Information Obtained From Compression Tests. For brittle metals, such as cast iron, and for nonmetals, such as building stone, concrete or brick, the only reading taken in a compression test is usually the maximum load in pounds. When divided by the original cross-sectional area, this reading gives the compressive strength of the material.

In acceptance tests for bronze castings (ASTM specification B 22–46 T) the requirement for class A material is that the deformation limit (which is defined as "that load which produces a permanent set of 0.001 in. in the given compression specimen", 1⅛ in. diam by 1 in. high) must reach 24,000 psi as a minimum; and that the permanent set in 1 in., under a compressive stress of 100,000 psi, must lie between 0.04 and 0.12 in. For class B the minimum "deformation limit" is 18,000 psi and the permanent set under 100,000 psi must lie between 0.10 and 0.20 in. For class C material, the only requirement is that the maximum compression under 10,000 psi shall not exceed 0.001 in. In essence, the requirements call for applying either one or two proof loads on each specimen, and measuring the change in length under each load.

Most other compression tests are run in order to obtain a stress-strain curve for the material in compression, both for its own value and for comparison with stress-strain curves in tension. In tests of high-strength aluminum alloys and alloy steels for aircraft purposes, it is necessary that this curve be carried at least up to the yield strength, which is defined as that stress at which the offset from the original straight stress-strain line corresponds to 0.2% strain. This curve must be sufficiently detailed to give values for the initial modulus of elasticity and for the slope of the tangent to the curve at various stresses above the proportional limit. These values are used in computing the buckling strength of parts subjected to compression under high stresses. To obtain the necessary accuracy, precision strain gages must be used, preferably reading on opposite sides of a specimen, unless previous experimentation has indicated that the stress distribution is sufficiently uniform for only one gage to be needed. It should be emphasized that, in any compression tests of metals, all strains should be measured between gage points on the specimen and not between the two bearing block faces, if accurate results are desired. Preferably the gage points should be located symmetrically with respect to the middle of the length of the specimen and not closer to the ends of the specimen than a distance equal to the width of the specimen.

The Torsion Test

BY THE SUBCOMMITTEE ON MECHANICAL TESTING*

TORSION tests provide a method for determining the modulus of elasticity in shear (sometimes called the modulus of rigidity), as well as for determining the shearing yield strength and the modulus of rupture or apparent ultimate shearing strength.

The torsion test is useful for testing such parts as axles, shafts and twist drills in the manner in which they are to be used. It offers advantages in the testing of brittle materials.[1, 2] At elevated temperatures the torsion test is of value as an index of forgeability.[3, 4] This test has also been used to determine values for the ultimate strength of cylinders subjected to internal pressure, utilizing that part of the torque-twist diagram lying beyond the elastic region.[5] Without uncertain correction, torsion test data are generally valid to larger values of strain than are tension test data.

A machine for making torsion tests consists essentially of (1) a twisting head, in which one end of the specimen

* Acknowledgment is made to F. M. Howell and F. G. Tatnall for their contributions to this article.

can be suitably gripped and by means of which a twisting moment can be applied to the specimen, and (2) a weighing head, in which the other end of the specimen can be gripped and by which the twisting moment, or torque applied by the twisting head, can be measured (Fig. 1). The gripping arrangements must be such that the axis of the specimen coincides with the axis of rotation. The deformation of the specimen is usually measured by a twist-measuring device or troptometer, which indicates the angular displacement of a point near one end of the test section in relation to a point on the same element of the specimen but near the opposite end of the test section.

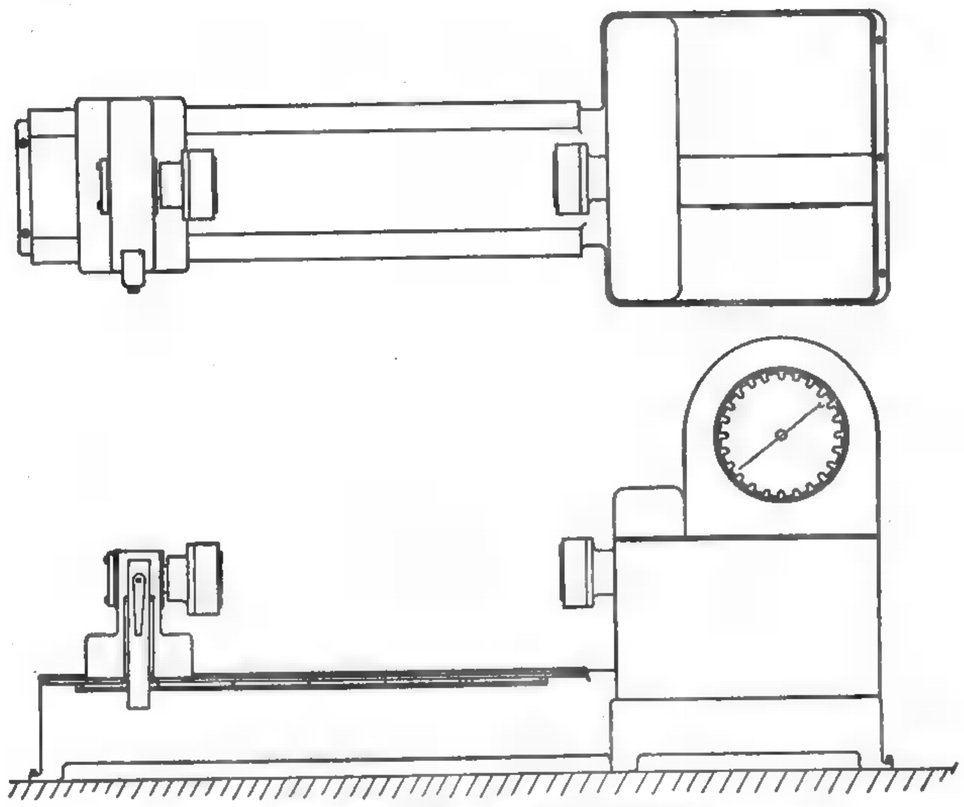

Fig. 1 Torsion-testing machine

Specimens that have a circular cross section are generally used for torsion tests. Solid specimens have the disadvantage that the stress varies from zero at the axis of the specimen to a maximum at the surface. A tubular specimen having a thin wall is generally preferred, because it provides more nearly uniform stress distribution throughout the cross section. For torsion testing, the use of thin-wall tubes is limited by those dimensions at which the tube will fail by collapse rather than by torsion.

The test specimen should be machined to a somewhat smaller diameter than the ends that are held in the grips, and a suitable fillet should aid in transition from one diameter to the other. The reduced section should be relatively short for the determination of ultimate shearing strength but, for the determination of yield strength and modulus of elasticity, a greater length is required. For the determination of ultimate shearing strength, suitable proportions for the reduced section are a length equal to about one half the diameter, and a ratio of outside diameter to wall thickness of 10 to 12; for the determination of yield strength and modulus of elacticity, the length should be at least 10 times the diameter and the ratio of outside diameter to wall thickness should not exceed 10.

The torsion test has not been standardized, primarily because there are few if any specifications that require torsion tests. The ASTM has published a "Tentative Recommended Practice for Torsion Tests of Cast Iron" (A260-42T) but none of the specifications of that society require that torsion tests be made.

When a cylindrical specimen, either solid or tubular, is twisted in such a way that the axis of twist coincides with the axis of the specimen, the specimen is subjected to pure torsion. The maximum stress occurs at the surface of the specimen. The shearing stress can be calculated by the following formula:

For tubes: $$S = \frac{16Ppd_1}{\pi(d_1^4 - d_2^4)}$$

For solid bars: $$S = \frac{16Pp}{\pi d^3}$$

where
S = shearing stress, in psi
P = force, in lb, at lever arm p, in inches
d_1 = external diam, in inches
d_2 = internal diam, in inches

This formula holds only as long as the strain is proportional to stress, but is commonly used for computing higher stresses and for determining modulus of rupture or ultimate shearing strength.

The total torsional deformation is measured as angular twist of one end of the gage length in relation to the other. In order to obtain the angular twist per inch of gage length, the total angular twist is divided by the gage length. The angular twist per inch of gage length can then be converted into shearing strain, in inches per inch, by multiplying by half the diameter of the specimen.

The modulus of elasticity in shear (sometimes called the modulus of rigidity) can be calculated from the following formula:

$$E_s = \frac{SL}{r\theta}$$

where
S = maximum shearing stress, in psi
L = gage length of specimen, in inches
r = distance from axis of specimen to the outermost fiber (half the diameter), in inches
θ = angle of twist, expressed in radians, in length L.

The yield strength is generally defined as the maximum stress developed by a torque producing an offset of 0.2% from the original modulus line, analogous to the method used for determining tensile yield strength. In "Tentative Recommended Practice for Torsion Tests of Cast Iron", referred to above, the yield strength is the maximum stress developed by a torque producing 0.001 radians per in. of angular twist beyond the line of proportionality. An offset of 0.001 radians per in. is the equivalent of a shearing strain of 0.0375% for the specimen, ¾ in. in diam, recommended by the ASTM for cast iron.

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Notched-Bar Impact Tests

By S. L. Hoyt*

If it were possible experimentally to apply known triaxial stress systems as easily as to apply simple tension stresses, a great deal of confusion would be eliminated from discussion of notched-bar impact testing. Although the notched bar often provides triaxial stress components high enough to induce brittle failure in steels, no satisfactory method has ever been devised for measuring or computing the stress components in notched bars. There are convincing indications that a given geometry of notch does not impose the same stress system when used with different materials.

For this reason, it is evident that the data from the notched-bar test are subject to limited interpretation. The test can be expected to indicate only that a given steel is or is not brittle when tested at a given temperature with a notch of given form and severity. When interpreted

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Prepared for the Subcommittee on Mechanical Testing.

within these limitations the comparison of results from one material with those from other materials can lead to a useful estimate of quality or to a correlation with the properties of other materials of supposedly similar composition. However, the limitations must be kept clearly in mind, and the test should not be misused.

The impact value is a simple evaluation of the notch toughness as a summation of load and deformation, and differentiates between different steels under the particular test conditions. The impact method is a positive method of securing a toughness value but has led to the false implication that the results correlate entirely with shock loading. However, while this is an impact method for determining energy absorption, it is not a test of impact behavior.

It is now quite generally recognized that tests of metal behavior under impact must be carried out at relatively high velocities before any peculiarity of behavior becomes evident. Typical "high-velocity tests" are ballistic tests of armor plate. In the field being discussed here, the notch actually dominates the test.

Impact Machines. Two types of machines are commonly used, the Charpy and the Izod, both of which employ the swinging pendulum. The conventional size of Charpy machine has a total available striking energy of 30 kg-m or 220 ft-lb. The specimen, supported at both ends as a beam, is broken by a single blow of the pendulum applied at the middle of the span. Ordinarily the specimen breaks at the notch, the two halves fly away, and the pendulum passes in between the two parts of the anvil. The height

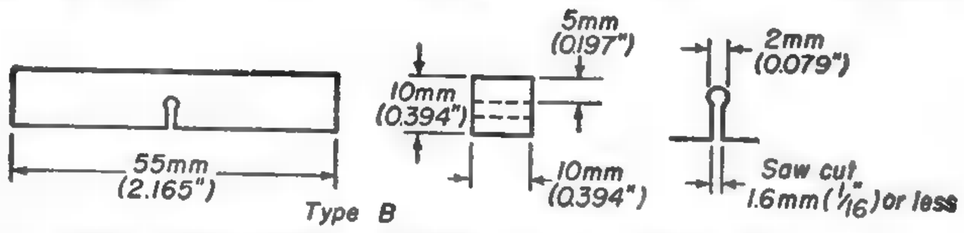

Fig. 1 Simple-beam notched-bar impact test specimen with keyhole notch, Charpy type (ASTM)

of the fall minus the height of the rise, gives the amount of energy absorption in deforming and breaking the specimen, plus friction losses and the energy of the flying parts, which is about 1 to 2 ft-lb. The instrument has a scale with moving pointer, which is calibrated in terms of energy to give the "impact value" of the test specimen. One or more specimens are broken to determine the impact value of the metal. Because of the sensitiveness of the test to variables, such as the machine finish of the

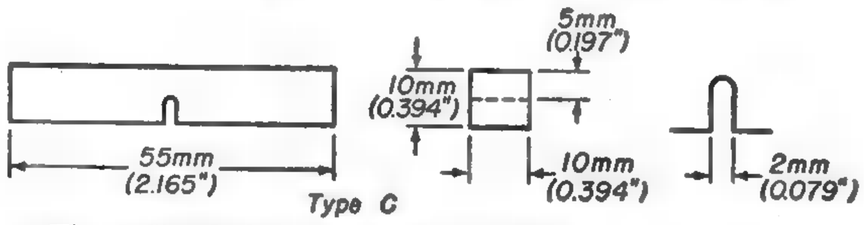

Fig. 2 Simple-beam notched-bar impact test specimen, Charpy type (ASTM)

specimen and the location and extent of nonmetallic inclusions, it is customary in steel specifications to require that three individual specimens should constitute a test. These may be appraised individually or assembled with other data for statistical analysis.

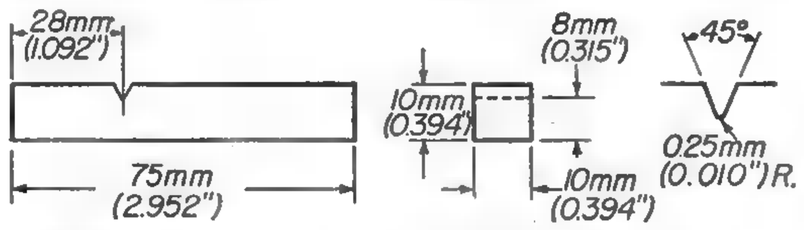

Fig. 3 Cantilever-beam notched-bar impact test specimen, Izod type (ASTM)

It is common European practice to report notched-bar impact test results in terms of energy absorbed per unit cross-sectional area. It should be realized that this expression does not permit translation of data from one type of test to another; consequently there appears to be little or no value in expressing results in this way.

The Izod machine is similar in principle but the test specimen is held rigidly in a vise, as a cantilever beam, with the center of the notch coincident with the upper face of the jaws. The capacity is usually 220 ft-lb. In this method, one half of the test specimen is broken off and the impact value is determined as before.[1]

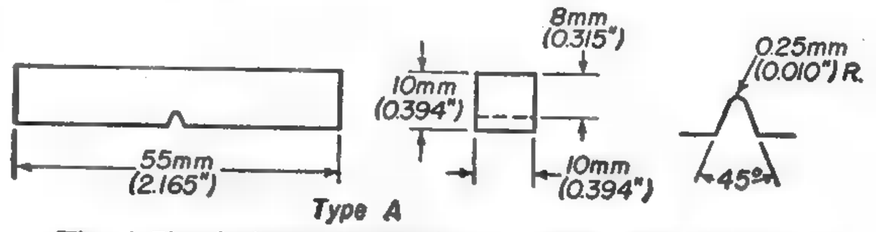

Fig. 4 Simple-beam notched-bar impact test specimen, V-notched Charpy type (ASTM)

Types of Specimens. In this country, two types of test specimens are generally used: the standard Charpy specimen (*see* Fig. 1 and 2) and the standard Izod specimen (*see* Fig. 3). However, a practice has spread of using a specimen of the Charpy type with the Izod notch. This specimen, known as the "V-notch Charpy specimen" is illustrated in Fig. 4. There should be no confusion in using the results of this method if they are labled "V-notch Charpy value". When a figure is reported as a "Charpy value", the first presumption is that the specimen was like that shown in Fig. 1 or 2, though it may have been like the one in Fig. 4. Since the Izod notch gives much higher values for tough steels, a high "Charpy value" (above approximately 50 ft-lb) may be assumed to relate to the specimen of Fig. 4. Results obtained in using one particular form of test specimen cannot be translated to another.

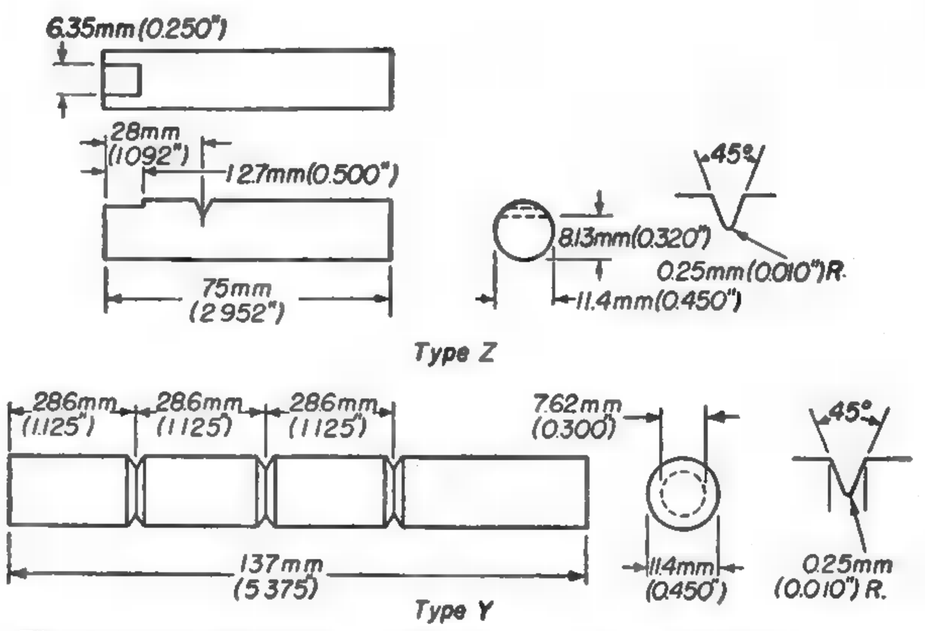

Fig. 5 Supplementary cantilever-beam notched-bar impact test specimens, Types Z and Y (ASTM)

Supplementary types of notched-bar impact test specimens are recognized by the ASTM, as shown in Fig. 5. These specimens, circular in cross section, have the advantage of lower machining costs. Attempts have been made to develop round specimens of the simple-beam (Charpy) type also. Although these specimens of circular cross section have been designed to give results equivalent to the corresponding rectangular specimens, such equivalence is not always obtained. Added difficulty is encountered in locating the specimen in the machine properly to maintain the relative position of notch and striking tup.

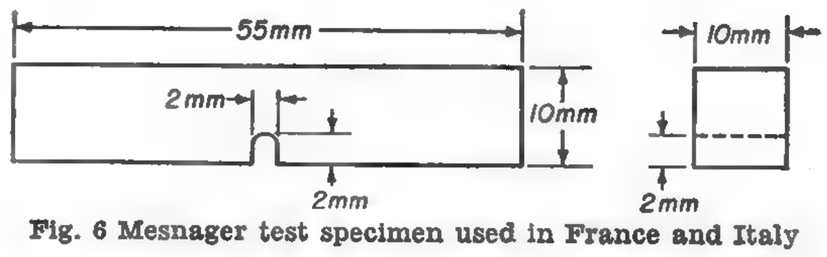

Fig. 6 Mesnager test specimen used in France and Italy

The "Mesnager" specimen is most frequently used in France and Italy, but the notch is too shallow for best results (Fig. 6). This specimen is broken in the Charpy machine. A number of types of specimens are recognized for making tension-impact tests (Fig. 7).

Perhaps the worst feature of practice in this field is that of testing V-notch Charpy specimens on the Charpy ma-

chine and reporting extra high impact values of about 80 ft-lb and more, even well above 100 ft-lb. In these instances, the test specimen has not broken (too shallow notch) but has been violently driven through the split anvil by the pendulum, meanwhile absorbing a large and unknown amount of energy. Obviously this situation results in absurd or fictitious values. Although the test data are unreliable in such cases, it is known at least that the metal has responded in a tough manner with that particular notch. A similar occurrence is possible in using the Izod machine. When the specimen is not broken by the blow, it rubs along the bottom of the tup, thereby absorbing considerable energy and falsifying the test results.

The notch of Fig. 1 is preferred by many because of the ease of making it and particularly because of the precision with which it can be reproduced. The hole is drilled with a No. 47 drill with a diameter of 0.0785 in. By placing the specimen in a fixture, this hole can be drilled tangent to the center line so that the depth of the section to be broken can be held to 5 mm or 0.197 in. The drilling operation leaves the scratches running around the hole, or in the most favorable direction to avoid causing low results in the test. The hole can be reamed out but that is seldom considered necessary. After the hole is drilled, a slot is opened to the surface by sawing, milling or grinding with care to avoid enlarging the hole. Cutting into the side of the drilled hole can be avoided by placing a copper wire in the hole while making the saw-cut. If the steel is too hard for drilling (about 400 Brinell or 40 Rockwell C) the notch can be made by grinding.

Test specimens that are to be broken in a hardened condition require a special technique. The hole cannot be drilled but, with suitable precautions, it can be ground to dimension. It is also feasible to drill the hole before hardening, insert a soft steel wire that will completely fill out the hole, and then heat treat the test specimen. This hole is subsequently opened to the surface.

The Izod notch, commonly used in Great Britain, is also quite widely used in this country. Its sharper root radius gives higher concentrations of stress than does the Charpy notch and its shallow depth gives a larger numerical spread between notch-tough and notch-brittle steels. On the other hand, reproducing the Izod notch requires greater care. This notch is virtually impossible to produce in hard steels. Furthermore, a great amount of work has shown that a shallow notch like the Izod is inadequate for the tougher steels and that as soon as the volume of deformed metal extends to the outer face, false impact values are obtained. The fictitious values that are obtained, particularly with V-notch Charpy specimens, have already been mentioned. However, this type of notched bar has been successfully used for the appraisal of considerable material, particularly for ordnance. In applications of this type, the properties of the material are such that the specimen always breaks under test.

Studies of the character of the machine finish in the notch have indicated that reproducible results may be obtained with some materials by using a milling cutter to make the notch, provided the milling cutter is periodically examined and kept in good condition. Some investigators advocate polishing the radius of the milled notch by using lapping compound on a wire of the correct radius, rotated by an electric hand drill.

Precautions Necessary for Reproducibility of Results. Three features of great importance are: making the notch correctly, locating the bottom of the notch properly, and placing the specimen properly in the machine. The other dimensions of the specimen should be held as shown. The accuracy which is usually maintained is plus or minus 0.001 in.; though if it will lower the cost of preparing test specimens, this can be increased to plus or minus 0.003 in. on harder steels and to plus or minus 0.005 in. on softer steels, without endangering the reliability of the results.

The impact machine should be known to conform to standard requirements, and to be of correct calibration. Frictional losses can be checked from time to time by permitting the pendulum to fall freely and then noting the decrease in the oscillations. The small fixture that is used to place the test specimen at the correct position on the anvil of the Charpy machine can also be used to check the zero position of the pendulum. The test specimen should be placed accurately on the anvil so that the tup of the pendulum will strike it opposite the notch. This placement can be properly made with the aid of the template. Furthermore, the anvil should be so designed that the test specimen clears the sides with no undue loss of energy from scraping.

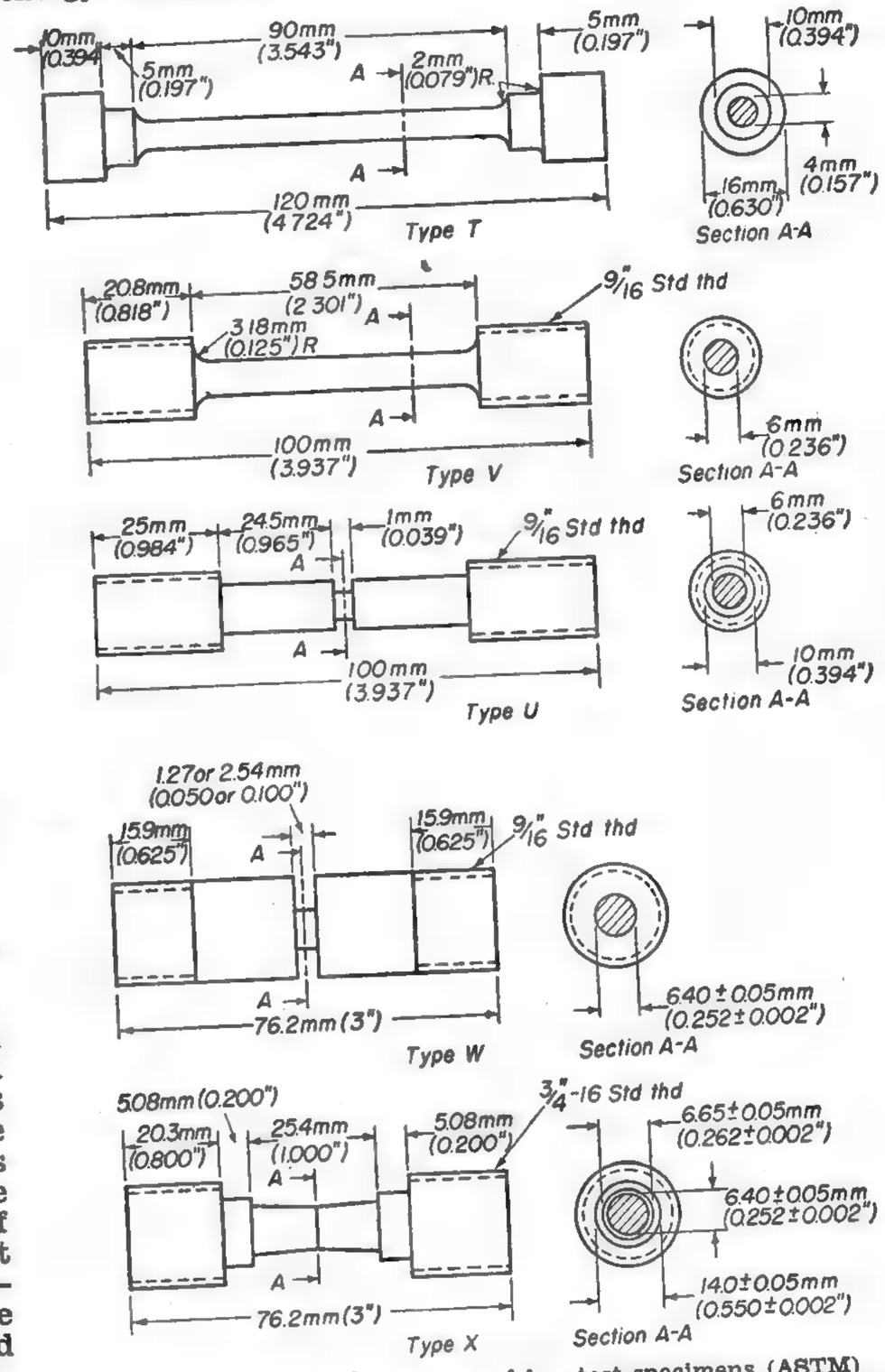

Fig. 7 Tension-impact notched-bar test specimens (ASTM)

The effect of variation of temperature in notched-bar testing is extraordinarily great. The laboratory temperature may vary as much as 30°F between summer and winter, and with some steels this is sufficient to affect the impact values greatly. To obtain reproducible results may require holding the temperature of the test specimen within a range not exceeding 10°F. The effect of temperature will be discussed at greater length in a later section.

Other factors that affect the consistency of the results are associated with taking the sample. Forgings and rolled sections have definite flow lines or fiber; nonmetallic inclusions are also drawn out in directions parallel to the direction of metal flow. If the length of the test specimen is parallel to the direction of the fiber, the impact value is higher—at times as much as twofold—than it is if the length is perpendicular to that direction. The direction of the notch in the test specimen may likewise have an effect on the impact value.

Heat treatment frequently alters the surface and affects the consistency of the test results. Usually this change is a decarburization, which increases the impact value, though it may be a carburization, which acts to lower the impact value. The discussion of such factors could be elaborated, but it is sufficient to say that every test specimen should be made by a procedure that insures having the metal in the desired condition. As a precautionary measure, at least 0.025 in. can be left on all faces for final

machining and grinding, and the notch can be made last.

Wide Specimens. It has been found valuable to test wide specimens for certain applications. A double-width specimen, shown in Fig. 8, ordinarily gives about double the impact value of the standard Charpy bar. Occasionally, however, the value is found to be no greater than that of the standard bar; and for certain critical service conditions such a material may not be desirable.

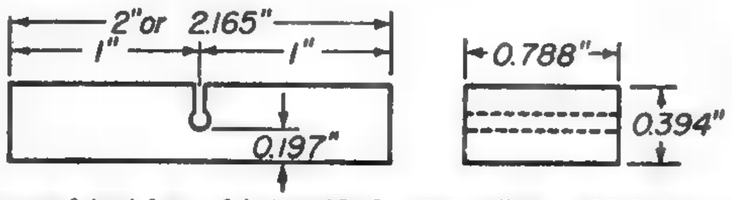

Fig. 8 Proposed test bar of intensified notch effect, which is the same as Charpy specimen except for being twice as wide

Effect of Temperature. Temperature has a pronounced effect of changing the energy absorption and fracture behavior of steel in a notched condition. This happens over a relatively narrow range and at approximately atmospheric temperatures for most ferritic steels that have not been heat treated. The sharpness of the change or "transition" from tough to brittle depends on the material and also on the notch geometry. Frequently the Charpy values will change from between approximately 25 and 30 to approximately 5 to 10 ft-lb over a temperature interval of 25 to 50°F, while the Izod values (V-notch) are changing gradually. With other steels, the two notches will show reverse effects.

Service failures corroborate the test results by pointing to the increased hazards of subnormal temperatures, and determinations of transition temperatures have come to be useful criteria of steel "quality" or applicability to the part in question. Size and shape (stress distribution) are important; a steel with a transition temperature of 30 to 40 F in the Charpy test may have a transition temperature above 100 F when tested as a large, rigid structure.

Transition temperatures of ferritic steels appear to be determined by the degree of oxidation, the amount of nitrogen and the extent to which it is "fixed" in a stable form, the coarseness of the structure, phosphorus and impurity elements, prior cold working or strain embrittlement, and structure. In other words, coarse structures and most active impurities raise the transition temperature and make the steel more susceptible to low-temperature embrittlement. Special attention must be given to deoxidation practice if it is desired to retain notch toughness at low temperatures. This factor of quality improves with deoxidation by manganese, silicon, and aluminum, or from rimmed steel to fine-grained, fully killed steel. See the article on "Properties of Metals at Low Temperatures".

Heat treatment is particularly effective; in fact, an effective liquid quench (complete martensitization) and a high tempering temperature put a hardenable steel in its best condition for low-temperature notch toughness.

The face-centered cubic, nonferrous metals[7] (copper, aluminum, nickel and others) remain notch-tough down to the lowest temperatures. This effect, which is presumably associated with the structure, recurs in the iron-base alloys or steels that are austenitic or face-centered cubic in structure. Examples are the stainless steels, such as 18-8, and the quenched Hadfield manganese steel.

Effect of Velocity. The effect of speed of straining is outside the scope of this article; however, it is found that increasing the velocity has the same embrittling effect as lowering the temperature.[3,4] This effect is relatively small, as compared with that of temperature, but has been demonstrated quantitatively.[5]

Nonstandard Tests. In technical practice, occasions arise that require the testing of materials and parts by using samples that do not conform to standards. There can be no set rule for such problems, but valuable advice can be had from the work of Tour.[2]

Interpretation of Test Results.[7] The interpretation of notched-bar test results necessarily involves certain strict limitations. Although steels are said to be notch-tough or notch-brittle, a given steel may behave in one way under one set of conditions and in another way under other conditions. Consequently, the broad problem of notched-bar testing is that of determining the severity of test conditions (notch geometry, temperature, and velocity) required to produce brittle behavior. If the service conditions are reasonably well understood, it should be possible to judge the adequacy of a steel. In important applications, this will involve a study of the service conditions and considerable testing of steel specimens, even including large or full-scale tests to bring in the size effect. Once the required level of notch toughness has been established, later testing can be simplified to a "go" or "no go" type. It may also be assumed that the steel composition, processing and treatment, as well as correct fabrication procedure, will have been established.

One of the best uses of the test is in comparing a steel with a standard known to be adequate for the service. The testing might include the effects of temperature, of specimen width, and of cold work or strain-aging, but the results would be interpreted in the following terms: adequacy of refining and deoxidation practice, steel composition and impurities, structure, homogeneity, heat treatment and so on. In such comparisons, the specimens of the material in question must be comparable in the other essential characteristics and properties with those that serve as a standard. With heat treated specimens, the grain size established prior to quenching must be carefully controlled, grain coarsening must be avoided, and the tempering must give the correct hardness and stress condition.

Notched-bar impact tests have been used as an index to the results of heat treatment. It has been noted that tempered martensite gives impact values superior to those obtained from other structures. It is sometimes extremely difficult microscopically or otherwise to distinguish between tempered martensite and tempered bainite. However distinct differences may be noticed in the Charpy results.

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Creep Tests

By J. J. Kanter*

CREEP is a continuing change in the deformation or deflection of a stressed member. In regard to metals and alloys, creep is generally associated with a time rate of deformation continuing under stress intensities well below the yield point, the proportional limit, or the apparent elastic limit for the temperature in question. The creep may be an effect of consequential magnitude at normal temperatures as well as at elevated temperatures, depending on the material under consideration or the degree to which freedom from continuing deformation is sought.

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Prepared for the Subcommittee on Mechanical Testing.

Character of Creep. Most of the available information concerning the character of creep has been gained from observations of specimens under constant tensile load and

at constant temperature. Extensive studies have been made of the interrelations among strain, stress and temperature by testing series of specimens under various combinations of load and temperature. A creep test is generally conducted for sufficient time to establish the character of the curve of creep strain versus time at the particular constant load and temperature in question. Such a test, to be significant, may require from a few days to several years. Tests of less than 1000-hr duration are generally regarded as rather insignificant in establishing reliable creep rates.

In Fig. 1 are illustrated two typical tensile creep curves based on results actually obtained under different loadings on two different alloy steels at high temperature. The strain designated as "total creep" is the net plastic deformation accumulated over and above the elastic strain immediately incident to the application of load. The initial creep on a specimen not previously strained is invariably rapid, but as the straining progresses, the rate of creep decelerates until, after an appreciable period, a constant rate is approximated. This initial straining at a decreasing rate is often termed the first stage of creep.

The second stage of creep is the strain that occurs either at a constant rate or in asymptotic approach to a constant rate. The design of stressed members is usually based on the rate of second-stage creep strain. The useful life of a structure is for some purposes adjudged to be the lapse of time before the termination of the second stage.

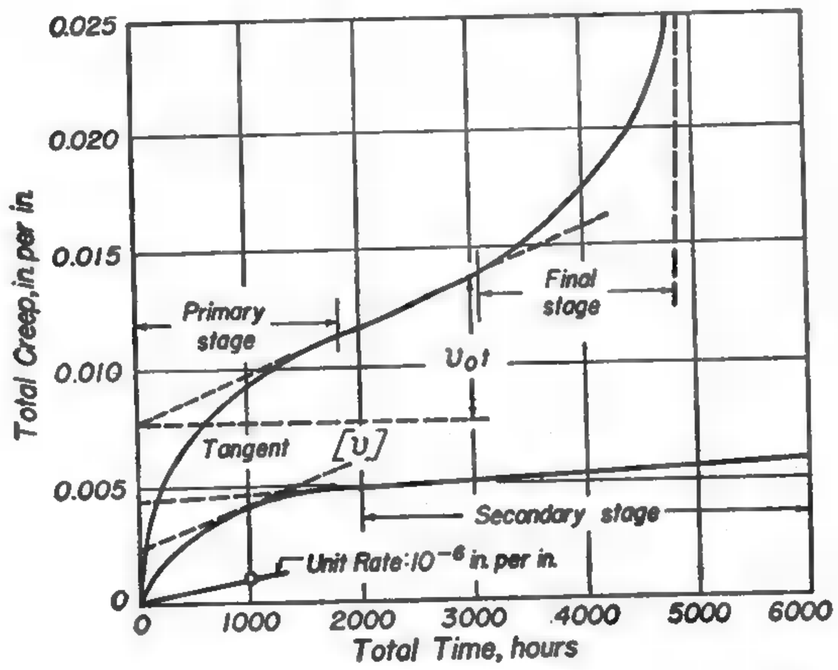


Fig. 1 Typical tensile creep curves obtained under different loadings for two alloy steels

In Fig. 1, the upper curve shows the second stage starting at slightly less than 2000 hr at a total creep of about 1% and terminating slightly beyond 3000 hr at a total creep of about 1.4%, where the rate of straining begins to increase. The lower curve shows no increase of rate up to 5000 hr, and tests are available in which the creep of metal specimens has continued in the second stage for several times this period. During the second stage of tensile creep, the cross-sectional area of the specimen remains sensibly unaltered, and thus the constant-load creep rate is usually reported, for practical purposes, as a constant-stress creep rate.

The third stage of creep is marked by an accelerating creep rate, leading to fracture. Although stress intensification and "necking" of the section contribute to the promotion of third-stage creep, studies of numerous materials have tended to show that this stage is ordinarily reached at deformations much smaller than those sufficient to produce rapid creep to fracture by stress intensification only. Such evidence is considered indicative of marked structural changes which strain, time and temperature produce in metals and alloys.

Creep-Testing Methods and Apparatus. The modifications of apparatus used in obtaining information concerning metals vary widely in form and purpose. Although creep has been studied chiefly under constant tensile load and temperature, numerous arrangements of apparatus have been devised for measurements in torsion, transverse bending, internal pressure, relaxation, variable loading and variable temperature. Ample descriptions of the equipment used for tensile creep testing up to 1931 are given by Tapsell.[1] Since the publication of the Tapsell book, a number of papers describing advances in tensile creep-testing technique have appeared in the publications of ASM, ASTM, AIME and ASME.

The ASTM has set up a recommended practice for creep testing[2] for the guidance of investigators seeking to evaluate the tensile creep characteristics of metals. No attempt has been made in this practice to prescribe a definite method of procedure or to specify apparatus, but rather to point out some of the possibilities, limitations and pitfalls of creep testing. It is recognized that creep investigation is still largely a subject for metallurgical research, and no hard and fast code of rules can be set up which might not prove detrimental to the best interests of progressive research. The tentative method of the ASTM attempts to cover only such fundamental considerations as the amount of extension, the effect of temperature, the tensile stress and the time. The ASTM method recognizes that since the characteristics which render a material resistant to extension under the conditions of test are not yet completely known, the only details of the procedure specified are those known to be important influences, and since others equally important may be discovered in the future, the recommended details of the method are largely advisory in nature.

Considerable latitude of practice is found among various investigators, in regard to the choice of test specimens. The gage lengths in use generally vary from ½ to 20 in., while diameters vary from 0.252 to 0.505 in. Longer gage lengths are preferred for delicacy of measurement where minute creep rates are of interest. For purposes of metallurgical comparison where the order of creep resistance is of primary concern, the 2-in. gage length is ordinarily employed. The use of this gage length not only simplifies the problem of specimen procurement, but also makes it possible to employ more easily constructed furnaces and simpler measurement techniques. Investigations of certain metal products are sometimes performed to advantage in apparatus designed to accommodate specimens in the form of strip, wire or tube.

Determination of the temperature of the specimen during the test is recognized in the ASTM practice as the most important single measurement in connection with creep testing, because small variations in temperature may produce large changes in creep rate. Care must be taken to insure accurate temperature measurement over the gage length of the specimen throughout the test. Reliable temperature measurements must be made at sufficiently frequent intervals to insure an accurate determination of the average test temperature.

It should be noted here that a great part of the creep data to be found in the early literature was obtained under conditions of test not acceptable under the ASTM practice. A confusion of creep values is to be found for certain compositions of steel. Though much of the discrepancy is traceable to differences of heat treatment and other manufacturing variables, a considerable part of the disagreement in the early literature must be attributed to lack of standardized technique and careful control of testing temperature.

Extension measurements are made through a number of devices, such as microscopes focused on targets within the furnace or extension arms extending beyond the furnace and actuating either optical levers or micrometer dial gages. Where total extensions are limited to the same order of magnitude as elastic extensions, it is important to have the elastic portion of the total extension accurately known.

The ASTM practice for creep testing, in recognition of the fact that much information pertinent to the intelligent evaluation of creep information has been lost through inadequate descriptions of materials used, recommends that essential information for identification of the materials tested be collected on a form, which provides not only a most complete description of the material, as to form, composition, and physical properties, but all kinds of grain size information, manufacturing data, and auxiliary test information. The code also adopts a tabular arrangement

for the reporting of the characteristics of the equipment used, intended to reflect the essential qualities of the measurements obtained.

In a carefully prepared preamble to the Joint ASME—ASTM Committee's compilation of available creep data,[3] the factors are summarized which experience indicates must be considered as having a possible influence on the creep characteristics of steels at high temperature. The recognized factors include melting process and practice, heat treatment, chemical composition, grain size, duration of test, number of tests and various other influences.

Significance of Creep. The first studies of industrial importance concerning creep in metals were published about 1922. They dealt with various steels and alloy structural members subjected to high temperatures in furnaces. These experiments served to demonstrate that commercial metallic materials, when used at elevated temperatures, underwent a steady rate of deformation under stresses well within the values allowed by good design practice and "safety factors" at that time.

As the temperatures of industrial processes steadily advanced and it was realized that troublesome deformations and even failure of equipment were being experienced at supposedly safe design stresses, the behavior of metals at elevated temperatures became the subject of critical inquiry. In 1924, realizing the industrial importance of these problems, the ASME and the ASTM established a standing research committee to study the effects of temperature on

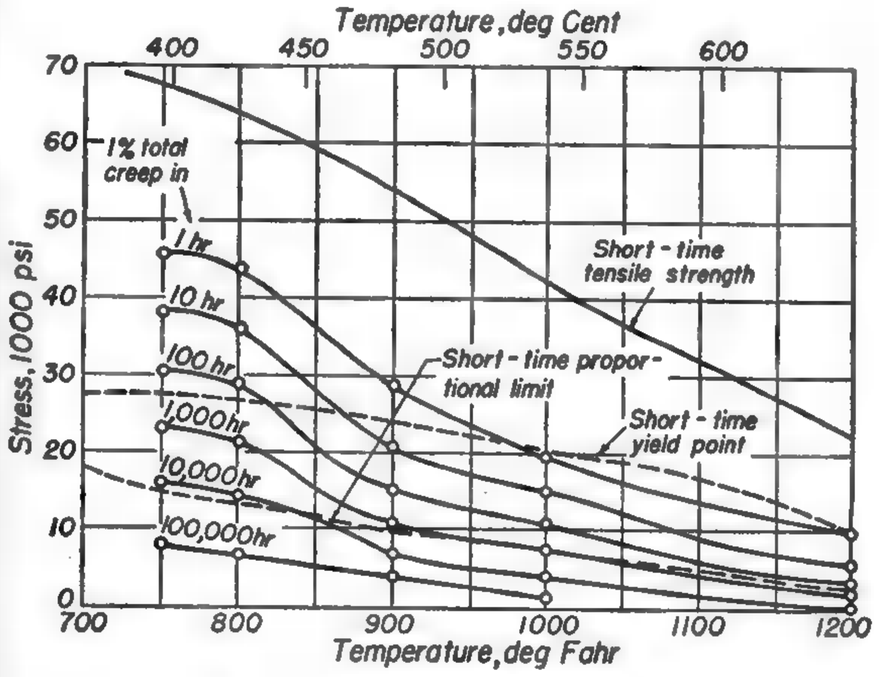


Fig. 2 Creep data for carbon steel

metals. This group has sponsored symposia, numerous reports and technical papers.

At first, it was felt that practical stresses, below which creep either did not take place or was of inconsequential magnitude, could be determined for the various materials at elevated temperatures. Creep investigations made from this point purported to show that proportional limits determined with sufficient delicacy might be regarded as "creep limits". Later investigations, in which refinements of creep measurements had been made, showed that considerable rates of creep could be measured at stresses well below the lowest proportional limits determinable by the most delicate means available. At the higher temperatures an increasing disparity was demonstrated between short-time tension test values and usable creep stress values, as illustrated in Fig. 2 by data for annealed cast carbon steel. It is now a commonly accepted fact that stress values from short-time tension tests are unreliable design criteria for applications at elevated temperature and that values determined by actual long-time creep testing are to be preferred. Although working stresses[4] based on tensile strength "safety factors" are still authoritatively used as bases of design stress for the temperatures at which creep is of inconsequential magnitude, the accepted basis of design for the higher temperatures is the selection of creep stress values.

Creep Strength. The practical aim of creep testing is ordinarily the determination of stress values, at temperatures of interest, upon application of which the amount of deformation occurring is limited to tolerance values over a period of time comparable to the anticipated working life of the member to be designed. Creep stresses, as so defined, are generally based on the rate of creep measured in the second stage and are justified as design values on the assumption that deformation during the useful life of the equipment is largely confined to this approximately uniform rate of creep. For some materials and purposes of application the deformation accumulating in the first stage must be taken into account. Constant-rate creep stress then becomes inapplicable and other values of creep stress are desired, based on the total deformation for the life period. The bulk of available creep stress data, however, have been determined in terms of either the constant creep rate or tangents to the time-deformation curve determined for some time of test chosen arbitrarily. An example of creep stress data for steel at elevated temperature is shown in Fig. 2, wherein a comparison is drawn with short-time values for tensile strength, proportional limit, and yield point.

Acceptability Tests for High Temperature. Since it is impracticable to make a long-time creep test on each heat of steel or heat treatment charge intended for service at high temperatures, considerable thought and study have been given to the development of some method of test which will assure that a particular lot of a given material has creep properties consistent with those dictated by the design requirement to which the material is to be applied. The requirements for such a test are that it can be performed within 24 hr, that it will detect off-color heats of material and that the conditions of reproducibility of test results, and correlation with creep data are such that mutual agreement can be reached between manufacturer and purchaser. Although a number of papers[5] have appeared concerning the development of such tests, it is too early to draw conclusions about the general usefulness of such tests for specification purposes.

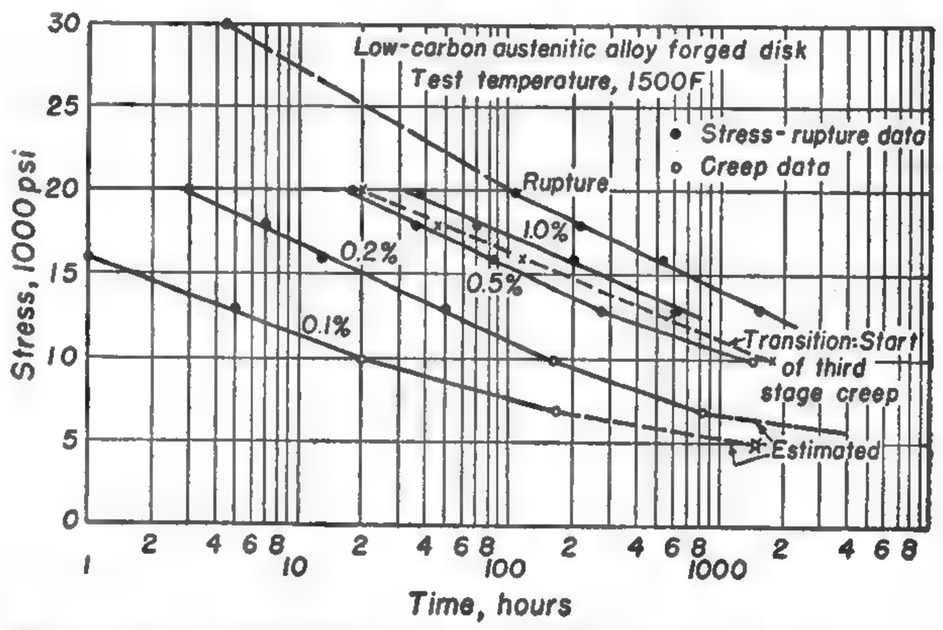


Fig. 3 Curves of stress versus time for indicated total deformations

Stress-Rupture Tests. Some high-temperature applications, such as turbosuperchargers, gas turbines, and jet aircraft engines, require materials to operate under rather extreme conditions of temperature and stress. In these applications the useful life may be of the order of several hundred or a thousand hours. In many of these applications, the permissible deformation is high or may not even be limited, and the only requirement is that rupture must not occur during the life of the part.

For evaluation of materials for this relatively short-time service, stress-rupture rather than long-time creep tests are used. For each temperature of interest, a series of tests is made over a range of stresses selected to cause rupture, over time periods from a few hours to several thousand hours. A log-log plot of the stresses versus the resulting rupture times for the tests usually shows a straight-line relation, except in instances in which surface or structural instability occurs, and in which a break in the straight line is observed. The data from stress-rupture tests are usually reported as the stresses for rupture in 10, 100, and 1000 hr, accompanied by the elongation measured at rupture.

In some instances, time-deformation characteristics are

not measured in stress-rupture tests, but these data may be obtained and, combined with creep test data, have been used to prepare design curves in which the relation between stress and time for certain total amounts of deformation ranging from 0.1 to as much as 5%, and the stress-rupture time curve are included on a single plot, shown in Fig 3. These design curves are very valuable to engineers for designing equipment for short life under extreme conditions when expected service life, temperature of operation, and permissible deformation are known.

References

1 H. J. Tapsell, "Creep of Metals", Oxford University Press, London, 1931

2 Recommended Practice for Conducting Long-Time High-Temperature Tension Tests of Metallic Materials. (E22–41) ASTM Standards

3 Compilation of Available High-Temperature Creep Characteristics of Metals and Alloys. Compiled by ASME-ASTM Joint Research Committee on Effect of Temperature on the Properties of Metals, 1938

4 Maximum Allowable Working Stresses for Ferrous Materials, ASME Boiler Construction Code

5 Correlation of Short- and Long-time Elevated Temperature Test Methods, Proc ASTM, 44, 186 (1944)

Fatigue Tests

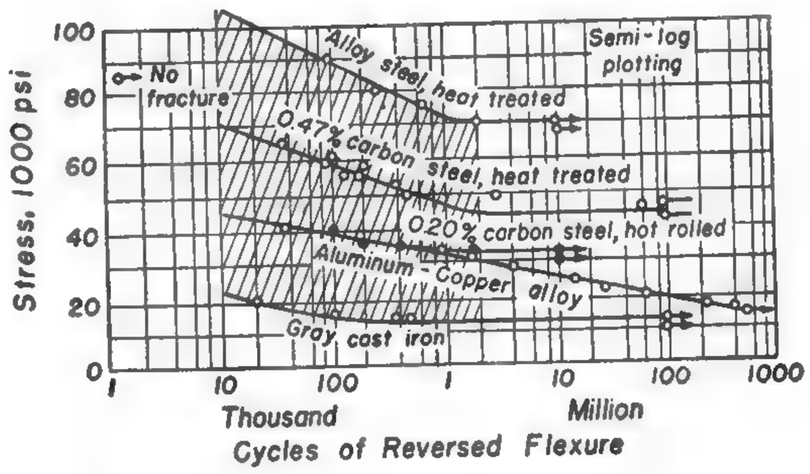
By H. F. Moore*

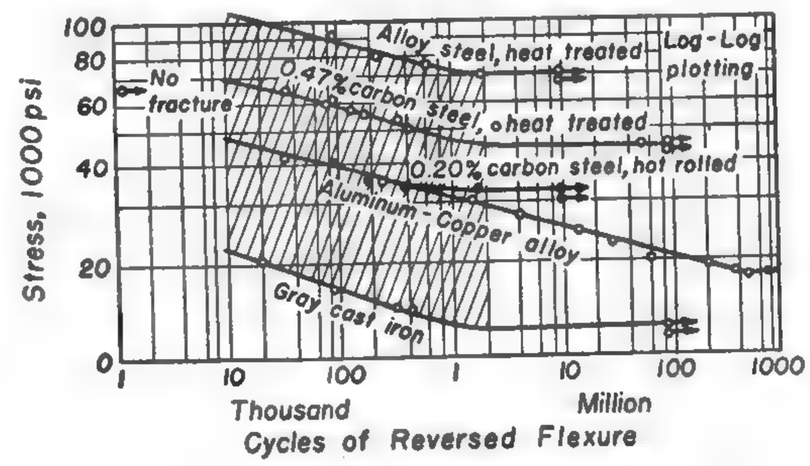
THE purpose of fatigue tests is to determine the resistance of a metal, or of a structural or machine part, to cycles of repeated stress. Metals are not perfectly homogeneous, but consist of crystals with planes of cleavage or slip oriented in many directions. When sufficient stress has been applied, slipping occurs on planes within the individual crystalline grains. At first this slipping may not be sufficient to cause harm. However, under ranges of stress sufficient to produce slip, continued repeated slipping, if sufficient in magnitude, causes minute cracks to form and to spread, gradually reducing the area of sound metal remaining in any cross section. One of the unsolved problems in the fatigue of metals is the exact determination of when and how, under repeated stress, harmless slip changes into harmful slip, causing the formation of a destructive, spreading fatigue crack. The end of such a crack is a minute area of highly localized stress, so there is a strong tendency for the crack to grow. The final fracture occurs with very little distortion or reduction of cross-sectional area. Formerly, the jagged appearance of the final fracture led to the natural but erroneous conclusion that the metal had "crystallized". It has now been determined that fatigue fractures start in the natural cleavage surfaces of the crystalline grains of a metal, or along crystal boundaries. Accordingly, the fracture has a "crystalline" appearance, but this appearance is the result of the fracture rather than the cause. The primary causes for failure of machine parts under repeated loads can often be ascertained by study of the fractures of the parts.

General Method of Procedure in Fatigue Tests. The method commonly used in fatigue tests consists in submitting specimens or entire structural or machine parts, to cycles of a known range of load of various magnitudes, and noting the number of cycles required for fracture, or for the attainment of a given specified "life" without fracture. The results of the test are plotted on a diagram (called the S-N diagram) in which maximum load or stress is plotted as ordinate, and the number of cycles for fracture as abscissa. The range of stress, or the ratio of minimum stress to maximum stress during a cycle, is stated. It should be noted that, for a cycle of partially or wholly reversed stress, the value is negative. The nature of the maximum stress should also be stated, whether tension, compression or shear.

In the United States, the stresses (or loads) are usually plotted to ordinary (Cartesian) co-ordinates, and the number of cycles of stress for fracture are plotted as abscissas to logarithmic co-ordinates. Cartesian co-ordinates for both ordinates and abscissas are sometimes used, and logarithmic co-ordinates for both ordinates and abscissas are frequently used, especially when it is not considered necessary to test for "life" beyond one or two million cycles. Which system to employ depends largely on convenience.

Figure 1 shows a typical set of S-N diagrams. The "endurance limit" of any metal is defined as the limiting stress below which the metal will withstand an indefinitely large number of cycles of stress without fracture. If the S-N curve becomes horizontal, the stress corresponding to the horizontal part of the curve is called the "endurance limit". If, however, the curve does not become horizontal, the term "endurance limit" is often applied to the stress





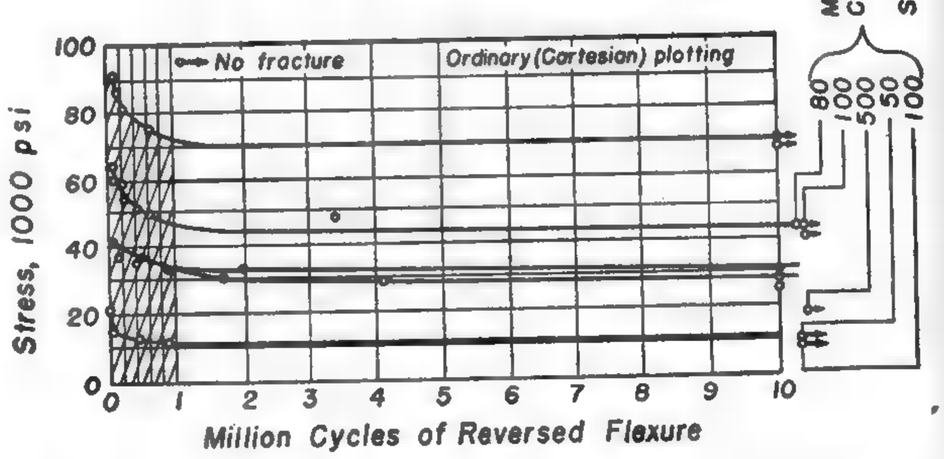


Fig. 1 Typical S-N (stress-cycle) diagrams for fatigue tests

corresponding to some specific number of cycles.* Table I presents data that are plotted in Fig. 1.

Apparatus for Fatigue Tests. Following are the essential parts of a fatigue-testing machine: (1) a drive for applying repeated cycles of stress to the specimen, (2) a means of measuring the maximum and minimum stresses applied during a cycle, (3) a counter for indicating the number of cycles of stress applied to the specimen, and

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In this edition the articles on "Fatigue Testing" and on "Corrosion-Fatigue of Metals" have been combined. Several paragraphs in this article were written by R. L. Templin for the 1939 edition.

* In such instances, the number of cycles should be stated.

(4) a device for stopping the testing machine automatically when a specimen breaks.[1,2,3]

Figure 2 presents, in diagram, several types of fatigue-testing machines in common use. In all the machines shown, power is supplied by direct motor drive or by belt drive. When a specimen breaks in any of the machines shown here or when there is a marked increase in deflection or stretch, a latch is released, opening the motor circuit and stopping the machine. All the machines shown in Fig. ■ are fitted with revolution counters (not shown in every sketch) to indicate the number of cycles of stress.

Table I. Values of Endurance Limits for Different Numbers of Cycles of Reversed Bending Stresses for Five Alloys

Number of Cycles of Stress	Endurance Limit, 1000 psi: Cr-Mo Steel (heat treated)	Carbon Steel (0.47% C) (heat treated)	Carbon Steel (0.20% C) (as rolled)	Aluminum Alloy 24 S-T (age hardened)	Cast Iron, (tensile strength 31,600 psi)
10,000	108	71	45	45	21
100,000	90	58	39.5	39.5	16
500,000	76	■	34	34	13
1,000,000	73	44	33	31.5	12
5,000,000	70	44	32	27.5	12
10,000,000	70	44	32	25.5	12
50,000,000	...	44	..	21.5	12
200,000,000	...	44	..	20	12
Indefinitely large[a].	70	44	32	..	12

(a) S-N curve horizontal

Figure 2*a* shows a rotating-beam machine, the most widely used type of fatigue-testing machine, known as the "R. R. Moore type". The specimen *S* is held in tapered chucks that are rotated by belt drive or by a directly connected motor. Two symmetrically placed loads are applied —one at *A*, the other at *B*—by the known weights *W* hung from an equalizer bar. As the specimen rotates, the weights set up cycles of completely reversed bending stress, and over the length *m* there is a uniform bending moment equal to $Wa/2$. The machine is equipped with ball bearings to minimize torsional stress caused by friction of bearings. The stress is computed by the common flexure formula.

Figure 2*b* shows a rotating cantilever-beam fatigue machine, a widely used type similar in principal to the rotating-beam machine shown in Fig. 2*a*. The weight *W* sets up cycles of reversed bending moment Wl at the critical section of the specimen. Rotating-beam machines for small specimens have been operated at speeds as great as 12,000 cycles of reversed stress per minute.

The machines shown in Fig. 2*a* and 2*b* are very simple and, if reasonably free from vibration, set up accurately measured stresses in round specimens. However, rotating-beam machines cannot easily be used for tests under any stress cycle other than complete reversal of stress. Such machines cannot be used to study the effects of surface conditions on the material from which the specimen is prepared, because the reduced portion of the specimen is machined below the original surface. For other than round specimens, rotating-beam machines can be used only at very slow speeds, because of the vibrations set up as a noncircular specimen revolves at a high speed.

Figures 2*c* and 2*d* show a vibratory fatigue machine. The specimen *S* is held in the jaws *J*, which can be moved up and down by screw *Q* to set up cycles of stress with various ratios of minimum to maximum stress. For partially or wholly reversed stress, the ratio of minimum to maximum stress in a cycle is negative. The magnitude of deflection of the specimen controls the total range of stress in a cycle and is determined by the adjustment of the variable-throw crank and connecting-rod *C*.

When the jaws are in any position that causes the deflection of the specimen to be greater in one direction than in the other, the stress cycle on the lower side of the specimen is not the same as on the top, although the total range of stress is the same. Under these circumstances, failure generally starts at the side that has the higher tension and the stresses on that side are the ones considered. Failure may start on the compression side in specimens that have unsymmetrical cross sections and in specimens that are under repeated direct axial stress; probably such failures start as shearing failures.

To determine the setup to produce a certain cycle of stress, the specimen itself is used as a dynamometer. The amount of force is computed that will be required for the desired maximum stress; the connecting rod is swung to one side, as shown in Fig. 2*d*; the required load is applied by weights *W*; and the deflection at some point along the length of the specimen is measured by the micrometer dial gage *D*. Then sufficient load is applied in the opposite direction by weights and a lever, to produce the desired minimum stress; the dial gage is read; and the connecting rod is attached to the specimen. The throw of the crank is adjusted by trial in order to give the desired total range of stress, and the vertical position of the jaws *J* is adjusted by the screw *Q*, until the desired ratio of minimum to maximum stress is indicated by the readings of the dial gage *D*, as the machine is turned over by hand.

At high speeds, corrections for inertial forces may be necessary. For making such corrections, the extreme dial reading should be noted while the machine is running;

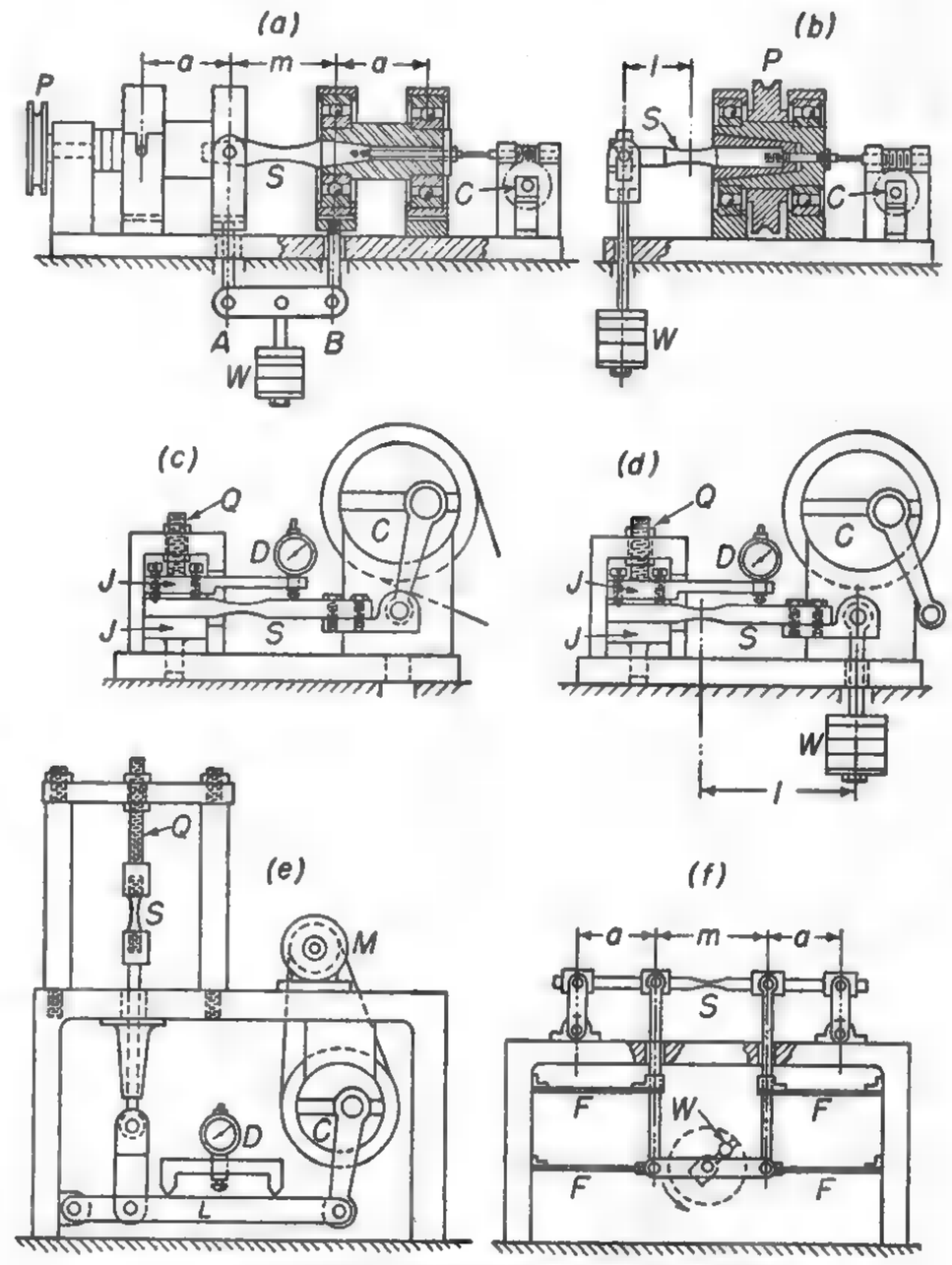

Fig. 2 Typical machines for fatigue testing

the plunger of the dial should be moved until it just touches the specimen at one extreme of its vibration. This reading is compared with the corresponding extreme reading when the machine is turned over by hand, and the change in force resulting from inertia can be estimated.

The vibratory type of fatigue-testing machine can be used for testing specimens with one surface in the condition that the surface of the metal will have in the machine or structural part. For example, a vibratory fatigue machine can be used to study the relative effect of rolled and polished surfaces on a structural part.

The plunger point of the dial gage *D* must be held out of contact with the specimen while the machine is running. In some machines, the force is measured by the deflection of a steel spring, attached to the specimen at one end and held in the jaws *J* at the other end.

Figure 2*e* shows a tension-compression (push-pull) fatigue-testing machine. The specimen *S* is pushed and pulled by means of the lever *L*, which is vibrated by the variable-throw crank and connecting-rod *C*. The maximum and minimum loads in a cycle of stress are measured by the deflection of the lever *L*, which is calibrated for deflection, and the deflection is indicated by the micrometer dial gage *D*. In some machines of this type, the load is measured by the deflection of an elastic ring attached directly to the specimen. The desired range of stress is obtained in a manner similar to that used for the vibratory machine shown in Fig. 2*c*, by adjusting the throw of the crank *C* and adjusting the position of the specimen by means of the screw *Q*. Under high speeds, inertial forces may be estimated, as for the machine shown in Fig. 2*c*.

Figure 2*f* shows a vibratory machine in which the vibrating force is supplied by means of the centrifugal force of a rotating weight *W*. If the weight *W*, the radius at which it rotates, and the speed of rotation are known, the force causing reverse flexure can be computed. As shown, the machine would set up cycles of completely reversed stress; but the steady force of a spring may be added to that of the centrifugal force of the rotating weight, and any desired ratio of minimum to maximum stress may be obtained during a cycle.

Alternating-current magnets have been used to set up cycles of repeated stress in a specimen. With magnetic excitation of cycles of stress, it is usually convenient, especially in large machines, to adjust the frequency of the exciting current, or the natural period of vibration of specimen and clamps, so that a condition of resonance is set up. During a fatigue test, the natural period of vibration will probably change slightly, and some system of control, usually electronic, is necessary in order to change frequency of current or to move weights to change the natural period of vibration so that resonance will be maintained up to the final stage of fracture of the specimen. A large fatigue-testing machine built by the Goodyear-Zeppelin Corp. is described in NACA Technical Note 637.

Fatigue-testing machines for cycles of repeated torsion, ordinarily operate by using a variable-throw crank and connecting-rod, in a manner similar to the crank–connecting-rod arrangement shown in Fig. 2*c*. Usually the maximum and minimum torsional moments that are set up are measured by the twist of a calibrated steel bar attached directly to one end of the specimen.

Test Specimens. Test specimens for fatigue tests may be classified in various ways. For this article it seems convenient to divide them into two classes: (1) specimens designed so as to avoid sudden changes of form known as "stress raisers", that is, sharp fillets, notches, keyways, screw threads, holes and the like, which set up high localized stresses; (2) specimens in which definite "stress raisers" are formed. The results of tests on specimens that have no stress raisers, give a measure of the fatigue strength of a metal under very favorable conditions; such data indicate the maximum fatigue strength that can be developed in a metal. The specimens with stress raisers are used (generally in connection with specimens that have none) to determine the sensitivity of a specimen to stress raisers. "Notch sensitivity" is the term frequently used. Sometimes stress raisers cannot be avoided in a machine part, and in some instances a metal of moderate strength (as shown by tests of "unnotched" specimens) but with a low notch sensitivity may serve better than a metal of higher "unnotched" fatigue strength and high sensitivity to stress raisers.

Figure 3 shows typical specimens for fatigue tests. Figure 3*a* shows the specimen commonly used for the rotating-beam machine of Fig. 2*a*. This is known as the "R. R. Moore type" of specimen. Figure 3*b* shows a notched specimen for use in the R. R. Moore type of machine in Fig. 2*a*.

Figure 3*c* shows an unnotched specimen for a rotating-cantilever fatigue machine like that in Fig. 2*b*, and Fig. 3*d* shows a notched specimen. Figure 3*e* shows a specimen for vibratory bending tests of sheet metal. Figure 3*f* shows a similar specimen in which a small hole acts as a stress raiser, for tests to determine notch sensitivity. Figure 3*g* shows one form of specimen for vibratory fatigue tests of plate metal or flats, and Fig. 3*h* shows another form; Fig. 3*i* shows a specimen for a vibratory bending test in which one surface (the top) is the as-rolled or the as-cast surface of the metal; Fig. 3*j* shows a specimen for direct tension-compression (push-pull) tests.

So that fatigue tests will develop the minimum variation in fatigue strength as a result of surface conditions, the surface of the specimen in the reduced section should be polished in a direction as nearly longitudinal (axial) as is feasible.[4]

The specimens shown in Fig. 3 are typical, but many other forms are in use. Wherever feasible, it is desirable to test actual parts. Many small parts, made in large quantities, can be tested easily in this way. Extensive

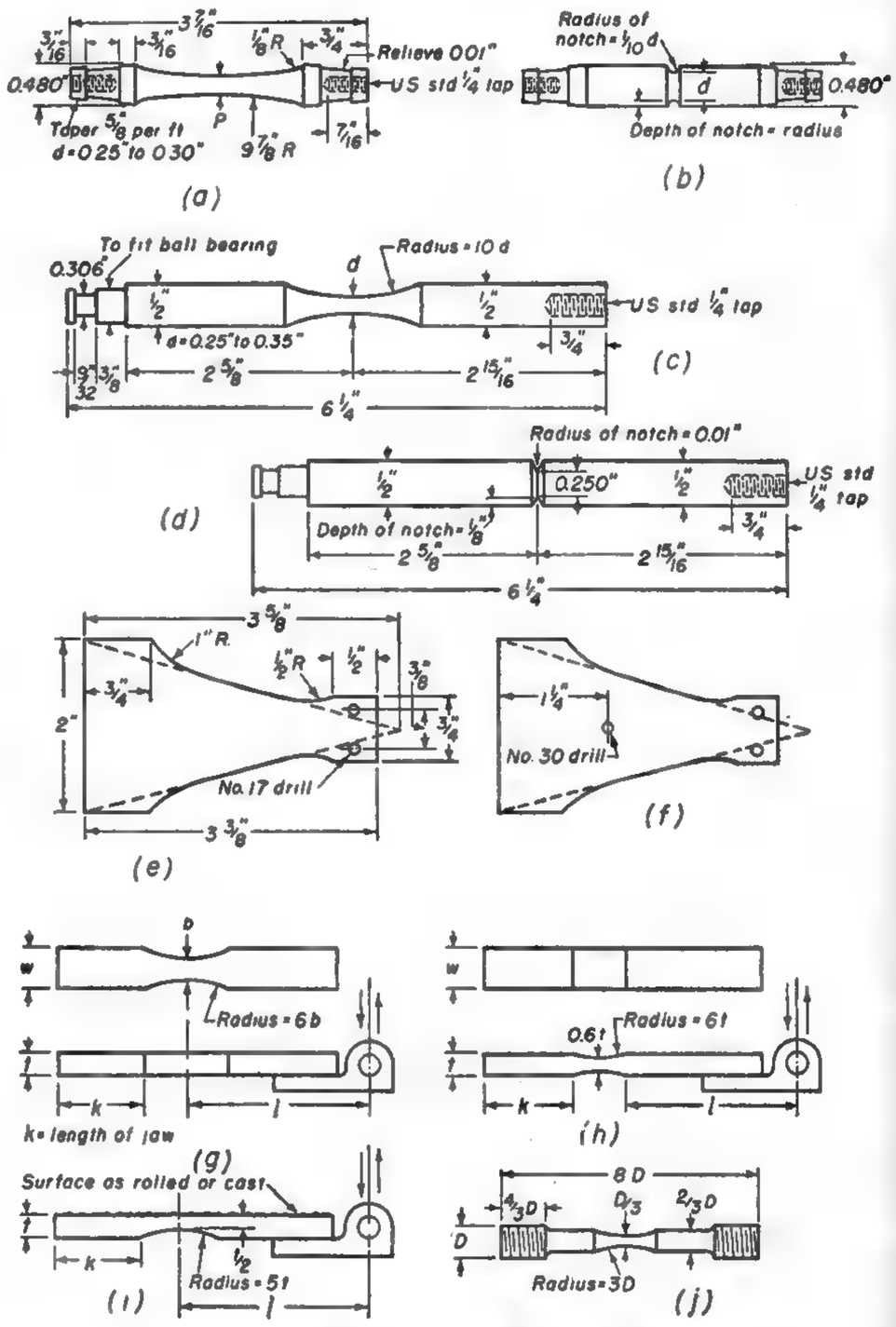

Fig. 3 Typical specimens for fatigue testing

The specimens shown in (*a*), (*b*), (*c*) and (*d*) are small specimens to be used in rotating-beam fatigue-testing machines (including rotating-cantilever beam machines). The specimen shown in (*a*) is used in the R. R. Moore type of rotating-beam fatigue-testing machine. The specimens shown in (*e*) and (*f*) are used for vibratory tests of sheet metal in the Krouse vibratory fatigue machine. The specimens shown in (*g*), (*h*) and (*i*) are for fatigue tests of plate, shape or bar material in vibratory machines. Since width and thickness will vary widely for different tests and for different testing machines, only general proportions are shown. Over-all length is not stated, because this will depend on the particular testing machine used, and on the size of stock available. The specimen in (*j*) shows general proportions for a tension-compression fatigue specimen. No standard sizes of fatigue specimen have been adopted; therefore, the specimens shown in this figure are to be considered suggestive forms rather than definite standards.

series of full-size fatigue tests have been made on springs, small shafts, bolts, and riveted, bolted and welded joints.

Number of Test Specimens Necessary for S-N Diagram. If the metal tested is of uniform quality throughout, a satisfactory S-N diagram *for one set of conditions* can usually be drawn from the test results for ▮ to 12 specimens. These specimens are tested under different maximum stresses, beginning with a maximum stress considerably higher than the estimated endurance limit for the maximum number of cycles to be used. Then each successive specimen is subjected to a stress smaller than that

applied to the previous specimen, until at least one specimen "runs out" without fracture at the maximum number of cycles required. The results for these tests are then plotted, and if the resulting S-N diagram shows only a small amount of "scatter" of results from an average line drawn to fit the plotted points, the test is regarded as complete. If there is considerable scatter, more specimens of the material in question are machined and tested. Then an S-N diagram is drawn to fit the test results.

If the maximum number of cycles prescribed is more than 100,000,000, more specimens will usually be required. If the purpose of the tests is not to determine the S-N diagram for the metal, but to determine the fatigue strength of machine or structural parts by tests of the parts themselves, the number of specimens required will depend on the purpose of the test. When tests are to be made under several different conditions, the number of specimens is, of course, increased. For example, it may be desired to study: (1) the fatigue strength of a metal under completely reversed bending, using unnotched and polished specimens, (2) the fatigue strength of notched specimens under reversed bending and (3) the fatigue strength of notched and of unnotched specimens under partly reversed bending, and under bending varying from zero to a maximum (one-way cycle of stress). For the tests of the unnotched specimens in reversed bending, from 6 to 12 specimens would be required. Tests of notched specimens (using only one type of notch) would increase the number to between 12 and 24. Tests of unnotched and of notched specimens under three different cycles of stress, would increase the total to between 36 and 72. If a thorough fatigue study of a metal were to be made, including all the above variables and others, such as specimens of several sizes, specimens with different notches or with holes or fillets, reversed and one-way fatigue tests in torsion, investigation of effects of surface condition, and corrosion-fatigue tests—if all these conditions were studied, the number of specimens required would be in the hundreds. The mechanical condition of the fatigue machine is important in obtaining consistent results.

Frequently, in tests of railroad rails and of structural parts, it is desired to know the resistance to a relatively few cycles of stress, for example, 100,000 cycles. In such instances it is not necessary to continue tests long enough to determine the endurance limit for indefinitely long life.[2] Tests that require up to 1,000,000 cycles of stress would give an allowance for length of endurance beyond the probable wide scatter of length of endurance for life under a given cycle of repeated stress. Under such circumstances, it is usually convenient to plot results on log-log paper since, above the endurance limit for indefinitely long life, the S-N diagram, plotted to log-log co-ordinates, is nearly a straight line ordinarily, and three or four points along this straight-line part of the S-N diagram locate the curve fairly accurately, even though the points do not indicate the stress at which this sloped line will change rather abruptly to a horizontal line.

Notes on the Use of Data From Fatigue Tests. When data concerning endurance limit are used, the number of cycles of stress employed as a basis for determining this value should be considered and stated in any report of results. For steel and iron, an endurance limit based on 10,000,000 cycles of stress is common. For nonferrous alloys, this number is usually higher, and for some of the light alloys 500,000,000 cycles is sometimes specified.

For many applications where repeated stress may occur, it is not necessary to determine the endurance limit for indefinitely long life. Instead it is more important to know the probable fatigue life at definite stresses above the endurance limit for indefinitely long life. However, in estimating the probable fatigue life of a part, it must be remembered that a slight decrease in stress causes a large increase in fatigue life, as measured by the number of cycles of stress for fracture. An examination of the S-N diagrams in Fig. 1, especially the shaded areas, will show this fact plainly. A "factor of safety" of two, for instance, on the basis of stress for a given fatigue life, would correspond to a "factor of uncertainty" of 10 to 20 on the basis of probable life for a given stress.[5] For example, if the estimated number of cycles of stress in a satisfactory life of a bridge member is 25,000, it would be unnecessary to determine the stress for an indefinitely large number of cycles; but it would be wise to determine the stress on the basis of a fatigue life of 250,000 cycles. As in most problems of design, the engineer must use sound judgment in applying the results of fatigue tests.

Because of the time and expense involved in making fatigue tests, various attempts have been made to devise accelerated fatigue tests; however, such tests frequently give misleading results. Regular long-time fatigue tests still seem necessary. No precise correlation has been found between fatigue strength and any other mechanical property; but probably yield strength, tensile strength and some type of ductility all have some effect on fatigue strength. Perhaps the closest relationship for the common structural metals is that between endurance limit and tensile strength.[1,4] The ratio between these two properties is called the *endurance ratio* and is sometimes reported.

The structure of a metal appears to have a definite effect on the resistance to repeated stress, but so far it has not been possible to express this effect in precise quantitative terms. Although relatively pure metals usually have lower endurance limits and lower tensile strength than alloys, their endurance *ratios* are frequently higher, perhaps because of greater uniformity in structure. The endurance ratio is higher also for annealed metal than for cold worked or for quenched metal. The greater ductility of annealed metal apparently aids in relieving any stress concentrations that may be present, possibly because annealed metal has very little residual strain, if any. Cold working by rolling, drawing, shot peening or other means, increases the yield strength of a metal considerably,[3,5] increases the tensile strength to a lower degree, and increases the endurance limit to a still lower degree. It is therefore apparent that the endurance ratio will vary with the amount of cold work. Superficial cold rolling or shot peening may be used to set up compressive stresses near the surface, which strengthen the metal against fracture by subsequent tensile stresses applied in service. Apparently there is an optimum degree of surface working above which the fatigue strength is decreased.

Since fatigue failure is far more likely to occur in a region of tensile stress than in a region of compressive stress, any residual tensile strain caused during heat treatment may seriously harm the fatigue strength. Under such circumstances, stress-relieving may be beneficial.

Effect of Range of Stress.[1,4,6] Most fatigue tests use cycles of completely reversed stress. From many results of tests made under cycles of tensile (or compressive) stress repeated but not reversed (one-way stress), and under cycles of tensile-compressive stress partially reversed, the following empirical formula has been found fairly reliable:[1,4]

$$S_{max} = S_e \left(\frac{3}{2 - r}\right),$$

in which r denotes the ratio of minimum stress to maximum stress during a cycle (r is negative for completely or partially reversed stress); S_{max} denotes the endurance limit for any given number of cycles of stress; and S_e denotes the endurance limit for the same number of cycles of completely reversed stress.* The direction (tensile or compressive) of maximum stress should be stated.*

For example, if the cycle of stress to which a part is repeatedly subjected ranges from a tensile stress to a compressive stress half as great ($r = -\frac{1}{2}$), and if the fatigue

* For aluminum alloys, the formula

$$S_{max} = S_e \left(\frac{2.25}{1.25 - r}\right)$$

agrees more closely with the results of fatigue tests.

* In another system of nomenclature, sometimes used, any given cycle of stress is considered to be made up of two components: (1) a constant mean stress, which is the algebraic average of maximum and minimum stress for a cycle (for example, this mean stress is zero for a cycle of completely reversed stress); and (2) a completely reversed stress equal to $\pm$ (maximum stress during a cycle − mean stress). Some recent writers define the endurance limit as the reversed stress component only, instead of defining it as the maximum stress during the cycle, as is done in this article. The two systems of nomenclature can be readily translated; see reference 1 (second item) and reference 6.

strength of the metal under completely reversed stress is 40,000 psi, then

$$S_{max} = 40{,}000 \left(\frac{3}{2-(-\frac{1}{2})}\right) = 40{,}000 \left(\frac{3}{2.5}\right) = 48{,}000 \text{ psi}$$

Under a cycle of stress varying from minimum tensile stress to maximum tensile stress four times as great as the minimum ($r = +\frac{1}{4}$).

$$S_{max} = 40{,}000 \left(\frac{3}{2-\frac{1}{4}}\right) = 40{,}000 \left(\frac{3}{1.75}\right) = 68{,}600 \text{ psi}$$

However, if this stress is greater than the yield strength of the metal, this result could not be used in design, because failure by yielding would probably take place before the stress of 68,600 psi was developed.

For various cycles of shearing stress, an empirical formula has also been developed.

$$S'_{max} = S'_e \left(\frac{2}{1-r}\right)$$

The symbols are similar to those given in the preceding formula. S'_{max} denotes the maximum *shearing stress* during a cycle (and also the maximum tensile stress under torsion). S'_e denotes the endurance limit for cycles of shearing stress completely reversed, and r denotes the algebraic ratio of minimum shearing stress to maximum.

Effect of Size of Specimen (or Part) on Fatigue Strength.[7] Tests at the University of Illinois showed endurance limits for steel specimens 1 in. in diam, which were about 20% lower than endurance limits for specimens of the same steel only ¼ in. in diam. Tests were made on 0.20% C steel, as rolled; on 0.35% C steel, as rolled; on 0.35% C steel, annealed; and on heat treated chromium-molybdenum steel. Tests at the Timken Laboratories showed very low endurance limits for steel specimens 6 or 7 in. in diam, but it is not certain whether these low values were caused by the size of the specimen or by the presence of defects in the steel. Fairly large defects are more likely to be present near a critical section in a large bar of steel than in a small bar.

Fatigue Tests at Low and Elevated Temperatures. A few test results have been reported for steels subjected to repeated stresses at low temperatures and, in general, these tests indicate that metals have higher endurance limits at temperatures below normal room temperature.

A considerably larger number of fatigue tests have been made at elevated temperatures. Earlier results were on carbon steels and stainless steels at temperatures as high as 1200 F, using a spring-loaded cantilever type of test machine. More recently, in studies of heat-resisting alloys for turbosuperchargers and gas turbine service, tests have been made at temperatures as high as 1500 F, using both fixed and rotating specimens of the cantilever type that gives completely reversed bending, in direct-stress test machines in which the stress was varied plus and minus from a mean tensile stress.

For plain carbon steel at temperatures above 1000 F, and for 18 Cr–8 Ni steel at 1200 F, the fatigue strength is higher than the stress that produces an appreciable rate of creep, and it is indicated that creep strength will be the controlling factor in design.

For the gas turbine alloys studied at 1200 F, the forged alloys had higher fatigue strength than the cast alloys, but in tests at 1500 F, the cast alloys surpassed the forged alloys in fatigue strength. Both at 1200, 1350 and 1500 F, the stronger alloys that were studied showed fatigue strength in excess of the steady tension stresses that will produce rupture in 1000 hr.

Effect of Overloading and Underloading on Fatigue Strength.[1,2,4] Occasional overloading of a specimen or of a structural or machine part may actually weaken the metal, if the overloading is repeated enough times. The application of repeated stresses above the endurance limit of the virgin metal does not always lower the endurance limit. The effect depends on the number of cycles applied in this overload stress. H. J. French and later investigators have recorded the existence of a "damage line", which may be defined as a line in the S-N diagram, separating the region containing conditions of stress and number of cycles that cause a lowering of the endurance limit from the region containing conditions under which no damage is done. Figure 4 shows an S-N diagram for which such a damage line has been determined by fatigue tests to fracture of many specimens that were subjected to various combinations of magnitude of stress and number of cycles of stress, applied before making the final test to destruction.

Understressing consists in subjecting a metal to a safe range of stress for many cycles of stress, before the metal is subjected to a fatigue test to fracture. This treatment sometimes increases the endurance limit of the metal,[1,4] in some instances as much as 25%.

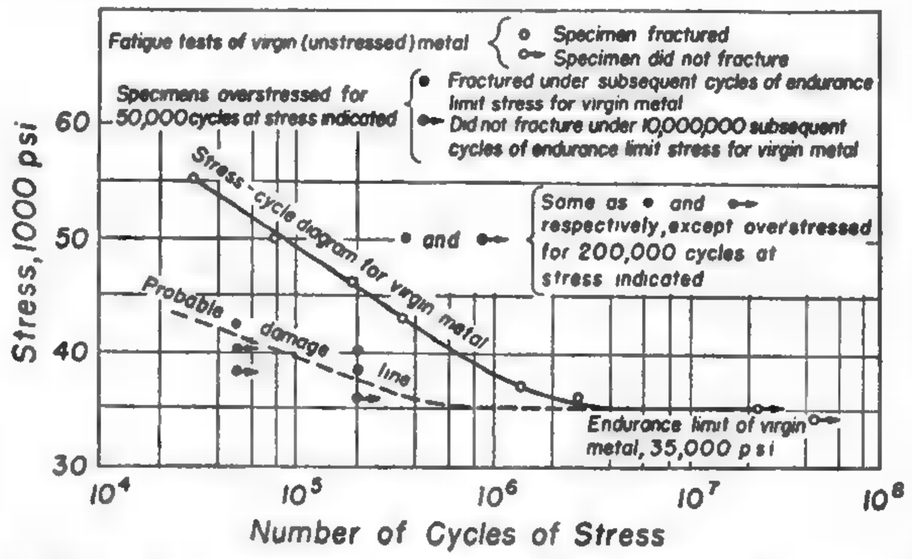

Fig. 4 Determination of "damage line" for a metal subjected to repeated stress.

The damage line is drawn *below* the results for overstressed specimens that failed under 10,000,000 subsequent cycles of stress equal to the endurance limit for virgin metal (35,000 psi), and is drawn *above* the results for overstressed specimens that did not fail. In actual determination of a damage line, many more overstressed specimens would be tested than the six specimens shown in this figure.

Effect of Corrosion on Fatigue Strength.[3,9] *Stressless Corrosion.* Many liquids and gases have a corrosive effect on most metals. The corrosion takes the form of a film, often only a few molecules thick yet able, in some instances, to give the metal beneath it a high degree of protection against further corrosion; also, the film on the metal usually has the power of self-healing, if cracked. Thicker films, which are characteristic of some metals under the action of a mild corrosive medium, usually lack this power of self-healing, and offer far less protection against the spread of corrosion, especially if the metal is being subjected to repeated stress, causing repeated strain on the film. Even when films do not stop the progress of corrosion, they influence the manner in which it proceeds, tending to localize attack at regions under cracks caused in the film by strain. This localized attack tends to produce pits in the metal, and to lower the resistance of the metal to stress, because of the intensification of stress that occurs at any notch or small hole in the metal. Oxide films are the most common on corroded metal, but phosphate and silicate films are sometimes found.

If an unstressed metal is exposed to corrosive agents or if, after being stressed, it is subjected to corrosive agents while the stress remains unchanged, the metal is said to be subjected to "static-stress corrosion", with a slight reduction in resistance to further damage under steady load, and a more serious reduction in resistance to cycles of repeated load. R. R. Moore's experiments on SAE 1045 steel that was corroded by a salt spray, without applied stress, showed an endurance limit 22% lower than the endurance limit of the same steel uncorroded. His experiments on duraluminum indicated approximately 35% reduction in endurance limit after static-stress corrosion.

Simultaneous Corrosion and Repeated Stress. *Corrosion Fatigue.* If a metal is subjected to a corrosive agent and at the same time is subjected to cycles of repeated stress, the protective film may be broken repeatedly. In steel, corrosion spreads through these cracks and forms relatively deep pits that act as stress raisers and greatly

reduce the fatigue strength of the metal. Almost all the common metals of construction are subjected to this action known as "corrosion fatigue".

In 1925 D. J. McAdam, Jr. began an extensive experimental study of corrosion fatigue. Even under pure water, the endurance limit may be reduced far below the limit recorded in air. In fact, no definite limit for endurance limit has been found for indefinitely long life under corrosion fatigue. In reporting the results in corrosion-fatigue tests, it is important to state the limiting number of cycles used in the test, and also the frequency of cycles of stress. In noncorrosion-fatigue tests, within wide limits, the frequency of cycles of stress is of very minor importance. In corrosion-fatigue tests under a low frequency of cycles of stress a longer time elapses for the corrosive action to accomplish its destructive work than in corrosion-fatigue tests run at high frequencies of cycles of stress; and the endurance, measured by number of cycles of stress, is consequently lower. Except in stainless steels, the endurance limit of alloy steels under corrosion fatigue (based on 10,000,000 to 100,000,000 cycles of stress) was found to be little, if any, above the corrosion-fatigue endurance limit for ordinary low-carbon and medium-carbon steels. The stainless steels were found to resist corrosion fatigue distinctly better than either plain carbon steels or other heat treated alloy steels.

In nonferrous metals, the effect of corrosion fatigue is so varied that no general statement can be made.

McAdam used two terms to express the amount of damage done by corrosion fatigue: "total damage", meaning the percentage reduction from the endurance limit in air, and "net damage", meaning the percentage reduction from the endurance limit of metal subjected to some definite period of "stressless" corrosion to the endurance limit of specimens that have been subjected to some definite routine of corrosion fatigue. From McAdam's data the following tentative relation is given between stress range and average rate of net damage: $R = CS^n$. In this equation, R denotes the rate of net damage in percentage per day, S denotes the range of stress in pounds per square inch during a cycle, and C and n are experimental constants. C is probably approximately proportional to the frequency for low frequencies, and nearly independent of frequency for high frequencies. Values of n vary from 2.6 to 5.7, as determined by Gough from McAdam's data.[9]

Interpretation of Fatigue Results. Several engineers have pointed out that the results of ordinary fatigue tests for small polished specimens, cannot be used directly, without modification, as a basis for the design of structural and machine parts that must be subjected to repeated stress.[10] This criticism is justifiable and where large numbers of small parts are produced, it is highly desirable to perform fatigue tests on sample parts rather than on conventional fatigue specimens. These tests should be made, if possible, under cycles of stress of the kind that the parts are expected to withstand in service (completely reversed stress, partly reversed stress, or stress repeated but not reversed, tension-compression load, bending load, twisting load, or a combination of these). The determination of the number and type of cycles of stress that a part will be required to withstand in service cannot ordinarily be determined in the laboratory; therefore, extensive field tests are frequently desirable. Often these field tests are conducted to determine exactly what stresses a part will be expected to withstand, and about how many of them must be withstood in a satisfactory period of service. Such field studies frequently involve the use of recording strain-measuring apparatus. The results should be considered approximations that may serve as guides, not statements involving a high degree of precision. In determining the magnitude of the "factor of safety" that must be used in designing a structural or machine part, usually the greatest problem is uncertainty concerning the corrosive mediums and the stresses that the part will have to withstand under reasonable service.

In laboratory fatigue tests on actual structural and machine parts, if a series of loads is used, of various magnitudes, the range of stress during a cycle may well show a ratio of minimum to maximum stress like that which will occur when the part is in service. Such fatigue tests of actual machine and structural parts are becoming quite common for springs, and are used, though somewhat less, for small crankshafts, crankpins, axles, lead sheathing for electrical cables, railroad rails, wire rope, welded joints, bolts and nuts, and many automobile and airplane parts. A considerable number of special-purpose fatigue machines are in use today, varying from machines to test a large number of small springs at once, to machines that have a maximum capacity of 50,000 to 200,000 lb, used for tests of wire rope, large shafts, axles, welded joints and the like.

For examining large parts and special pieces, the cost of preparing many specimens, and of conducting many tests, is prohibitive. Instead, fatigue tests of small specimens may be used as a basis for design, not only by considering their immediate results, but also (after further tests or relative estimates) by making allowance for the effects of size (and possibly of shape), of surface condition, of stress raisers (such as keyways, fillets, holes, grooves, notches, screw threads), of corrosive conditions, and of the ratio of minimum stress to maximum stress during a cycle to be expected in service. The details of the procedures used in fabrication will affect the fatigue properties of structural components.

Frequently the stress-concentration factor for a notched specimen or for a machine part can be determined by photoelastic tests of models or by mathematical analysis. The actual *strength-reduction factor,* because of the given notch or other stress raiser, may be determined by test, as follows: Make a series of fatigue tests on unnotched specimens with critical section the same in size and shape as the critical section of the machine or structural part being studied—or as nearly that size and shape as is feasible. Draw the S-N diagram for these tests. Next make a series of tests on specimens with the critical section the same except for a notch, or other stress raiser, and draw the S-N diagram. Then, for any desired number of cycles of stress, determine from the S-N diagram the ratio of endurance limit for unnotched specimens to endurance limit for the specimens with the stress raiser. This ratio is the *strength-reduction ratio* for the given size and shape of notch in the metal used, and for a given size of critical section.

The available data indicate that the actual *strength-reduction ratio* is less than the theoretical stress-concentration factor. This is caused, in part at least, by localized yielding at points of high stress concentration and the resultant lowering of the "high peaks" of stress there. In high-strength alloy steels, the actual reduction in strength of parts because of stress raisers, sometimes approximates the reduction indicated by the theoretical stress-concentration factor. For lower-strength steel and for cast iron the strength-reduction factor is distinctly less than the theoretical stress-concentration factor. Fatigue tests of notched specimens and of specimens with fillets, holes, or screw threads, are desirable, as well as tests of polished specimens without stress raisers. From such tests, some estimate can be made of the actual strength-reduction factor to be used.

To date (1947) the highest strength-reduction ratio that has been found in fatigue tests at the University of Illinois, is 3.85 at the root of U. S. Standard screw threads in bolts made of heat treated alloy steel. For similar bolts made of structural steel the strength-reduction ratio was 2.84.

In fillets and rounded notches, strength-reduction ratios as high as 2.5 have been observed, although strength-reduction ratios from 1.5 to 2.0 are more common. For cast iron, the strength-reduction ratios observed are lower than for steel, ranging from about 1.1 for soft gray cast iron, to about 1.6 for certain high-strength cast irons. This does not mean that gray cast iron is stronger than alloy cast iron, or that alloy cast iron is stronger than alloy steel. It does mean that the gain in strength to be expected from the use of alloy steel in parts with notches, grooves or fillets is less than would be indicated by comparative tests of unnotched fatigue specimens of alloy steel and of cast iron.

The designer must consider the effect of size on the

fatigue strength of the part that is being designed. If the diameter or thickness is more than ¼ in., 15 to 25% reduction in fatigue strength should be allowed, below the strength shown by tests of ¼-in. specimens with stress raisers similar to those in the part. For pieces with thickness or diameter greater than 2 in., adequate data are lacking, concerning the effect of size, although tests of specimens up to 2 in. in diam show a negligible increase in size effect above ¾ in. in diam.

The designer should consider probable surface conditions of any part that is being designed to resist repeated stress. A rough surface may reduce fatigue strength by as much as 25%, while cold rolling or shot peening, if performed properly, may *increase* the fatigue strength appreciably, in some instances as much as 25%. The designer should give careful attention to the possibilities of corrosion and corrosion fatigue, and should attempt to minimize damage by protective coatings or otherwise. If such protection is not possible, and corrosive agents are to be present while the part is undergoing repeated stress, a large reduction should be allowed—perhaps as high as 75%—in the fatigue strength of the part.

Of course, the preceding paragraphs do not tell the designer what actual stress conditions his machine part will be expected to withstand in service. That problem cannot be solved generally in the laboratory. It requires experience with other parts in similar service and sometimes requires field tests. However, if the applied stress to be withstood in service can be estimated with a fair degree of accuracy, the above considerations of size, stress concentration, strength reduction, surface conditions, range of stress in service, and corrosion, should enable the designer to use the data of laboratory fatigue tests of small polished specimens with safety and economy.

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Bend Tests for Ductile Metals

By F. S. Mapes*

THE bend test is one of the simplest and least expensive of the mechanical tests used in evaluating the properties of metals. Before modern equipment and precise measurements were demanded, the bend test served as a guide to the ductility of metals and was particularly useful in control or acceptance testing where involved interpretations were unnecessary. For such purposes the test can be made without equipment for indicating the load and without close attention to details of procedure. Probably these factors alone justify retention of the bend test among more comprehensive and complex modern tests.

A rather large variety of bend test specimens and procedures have been used, as dictated by precedent, available testing equipment and the materials or products under consideration. Few standard procedures have been incorporated into specifications of Federal agencies and the present standards of the American Society for Testing Materials.

Frequently it has been stipulated that the bend test specimen be wrapped around a pin or mandrel of given diameter, but experience shows this to be impractical if not impossible, without the use of specially designed fixtures. Still other procedures require that the bend occur between rigid supports and under a loading nose. The more modern conception tends to favor the so-called "free bend" rather than a restricted or constricted bend, but not in testing full-section pipe, tubing and the like.

Many existing specifications require a 90, 120 or 180-deg bend of a prescribed specimen around a mandrel or pin of given diameter. The test specimens are usually rectangular in cross section, with rounded edges. When a press or compression-testing machine is used, a suitable means of support and loading, as shown in Fig. 1, should be provided. There are many modifications or variations in test procedure that will produce essentially the same bending result. The types of bend-testing fixtures can be used for pipe, tubing, rods or bars.

In the free-bend test, as prescribed by the ASTM method, the object is to make preliminary bends outside the actual test section and without introducing local stresses or strains in the section that eventually will have the greatest bending. Such initial bends, located at approximately third points along the specimen, should be equidistant from the center test section. These bends may be made by clamping the specimen in the jaws of a vise and bending the ends by hammering; or by setting the specimen on supports, as in Fig. 1, and loading at the third points. Where volume repetitive testing of this type is involved, an arrangement such as that shown in Fig. 2 is useful. This arrangement has the added advantage of

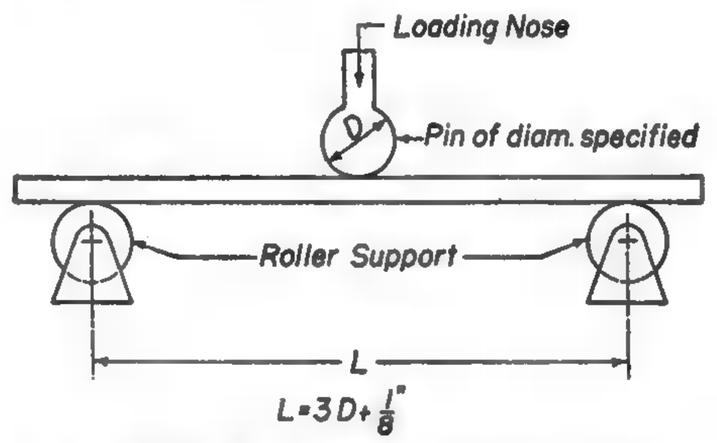

Fig. 1 Typical test fixture for restricted bend

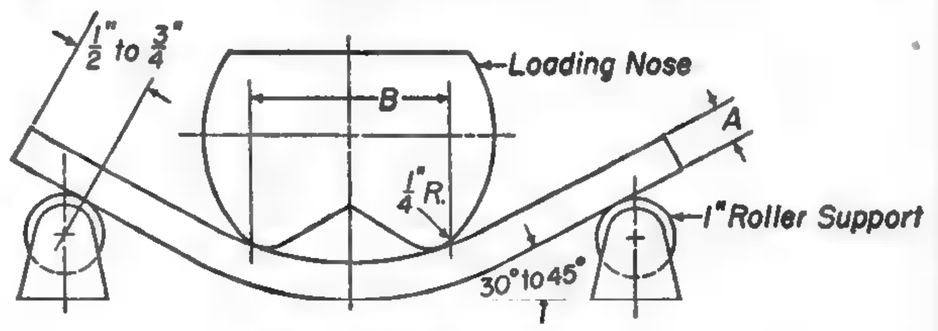

Fig. 2 Preliminary bend setup

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Prepared for the Subcommittee on Mechanical Testing.

producing the same angle of bend at each third point. The initial bend angles are not critical and may vary from 5 to 30 deg, depending on the material under test. It is recommended that the angles at each third point be as nearly alike as possible, to facilitate testing.

To complete the test, the specimen is tested as a strut by applying compression at the ends, in either a vise, a

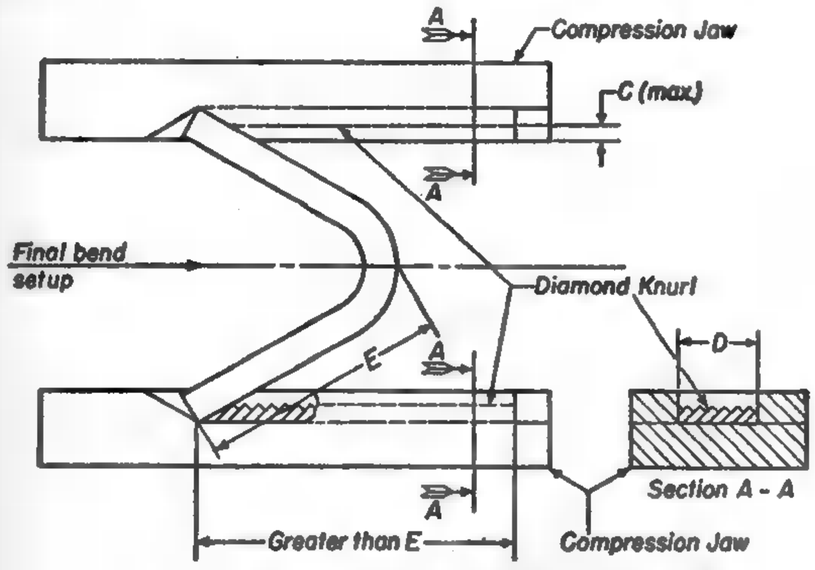

Fig. 3 Test fixture for completing free bend

press or a testing machine. Again, testing may be facilitated and the danger from slipping may be overcome by use of a fixture such as the one shown in Fig. 3.

In testing certain nonferrous alloys, procedures have been followed that are essentially the same as those already mentioned. When practicable, materials or products are tested in full section and restricted bend methods are ordinarily used. Figure 4 shows a method whereby test specimens are bent around dies of various radii to determine conformance to specification requirements or to find the minimum diameter of bend that the material will take without fracture. When testing round specimens, the dies are grooved to a depth equal to about one third the diameter of the specimen with a radius to fit.

As far as the restricted bend tests are concerned, the end point of the test is reached when, as required by material specification, the required angle of bend has been accomplished without rupture of the outer fibers, or when the bend has been sufficient to produce the required elongation in the outer fibers.

In the free-bend test, the evaluation is the measurement of elongation in the outer fibers at the time when rupture occurs or when the specimen has been flattened without failure.

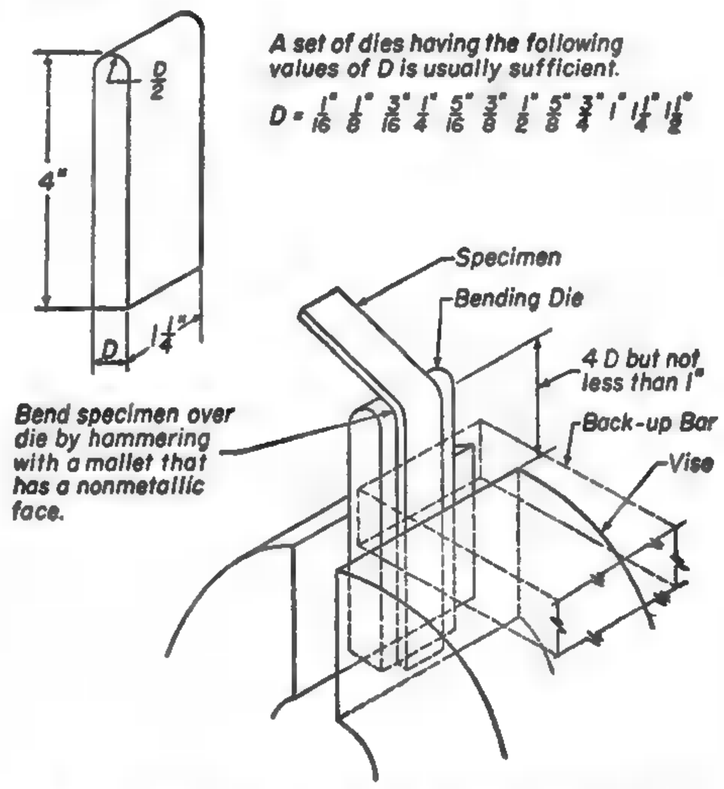

Fig. 4 Sketch showing die and specimen in vise

In bend tests, the speed at which bends are produced may or may not be important, depending on the material.

When elongation is to be measured, the gage length is laid out at the section of maximum bending and in the center third of the width of the specimen. A gage length of 0.3 in. is recommended for specimens ¼ to ½ in. thick, and a gage length of 1 in. for specimens more than ½ in. thick. Measurements of elongation are not generally required for specimens less than ¼ in. thick. Following completion of the bend, the final gage length is measured with a flexible scale or equivalent, or the radius at the outside of the bend may be measured and the elongation computed.

Bend Tests for Hard and Brittle Metals

By T. H. Gray*

THE transverse bend test is used for the evaluation of strength and toughness of hard and brittle metals such as hardened tool steels, sintered carbides and cast iron. Reliable tension tests become increasingly difficult to make as the hardness of steel increases to more than 600 Bhn, whereas the bend test involves fewer difficulties and is perhaps more significant at high hardness than at low. The utility of the bend test is increased further by the simplicity of the test specimen, which normally consists of a plain rectangular beam; by the ease of testing, since the test requires only that the beam be supported near the ends and loaded at the center; and by the rapidity of obtaining results, since the breaking load serves as a measure of strength. The amount of flexure of the beam under load may be utilized as a measure of ductility.

When the bend test is applied to materials of low ductility, such as cast iron, hardened tool steel, sintered carbides and even ceramics, there is naturally more scatter in the results than when ductile metals are tested. As much as 25% variation in strength has been observed between duplicate bend tests on hardened tool steel. For this reason it is desirable to make a sufficient number of bend tests on each lot or treatment to establish a mean value and the range of variation from the mean.

In practice, the bend test consists in supporting at two places a rectangular, square or round beam specimen of the material to be tested, and applying a concentrated load to the center of the beam until fracture occurs. The rate of loading is unimportant in brittle materials as long as it remains lower than the speed of shock loading. The breaking load, sometimes referred to as the "flexure" or "transverse breaking load", is often expressed in pounds, but a more satisfactory manner of presenting the strength of the material is to convert the load in pounds to a stress value. In this way corrections are made automatically for specimens that vary somewhat in size.

The highest tensional stress in the beam section determines rupture and is given by:

$$S = \frac{3\ PL}{2\ bh^2} \text{ for a rectangular beam,}$$

$$S = \frac{2.546\ PL}{h^3} \text{ for a round beam}$$

where:

P = concentrated load, in pounds
L = span, in inches
h = beam thickness, in inches
b = beam width, in inches

The point of highest stress is located at the intersection

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Prepared for the Subcommittee on Mechanical Testing

of the plane of load application, section *a-a* in Fig. 1*a*, with the bottom surface of the beam.

When rupture occurs within the elastic range of the material, *S* will represent the stress at the outer fiber (Fig. 1*b*). On the other hand, if the material possesses ductility sufficient to enable rupture to occur after plastic yielding (Fig. 1*c*) the actual stress is no longer *S* but some lower value, since the flexure formula is based on a stress distribution that increases linearly from the neutral axis to the outer fiber. For this and other reasons, rupture strength in bending, calculated as *S*, is often considerably higher than that in simple tension. Because of this, there is no established constant relationship between the two, although the bend test will usually rate specimens in the correct order with respect to tensile strength on materials of negligible ductility.

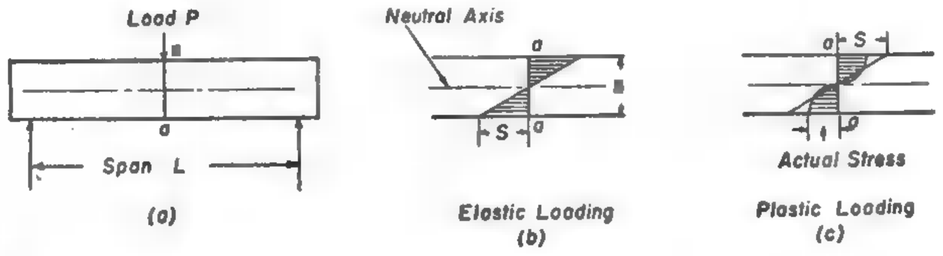

Fig. 1 Stress distribution in a beam under a concentrated bending load

The stress calculated by the preceding equations is called "bending stress" in this article, and the stress when rupture occurs is called "bending strength", obviously a more descriptive phrase for the textbook equivalent, "modulus of rupture". Though values of unit stress are reported, the need for specifying the dimensions of the specimen is not circumvented, since strength is influenced somewhat by specimen size, shape and span.

Bend Tests of Cast Iron. The transverse bend test functions satisfactorily as an acceptance test for cast irons, for which purpose it has been standardized by the ASTM.[1] For cast irons, both the loads and deflections are usually measured and the maximum load in pounds and the maximum deflection in inches are determined.

Square and rectangular bars are used, but both the ASTM and the British Engineering Standards specifications now include cylindrical transverse test specimens of several sizes and lengths. In the United States, three sizes of transverse test specimens are specified by the ASTM, as shown in the article on preparation of test specimens, page 86. In general, aside from the dimensions of specimens, lengths of span and maximum rates of loading, the ASTM leaves to the individual tester the determination of the type of supports, the rate of loading (below the maximum), the method of loading, measurement of deflection, and design of loading fixtures.

Table I. Comparison of Bending Strength and Tensile Strength of Cast Irons

Cast Iron	Bending Strength, psi	Tensile Strength, psi	Ratio of Bending Strength to Tensile Strength
1	79,200	38,800	2.04
2	100,900	54,200	1.87
3	82,700	43,000	1.93
4	87,200	45,000	1.94

Cylinders or knife edges are the recommended types of beam supports; the knife edges have a definite radius. The load is applied to the specimen at the center of the span, through a ball or cylindrical surface that usually has the same radius as the supports. The maximum rates of loading specified by the ASTM are such as to produce rupture in not less than 15 sec for the 0.875-in. diam bar, 20 sec for the 1.20-in. diam bar, and 40 sec for the 2-in. diam bar. These rates may be exceeded somewhat without affecting the results appreciably.

Other precautions should be taken in the performance of the standardized bend tests on cast irons, particularly in the preparation of the specimens. The general practice has been to cast the test bars to size, but it has been recommended[2,3] that they be cast oversize and machined to final size, for several reasons. Machining removes the surface irregularities (which act as stress raisers) inherent in the casting of iron. The presence of blowholes, pinholes and cracks is more clearly revealed. An additional advantage is the elimination of elliptical sections that occur frequently in the casting of cylinders.

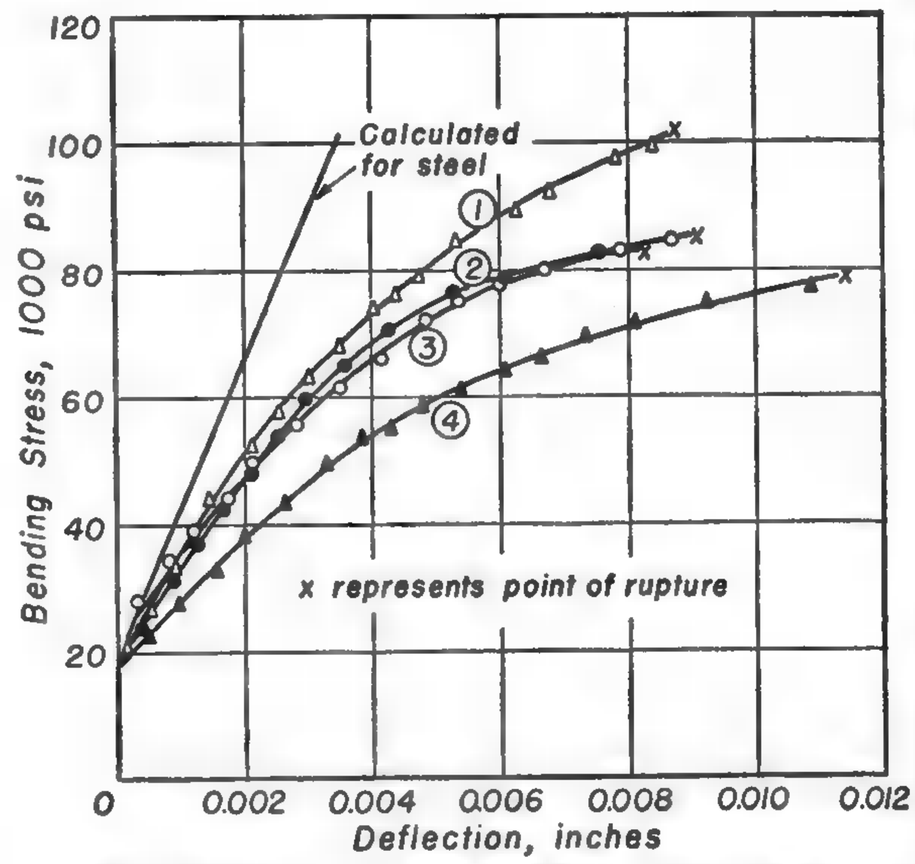

Fig. 2 Bending stress versus deflection of cast irons

The measured cross section of the specimen should be used rather than the nominal size, in determining the strength of cast irons, because the use of the nominal cross section introduces errors in the comparative values of strength. For this reason, as well as for purposes of standardization and for comparisons of test results, it is highly advantageous to use standard specimens and of as few sizes as possible.

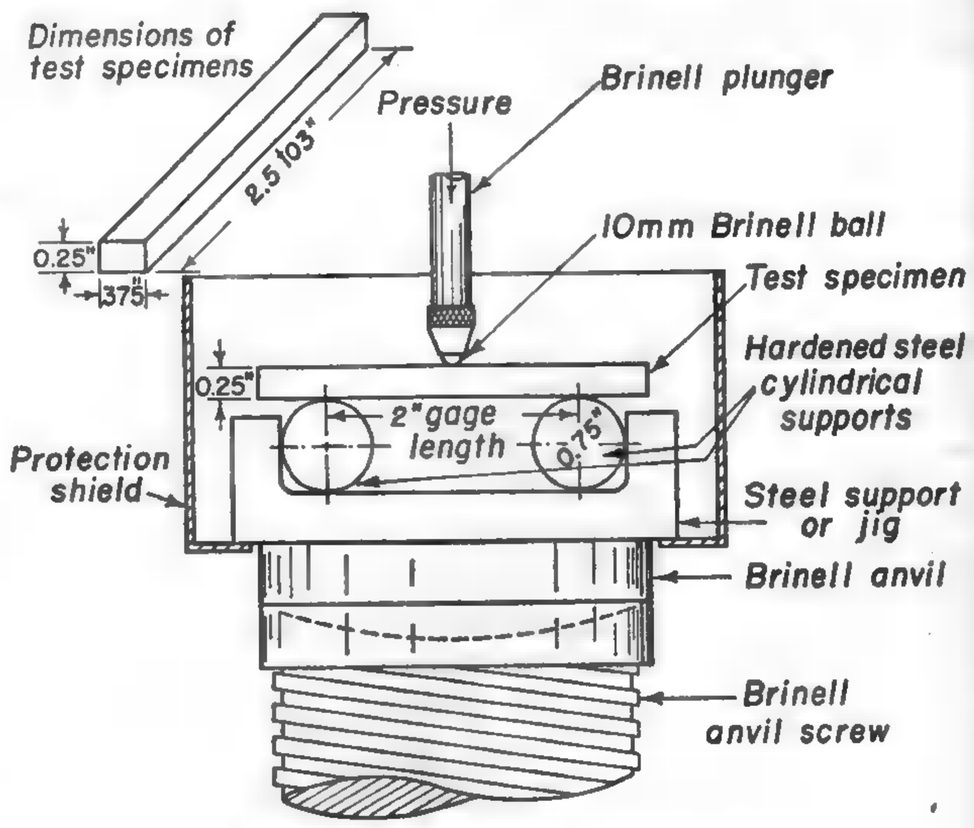

Fig. 3 Fixture for bend tests of hardened steels

It is not possible to limit the number of sizes of test specimen to one, since it is desirable that the size of the specimen should conform closely to the thickness of the actual casting because of the effect of different rates of cooling on the strength of cast irons.

To demonstrate the effects of such variables as heat treatment, microstructure and composition, it is often advantageous to use much smaller specimens than are specified by ASTM for bend tests on cast irons. Smaller specimens are preferably square or rectangular in cross section to facilitate testing. Satisfactory test results, shown in Fig.

2, have been obtained on cast-iron bars, 0.5 in. sq and 2.5 in. long with a 2-in. span. The load was applied to the bar through a 10-mm Brinell ball, by means of a Brinell tester. The values in Table I illustrate that these bend tests rate the cast irons in the same order of strength as tension tests, provided sufficient care is taken in the preparation of specimens and in performance of the tests.

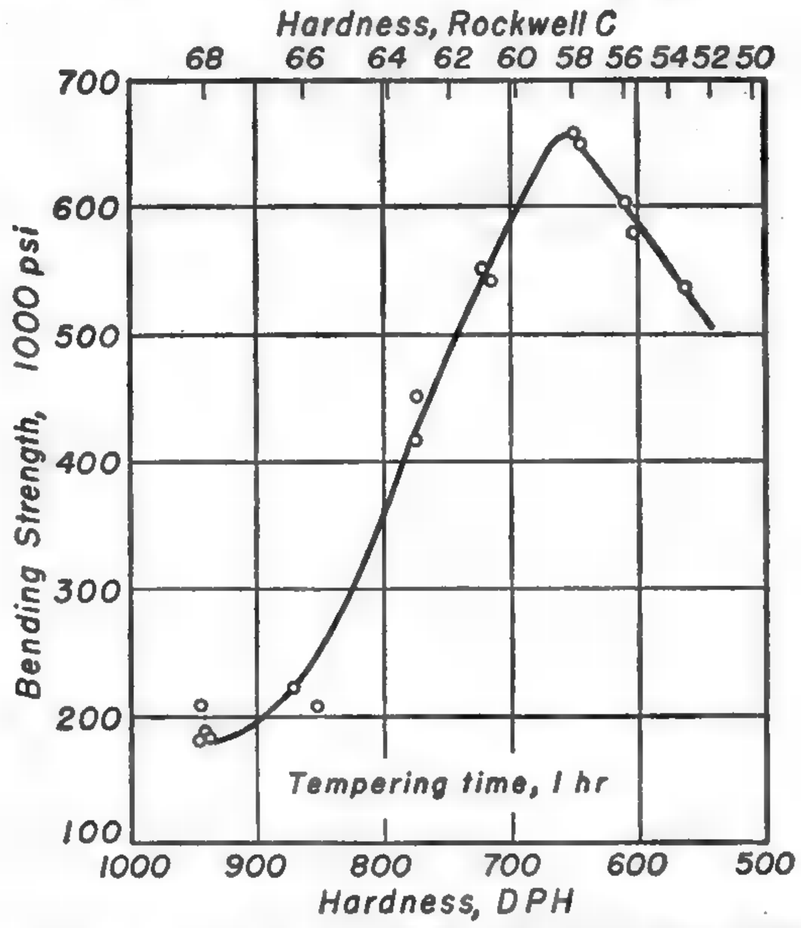

Fig. 4 Results of tests on 1.1% C tool steel, quenched in brine from 1475 F and tempered at 70 to 350 F

It is recognized that there is no definite factor for a general correlation between tensile and bending strengths, particularly since failure may occur in the elastic range in one instance, and after appreciable plastic flow in another. However, if the ductility varies inversely with strength, a fairly good correlation exists, as noted in the values in Table I.

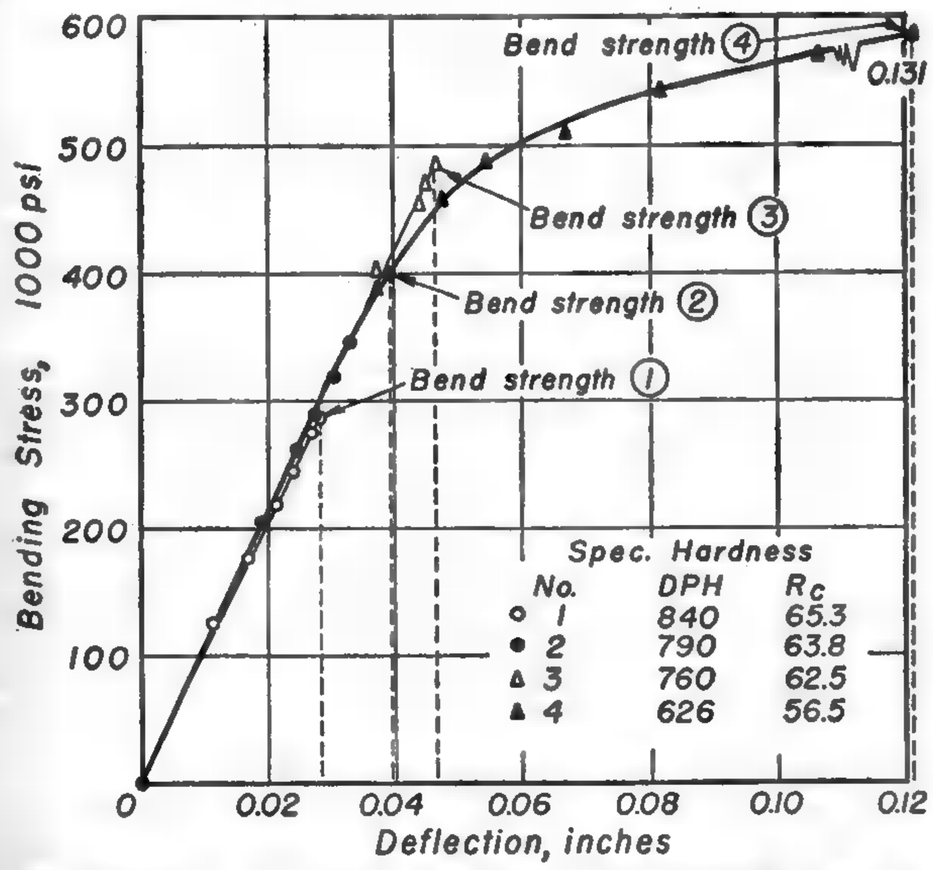

Fig. 5 Bending stress versus deflection of Cr-Mo-Si tool steel, 0.88% C, 1.1% Cr, 0.4% Mo, 1.43% Si. Dimensions ¼ by ⅜ by 3 in. Gage length 2 in.

Bend Tests of Hardened Steels. If bend tests are carefully conducted, they offer some advantages over other types of tests for evaluating the breaking strength of hardened steels of negligible ductility. Comparisons of strengths are more readily obtained than with the tensile test, and the bend test is more sensitive to slight variations in properties than the standard Charpy and Izod impact tests. Since many tools are stressed in bending, bend tests may provide a direct measure of the resistance of tool steel to failure in service.

There have been no attempts to standardize the bend testing of hard steels; consequently test specimens of various shapes and dimensions have been employed, as well as several testing methods. The test specimens and

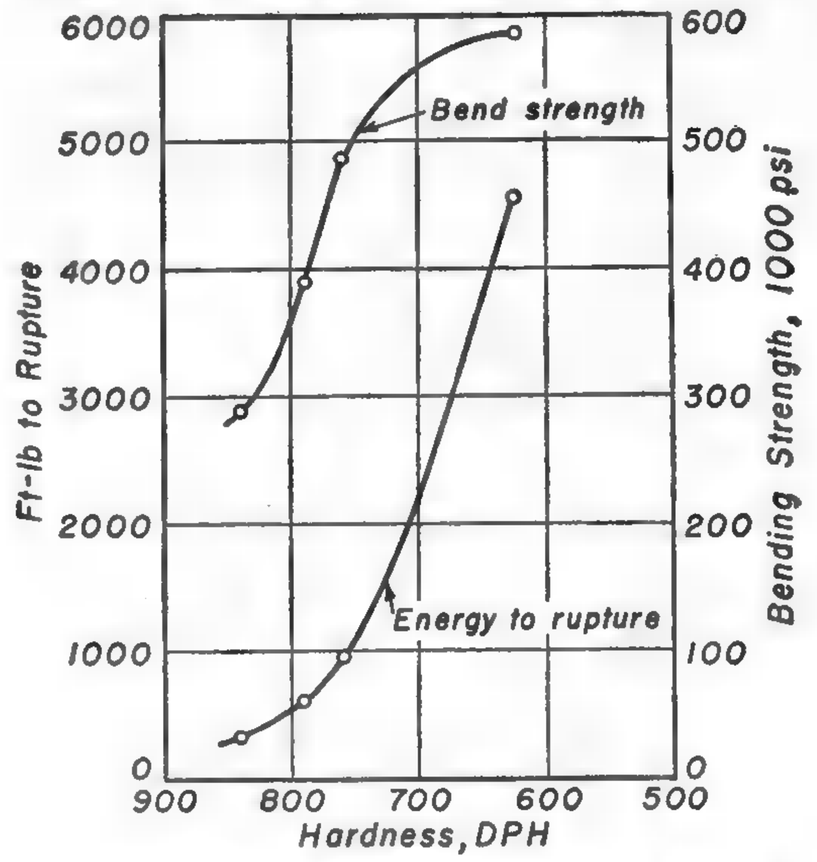

Fig. 6 Foot-pounds required to rupture Cr-Mo-Si tool steel in bending (0.88% C, 1.1% Cr, 0.4% Mo, 1.43% Si). Dimensions ¼ by ⅜ by 3 in. with a 2-in. span

fixtures are much smaller than those specified for cast irons and much shorter spans are used. The sizes of specimen tested range from 21/32 in. in diam, 7 in. long[4] to 0.072 in. in diam, 2 in. long.[5] Many tests have been made on rectangular bars ¼ by ⅜ by 3 in.,* with a 2-in. span.

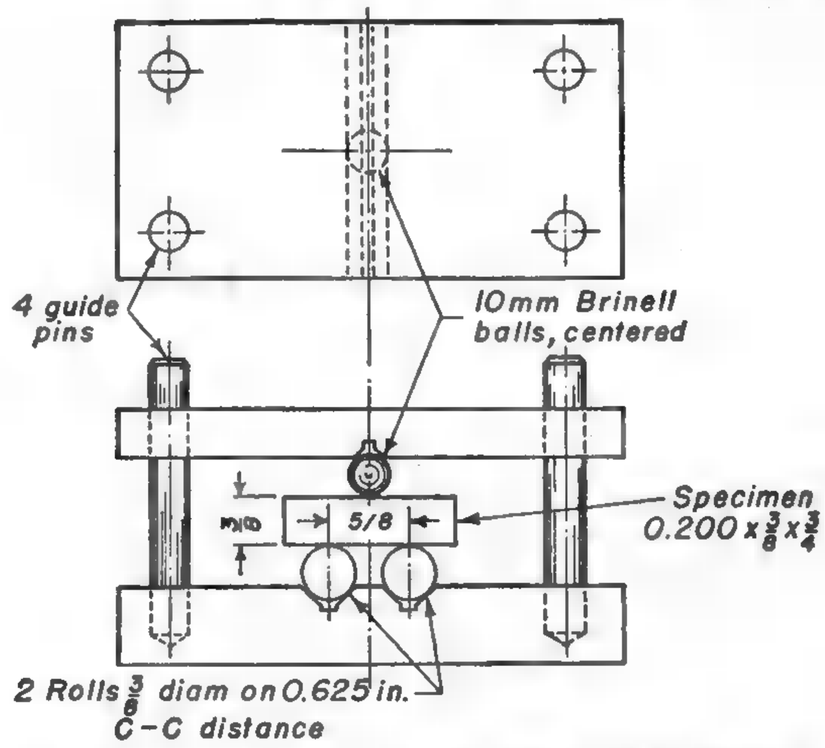

Fig. 7 Apparatus for determining the bend strength of sintered carbides. (Firth Sterling apparatus)

$$S = \frac{3PL}{2bh^2} = \frac{0.9375\,P}{bh^2}$$

S = bending strength, in pounds per square inch
P = breaking load, in pounds
L = C-C distance between supports
b = width of specimen, in inches
h = thickness of specimen, in inches

A fixture for performing bend tests on these specimens is shown in Fig. 3. The bars of this size should be surface ground to ± 0.001 in. of their final dimensions before testing, and the edges should be chamfered. The tolerances can

* Research data, Westinghouse Electric Corporation

be increased for larger specimens. Decarburization should be avoided or removed by careful grinding after hardening.

Testing fixtures consist of two supports for the beam specimen (either knife edges with a definite radius on the bearing edges or two hardened steel cylinders), a jig for holding the supports and test specimen, a means for protecting the operator from flying fragments, and a mechanism for applying the load. Loading with a ball at the center of the span yields more consistent results than loading with a knife edge or roll. Any of the usual laboratory testing machines that apply a load may be utilized conveniently for performing the bend tests.

The magnitude of the beam deflection can be measured conveniently by placing one end of an extension bar above or under the test specimen midway between the supports, and placing the other end of the bar under a dial indicator. An electric strain-gage can be placed very easily on the under side of the specimen for the same purpose. As a rule, deflection measurements are not made, since the failure of a fully hardened steel bar often occurs within the elastic range.

Typical results of bend tests on a hardened tool steel containing 1.1% C are shown in Fig. 4. As-quenched steels contain an appreciable amount of residual stress. Presumably because of these stresses and the inability of the hardened steel structure to accommodate itself to the load, the strengths at full hardness are low and the failures are brittle, with the specimens often shattering into fragments. Relief of these stresses and increased plasticity, resulting from tempering treatments, reduce hardness and greatly increase the bending strength of the steels. The shear component in the fracture of bend-test specimens also appears when the steels have been tempered to a hardness less than that for maximum bending strength, and shattering no longer occurs.

When deflections of the beam under the load are measured in conjunction with the bending stresses, curves similar to those of tensile stress versus strain are obtained, as illustrated in Fig. 5. These curves indicate that hardened and slightly tempered steels, of 760 DPH (62.5 Rockwell C) or more, rupture while they are still being deformed elastically.

The energy required to produce rupture, a quantity commonly accepted as an indication of toughness, can be obtained from Fig. 5 by computing the area under the curves up to the point of rupture. In Fig. 6 are shown values of energy in foot-pounds required to rupture hardened Cr-Mo-Si tool steel tempered to different hardnesses.

Bend Tests of Cemented Carbides. Bend tests have been applied with varying degrees of success in evaluating qualitatively the resistance to breakage of sintered carbides. Cursory attempts to standardize the test have been made by several manufacturers. Some have maintained that the size of the test specimens should correspond to the size of carbide products in service, so that a closer correlation can be made between the results of bend tests and service failures. As a result, many different sizes of test specimens have been used.

Several producers have tentatively accepted a carbide test specimen 0.20 by 3/8 by 3/4 in. with a 5/8-in. span. The bars are surface ground to within ±0.001 in. of their final dimensions; the grinding wheel moves longitudinally to avoid transverse scratches. One example of test apparatus, illustrated in Fig. 7, shows a specimen mounted in a jig ready for testing.* In this particular procedure, a 10-mm sintered carbide ball is used to apply a concentrated load slowly to the center of the test bar, by means of a hand-wheel on the testing machine. Typical values of bend strength range from 200,000 to 400,000 psi.

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* Data from Firth Sterling Steel & Carbide Corp.

Mechanical Testing of Sheet Metals

By John R. Low, Jr.*

SHEET and strip products are almost invariably subjected to cold forming operations of one type or another in the process of fabrication, and therefore must be examined for "forming quality" as well as for the usual mechanical properties essential in structural materials. As a result of this additional requirement and of the wide variation among the types of forming operation to which a sheet may be subjected, a great many technological tests have been devised, simulating certain specific types of forming operations. Most of these special tests have not proved generally useful as routine testing methods and will therefore not be described in this article. A list of the more important of these special tests will be found on page 130, with references to the original articles in which they are described. At present the most widely used tests for sheet metals are the tension, indentation hardness, bend, and Olsen or Erichsen "ductility" tests. In addition to these, the "tear-length" tests for directionality, the Tour-Marshall bend test for strip, and a number of cup-drawing tests (small-scale deep drawing of cylindrical cups) are in more or less common use.

Tension Testing of Sheet Metals. The general features of the simple tension test are described in the article on "The Tension Test", page 105; and the ASTM sheet-metal specimen employed universally is described in the article on test specimens, page 86 in this Handbook. Three results of tension tests are normally reported for sheet metals: the yield point or the yield strength, the tensile strength, and the elongation in 2 in. The yield point may be determined by the so-called "drop-in-load" method, the divider method or the low-magnification autographic method, all of which are described in the article on "The Tension Test". The drop-in-load method is usually limited to the testing of steel sheet in the annealed condition, which exhibits a true yield point.

All three of the above-mentioned methods for determining yield point may be influenced by the skill and judgment of the operator, the care used in preparing the specimen, the speed of testing, and similar factors. Despite such possibilities for variation in the results, these measures of the yield stress have proved useful when a great many routine tests are required for purposes of control. When a more precise measurement is required, it is customary to determine the 0.2% offset yield strength by using sensitive strain gages.

No special comment is required concerning the determination of the tensile strength of sheet specimens, but the

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Prepared for the Subcommittee on Mechanical Testing.

measurement of elongation deserves mention, as well as the influence of specimen shape on the value obtained. It is common practice, particularly with specimens of 2-in. gage length, to reduce the width at the center of the gage length deliberately by a few thousandths of an inch in order to be certain that fracture will occur midway between the gage points. It is not always recognized, however, that some materials are quite sensitive to the amount of such tapering or "waisting" of the specimen and that the elongation values obtained may be appreciably influenced by seemingly unimportant variations in the amount of taper from the ends of the gage section to the midpoint.[1]

Up to the present time no adequate method has been devised for the measurement of reduction in area at fracture for sheet specimens. In testing the heavier gages of the less ductile materials, the method suggested by MacGregor[40] for plate specimens may be used, but the measurements required cannot readily be made with adequate precision in the more common lighter gages (less than 0.062 in.) or in the ductile materials where considerable necking occurs. For this reason, reduction in area is almost never reported in tension testing of sheet metals.

Compression Testing. In compression testing, the ratio of the length of the specimen to the least cross-sectional dimension must not exceed a certain minimum value (usually 3 or 4) if buckling is to be avoided. This requirement is easily met in metal products with heavy sections, but, in the testing of sheet and strip, the required use of extremely short specimens would add greatly to the experimental difficulties of the test. For this reason a number of test methods have been devised which, by one means or another, provide sufficient lateral support in a fairly long specimen, without introducing frictional forces great enough to influence the test results appreciably. These methods are used only to determine the compression yield strength and cannot be used to obtain stress-strain data much beyond yielding.

In the "pack" method[33, 34] a number of samples are pressed together and the top and bottom surfaces of the pack are carefully machined parallel. To avoid the necessity of machining a large number of samples for each test, and the tedious adjustments inherent in the pack method, several special fixtures have been developed for testing single sheet thicknesses. Two of these [35, 36] simply use flat plates pressed against the specimen surfaces and depend on lubrication and careful adjustment of the pressure to minimize frictional effects. In a third method,[37] the lateral support is provided by a series of small rollers pressing against the two flat surfaces of the specimen.

The so-called "cylinder method"[38] consists of forming a small cylinder by rolling a sample of the sheet and joining the edges by soldering. The results obtained through the use of this method appear to be reliable, provided the proper cylinder diameter–sheet thickness and length-diameter ratios are employed to obtain simultaneous yielding all around the periphery.

Hardness Testing. The Rockwell test is almost universally used for testing the hardness of sheet steel. The particular load and indenter combination varies with the material and the thickness of the sheet to be tested. For example, the standard B scale is used for 0.033 in. and heavier steel sheets, the F scale for thickness between 0.025 and 0.033 in., and the Rockwell superficial tester for thickness less than 0.025 in. (*See* "Hardness Testing", page 93, for definitions of hardness scales.) Pack hardness testing of several sheets piled on top of one another is sometimes resorted to for purposes of comparison, but this practice is not recommended since the values obtained are frequently unreliable and cannot be correlated with the results of tests made on a single thickness, using lighter loads.

Erichsen and Olsen Type of Ductility Tests. The general principle of the Erichsen type tests (commonly called "cupping" or "ductility" tests) is illustrated in Fig. 1. The sheet is held between two ring-shaped clamping dies while a punch, usually hemispherical, is forced against one side of the sheet until fracture occurs. The height of the dome thus produced is measured by a dial gage, with plunger resting on the top surface of the sheet during deformation, or by measuring the movement of the punch. This "depth of cup", usually reported in thousandths of an inch (Olsen) or hundredths of a millimeter (Erichsen), is taken as measure of the ductility. Some machines are also equipped to measure the punch force applied, and a sudden drop in pressure on a gage is taken as the end point of the test; otherwise, the end point is determined by observing the sheet and noting the first appearance of fracture. Besides measuring ductility, this type of test is used also to detect surface roughening of the deformed sheet, resulting from large grain size.

Since Erichsen[2] first described a machine of this type, there have been numerous proposals for modifications of the original design. Most of these later cupping tests differ only in details, such as the die or punch dimensions, the shape of the specimen (round or square), or the method of clamping the sheet. These later modifications are the Olsen test,[3] the Guillery test,[4,5] the Persoz test,[6] the Avery test,[7] and the Amsler test.[8] The clamping dies and punch may be actuated hydraulically or by means of a screw.

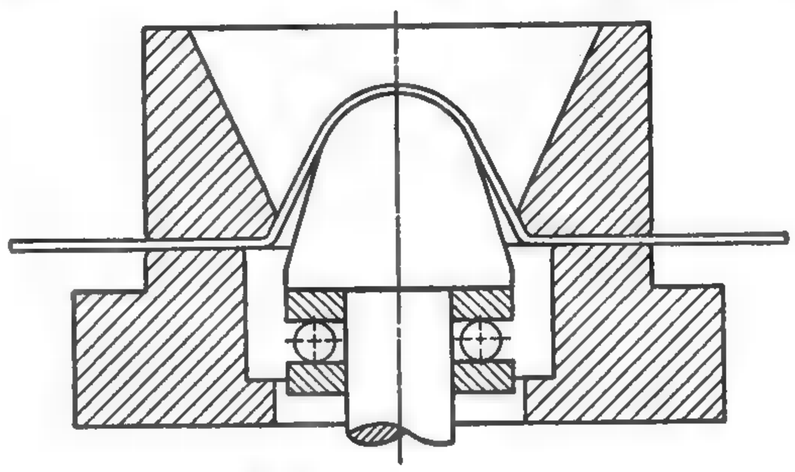

Fig. 1 Vertical section through Erichsen tester

Although it is generally agreed that the cupping test is unsatisfactory in many ways, nevertheless it is frequently included in routine testing programs. It has the advantage of being rapid; no special preparation of the specimen is required; it does indicate the general condition of the material and will indicate wide variations in ductility. Besides the conventional quantitative measurements of cup depth and maximum pressure, a qualitative evaluation of the drawn surface texture and the location and character of the break is sometimes used by experienced operators to determine the suitability of the product being tested for a particular application. On the other hand, it has been shown repeatedly[9] that test results on the same lot of material may vary widely from operator to operator or from machine to machine. This lack of reproducibility is caused, in some measure, by variations in clamping pressure, by the smoothness of the clamping dies or the punch, and by the amount of lubricant applied to the sheet surface. In addition, a variation in the speed of testing or failure to stop the test at precisely the same end point each time will contribute to this lack of reproducibility. More recent machines apply the clamping pressure hydraulically and automatically maintain it at a fixed ratio to the punch pressure.

The test results are sensitive to variations in gage.[10,11,12,13] The depth of cup increases approximately linearly with thickness (approx 0.6 mm per 0.010 in.) and various formulas and graphical methods have been devised for correcting for this factor.[11,13] The width of the specimen also affects the results; the depth of cup increases as the width of the specimen decreases, because of a "drawing in" of the edges under the clamping die.[10,12]

Bend Testing. The bend test, in one form or another, is one of the oldest applied to sheet metals, and is still one of the most widely used, despite the fact that no standard method of procedure has been accepted. At the present time bend tests range all the way from simple hand bending of a corner of a sheet to the quantitative measurement of resistance to bending in such machines as the Tour-Marshall flexure machine for thin sheets.

In general, the bend test is used either to determine forming limits, that is, minimum bend radius without failure for a 90-deg or 180-deg bend; or to determine the

yield point in bending, where this value must be controlled within narrow limits—for example, in light-gage sheet to be formed in high-speed automatic machines. For the determination of forming limits in bending, it is customary for the testing laboratory to design and construct the necessary tools, which are then used in either a Universal testing machine or in a hand brake. One of the most common bend test specifications requires that the material be capable of being bent flat upon itself (180-deg bend, zero radius) without rupture. In making this particular test, it is common practice to clamp one end of a strip of metal in a vise having either square or rounded jaws and to start the bend by hand or with pliers. After the strip has been bent slightly more than 90 deg, it is removed from the vise and either squeezed or hammered flat, after which the bent edge is inspected for cracks.

Cup-Drawing Tests. While not in general use for routine testing, the drawing of small cylindrical cups from flat circular blanks is sometimes used as a method of evaluating the forming quality of sheet materials.[41,42,43] Most commonly, cups of a given diameter are drawn, using a series of blanks having progressively increasing diameters. As the blank diameter is increased, a limiting size is found above which the material fails in drawing. This limiting blank diameter is then taken as a measure of the forming quality of the material being tested. Tests of this type may be carried out by using small laboratory presses such as the Wazau,[14,15] AEG,[16] or modified Erichsen[10] machines. Certain investigators advocate the use of commercial presses, in order to insure that the drawing speed will equal that used in full-scale drawing operations.[41,42]

Tests for Mechanical Anisotropy. In the series of processes for hot and cold reduction and annealing required to produce metals in sheet form, there is a strong tendency for preferred orientations of the individual crystals to develop. Consequently, sheet materials frequently exhibit a variation in mechanical properties if the direction of testing in the plane of the sheet is varied. This variation of properties, particularly resistance to plastic deformation, causes irregular flow during forming. The most common example is formation of "ears" in drawing cylindrical cups.

One test for evaluating the so-called "earing" tendency or "directionality" is the tear-length test.[10] In this test, two parallel slots are made in the edge of the sheet, the tab thus formed is gripped in a pair of pliers or a slotted key, and a triangular-shaped piece is torn from the sheet. The direction of tearing may be parallel to the rolling direction or at 45 deg, or at 90 deg, and any variation in the length of the triangular piece thus removed is an indication of anisotropy. (See Fig. 2.) Where equipment is available, laboratory scale cup-drawing is frequently used for this same purpose. Recently Baldwin[39] has shown that the ratio of the change in thickness to the change in width in the tensile test may be used for determining "earing tendency". The value of this ratio is compared for test specimens cut in several directions in the plane of the sheet.

Stretcher-Strain and Fluting Tests. The nonuniform type of plastic flow associated with the yield point behavior typical of annealed low-carbon sheets results in the formation of shallow, irregular depressions in the surface of the sheet in many stamping operations. Such surface markings, called "stretcher strains" or "Lüders lines", are highly undesirable where a smooth surface is required, and it is generally necessary to eliminate this behavior by temper rolling the sheet lightly (1 to 2% reduction) or by roller leveling. Another objectionable feature of a sheet exhibiting a yield point is the "fluting" which occurs when such a sheet is bent around a mandrel. Instead of forming a smoothly curved surface, such materials conform to the curvature of the mandrel by forming a series of sharp kinks separated by plane surfaces.

The tendency to stretcher strain, which may be detected in the tensile test, is directly proportional to the amount of yield point elongation. An Olsen or an Erichsen test of a specially prepared specimen may also be used to detect stretcher-straining. The specimen illustrated in Fig. 3 is prepared by drilling a hole at the center of the standard square specimen and then cutting a slot from one edge into the central hole. The specimen is deformed in the usual manner and the localization of deformation at the edge of the hole makes it possible to detect even a very slight tendency to stretcher strain.

Fluting tests are usually conducted by bending the sheet to be tested to successively smaller diameters around a series of mandrels or in bending rolls. The smaller the diameter of the cylinder to which the sheet can be bent without fluting, the less the fluting tendency.

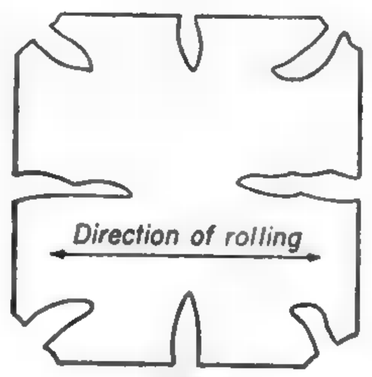

Fig. 2

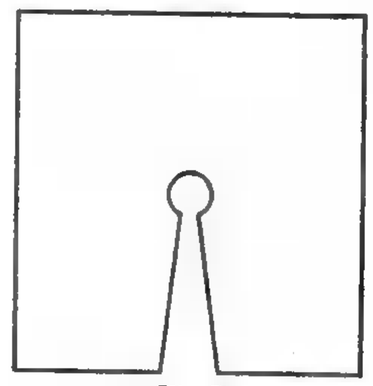
Fig. 3

Fig. 2 Tear-length specimen (after Jevons)
Fig. 3 "Stretcher-strain" test specimen

Additional Sheet-Testing Methods. A great many special purpose tests have been devised, usually to evaluate deep drawing or forming quality, but they are not in general use. A number of these are listed below, together with references to the papers in which they are discussed: drawn wedge or Sachs test,[14,17,18,19] wedge-cup test,[18,20,21,22] K.W.I.E. hole expansion test,[8,22,23,24,25] fluid pressure cup test or Jovignot test,[8,10,26,27,28,30] slotted strip test,[31] and stretch-drawing test.[32]

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Mechanical Testing of Bars, Plates and Shapes

By A. P. Spooner* and F. M. Howell*

FOR both ferrous and nonferrous materials, the mechanical test most frequently specified for bars, plates and shapes is the tension test. Hardness and bend tests are also often used.

Ferrous Materials

Bars. For testing hot rolled bars, the section size of the tension test specimen is normally the same as that of the bar, provided such a specimen does not exceed the capacity of the testing machine; usually an 8-in. gage length is used. Machined test specimens of standard size (0.505 by 2 in.) are used for larger sizes and generally for heat treated steel.

Occasionally, in conjunction with the tension, bend and Brinell tests, notched-bar impact tests of the Charpy or Izod type are made on heat treated bars.

To ascertain special properties, ordinarily in connection with research investigation, other tests are used, such as compression, torsion, shear, deflection, damping, torsional impact, weldability, machinability, wear resistance, drift, cavitation, tests at elevated temperatures, short-time tension tests and long-time tension tests (creep, relaxation and rupture), tests at low temperature such as impact and tension, fatigue tests, and special hardness tests such as Rockwell, scleroscope, Vickers, file, Monotron and microcharacter.

The mechanical testing of bars in the untreated condition is usually confined to the tension or bend test or both. For untreated bars, the carbon range and often the manganese range is not specified, although sometimes a maximum figure is given. For annealed steel with standard chemical limits, Brinell hardness is limited to a specified maximum value. Both maximum and minimum values of tensile strength or hardness may be specified for quenched and tempered or normalized and tempered bars, but the range should be equivalent to at least 0.3-mm diam of Brinell indentation.

The close relationship between hardness and tensile strength is shown in the hardness conversion tables in this Handbook. Since the two properties cannot be controlled independently, only one needs to be specified.

Test specimens taken from bars are almost always cut out in a longitudinal direction, that is, parallel to the axis of the bar. Usually the size of stock precludes the cutting of specimens in any other direction. Machined test specimens are cut from the center of small bars. However, when bars of larger sizes are to be tested, the specimens are taken midway between the center and the surface. There is no distinct dividing line determining from which of these two locations a specimen should be cut for testing a given bar. In bars larger than 1 to 1½ in. in diam, the test specimens are usually cut from the midway point.

The end-quench hardenability test may be applied to alloy steel bars containing between 0.20 and 0.60%C. With standard chemical ranges, either maximum or minimum hardenability can be used. When limited by both a maximum and minimum standard hardenability range, wider latitude than standard is required for the composition. When working to a minimum and maximum standard hardenability range, more uniform response to heat treatment is obtained than when using the standard chemical ranges. The end-quench hardenability test is not satisfactory when applied to carbon steel.

Plates and Shapes. Because plates and shapes are almost always used in the as-rolled condition, the tests applied to them are usually fewer and less complicated than tests applied to bars, in which properties are frequently enhanced by heat treatment.

Tension and bend tests are commonly specified by the trade to determine the suitability of plates and shapes for the intended purpose. The conventional tension test specimen is cut approximately 18 in. long by 2 in. wide, and is machined over the gage length to a width of 1½ in. With this specimen, percentage elongation is measured in 8 in.

When structural materials such as beams, angles and universal plates are to be tested, the coupons are cut parallel to the rolling direction, which is ordinarily the direction of the major stresses.

Sheared plates of first quality are usually tested in the same manner as the structural material, although in some specific instances tests are required in the transverse direction, at right angles to the major rolling direction.

The standard test specimen, 0.505 by 2 in., may be used when the material is so thick that the load required to break the conventional specimen is beyond the capacity of the testing machine. Extensometers are used only occasionally in testing plates and shapes.

In the bend test, a standard test coupon is bent cold to certain prescribed limits, depending on the hardness and thickness of the material. The bend test furnishes information concerning the suitability of the material to withstand forming by the fabricator.

The homogeneity test is specified for the higher grades of plates, particularly steel for use in fireboxes and high-pressure installations. This test is made by nicking and breaking a piece of the broken tension test coupon and examining the fracture for cavities and segregation.

Other tests that have a restricted application include hardness and low-temperature impact tests. Low-temperature impact tests are occasionally specified by fabricators of pressure vessels. The Charpy Keyhole specimen is the commonly accepted standard.

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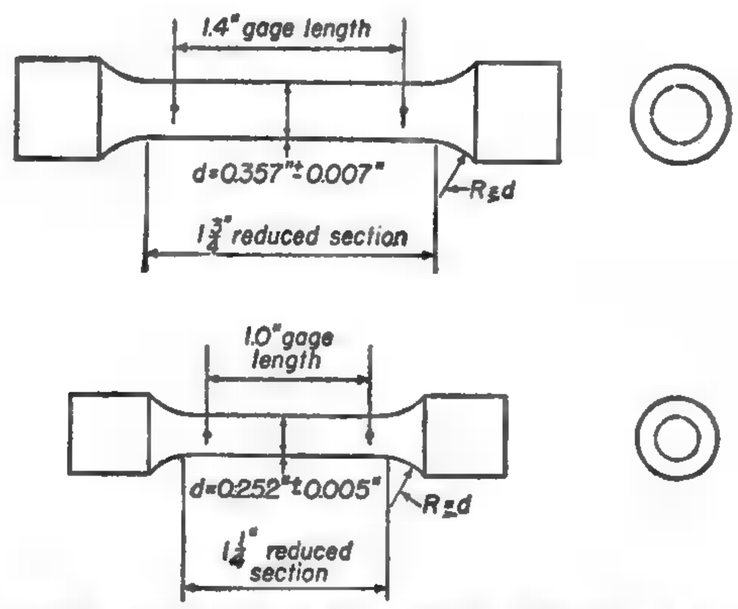
Nonferrous Metals

The tension test is used much more than any other for evaluating the acceptability of nonferrous rods, bars, shapes and plates. The bend test, next in importance, determines suitability for forming. Occasionally hardness tests such as Brinell and Rockwell are required.

Tension Tests. Rods, bars and shapes are tested in full size when practical. When a machined test specimen is necessary it is permissible to remove enough material from the test section of the specimen to meet the limitations of the testing machine. It is also permissible to machine a specimen to the form and dimensions of the standard tension specimen ½ in. in diam (*see* Fig. 3 of the article on page 87) or to a smaller size proportional to this specimen. Examples of specimens of smaller size are shown in Fig. 1. The gage length for the measurement of elongation is often 2 in. regardless of the size of the specimen; but to minimize the effects of specimen size on results of elongation, the gage length should be four times the diameter or distance across flats of the test section (in octagonal, hexagonal or square cross sections). For rods, bars and shapes as large as 1½ in. in diam or thickness the axis of the test specimen should coincide with the axis of the piece. For larger sections, the axis of the specimen should be located midway between the center and surface of the piece.



NOTE. If desired, the length of the reduced section may be increased to accommodate an extensometer.

Fig. 1 Examples of small specimens proportional to standard ½-in. diam specimen (ASTM E8–46)

In testing bars and shapes less than ½ in. thick, a specimen is frequently used that has the dimensions of the standard tension test specimen for sheet, with a reduced section ½ in. wide and 2¼ in. long. (*See* Fig. 2 of the article on page 87.) For testing plate thinner than ½ in., a specimen of this type is used. For plate ½ in. thick or more, the standard tension specimen ½ in. in diam is used. When plate no more than 1½ in. thick is to be tested, the axis of the specimen should be midway between the two surfaces of the plate, but for thicker plate the axis should be midway between center and surface.

Tension tests are usually made to determine yield strength, tensile strength and elongation. The yield strength for most nonferrous materials is specified as the stress corresponding to an offset of 0.002 in. per in. The yield strength is readily determined by a testing machine that is equipped with an autographic extensometer, which draws a load-strain curve as the test is being made. Yield strength is sometimes specified and determined as the stress correponding to a definite amount of extension under load; in this case the yield strength can be determined either with an autographic extensometer or merely an indicating extensometer. It is recommended that all tension tests be made in accordance with ASTM Standard Methods of Tension Testing of Metallic Materials.

Bend Tests. Bend test specimens from rods, bars or shapes are frequently of full cross section. When machined specimens are used, they are ordinarily either ¾ in. in diam or of rectangular cross section, having a width of approximately 1 in. or at least six times the thickness. The edges of such specimens may be rounded slightly before testing. For material no more than 1½ in. in diam or thickness, the bend test specimens are generally machined from the center of the section. For testing material of greater diameter or thickness, specimens are usually machined from the material midway between the center and the outside of the section. The bend test consists of bending the specimen, usually 180 deg, around a mandrel of specified diameter or radius. To pass the test satisfactorily the specimen must withstand the required bend, without evidence of fracture on the outside.

Hardness Tests. Brinell hardness tests of nonferrous materials consist of applying to a specimen a load of 500 kg through a ball 10 mm in diam for at least 30 sec, and determining the Brinell hardness by measuring the diameter of the impression in the specimen. For testing very small specimens or very thin specimens, it is sometimes necessary to make Brinell hardness tests with a ball of smaller diameter. For such tests, the ratio of the applied load (in kilograms) to the square of the ball diameter (in millimeters) should be five. Considerable care is required to make accurate Brinell hardness tests. To make sure that the results will be reliable such tests should be performed in strict accordance with the ASTM Standard Method of Test for Brinell Hardness of Metallic Materials.

Rockwell hardness tests are sometimes required for nonferrous materials. Rockwell hardness scales are numerous and involve different penetrators, major loads and dial figures. No attempt is made here to list all these combinations, since they can all be found in the article on page 93 of this Handbook and in the ASTM Standard Methods.

Mechanical Testing of Tubular Products

By A. W. SIMPSON*

TENSION, compression, hardness, impact, creep, fatigue, and other standard mechanical tests are made on specimens machined from tubular products. Modification of the standard specimens may be required on account of the curvature and the limited wall of the tube or pipe. In addition, special mechanical tests are applied, depending on the intended use and the kind or grade of metal.

Tension Tests. The evaluation of the mechanical properties of tubular products is usually obtained from a tension test of a longitudinal strip. The standard turned tension test specimen, 0.505-in. diam, is rarely used, since it can be obtained only from heavy-wall pipe. With the strip specimen, accurate measurements of the reduction of area after rupture are unobtainable, and the ductility is judged by the measurement of the elongation in a given gage length, usually 2 in. The elongation is not constant for all sectional areas but it increases as the sectional area of the test specimen increases. Consequently, when heavy-wall pipe is being tested, a change to the standard turned tension test specimen with an area of 0.2 sq in. results in a lower elongation than that which will be obtained with a strip tension test from pipe of the same weight. Subsize turned tension test specimens are frequently machined from pipe with walls between ¼ and ½ in. thick. The elongation values are then adjusted by the rule that the gage length shall be four times the diameter of the specimen. The over-all length of the subsize specimen is the same as for the standard specimen, 0.505 in. in diam, if it is desired to attach an extensometer with a 2-in. span. For nonferrous metals, the specimen blanks from light-wall tubes are machined to a rectangular section; from

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Prepared for the Subcommittee on Mechanical Testing.

tubes that have a very light wall, blanks may be hammered flat on a hardwood block with a rawhide mallet.

Tension tests are frequently made requiring the full section of the pipe. For such a test, a short length of pipe is fitted with a hardened steel plug in each end and is pulled in the tension-testing machine by suitable gripping jaws, shown in Fig. 6 of the article on page 88.

Flattening Tests. This kind of test is made on short sections or crop ends of pipe by compressing them between parallel plates. The closeness of approach of the parallel plates depends on the grade of material and the dimensions of the pipe. In general, flattening tests are not feasible on pipe with diameter to thickness ratios lower than 10. No break or crack in the wall of the pipe should occur within the limits of approach of the parallel plates. Certain nonferrous tubes are subjected to a flattening and doubling-over test with the doubled-over bend at right angles to the longitudinal axis of the pipe.

Bend Tests. Bend tests are made on suitable lengths of pipe, usually in the smaller sizes, for nonferrous metals and the milder grades of steel. The test is made cold around a cylindrical mandrel several times the diameter of the pipe. The mandrel is provided with a groove to fit the outside diameter of the specimen. No cracks should be developed and no welds should be opened in testing.

Drift Gaging. Drift tests of pipe are made to verify the roundness of the pipe and to test for a minimum inside diameter. This is accomplished by passing a cylindrical mandrel or a ball of specified dimensions through the pipe without sticking.

Expansion Tests. Expansion tests of tubes are made in order to determine the tightness of a longitudinal weld and the soundness of the metal or its freedom from flaws and surface defects. This is accomplished by forcing a tapered pin of specified dimensions a prescribed distance into the end of the tube, thereby expanding it. Failure may occur by splitting at the weld or in the tube wall.

Crushing Tests. These tests are made on mild steel grades and on some grades and sizes of nonferrous tubular products to disclose the general ductility of the metal and to develop surface flaws. A short length of tube is loaded axially in compression until it is reduced a specified amount in length. The metal should not break or crack.

Crushing tests are satisfactory only for a limited range of sizes of tubular products. Difficulties in obtaining good test behavior are encountered when testing tubular products that have large ratios of outside diameter to wall thickness, as well as when testing those that have small ratios. In the first instance trouble comes from the difficulty in keeping crushing specimens truly circular and loading them uniformly. At the other end of the range, with sizes that have a small bore and a heavy wall, the specimens possess so much inherent stability that they will not crush in a manner similar to that of the intermediate size of tubular specimens.

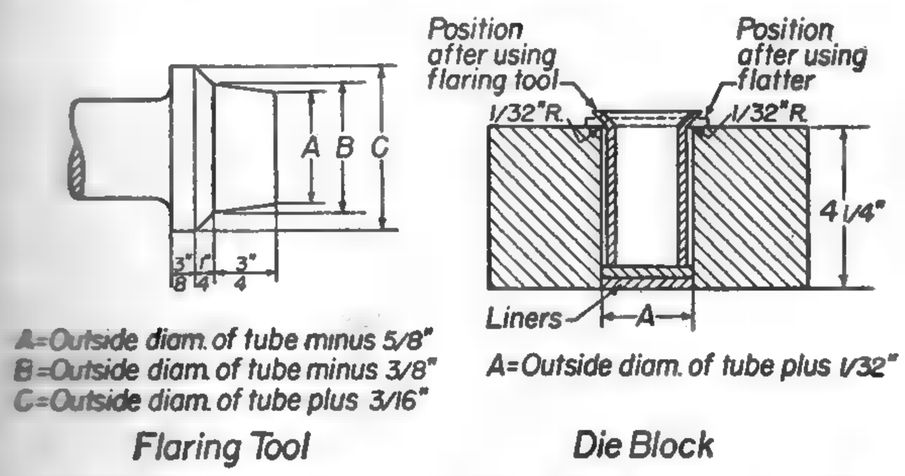

Fig. 1 Flaring tool and die block for flange test (ASTM)

Flange Tests. Flange tests are made on short test sections cut from tubes of nonferrous metals or of mild steel in order to show the ability of the tubes to withstand a flanging operation. The flange is made on one end of the specimen by using a flaring tool and a die block of specified dimensions (*see* Fig. 1). The flange is turned over at right angles to the body of the tube and should not show a crack or flaw in the metal. The outside diameter of the flange varies with the kind of metal.

Pressure Tests. Pressure tests involve the use both of pneumatic pressures and of hydrostatic pressures to determine whether a vessel is leakproof for gases as well as for liquids. Hydrostatic pressure is most frequently employed to determine the resistance of the material against internal or external pressures. The test may continue to destruction or it may be simply a proof test for inspection purposes. The proof test consists of the imposition of a momentary pressure of specified magnitude in order to determine the soundness of welds and the tightness of joints. The time of holding the hydrostatic pressure on the test piece varies. For the routine commercial testing of pipe, the duration of the test will not exceed 5 sec, but for special pressure vessels the test may last for hours. The pressure is limited to a value not greater than that prescribed by Barlow's formula,

$$P = \frac{2St}{D},$$

where P = the pressure, in psi
S = the maximum allowable fiber stress, in psi
t = the thickness of the metal, in inches
D = the outside diameter, in inches

Bursting tests are made on pipe, tubes and cylindrical pressure vessels, by using a suitable hydraulic pump to increase the pressure gradually to the maximum. With preliminary measurements of the average outside diameter and wall thickness, the maximum fiber stress at bursting can be calculated by Barlow's formula, already given.

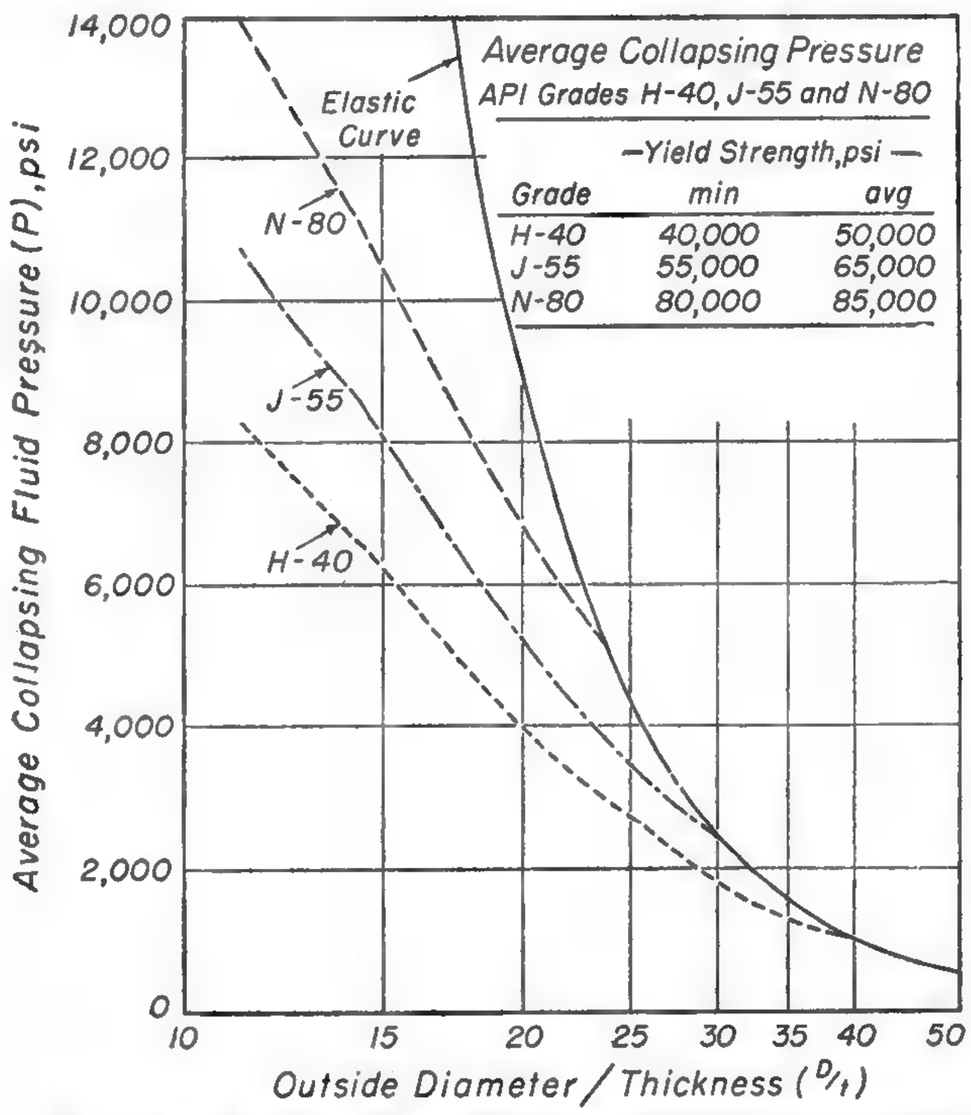

Fig. 2 Effect of D/t ratio on the average collapsing fluid pressures for certain grades of steel

At times, inspection tests for tubular products call for the measurement of the permanent set of the material after applying a stated maximum internal pressure. High-pressure gas cylinders are tested while immersed in a jacket containing a known volume of water. When the maximum pressure is applied within the cylinder, the volume expansion of the cylinder is measured by the displacement of water from the jacket. After the pressure has been relieved, the permanent set of the cylinder is indicated by the change in the volume of water in the jacket. The permanent set may be not more than ▪ or 10% of the total expansion while under the maximum pressure. The exact figure depends on the specification.

The need for subjecting the pipe to external fluid pressure is less frequently encountered. For certain uses, however, tests under external pressures are important. For the setting of casing in oil wells, the resistance of the material to external fluid pressure must be known in order to determine the safe setting depth. The tests to discover this point are called collapse tests. The collapse test is made on either an open-end specimen or a closed-end specimen placed in a heavy cylindrical jacket capable of withstanding high internal hydrostatic pressures. The open-end specimen projects through the jacket heads, which are provided with packing glands to hold the pressure. The closed-end specimen is used as a capsule short enough to fit inside the jacket, which is then provided with solid heads. The ends of the closed-end specimen are sealed by mechanical means or by welding circular plates over each end. For either the open-end or the closed-end test the hydraulic pressure is applied gradually, with a hydraulic pump, at a rate that will permit reading the maximum pressure on an indicating gage when the specimen collapses. Either a mercury column or a Bourdon-tube gage may be used. To obtain reliable results equipment must be available for calibrating the pressure gage at frequent intervals. The length of the collapse-test specimen should be at least ten to twelve times the outside diameter in order to eliminate the end effect on the collapse value. Original measurements of the wall thickness are made at both ends of the specimen to obtain the maximum, the minimum, and the average wall. Original measurements of the outside diameter are also made at intervals along the length in order to obtain the maximum, the minimum, and the average outside diameter. The ratio D/t is determined by using the measurements of the average outside diameter nearest the collapse lobe and the average wall thickness at both ends of the specimen. Collapse for failures that are plastic depends principally on the D/t ratio of the pipe and on its yield strength. This is illustrated by the curves of Fig. ▮ which, with the formulas that follow, apply to steel pipe.

For values of D/t of approximately 14 and up to and including the point of intersection of each curve for plastic failure with the elastic curve, the collapse value,

$$P = YS\left(\frac{2.503}{D/t} - 0.0460\right)$$

where P = the collapse value, in psi and YS = the average longitudinal tensile yield strength, in psi.

For values of D/t less than 14 approximately

$$P = \frac{2\ YS}{(D/t)^2}\left(\frac{D}{t} - 1\right)$$

For failures that are elastic

$$P = \frac{62.6 \times (10)^6}{\frac{D}{t}\left(\frac{D}{t} - 1\right)^2}$$

This formula, which applies to steel pipe, is a practical modification of the more general theoretically determined elastic curve equation,

$$P = \frac{2\ Et^3}{(1 - r^2)\ (D_1)^3}$$

where E is the modulus of elasticity and
r = Poisson's ratio
D_1 = the diameter at the midpoint of the wall = $D - t$.

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Mechanical Testing of Wire

By H. C. Boynton* and H. J. Godfrey*

A description of the mechanical testing of wire must necessarily be general because of the many shapes of wire—round, flat and irregular—and the many kinds of metals and alloys, including iron, steel, copper, brass, bronze and aluminum, that are used in producing wire with or without protective coatings. Information regarding the mechanical testing of any particular material should be obtained from a specification or other authoritative sources.

Since there may be some question concerning the distinction between flat wire and strip, the following definition* is given:

"Dimensionally, flat wire is a product having a width greater than its thickness; the maximum width is ½ in. and the cross-sectional area does not exceed 0.050 sq in. Steel products which exceed those dimensional limits are classed as cold rolled strip, cold finished bars or shaped wire. A product with a raw slit edge is classed as cold rolled strip."

Similar nonferrous products are made in considerably larger sizes.

A number of tests are used to determine the strength and ductility of wire. The processing of certain types of wire is such that the finished material is definitely anisotropic, requiring various types of tests to determine its physical characteristics completely.

The mechanical tests usually employed are the following: (1) tension, including measurements of elongation and reduction of area, (2) torsion, (3) bend, (4) wrap, (5) fatigue, (6) hardness.

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Prepared for the Subcommittee on Mechanical Testing.

* Steel Products Manual on Flat Steel Wire, Section 17, AISI, February 1942.

Sampling. Specimens for testing may be obtained by cutting from the ends of the coils immediately after processing or before fabrication into the desired product, or at both times. Since these coils contain many thousands of feet, sometimes miles, of wire in the fine sizes, the desired samples are cut to meet the customer's specifications.

Tension Tests. These are usually made in a hydraulic or screw type of testing machine equipped with special hardened steel jaws, which ordinarily have serrated tooth grips. For the testing of fine round wire or thin flat wire, grips of the drum or snubbing type are necessary to prevent jaw breaks.

The speed of testing has been found to influence the tensile strength of wire. For example, with hard drawn copper a maximum speed of 3 in. per min is suggested by ASTM Specification B 1-40 when a specimen 60 in. in gage length is used.

The elastic properties, such as proportional limit and yield strength, are sometimes required, particularly on tempered and hard drawn spring wire. This information is obtained either by extensometer readings or autographic recording devices. The proportional limit of a cold drawn wire is rather difficult to obtain and depends largely on the accuracy of the extensometer.

Elongation Tests. The test for elongation is made at the same time as the test for tensile strength. Two methods are used: (1) The gage length (usually either 10 in. or, for wire ⅛ in. in diam and larger, four times the diameter) may be marked on the sample before testing, and the actual or "recovered" elongation may be measured directly on the test specimen after fracture. Or (2) an extensometer or strain gage may be clamped on the specimen in the tensile machine and the total elongation may be observed visually at the time of the fracture. Method 2

will yield figures somewhat higher (about 1% on hard drawn wire) than those obtained by "recovered" elongation measurement.

In the testing of hard drawn copper the elongation is measured on both 10-in. and 60-in. gage lengths, depending on the size of the wire. The elongation in 60 in. is measured between the jaws of the testing machine. The zero reading is taken with a 10% load on the wire and the final reading is taken at the time of fracture.

Reduction of Area. This test is made on the tensile test piece. The original diameter is obtained by a micrometer reading to 0.001 in. for large wire and 0.0001 in. for fine wire. After fracture the reduced diameter is measured with a pointed micrometer.

Torsion Test. A torsion test on round wire is made by clamping a sample between two jaws, usually 8 in. apart, one fixed and the other free to rotate. The specimen is kept straight by a weight attached to the fixed jaw. The movable jaw is rotated by power or by hand at a constant speed and the number of twists necessary to fracture the wire is recorded by a counter.

The number of twists for any given type of wire is not comparable unless computed on the basis of a gage length of 100 wire diam. An additional torsion test sometimes used for oil-tempered spring wire is called "reversed torsion". A specified number of forward and reverse twists is required for a given size and grade of wire and the fracture should be a square break normal to the axis without splits or cracks.

Bend Tests. These tests are made on round wire by clamping the wire between jaws of exact radii, ordinarily a function of the diameter of the wire. The upper part of the wire is free to move as it is being bent alternately right and left through an angle of 180 deg. The minimum number of bends to fracture the wire is specified. The figures obtained from the bend test generally correlate well with the figures for reduction of area; that is, high bends accompany a high reduction of area.

Bend tests are also made on flat steel wire, usually on material containing less than 0.25% C. The severity of the bend test depends on the classification of the material as listed in the AISI Manual 17.

Another form of bend test for very fine round wire is the kink test. For this test a loop is made in the wire and then tension is applied by hand, causing the wire to kink. Some specifications require that the wire should not fracture when kinked; others require that the kink should be opened a desired amount without fracturing.

Wrap Tests. Wrapping may be done manually or by a special machine. Some users specify that wire must be capable of winding on its own diameter or a larger one. The wrap test is employed for testing the ductility of the metal and users may demand winding "on or off" certain size mandrels without fracture. When wrap tests are made for determining the adherence of a coating, a larger size mandrel is specified than for testing the ductility of the metal alone. (ASTM Specification A 122-41). Wrap tests are regularly specified for bare or zinc-coated iron and steel wire and for bronze wire.

Fatigue Tests. These tests are not a part of conventional specifications but are sometimes made when it is desired to know something about the life of the wire under alternate bending stresses. Fatigue tests on round wire are usually made on a "rotating-strut" machine. Flat wire may be tested on machines of the repeated-flexure type. It is important to make fatigue tests on wire without machining the surface, because the surface condition is of prime importance. The rotating-strut machine was developed for round wire in order to have the fatigue fractures take place away from the gripping points. The bending stresses are zero at the gripping points and maximum at midlength of the specimen.

Hardness Tests. The Rockwell hardness test, although sometimes made on round wire, is generally used for flat wire. For thin-gage flat wire the Rockwell Superficial hardness tester must be employed. If wire is so thin that the impression made by the ball or diamond cone shows through on the underside of the strip, the test is of little value. In such an instance the tension test is substituted. The hardness test procedure for flat steel wire as suggested by the AISI is as follows:

Carbon Content, per cent	Treatment	Thickness, in.	Test Procedure
0.25 max	All tempers	0.040 and heavier	Rockwell B
0.25 max	All tempers	Less than 0.040 to 0.010 incl	Rockwell 30-T
0.25 max	All tempers	Less than 0.010	Tension Test
More than 0.25	Annealed or hard rolled	0.040 and heavier	Rockwell B
More than 0.25	Annealed or hard rolled	Less than 0.040 to 0.010 incl	Rockwell 30-T
More than 0.25	Annealed or hard rolled	Less than 0.010	Tension Test
More than 0.25	Tempered	0.025 and heavier	Rockwell C
More than 0.25	Tempered	Less than 0.025 to 0.015 incl	Rockwell 30-N
More than 0.25	Tempered	Less than 0.015 to 0.005 incl	Rockwell 15-N

Hardness tests, if specified for round wire, are made either directly on the round surface or on a flat surface prepared by filing or grinding. If tests are made directly on the round surface a correction factor must be used.

Mechanical Testing of Forgings

By A. O. Schaefer*

THE tension test is the mechanical test most frequently applied to forgings, although hardness tests and bend tests are often used and a number of standard specifications require these tests. In the United States, notched-bar impact tests are seldom applied to forgings except to those used in aircraft and ordnance.

Tension Tests. The standard machined tension test specimen, 0.505-in. diam and 2-in. gage length, is most frequently used, although smaller specimens of the same proportions (0.357-in. diam, 0.252-in. diam, and even 0.125-in. diam) are used when the size of the forging or the location of the test specimen does not permit taking a test specimen of the standard size.

Tension tests from forgings are generally taken from extensions or prolongations when the size of the forging permits. Tension tests from smaller forgings and from closed-die forgings may be taken from one or more forgings in a melt or heat treatment group by cutting up a representative forging or forgings.

It is desirable to take tension tests from locations that are representative of the entire forging. For this reason, it is usually required by forging specifications that the prolongations or extensions provided for tests be of the same size as the forgings they represent. Test specimens are usually taken at sufficient depth from the surface to be fairly indicative of the condition of the forging. It is usually specified, for solid forgings, that they be taken at half-radius; and for hollow or bored forgings, that they be taken at mid-wall thickness. When forgings are heat treated by a process including a liquid quench, test specimens must be taken at sufficient depth to avoid end effect, or allowance for it will have to be made in design calculations. Test pieces from forgings that are cut up for testing purposes are usually taken from either the center of the section, or from the most highly stressed location.

Some forging specifications permit taking representative tension test specimens from bars or billets that have received approximately the same amount of forging work as the pieces they represent, and that have been treated together with them or in the same way. Such tests are usually considered an indication of the quality of the steel from which the forgings are made. They indicate that it

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Prepared for the Subcommittee on Mechanical Testing.

is possible to obtain in the forgings themselves properties of the order revealed in the tests, rather than that such properties are to be found in the forgings.

It is to be expected that a difference will be found in the results of virtually all the common mechanical tests, between specimens taken parallel or perpendicular to the direction of the hot mechanical working. The forging manufacturer usually applies forging work in such a way as to leave flow lines in the optimum direction. Therefore it is frequently stated that test specimens should be taken in the direction in which the forging had greatest distortion. This means longitudinal or axial test specimens for shafts and similar forgings, and tangential or transverse test specimens for rings or upset disk forgings. There are notable exceptions to this rule, including ordnance forgings, pressure vessels, and other forgings subject to stress in service in a direction perpendicular to the direction in which the forging is most extended in manufacture. Specifications for such products generally recognize that the ductility to be expected in transverse tests is less than that to be expected in longitudinal tests.

The number of tension test specimens necessary to represent a forging or forgings can be determined only after due consideration of a number of factors. It is impossible to state a comprehensive set of rules to cover all possibilities. In general, it might be said that fewer tests are necessary for untreated or annealed carbon steel forgings than for heat treated alloy steel forgings. Size is an important factor. For representative tests which are frequently applied, small forgings may be grouped as those from a single melt, those heat treated in one charge, and so on. Forgings heat treated in continuous furnaces are often tested by taking specimens at intervals from the product of the furnace.

Large forgings and those subject to severe stresses in service are usually tested individually. As the size and weight of forgings increase, it may be necessary to test forgings in more than one location. Thus ship shafting more than 7000 lb in weight is tested on both ends. Turbine or generator rotors subject to high rotative stresses are tested at a number of locations, including tangential or radial specimens from the bodies and tangential or longitudinal specimens from the shaft ends. Forged pipe and pressure vessels may be tested either longitudinally or transversely and pinion forgings are tested transversely from locations representing the condition of the teeth.

Bend Tests. Bend tests in some form are often required for forgings, particularly those for marine propulsion units. Usually not more than one bend test per forging is specified, regardless of the number of tension tests, and this one is taken from the end of the forging representing the top end of the ingot. Bend tests are also required for pressure vessels, such as boiler drums. Forged pipe is tested by cold bending a piece or by a flattening test made on a section of the pipe. Both of these tests approximate in value the conventional bend test made on a machined bar. It is usually required that a bend test specimen be bent cold 180 deg around a pin of stated diameter, although the angle of the bend may be decreased in tests applied to harder forgings.

Hardness Tests. Hardness testing ranks next in importance for its application to the testing of forgings. Hardness testing may be applied to every forging of a group from which only representative tension test specimens have been taken. In this instance the test is made to give an indication of the uniformity of the group. In general, hardness testing is specified for forgings when no tension tests are to be made. In such forgings, the results of the hardness test indicate the strength of the material.

The Brinell machine is standard equipment for the hardness testing of forgings. It is highly desirable, and usually required for important forgings, that the Brinell hardness-testing equipment be standard, that is, imposing a load of 3000 kg on a 10-mm diam ball. Other devices may be utilized for the Brinell hardness testing of forgings when such standard equipment is not available. One of the testing aids most commonly used is the Brinell meter, which consists of a standard Brinell ball held in a fixture that exposes one side of the ball to the surface of the forging to be tested, and the other to a bar of known Brinell hardness. One blow of a sledge leaves an impression both in the forging and in the standard specimen. The unknown hardness of the forging is determined from the known hardness of the standard specimen by multiplying by the inverse ratio of the squares of the diameters of the impressions. Another type of equipment strikes the ball by means of a calibrated coiled spring.

More accurate readings are obtained by small portable hydraulic machines adjusted to give a true 3000-kg load, or standard Brinell machines may be mounted on rigid supports in such a way that large forgings may be placed under them. Smaller forgings may be tested on standard machines.

The scleroscope hardness is used for forgings that are practically finished and consequently should not be marked on the surface by Brinell or Rockwell hardness testing.

Hardness readings should be taken after removal of sufficient metal from the surface to avoid effects of decarburization. When the hardness of the forging is critical, it is advisable for producer and consumer to agree in advance on the exact location of the test.

Notched-Bar Impact Tests. It is not usual to specify that notched-bar impact specimens be taken from forgings, except from those subject to similar stress conditions in service, or from those in which the impact test is utilized as an indication of the effectiveness of the quenching treatment. Bars should be taken from locations selected on the same basis as those for tension tests. In general more impact test specimens are required, and the results are averaged to allow for the variations in results.

Other Tests. Compression tests, torsion tests, fatigue tests and creep tests are seldom applied to forgings except for research purposes. In addition to the conventional tests already enumerated several others have been applied to certain products. Railroad axles are sometimes tested by allowing a weight to fall on them from a specified height, measuring their deflection and examining them for cracks. Pressure vessels, pipe, headers, and so on are usually tested hydrostatically at 1½ to 2 times the working pressure.

Mechanical Testing of Castings

By A. Allen Bates*

TENSION and hardness tests are the two tests most commonly applied to castings as well as to wrought products. The methods of making these tests are the same for both classes of products. The standard machined specimen, 0.505-in. diam and 2-in. gage length, is generally used for tension tests of castings; the values usually recorded are those for tensile strength, yield point, percentage elongation in 2 in., and reduction of area.

The great variety of sizes and shapes among castings requires that particular thought be given to the method of locating test specimens in relation to the castings. Occasionally it is desirable that test specimens be cut from actual specimen castings at sections determined jointly by the customer and the foundry; for example, at sections of maximum service stress.

More frequently, test coupons are cast as protuberant bosses on the body of the casting. These coupons may be detached by flame cutting or sawing, without injury to casting or to coupon if reasonable care is taken in the operation. When the casting is to be heat treated, it is customary to make not more than a partial detaching cut before treatment.

A third and common method is to cast test coupon blocks outside the casting but attached to it. In this

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Prepared for the Subcommittee on Mechanical Testing.

method, as in the previous one, care must be taken, first, to insure the soundness of the coupons by designing, locating and gating them properly and, second, to prevent bleeding of the casting or other harmful effects.

A fourth and frequent practice is to cast corresponding test blocks and castings simultaneously but separately. This method is often preferred because it introduces no problem in the successful pouring of a sound casting. When this unattached type of specimen is used—or the second and third (attached) types mentioned above—the tests should be regarded more as a measure of the metallurgical characteristics of the metal than as determinations of the actual mechanical properties of the castings.

The number of tests required for reasonable representation of the castings must be a matter of agreement between customer and foundry. Experience is needed to determine this number judiciously, because of wide variations, depending on the nature of the casting, the kind of service that it must perform, and other factors.

Bend Tests. Bend tests are sometimes required, especially when the castings are designed for applications in which pronounced vibratory or shock stresses will be encountered or fabrication by welding is involved, or both. The bend test is usually performed on a machined bar that has a rectangular cross section, 1 in. by ½ in., and slightly rounded corners. The specimen is generally required to bend cold around a pin 1 in. in diam to some agreed angle, as 120 or 90 deg, without cracking on the outside of the bent section.

Hardness Tests. Because of its speed and simplicity, the hardness test is by far the most frequently used of all mechanical tests for castings. The Brinell hardness test is the one most commonly used for castings as well as for wrought products. It is carried out in the various ways described in the section on testing of forgings, page 135. Rockwell and scleroscope tests are usually made only in special instances; for example, when the relatively large Brinell impression is undesirable or when the castings are of such size as to make them particularly suited to test by Rockwell or scleroscope machine.

The hardness test is sometimes applied to all the castings of a given group for the purpose of assuring uniformity. This testing is frequently done by the foundry for its own information and protection. Conversion relationships among Brinell, Rockwell and scleroscope hardness test values are only approximate at best and should not be used for comparison of castings that differ greatly in chemical composition or heat treatment.

Transverse or Flexure Tests. A rather special test known as the "transverse" or "flexure" test is commonly applied to cast iron to determine a "modulus of rupture" or "modulus of shear". The test, commonly performed in a tension-testing machine, consists in loading transversely a round test bar that is supported at both ends. Test bars are machined or otherwise prepared for testing, depending on stipulations in individual orders or contracts.

The diameters used are commonly 0.875, 1.20 and 2.00 in. with corresponding lengths of 15, 21, and 27 in. The distance between supports would be respectively 12, 18 and 24 in. Load to rupture and deflection at rupture are measured and applied to the following formulas. Standard specifications do not include the minimum values to be obtained, but leave this decision for agreement between purchaser and consumer.

$$\textit{Modulus of Rupture} = \frac{2.546\ LS}{D^3}$$

where L = span length or distance between supports, in inches

S = breaking load, in pounds

D = diameter of test bar, in inches

$$\text{Modulus of Elasticity, psi} = \frac{\text{Load in pounds} \times 1194}{\text{Deflection, in inches}}$$

Typical details of this test are given in ASTM Specification A 48-46.

Other Tests. Hydrostatic pressure tests are applied to castings for special uses involving high temperature, high pressure, or both; for example, certain valves, fittings, flanges and such. Other tests—creep, endurance and the like—are used for special investigations or development.

Reference. AFA Cast Metals Handbook.

Mechanical Testing of Weld Metal and Welded Joints

BY THE SUBCOMMITTEE ON WELDING AND CUTTING*

MANY products and structures, such as pressure vessels, ships, tanks, buildings and machinery, fabricated by fusion welding, are made under some form of specification that requires inspection by the purchaser. In certain welding applications the inspection must conform to a particular code of construction requirements, and tests are specified to govern the qualification of the welding operator or the quality of the welding performed.

Strength and ductility are the mechanical properties most frequently measured in order to determine the quality of weld metal and welded joints. The tests that are used for evaluating these and certain other mechanical properties, will be described in this article. For a brief discussion of the inspection of welds by nondestructive methods, the reader may refer to the article on page 71 of this Handbook.

Tension Test. The specimen for a tension test of a welded joint is usually taken transversely, with the weld in the center of the specimen, as directed in the ASTM standard for flat-plate tensile specimens (Fig. 1). The weld reinforcement may be removed or not, depending on the information sought.

It is customary to obtain only the tensile strength and the location and type of failure from a joint type of tensile specimen. Values for yield point and ductility

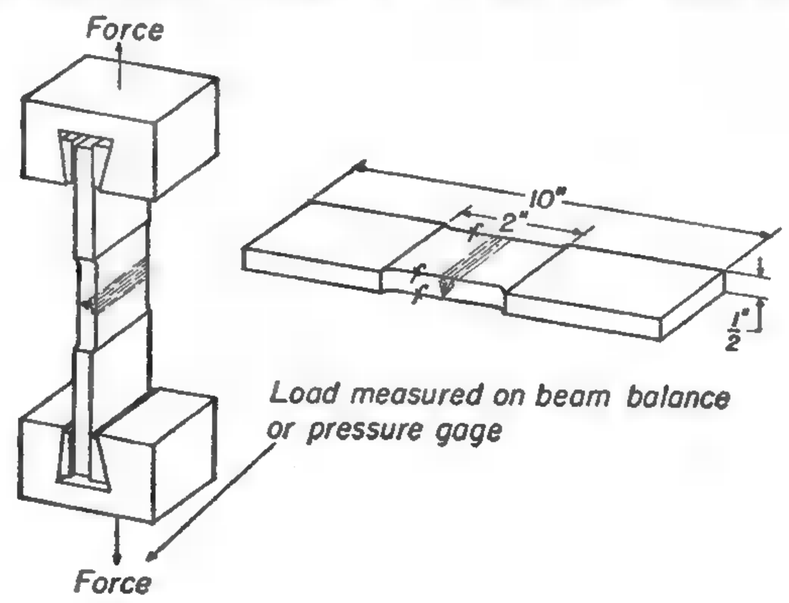

Fig. 1 A tensile specimen for testing welds

are sometimes obtained but usually they have little significance because of the nonhomogeneity of the reduced section of the specimen, which is composed of both base metal and weld metal. For high-strength welds that are stronger than the plate, the yield point will be that of

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Some of the information contained here has been abstracted from an article prepared for the Subcommittee on Mechanical Testing by A. J. Raymo, Works Manufacturing Engineer, The Baldwin Locomotive Works, Philadelphia.

the base metal and the elongation will be confined only to the plate. For welds that are weak in comparison with the plate, the yield point will be that of the weld metal and the elongation will be principally in the weld. The ductility of the weld metal in a joint is evaluated best by means of the free-bend test.

In order to obtain the tensile strength, yield point, elongation, and reduction of area of the weld metal, specimens entirely of weld metal are taken longitudinally

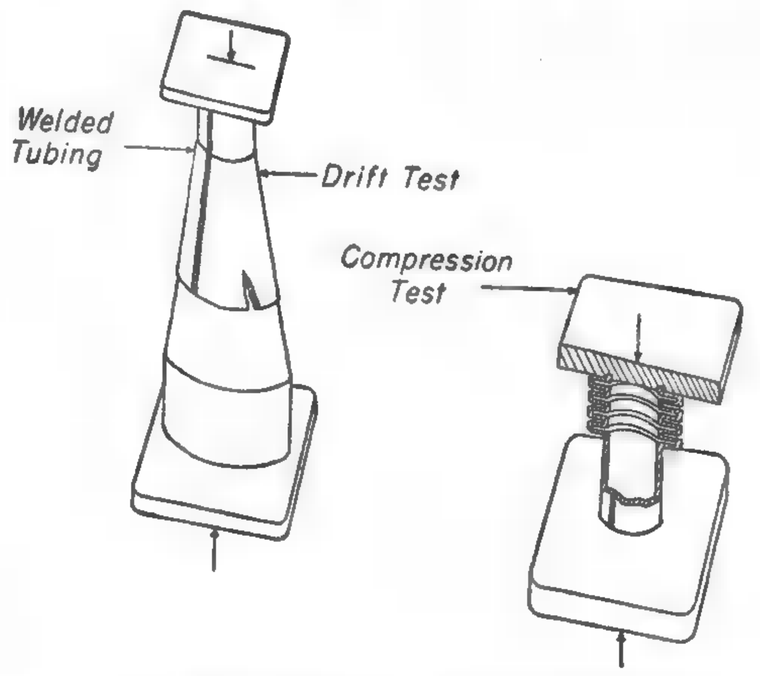

Fig. 2 Drift and compression tests for welded tubing

from the weld. A specimen 0.505 in. in diam can be taken from welds made in plate 5/8 in. thick or more. Specimens proportionately smaller can be taken from welds in thinner plate; for instance, a specimen 3/8 in. in diam with 1.5-in. gage length may be taken from a 1/2-in. test plate. The tension test specimen that is all weld metal gives reliable data concerning the mechanical properties of the weld metal, and is required by the ASME Boiler Construction Code and by the AWS specifications for filler metal.

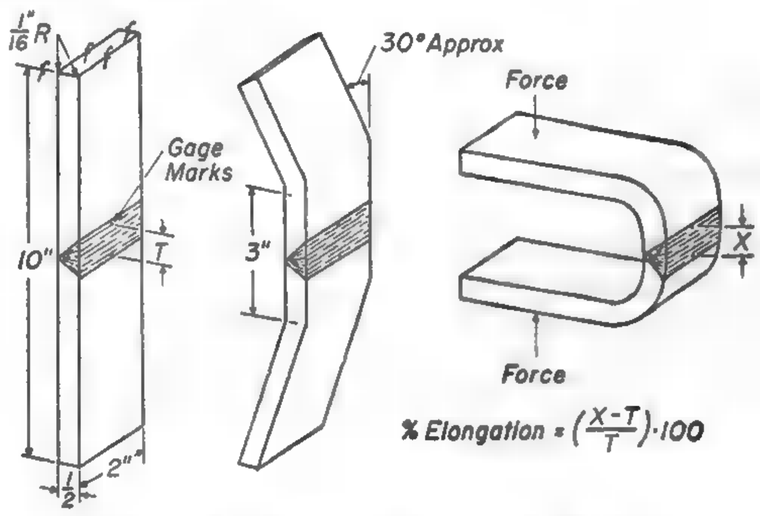

Fig. 3 A bend test for testing welds

For evaluation of fillet welds, a tension test is used to determine the tensile strength, and a guided bend test is used to determine the soundness, fusion and ductility. The tension test is commonly applied to a specimen formed by fillet welding two splice bars to opposite sides of two butted test bars; the fillet welds are made either longitudinally or transversely along the edges of the splice bars. In either design, the resulting failure of the fillet weld is a shear failure and the stress is recorded in pounds per square inch of weld throat or in pounds per linear inch of weld, which serves as a ready means of comparison for any average size of fillet.

Drift Test. From thin-wall welded tubing, it is impossible to obtain the regulation tension test specimens, and a drift test (Fig. 2) has been devised to determine the strength of the weld. This simple test consists in forcing a tapered, hardened steel drift into the end of the tube that has been welded longitudinally. The drift may be driven by a hammer, or forced in with a press; pressing is the more desirable method because it eliminates shock. The end of the tube is gradually expanded until it splits, usually outside the welded area, showing the weld to be stronger than the base metal and to have adequate toughness and ductility. The distance to which the drift is forced into the tube, may be taken as a measure of the ductility of the welded tube. Since this test stretches the welded joint, the action is quite similar to that of the tension test.

Crush Test for Flanging Qualities. A short length of welded tubing, when placed axially in a compression machine and loaded, will collapse like a bellows and, in doing so, will be subjected to shear, tensile and bending stresses. This qualitative test for ductility affords a good evaluation of the flanging qualities of the welded tube. Of course, a simple flanging operation is an adequate test of the ability of the welded tube to withstand flanging operations, but flanging is less severe than the crush test.

Hydrostatic Tests. The hydrostatic test may be used as a destructive or a nondestructive test. The destructive hydrostatic test, an extension of the tension test, is applied in some instances to pressure vessels and closed containers in order to determine the ultimate strength of them, as well as to ascertain the character of the failure. However, this form of test can be applied only in connection with design studies and research and is not necessarily a test of the weld joint, since the vessel may rupture at a place apart from the weld. A test of this type is a test of the entire structure and will reveal the weakest section, whether weld or base metal.

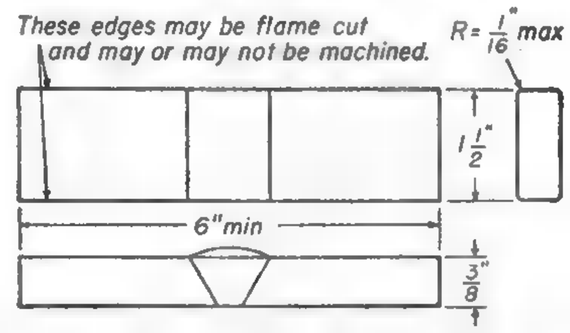

Fig. 4 A specimen for face-bend and root-bend test (AWS)

Weld reinforcement and backing strip, if any, should be removed flush with the surface of the specimen. If a recessed strip is used, this surface of the specimen may be machined to a depth not greater than the depth of the recess in order to remove the strip; however, in such instances, the thickness of the finished specimen should be that indicated above.

The nondestructive hydrostatic test is essentially a proof test, made to determine whether or not the vessel or container being tested, contains leaks, and whether it will withstand working pressures. This type of test may be made with a variety of mediums, such as water, oil, or air, and the pressures applied will depend on the mediums used and the individual container that is being tested. In general, the test pressures that are used range from 1¼ to 2 times the working pressure of the design.

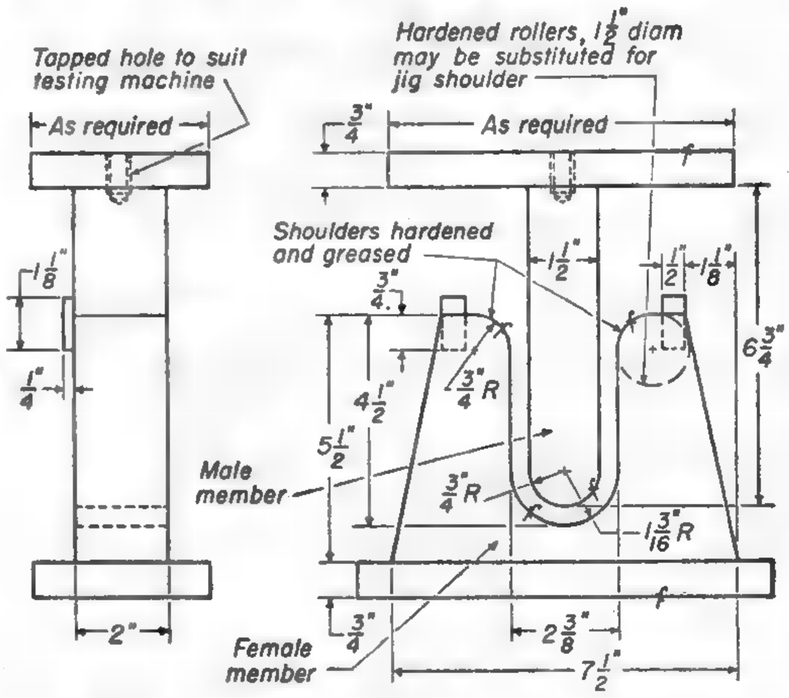

Fig. 5 A test jig for making a guided bend test (AWS)

Tension-Impact Tests. The tension-impact test has been developed in order to permit evaluation of the effect of rate of straining. The advantage of such a test is that all zones of a welded joint can be tested in impact. The test results are expressed in foot-pounds of energy required to break the specimen, rather than in pounds per square inch. For further discussion of the tension-impact test the reader may refer to page 114 of this Handbook.

Shear Tests. Shear tests of fillet welds can be conducted about as easily as tension tests. The shearing strength of a joint can be evaluated conveniently in terms of pounds per linear inch of failure in the weld. This value is computed by dividing the maximum force by the sum of the lengths of the welds that ruptured.

Spot welds are sometimes tested by means of a lap shear test. The specimen for this test is prepared by lapping two strips of metal and joining them by means of a single spot weld. The specimen is then pulled to failure on a standard testing machine. Failure may occur either by shear of the weld metal or by tearing of the parent metal. Shear strength is usually expressed in pounds per spot weld.

Bend Tests. Since the tension test, using flat specimens, gives no quantitative measurement of the ductility of the welded joint, the free-bend test has been devised to furnish this much-needed information. Free-bend tests yield quantitative data independent of the thickness of the specimen, provided the width is at least three times the thickness. However, the ASME Boiler Construction Code calls for a width one and one-half times the thickness.

Figure 3 shows the design of the free-bend specimen and the method of preparation. After the initial bends have been made, the specimen is placed as a strut in a vise or press and is bent until failure occurs on the outside bent surface between the gage marks, or until the specimen is bent double. Corner cracks are not considered failures. Any failure on the surface is not considered such until its greater dimension is 1/16 in. or more. The elongation of the outside fibers is measured directly with a flexible scale, or it can be calculated from the curvature by the formula $100t/2R$ where t is the thickness and R the radius to the neutral plane. The ductility can also be measured by means of a bend extensometer; however, direct measurement is more satisfactory. For specimens ½ in. or more in thickness, a heavy press or tension-testing machine is desirable.

The guided bend test is for determining the soundness of welds and is ordinarily used to check the ability of an operator to make satisfactory welds. Fillet-welded or butt-welded joints are made in plates, from which are machined two specimens 1½ in. wide. (Fig. 4). These specimens are bent 180 deg in a special bending fixture (Fig. 5) with the root or face of the weld in tension. This test is usually evaluated on a "go or no go" basis; bending through a certain angle (usually 180 deg) without failure is accepted as an indication that a satisfactory weld has been made. In certain instances, plates thicker than 3/8 in. are used and specimens 3/8 in. wide are cut from them and tested in side bending.

Root-break and side-bend tests are new forms of the bend test that have been introduced to reveal lack of soundness in welded joints, but as yet they have not met with general acceptance. The root-break test is applied by bending the specimen backward, so as to stretch the bottom of the V of a single V-weld; this test is particularly effective in revealing lack of penetration and soundness at the bottom of the V. The side-bend test is applied by bending a thin specimen, taken transversely across the welded joint, so that the length of the weld is perpendicular to the plane of the specimen. This test is said to be particularly effective in revealing lack of side-wall fusion in the V or groove.

Specific Gravity. This test is made to determine whether the weld metal is free from fine porosity. The specimen of weld metal is usually ⅝ in. in diam by 2 in. long. The weight and volume of the specimen are determined carefully; the weight in grams divided by the volume in cubic centimeters gives the specific gravity. For ferrous weld metal of highest quality, a specific gravity of 7.80 or greater is required.

Nick-Break Test. This test consists in rupturing, with a sudden blow, a specimen notched in the edge of the weld. The nick-break test is a homogeneity test indicating the soundness of the weld by showing on the fractured surface (1) whether complete penetration has been obtained, (2) the presence of oxide or slag inclusions, and (3) the degree of porosity, which should not exceed six gas pockets or holes per square inch of fractured surface. The maximum dimensions of any defect should not exceed 1/16 in.

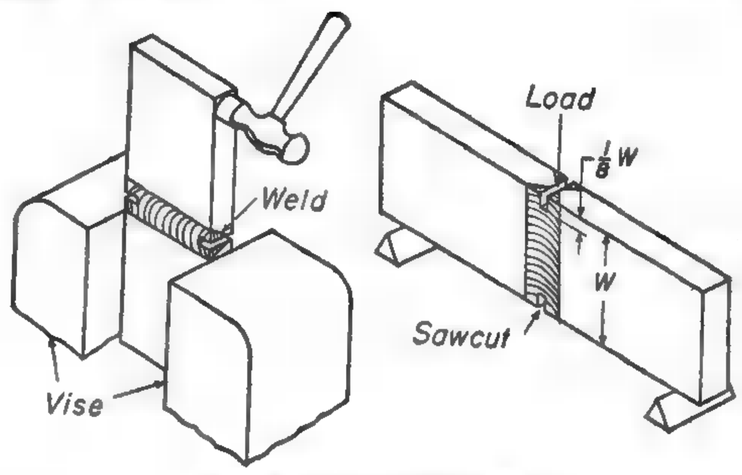

Fig. 6 A nick-break test

The materials required for making the nick-break test are a vise or anvil, in or against which the specimen is clamped; a heavy hammer for applying the blow; and a specimen 1½ T wide plus ½ in., slotted at the edges by a hacksaw to a depth not greater than ¼ in. No machining is required on the specimen. With material ½ in. thick or more, the specimen may be laid on supports about 6 in. apart, and may be fractured by a power hammer or by a falling weight of sufficient intensity to cause sudden fracture. Examination of the fractured surface will reveal the presence of porosity, oxide, or lack of fusion.

Although the nick-break test is extremely simple, it is severe and weld metal and welding must be of good quality to pass. This is one of the tests that has long been used for the qualification of processes and welders in the ASME Unfired Pressure Vessel Code for paragraph-U69 quality vessels. The specimen is shown in Fig. 6.

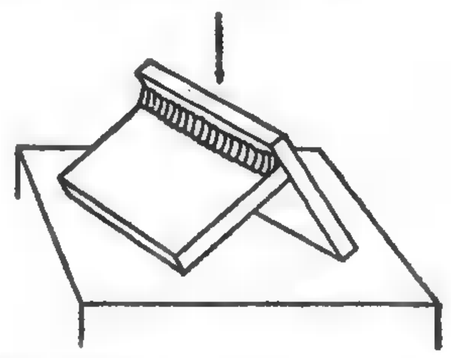

Fig. 7 A test specimen for fillet welds

For fillet welds, a test equivalent to the nick-break test is applied to a so-called "fillet-weld break specimen" (Fig. 7). This specimen is formed by fillet welding one flat plate or bar at right angles to another, in such a manner that by application of pressure or a blow to one edge of the specimen, the fillet weld can be opened at its root. The resulting fracture in the weld reveals any lack of penetration or lack of soundness.

Impact Tests. The Izod and the Charpy impact tests are generally used. These tests are carried out by fracturing a notched specimen with a swinging pendulum and measuring the energy absorbed in breaking the test specimen. The tests are described on page 112 of this Handbook.

In testing the impact strength of welds, it is customary to make at least three specimens, placing the notch at the bottom of the weld in one, at the side in another, and at the top in the third, and taking the average of the three results as the impact value in foot-pounds.

Hardness Tests. The hardness test is used considerably in the laboratory but has not been used in the field to any great extent for testing welds, except for determining the hardness of built-up rail ends.

Inspecting and Testing of Bolts, Screws, Nuts, Studs and Pins

BY THE SUBCOMMITTEE ON BOLTS*

THIS article presents the requirements and procedures involved in inspecting and testing bolts, screws, nuts, studs and pins.

Sampling. When a shipment comprises a number of kegs or boxes, it is suggested that one or more samples should be taken from each container in order to test the average quality of the shipment as nearly as possible.

Mechanical Inspection. The physical dimensions are determined by suitable rules, gages, micrometers and special instruments. Thread dimensions and tolerances for the several classes of threaded products are specified in the standards of the American Standards Association.

Hardness Tests. The Brinell hardness test is generally used when the size, shape and character of the part permit. For routine testing in the shop, the Brinell hardness determination on headed parts should be made near the center on the upper surface of the head. For purposes of arbitration and for approximating as nearly as possible the tensile strength of the bolt, the Brinell impression should be made on a transverse section of the threaded part of the piece, at a point ⅛ diam from the center.

The Rockwell C scale is used on hard surfaces of sufficient thickness. The Rockwell A scale may be used on some thinner parts where the C load breaks through. The Rockwell B scale is used on soft surfaces where the size, shape or application of materials will not permit the use of the Brinell tester.

Although its use is not standardized, the file often serves as a guide in estimating the hardness and uniformity of surface hardened parts, especially where resistance to abrasion is of major importance.

Tests for Tensile Strength. The tensile strength of bolts should be measured in a tension-testing machine with the load applied between the head of the bolt and a nut or threaded fixture, with enough thread engagement to assure that the full strength of the bolt is measured. The nut or fixture should be assembled on the bolt so as to have at least three bolt threads exposed between the bearing faces of the nut and the bolt head. Results from tests in which failure occurs by thread stripping are worthless.

When large bolts from ⅞ to 1⅜ in. in diam are to be tested, if the tensile equipment is not adequate for testing full-sized bolts, the shanks of the bolts should be turned down to a suitable gage size concentric with the bolt axis. The head and threaded sections should be left intact. For still larger bolts, a standard tension test specimen should be machined from the bolt shank, but its axis should be taken midway between center and surface of the bolt.

An excellent method for writing specifications is to state the minimum load in pounds for the yield strength or tensile strength that a given specific part should sustain. When the strength per square inch is required, it should be calculated by dividing the actual load by the area computed from the average of the root and pitch diameters.

When bolts are too short for tension testing the Brinell or Rockwell hardness is used as an indication of strength.

The tensile strength of unthreaded sections is calculated on the minimum cross-sectional area. In the testing of a threaded section, if the part breaks outside the threaded length, the area of the section that breaks should be used for the calculation.

A threaded section may be considered as a cylinder strengthened by one or more spiral ridges which are the threads of the screw. This strengthening effect of the threads is usually greater on the yield strength than on the tensile strength. Since a straight piece turned from a threaded part may give a result somewhat different from that of the threaded part itself, the actual piece should be tested whenever possible.

Tests for Yield Strength. The yield strength is determined in the tension-testing machine as the load is being applied for the determination of the full tensile strength of the piece. The yield strength is indicated by the "drop of the beam" on low-carbon ferrous materials having a yield point. On stronger material, since yield strength corresponds to the beginning of permanent plastic flow, it can be measured by dividers, extensometers, autographic attachments, beam hesitation or pointer hesitation.

Elongation and Reduction of Area. Since a bolt normally breaks in the threaded section in a tension test, and since the plastic flow of the material is greatly hampered by the notch and strengthening effect of the threads, determinations of elongation and reduction of area are not commonly made.

Head Test. To determine whether there is proper union between the head and shank, samples may be tested by placing the bolt sideways on a block of steel, with the head just over and against the square edge. The head is then hammered to determine whether the steel deforms plastically or ruptures without plastic flow.

Bend Test. Although it is not standardized, the bend test is used on the shanks of bolts as an aid in judging toughness and ductility. The bend test is made in the tension-testing machine with a specially designed fixture holding adjustable rolls to accommodate the bending bolt as it is forced down by the mandrel, which has a rounded end with the same radius as the bolt radius. A screw press is used for case-hardened parts that should deform plastically to some extent before complete rupture of the core. The bend test does not apply to threaded sections because the notch effect of threads produces low, erratic results.

Shank Fracture Test. The shanks of the threaded products may be fractured to show visible defects such as piped steel, seams, or coarse grain structure. Usually these defects can be seen by the naked eye or through a hand lens.

Shear Test. Shear tests are made best in a special shear block with holes in the block and in the plunger to hold the specimen rigidly in alignment. The holes must be closely fitting and the block and plunger made of hardened steel or with hardened steel inserts. The block is used in the tensile machine and the results are expressed in pounds load or pounds per square inch of sheared section.

Thread Stripping Test. The strip test for threads is applied to nuts and made in tension on a tension-testing machine. The sample nut is assembled on a hardened threaded mandrel and the load is applied until the threads in the nut are stripped. The test result is not significant if the threads of the mandrel are damaged. To convert the load to tensile stress in the mandrel the mean area of the threaded section should be used.

Inspection of Protective and Decorative Coatings. A protective coating may or may not be decorative. A decorative coating, however, must always be protective.

The decorative quality of coatings is usually determined by visual examination. The protective quality of coatings may be subjected to tests on the unthreaded portions of a part and on such surfaces as may be considered significant.

Outdoor Exposure. An outdoor exposure test, although quite reliable, usually involves too much time.

Salt Spray Test. The salt spray test is in general use for checking the corrosion resistance of coatings. The test should be conducted in a closed cabinet in which a solution of salt (NaCl), 20% by wt, is atomized continuously so as to give a visible fog in all parts of the cabinet. Pieces under test should be suspended or supported in such a manner that the solution will not be retained in pockets. The temperature should be 92 to 97 F. The pieces should be free from protective films other than the coating in question, and should be exposed until corrosion appears on the underlying metal. The solution should be changed frequently to avoid concentration by evaporation or contamination with zinc or iron chlorides. For details see ASTM Method B 117–44T.

Measuring the Thickness of Coating. To determine whether the coating is thick enough to give satisfactory protection, the thickness may be measured under a microscope, by micrometer, or by chemical determination.

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NONDESTRUCTIVE INSPECTION

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Radiography of Metals

BY KENT R. VAN HORN*

X-RAYS, a form of radiant energy or electromagnetic waves, were first detected by Roentgen in 1895, and are frequently called "Roentgen rays" in honor of the discoverer. X-rays are similar to light and other radiation of the electromagnetic spectrum in that they travel in straight lines, traverse space without transference of matter, affect a photographic film, and are not influenced by either electric or magnetic fields. The various electromagnetic vibrations differ essentially in wave length; the gamma rays emitted during the disintegration of radioactive elements are the shortest,* then the X-rays, followed by the ultraviolet, the visible, infrared, radio and other forms. The shorter wave lengths are less absorbed by matter and are consequently more penetrating. Thus, gamma rays and X-rays penetrate material that is opaque to visible light.

Light is transmitted through different types of glass with varying degrees of absorption. Similarly, all materials do not possess the same degree of X-ray transparency. The absorption coefficient of X-rays is roughly proportional to the density of the absorbing medium. More precisely, the absorption coefficient increases with the atomic number of the absorbing atoms, the number of atoms per unit volume and the X-ray wave length. Consequently, a sound section of steel will absorb more radiation than a similar section of aluminum. It is possible, therefore, to locate regions differing appreciably from the surrounding material in density. These relations are the basis of the science of radiography, which may be defined as the nondestructive testing of matter by utilizing radiant energy (either X-rays or gamma rays). The experimental procedure consists of passing radiation through the specimen and detecting or measuring by some means the various intensities of the emergent beam. The present article is confined to X-ray radiography. However, much of the discussion of general technique and interpretation also applies to the gamma ray.

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* The cosmic rays have a shorter wave length than the gamma rays but their nature is controversial.

Generation of X-Rays, and Apparatus. X-rays are produced when matter is bombarded by a rapidly moving stream of negatively charged particles (electrons); that is, when the electrons are suddenly stopped by matter, a part of the kinetic energy is converted to energy of radiation (X-rays). The essential conditions[1] for the generation of X-rays are: (1) a source of electrons (cathode rays) proceeding toward the target; (2) a target (anode) located in the path of the cathode rays; (3) a difference in potential between the cathode and the target, by means of which the requisite velocity is given to the electrons during their passage across the intervening space, so that when the target is bombarded, the necessary X-rays will be propagated.

The first two requirements are incorporated in the X-ray tube, which may be of two types. The first is a gas (ion) tube, where the source of electrons is a residual gas that is ionized; the second (electron) type is a highly evacuated glass bulb, cylinder or doughnut containing either one or, in special tubes, two tungsten wire filaments, which emit the cathode rays, and either a button, solid or hollow target. The tubes constructed for higher voltage (1 to 8 million volts) consist of many sections so that the velocity of the electrons can be accelerated in stages before striking the target. Radiographic tubes may or may not be self-rectifying.

The third condition, a difference in potential, is obtained by storage batteries, several types of transformers, electrostatic generators and magnetic induction generators. The high-tension a-c closed-core transformer is used for industrial installations from 45,000 to 500,000 volts. The electrons are accelerated in the 1 to 2 million-volt units by low-frequency resonance transformers.[2] Similar voltages can also be obtained by electrostatic generators (Van de Graff)[3] where the charges are transferred on a moving insulated belt to a high-voltage collector. The potential thus accumulated is applied to the tube terminal. The magnetic induction accelerator[4] (Betatron) offers the most promise for producing high-energy X-rays, from 2 to 100 million volts. This accelerator consists of an electromagnet and a doughnut-shaped vacuum tube. The electrons shot into the vacuum tube are continually accelerated in a circular

path until the desired velocity is attained, at which time the orbit is magnetically expanded and the electrons strike the target.

Accessory equipment for the transformer type of power that is used so extensively in industry today consists of: (1) an autotransformer for controlling the input to the high-tension transformer; (2) a means of current rectification, generally valve tubes; many of the recent installations are equipped with self-rectifying X-ray tubes that have cooled targets; (3) a device for regulating tube current; (4) separate transformers for supplying the filament current of the X-ray and valve tubes; additional windings on the high-tension transformer or insulated storage batteries are also satisfactory as a filament supply; (5) instruments for measuring voltage, such as a calibrated primary transformer voltmeter, electrostatic voltmeter, sphere gap, or spectrometer.

Radiographic units may be of a permanent type where the location of the apparatus is fixed, or of a portable type that may be moved throughout a plant quite easily.

Protection.* X-rays and rays from radioactive substances are potentially dangerous to all exposed persons, so that adequate safeguards must be employed. Overexposure of local areas of the body may result in the production of skin burns and ulcers, which may develop into cancers after a period of several years. Overexposure of the entire body may lead to the production of severe anemia or even leukemia; also the genetic cells may be injured and sterility can occur.

A potential health hazard exists in any area where the daily amount of radiation measured in air exceeds 0.1 roentgen.* An intensity of 0.1 roentgen per day, or 3 roentgens per month is allowable; however, that amount is accepted as the tolerance limit for an individual. Since X-rays and radiation from radium cannot be perceived by ordinary sensory means, it is the responsibility of the management to protect the personnel adequately.

Necessary safeguards consist essentially of shielding all X-ray sources so that no radiation hazard exists, or of barring all persons from areas in which such a hazard is present. Radiation barriers are to be preferred whenever practicable. In considering the use of shielding, it must be emphasized that shielding of the direct beam alone is not sufficient because of dangerous secondary or scattered radiation from objects in the path of the direct beam.

Detailed safety and health recommendations for the industrial use of X-rays and radium are embodied in the new safety code,[5] and should be followed constantly. Particular attention must be directed to the proper use of interlocking controls and switches that will interrupt the high-voltage supply to X-ray tubes if persons attempt to enter dangerous areas; to the proper use and frequent checking of shielding materials to eliminate possible hazards; and to proper identification and handling of radium.

All persons casually exposed to X-rays must be protected, but the health of the personnel working with these rays should receive special attention. Before employment, all such workers should have a blood count and a complete physical examination, with particular emphasis on their medical or exposure histories. These workers should be re-examined annually, and blood counts should be made at regular intervals (60 to 90 days).

Methods of Detecting X-Rays. X-rays are detected by their effects on matter; these effects may be visible and either temporary or permanent. Thus X-rays are detected by a photographic emulsion, a fluorescent screen, ionizable gas and electron multiplier tubes. Inasmuch as the photographic emulsion is generally used for industrial radiography, the other methods will be mentioned briefly.

Vapors and gases such as sulfur dioxide, ethyl bromide, and methyl iodide are readily dissociated by X-rays but difficulties are encountered in measuring the ionization without secondary effects. Tedious manipulation is required, and further, the average intensity over an entire region is measured, not the variations from point to point. Thus, an ionization chamber would be unsuitable for revealing small defects in large castings.

The visible fluorescence excited by X-rays on screens of calcium tungstate, zinc sulfite or barium platinocyanide is utilized for the inspection of metals of low density, but only to a limited extent. On fluorescent screens variations in brilliancy (glow) correspond to different degrees of transparency of the exposed object, so that the dense structures causing less glow appear darker, which is the reverse of the effect on photographic film. The fluoroscope offers the advantages of speed and economy but unfortunately does not integrate X-ray energy as a film emulsion does; therefore much larger quantities of radiation are required to penetrate the same specimen. Furthermore, the record is temporary and the sensitivity is inferior, ranging from 1/5 to 1/15 that of a film.

The electron multiplier tube (Geiger-Mueller counter)[6] in the past has been considered unreliable because of variations in response and life. However, recent developments indicate that this is a stable, long-lived and sensitive means of recording X-ray energy quantitatively. It is being used currently on diffraction apparatus for the precise measurement of X-ray intensities and undoubtedly will find future application in the radiography of metals.

An X-ray paper is marketed that costs about one-half as much as a film and differs in several significant characteristics. The contrast of the paper is 40% less than that of the film, and the range of useful densities (latitude) is more limited, because of the reflection of some light from the surface. However, X-ray paper may be satisfactory for certain uses; for example, in the examination of a large number of similar parts where previous tests with films have indicated that objectionable defects would be adequately disclosed.

X-rays and gamma rays, similar to light, produce on a photographic emulsion a latent image which is permanent and reproducible.[7] Dupletized films designed especially for X-ray service consist of two thick sensitive layers, separated by a cellulose acetate base. Since 1939, special films have been manufactured for industrial radiography. Some of these films are for "direct" exposure to X–radiation and others are of the "screen" type; that is, they are used with intensifying screens. The image registered on the negative depends on the variations in absorption of X-rays by the object and on the characteristics of the emulsion.

The important qualities of films are contrast, latitude and speed. Industrial X-ray films available have various speeds. In general, the speed is a function of the grain size—the coarser the grain, the faster the film; fine-grained films, although slower, give better registry of details. Radiographic sensitivity is greatest with high-contrast emulsions. However, with maximum differentiation of detail (contrast), the range of useful film intensities (latitude) is diminished. In other words, a high-contrast emulsion will reveal minute defects in a certain section but will not record clearly, during the same exposure, images of regions appreciably thinner or thicker. Sufficient latitude will allow for unavoidable variations in exposure and development as well as for reasonable differences in thickness. Generally, emulsions that offer a compromise of contrast and latitude are desirable, although for some conditions requiring extraordinary sensitivity, high contrast alone may be specified. Preferred film sizes for the radiography of castings are 14 by 17 in., 11 by 14 in., 8 by 10 in., and 5 by 7 in., while the narrower sizes for welds are 4 by 10 in., 3½ by 17 in., and 7 by 17 in.

X-ray films are developed and fixed by the tank method in solutions designed to give extreme contrast and negligible chemical fog. Films can be processed manually or, when the production is large, by a machine.

Accessory Equipment. No attempt will be made to describe the many radiographic accessories. However, a few of the important features that appreciably affect the applications or limitations of radiography will be mentioned.

A decided reduction of exposure time can be obtained by employing intensifying screens. A screen consists of an intensifying compound—usually calcium tungstate, infrequently zinc silicate or zinc sulfite—mixed with a cellulose binder and coated on a cardboard support. When calcium

* Condensed from a contribution by Phillip Drinker, Harvard University School of Public Health, Cambridge, Mass.

* The roentgen is that quantity of X-rays or gamma radiation having associated corpuscular emission (secondary beta radiation) producing in 1 cu cm of air, ions carrying one electrostatic unit of electricity of either sign.

tungstate or similar material is exposed to X-rays or gamma rays, visible and blue light is emitted to which a film emulsion is highly sensitive, thereby accelerating the exposure effect. Two screens are used ordinarily, one in front and the other behind the film, although superior definition but less speed is procured with only one screen. The particle size of the calcium tungstate is important, since coarse grains increase the speed, while fine grains are more conducive to sharpness (definition). Zinc sulfite has recently attracted attention because the speed in exposures below 100-kv peak exceeds that of calcium tungstate.

Metal foils—particularly lead, but sometimes copper or aluminum—slightly decrease the exposure period in certain voltage ranges and improve the quality of the negative. A lead-foil filter (about 0.005 in. thick) placed on each side of the film will reduce film fogging by absorbing some of the secondary radiation.

For interpretation, negatives should be viewed near a source of diffuse illumination that will reveal detail in areas of both average and extreme blackening without glare. The color of the light is of no optical consequence although bluish-white is preferred. Mazda, fluorescent and photoflood lamps are the common sources of illumination. Photoflood lamps require adequate cooling by fans or water cells so that the film will not be overheated.

Film darkening is usually expressed in H and D units (standard density scale of Hurtel and Driffield). This is defined as the reciprocal of the transparency of the film (blackening = log 1/T; that is, a film that reduces the transmitted light to 1/10 of its original brightness has an H and D value of 1.0). Film blackening can be precisely measured by a microphotometer. A density difference of 0.1 is considered the standard minimum value of detection. Detail is perceptible, with adequate illumination, as high as 4.0. Film densities of 2.0 to 2.5 are common for good practice and serve as a relative standard for comparing technique. Formerly, 0.7 was preferred and some still adhere to this value. It is desirable to use a darkening value in the range where the characteristic curve of the film is a straight line. However, with the new fine-grain high-contrast films (with continuously increasing slope of the characteristic film curve), the contrast increases with the degree of blackening, and therefore greater film densities are now being specified.

Sensitivity of Radiography and General Technique. The minimum perceptible variation in density (sensitivity) within a specimen is a measure of the over-all accuracy of the radiographic method. The sensitivity may be expressed as the smallest thickness of discontinuity in inches that is revealed on the radiograph, or as the percentage of the total thickness examined which is represented by the smallest discontinuity detectable. Of the factors that affect sensitivity, some may be controlled, but others are permanent limitations imposed by the apparatus.

The type of target in the X-ray tube, the material supporting the target, the size of the focal spot, and the method of rectification cannot be altered.[8] The higher the atomic number of the target metal, the more penetrating (shorter) the wave length of the X-rays, although this is accompanied by decreased contrast. The focus of the X-ray tube is not a point source but occupies a fixed area; consequently, the smaller the focal area, the better the definition. Rectification units of the same peak kilovolt capacity have dissimilar distributions of wave length (mean voltages), thereby generating different proportions of long and short wave lengths.

Among the important controllable factors that affect sensitivity is the quality of the radiant energy. The radiation emitted from the tubes having tungsten targets varies over a considerable range of wave lengths and is related to the voltage applied to the tube. As the potential increases, the wave length of maximum intensity decreases with a corresponding reduction in contrast and sensitivity. Consequently, it is desirable to employ the lowest potential that will penetrate a certain thickness in a reasonable period of exposure.*

* Exposure charts are available for various thicknesses of metals under different conditions.[9] However, these data will not apply to all situations because of the difficulty in reproducing radiation with a constant potential and variations in films or screens.

The sensitivity is reduced by the fogging effect produced by scattered (secondary) radiation from the specimen and surrounding objects. Secondary radiation consists of primary X-rays that are scattered through wide angles with no change in wave length and X-rays of longer wave length, characteristic of the absorbing substance, generated by ejected electrons. The quantity of secondary radiation increases with the applied voltage[10] and the number of atoms encountered (thickness of the material). Fortunately secondary radiation may be greatly reduced by the use of diaphragms, or lead or copper screens. The recently available multimillion-volt apparatus makes it possible to obtain more penetrating (less absorbed) radiation, thereby reducing the secondary effects compared with those from lower-voltage X-radiation.

Additional undesirable radiation causing fogging, but primary in nature, is that proceeding directly from the X-ray tube to the film, without passing through the object. This can be eliminated by shielding technique, using lead shot, lead sheet, or immersing in suitable solutions.

The sensitivity of radiography is influenced also by the focus of the X-ray tube in its geometrical relation to the film and to the location, size and orientation of discontinuities. Although the focal area is fixed, definition can be improved by increasing the distance from tube to film. This expedient is limited because of the corresponding increase necessary in exposure time, since the intensity of X-rays or gamma rays, similar to that of light, decreases inversely as the square of the distance from the source of emission. As the source approaches the film, the exposure angle is enlarged, which induces a nonuniformity of film density. It is, therefore, desirable to use the longest tube-to-film distance consistent with a reasonable exposure period.

Discontinuities may occur in any part of the specimen and may be oriented at any angle to the incident X-rays. As the distance is increased from dicontinuity to film, or the diameter of the discontinuity is decreased, the actual sensitivity is proportionately diminished. Consequently, if imperfections are more likely to exist in a certain section of a casting, this section should be placed adjacent to the film during examination. A longitudinal cavity or crack may necessitate several exposures at different angles so that the void presenting too small a variation in thickness for detection in one direction may be revealed in another where the path of the X-rays coincides approximately with the longitudinal axis of the discontinuity.

The important factors influencing the sensitivity of radiography have been briefly described and the desired practice has been indicated. Various governmental agencies have adopted specifications to insure that a satisfactory technique is employed. Penetrameters made of an alloy of the same density as that to be inspected, and containing synthetic voids or defects, are exposed with the specimen according to certain specifications.

When influential factors are carefully controlled, voids 0.5 to 1.0% of the thickness of an aluminum alloy or steel will be revealed on the radiograph. However, a sensitivity of 2% is relatively easy to obtain and is sufficient to meet the requirements of the various specifications for castings and welds. The significance of these values is that variations of composition or thickness less than the percentage of sensitivity will probably escape detection. Radiography should not be applied in these instances.

Interpretation of Radiographs. A radiograph is a shadow picture of material more or less transparent to radiation. The X-rays darken the film so that regions of lower density, which readily permit penetration, appear dark on the negative in comparison with areas of higher density, which absorb more of the radiation. Thus, a cavity in metals is recorded as a darker area, whereas copper segregation in an aluminum alloy registers as a lighter area.

The general appearance of the familiar discontinuities encountered in castings or welds will be described because of the extensive applications of radiography in these fields. In castings, certain sections that are thinner because of the design, and intentional cavities, such as cored holes, are regions of low density and are revealed as darkened areas. Specimens containing variations in thickness caused by the unintentional absence of metal are also

more transparent, resulting in darkening of the film. Excess metal and inclusions more dense than the base metal appear as light regions. The common casting discontinuities may be recognized on the negative by the following characteristics:*

1 Surface roughness appears as irregular white or dark areas with a smooth contour. The coloration depends on whether the surface protrudes or is depressed. The surface irregularities of the actual casting must be compared carefully with the radiograph and identified before an attempt is made to interpret the internal discontinuities.

2 Gas cavities, blowholes and minute gas porosity appear as well defined, spherical or rounded darkened areas. Hydrogen or other gas porosity in aluminum alloys is represented by round, dark spots and is generally distributed through the section or entire casting. In coarse-grained aluminum alloy castings these voids tend to be curved or elongated.

3 Inclusions such as foreign material, slag, oxide or sand, appear as regular or irregular areas. The areas may vary in intensity and are either lighter or darker than the background, depending on the relative densities.

4 Segregation may be well defined or may appear as mottled areas, either regular or irregular in shape and lighter or darker than the background.

5 Shrinkage cavities and shrinkage porosity (pipe or sponge) are represented by filamentary or dendritic dark regions of irregular dimensions and indistinct outline. These voids are localized. Shrinkage porosity is lacy or honeycombed and not a continuous cavity.

6 Microshrinkage in magnesium alloys appears on a radiograph as dark, feathery streaks or irregular dark patches caused by shrinkage in the grain boundaries.

7 Misruns appear as very prominent darkened areas of variable dimensions with definite smooth outlines where the metal failed to fill the section.

8 Cold shuts are represented by dark lines or bands with variable lengths and definite smooth outlines that tend to be curved (meniscoid). Cold shuts occur where the metal has come together but has failed to unite and the contact surfaces are oxidized.

9 Hot cracks are represented by darkened lines of variable width and often possess numerous branches that follow the outlines of the dendrite. A cold crack, originating from residual or external stresses, is a straight dark line usually continuous throughout its length.

The origin and identification of flaws in steel welds have been studied exhaustively.[11] The discontinuities in order of prevalence of occurrence are: (1) slag inclusions, (2) porosity, (3) cracks, (4) incomplete fusion between the weld and base metal or between two layers of weld metal. All these imperfections are less dense than steel itself and are recorded as darkened regions on the radiograph. With the exception of incomplete fusion, which is represented by a dark line of variable width parallel to the scarf, the discontinuities in steel when recorded on a radiograph, resemble similar discontinuities in sand castings.

The significance of imperfections in steel welds in boilers, pressure vessels and such, has received much attention, and general agreement has been reached on the correlation between their radiographic appearance and the effects on the strength of welds. Standard films illustrating the size, shape and location of permissible or rejectable flaws in steel welds have been prepared by the ASME-API, U. S. Navy and U. S. Army Ordnance,[12] and are used extensively in industry.

Standards for acceptance cannot be so easily formulated for castings, and are expensive and time-consuming to develop. Thus films representing permissible or rejectable discontinuities have been obtained after laborious testing of castings under conditions approximating actual service. The established standards apply specifically to castings of the design tested and not to other types of castings. Nevertheless, progress has been made in establishing standard films for some castings by this procedure. Also, certain types of discontinuities are undesirable in any types of casting. Accordingly, the U. S. Navy[13] has developed acceptance standards for steel castings, and the Army Air Corps, for structural aircraft castings of aluminum and magnesium.[14] The standards are more or less generalized and the appearance of the discontinuities on the radiographs of castings is related to tests approximating service conditions.

Radiographic Applications. In the metal industries, radiography has been used primarily for the inspection of castings and welded products. The examination of wrought metal, such as forged, rolled or drawn sections, is very limited because of the uniformly dense structure and the unlikely existence of flaws large enough to be detected by the radiographic method. Therefore, the commercial value of radiography depends on the nature of the material to be tested.[15] The most extensive applications[16] of radiography to steel, aluminum and magnesium are:

1 For welds.
- (*a*) An aid in the development of welding procedures,
- (*b*) Routine inspection of pressure vessels, boilers and such, according to specification,
- (*c*) Intermittent checking of the quality of less critical products,
- (*d*) Determining the quality of repaired areas.

2 For castings.
- (*a*) An aid in the development of casting technique,
- (*b*) Routine inspection of critical castings,
- (*c*) Percentage or spot examination of less critical castings,
- (*d*) Determining the quality of areas salvaged by welding,
- (*e*) Locating core wires, chaplets and the like in complex castings.

3 For forgings.
- (*a*) An aid in the development of forging practices,
- (*b*) Routine inspection of critical parts. Used only to a limited extent for forgings, because of the very infrequent occurrence of discontinuities of a size detectable by radiography.

4 For assemblies.
- (*a*) Determining location and dimensions of internal components,
- (*b*) Inspecting quality of soldered or brazed joints,
- (*c*) Locating foreign materials, drills and such in complicated assemblies.

5 For plastic and other nonmetallic parts.
- (*a*) In the development of operating procedures.
- (*b*) Routine inspection.

Special Applications. *Fluoroscopy.* Fluoroscopy consists in observing the emergent radiation from an object on a fluorescent screen rather than on a photographic film. This method is used for both routine or percentage inspection and for development of operating technique for aluminum and magnesium castings (up to 1 or 1.5 in. thick) and for plastic parts. Recently, greater screen brightness has been obtained by improvement in fluoroscopic screens, and technique permitting short focal distance. Rotation of the part[17] during exposure makes possible the detection of discontinuities, in certain castings, not revealed by the more sensitive method using X-ray film. The best sensitivity obtainable for an aluminum alloy is 4%. Equipment can be safe, shockproof and highly mechanized by a conveyer system.

Photofluoroscopy. Apparatus is available for photographing on high-contrast film a larger image appearing on a fluoroscopic screen. The film can be enlarged or projected on a screen, thereby improving the sensitivity. This process provides a permanent record and reduces film costs. The sensitivity is intermediate between that of the film and of the fluoroscopic screen; that is, under good conditions in thin sections of an aluminum alloy, 0.5% for film, 3% for photofluoroscopy and 4% for fluoroscopy. Photofluoroscopy is used for routine or percentage inspection of light metal sand and die castings or nonmetallic parts.

Spot Weld Radiography. During the war it was desirable to develop apparatus especially for the examination of numerous spot welds in thin aircraft sheets of the strong aluminum alloys. Low-voltage (20 to 45 kv) apparatus, beryllium-window X-ray tubes and close-fitting tube heads gave good sensitivity in a one-second exposure.[18] An X-ray

* No attempt has been made to present definitions from a particular organization, technical group or governmental agency. It is hoped that the descriptions are sufficiently general to apply to all metal castings.

tube on a long flexible cable, operated by remote control, made possible the production examination of numerous spot welds. Radiographs indicate reliably the strength and quality of spot welds in the aluminum alloys (24S-T4 and 75S-T6) and therefore have been used for both control and development of welding procedures.

Ultra High-Speed Radiography. The trend in industrial radiography has been toward the penetration of greater thicknesses of steel in shorter times. This progress in reducing exposure time is carried to the extreme in ultra high-speed radiography.

A cold-cathode tube has been developed that will pass very high currents, 2000 to 3000 amp, in one millionth of a second.[19] With intensifying screens, thicknesses up to 1 in. of steel can be examined. It is possible to reveal bullets passing through armor plate, jacket failure inside a gun, the explosion of a shell or the internal deformation of a golf ball on impact with the club.

Microradiography. In microradiography thin sections of metal (0.005 in. or less) are exposed at low voltages with a film that can be magnified. The sensitivity is obtained by regulating the voltage in the low range where high contrast is obtainable (8 to 40 kv) or by selecting an X-ray tube with target material appropriate for the alloy to be examined.[20] By variation of target material, chemical constituents can be identified because of the variations in absorption characteristics. Special fine-grained film emulsions make it possible to obtain magnifications of $\times 50$ to 200, thereby recording more detail than in standard radiography. Microradiography has two fields of application: (1) to show minute voids in metals, such as the appearance of fine shrinkage or gas cavities, and (2) to reveal the distribution and appearance of the constituents in alloys. Microradiography has the advantage of distinguishing the structure below the surface without depending on the etching behavior or the hardness of the microconstituents. However, the magnification is much less than that obtainable by metallography.

Gamma Ray Radiography. Gamma rays are also used for radiography. The source may be radium, radon or mesothorium, all of which emit radiation of considerably more penetrating wave length (less contrast) than that of X-rays. Gamma radiation differs from X-rays in several other important qualities. The wave lengths of gamma rays are characteristic of the source and cannot be regulated for contrast or variable thickness. An advantage of the gamma radiation which improves the sensitivity is the small absorption and low scattering power, resulting in appreciably less fogging than that produced by low-voltage X-rays. The net effect of the two compensating factors, lack of scattering and low contrast, is that the sensitivity of the gamma ray is inferior to that of the X-ray for most applications. The sensitivity of gamma ray radiography is between 2 and 5%.

Other important considerations which limit the use of gamma rays in radiography are the expense and time required for testing. Because the rental or purchase of only a small quantity of radium is feasible, exposures of the order of 10 to 16 hr would be required for penetrating steel sections ½ to 6 in. thick. Gamma rays are not directional but are emanated spherically, permitting many specimens to be distributed suitably about the source and examined simultaneously. Even so, the number of exposures during a specific time is relatively small compared with the large number that could be obtained by the X-ray method in the same period.

The gamma radiation is attractive for applications where absence of apparatus and ease of arranging exposures are desired. The technique has been developed and the details are described.[21, 22, 23]

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Magnetic Particle Inspection

By R. R. Moore*

MAGNETIC particle inspection is a nondestructive method of detecting the presence of cracks, laps, bursts, tears, splits, seams, inclusions, segregations, laminations, shrinks, cold shuts, porosity, lack of fusion and similar discontinuities in ferromagnetic materials, such as iron and steel. This method will detect discontinuities that are open to the surface, but too fine to be seen with the naked eye. Magnetic particle inspection will readily detect discontinuities that lie slightly below the surface and, with special technique, will detect discontinuities that are more deeply seated. The location of the discontinuity is indicated and the approximate size and shape are outlined. The method is applicable to billet bars, tubes, forgings, comparatively thick sheet, and bodies that are irregular in shape, such as machine parts and structural members. It is not applicable to nonmagnetic materials.

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Procedure. The work piece to be inspected is magnetized and then covered with fine magnetic particles, or the magnetization and application of the particles may occur simultaneously. The magnetic particles may be held in suspension in a liquid that is flushed over the piece, the piece may be immersed in the suspension, or the particles, in the form of dry powder, may be dusted over the surface of the object. The presence of a discontinuity is disclosed by the formation and adherence of a particle pattern on the surface of the work piece over the discontinuity. This pattern, known as an "indication", assumes the approximate shape of the surface projection

of the discontinuity. A magnetic particle indication of a seam in a connecting rod is shown in Fig. 1 and that of a crack in a crankshaft is shown in Fig. 2.

Development of Indications. The magnetic particles display a preference for adhering only at the particular locations of discontinuities, because the lower magnetic permeability across discontinuities, compared with that of the iron or steel body in which they are located, causes the magnetic field to pass around them, in following the path of least reluctance, as shown in Fig. 3 and 4. When a discontinuity is open to the surface, the magnetic field

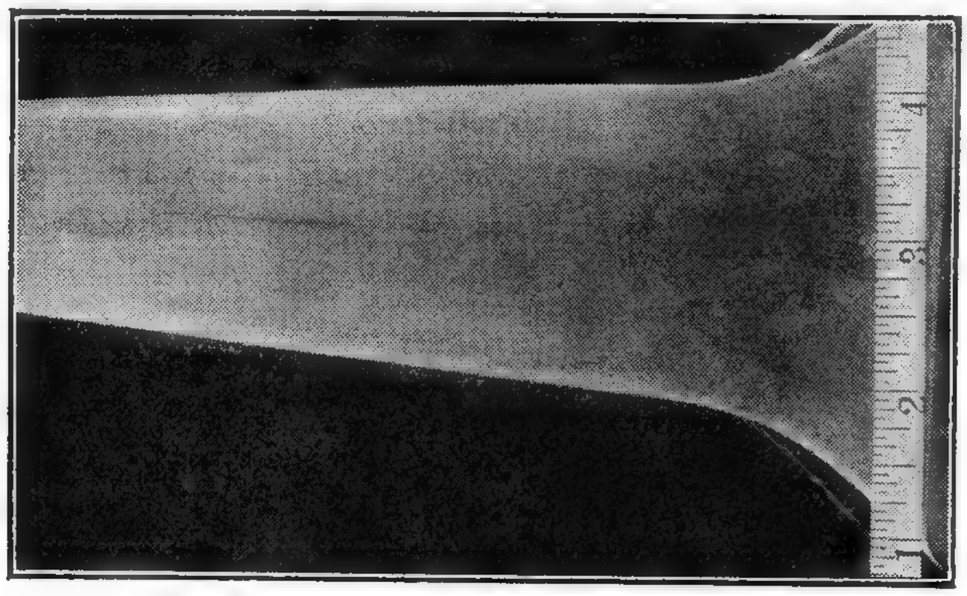


Fig. 1 Magnetic particle indication of a seam

leaks out to the surface and forms local magnetic poles that attract the magnetic particles, thus forming an indication of the approximate shape and size of the discontinuity. When fine discontinuities do not extend to the surface, some flux may still be deflected to the surface, but the leakage is much less and fewer particles are attracted; consequently a weaker indication is obtained. If the discontinuity is too far below the surface, the flux may find a path around the discontinuity without leaking out, and therefore no indication will be obtained. Blowholes and other large discontinuities located below the surface, may give quite large and prominent indications, because of interrupting a larger portion of the magnetic field.

Direction of Magnetic Field. To be detected by this method, a discontinuity must interrupt or distort the magnetic field sufficiently to cause external leakage. Fine, elongated discontinuities, such as inclusions, seams and some cracks, require that the magnetic field be transverse to the long axis of the discontinuity. If the magnetic field is parallel to the long axis, no indication will be obtained, because the thin slice of the magnetic field that is interrupted does not have sufficient magnetizing force to attract the magnetic particles in appreciable quantity. Although indications are obtained when the flux direction is at an angle of less than 90 deg to the discontinuity, the strength of the indication decreases as the angle becomes smaller, as illustrated in Fig. 5.

Because fine discontinuities may exist at any angle of orientation in a metal object, it is necessary to perform magnetic particle inspection by magnetizing in two directions so that the magnetic field of one direction is at 90 deg to that of the other. Small parts are commonly magnetized parallel to the major axis and also at 90 deg to it. Blowholes are more nearly equiaxial and therefore usually require magnetization in only one direction for their detection. Because of their larger size, blowholes generally cause greater distortion of the magnetic field, and are detected at greater depths below the surface than are fine discontinuities. Blowholes have been detected as far as 1 in. below the surface by careful regulation of magnetizing current and indicating medium.

Magnetizing Methods. The magnetic field may be produced in a direction parallel to the long axis of the work piece by placing the piece in a solenoid excited by electric current, so that the long axis of the piece is parallel to the axis of the solenoid. The metal part then becomes the core of an electromagnet and is magnetized by induction from the magnetic field created in the solenoid. Very long articles are magnetized in steps, by moving the solenoid or coil along the length, as shown in Fig. 6. This is referred to as longitudinal magnetization and is used to detect transverse discontinuities in parts of this type. If the work piece is very short, it can be magnetized parallel to any axis by being placed in an appropriate position in the solenoid. Magnetization of this type is hardly "longitudinal" and may be called "bipolar" more appropriately because an external pole is formed at each end of the axis along which it is magnetized. Longitudinal or bipolar magnetization can also be produced by making the work piece a link in a magnetic circuit or by placing it in a magnetic field created by a strong permanent magnet or electromagnet. To magnetize shafts, drums, girders and many other parts too large to be placed in a fixed or permanent solenoid, a flexible electrical cable (about No. 2/0 or 4/0) may be coiled around the part and then a current may be passed through the cable so that it acts temporarily as a solenoid.

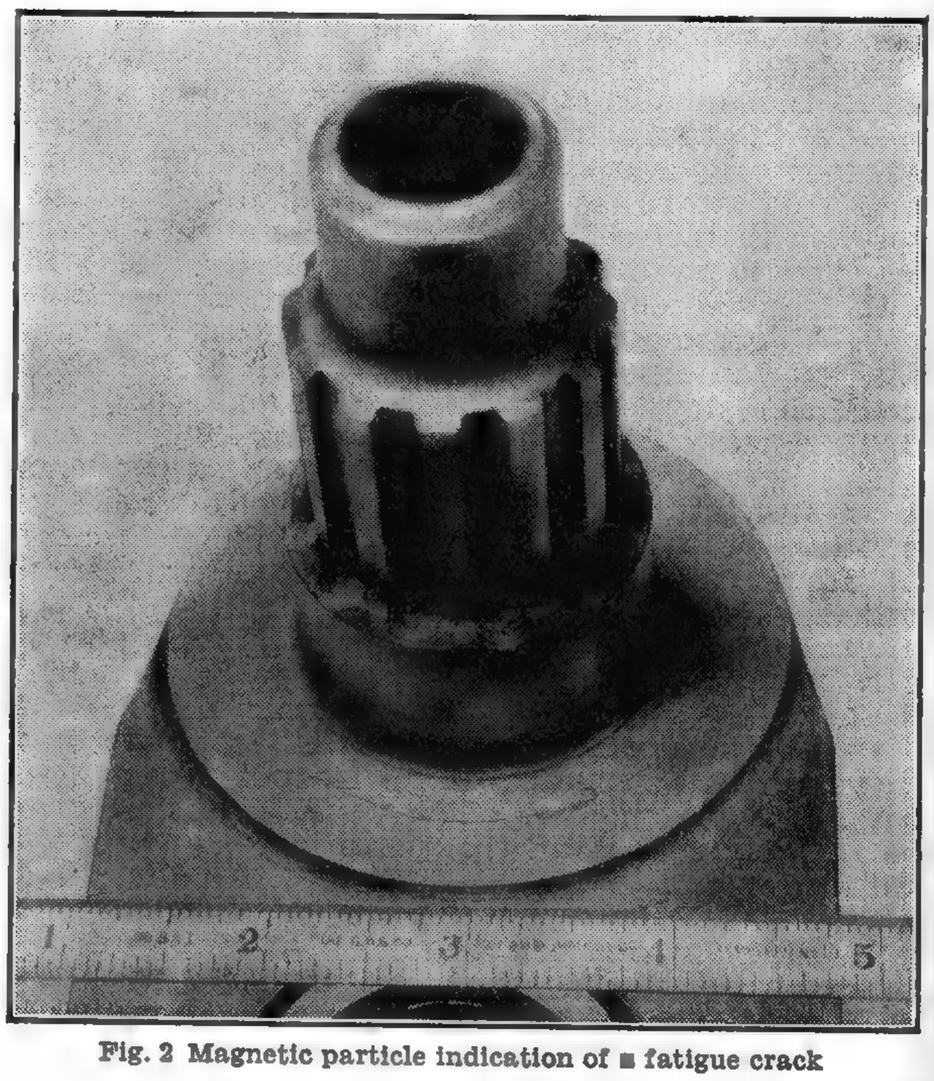


Fig. 2 Magnetic particle indication of a fatigue crack

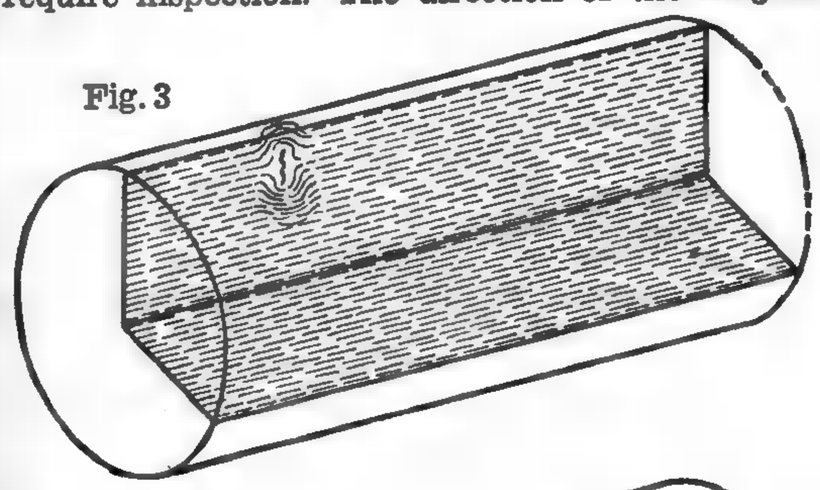
The strength of the magnetic field induced in a part by the solenoid method, depends on the magnetizing force, which is the product when the current is multiplied by the number of turns of the cable or wire. For a given magnetizing force, the induced field depends on the size and shape of the part, and on the magnetic properties of the iron or steel involved.

A magnetic field transverse to the long axis of the work piece is readily produced by passing the magnetizing current through the piece along this axis, as shown in Fig. 7, which illustrates circular magnetization of a crankshaft. The article is magnetized by induction from the magnetic field that is formed in and around any conductor carrying an electric current. The magnetic field is represented by a series of concentric circles centered on the axis of the conductor, as shown in Fig. 4, and often is referred to as "circular magnetization". The magnetic field, though circular in form, is transverse to the axis of the article, and therefore can be used to detect discontinuities that lie approximately in the direction of the axis. To obtain circular magnetization, hollow parts, such as cylinders and piston pins, should be mounted on a conductor bar located on the axis of the part. Then the magnetizing current should be passed through the bar. This procedure is preferable in order to obtain magnetization of the inner surface, because a current through a hollow part does not magnetize the surface of the bore. The strength of the magnetic field induced in a part by passing an electric

current through it, or through a conductor located on its axis, depends on the strength of the current as well as on other factors. The magnetic field induced by a given strength of current depends on the size and shape of the part and on the magnetic properties of the particular iron or steel involved.

The procedure is somewhat different for large castings, forgings or weldments; such large parts cannot be handled in the same type of equipment as that found efficient for small parts. On large pieces, it is common practice to use clamps, leeches or prod-contacts attached to flexible electrical cables, an arrangement that enables the operator to pass the magnetizing current through local areas that require inspection. The direction of the magnetizing

Fig. 3



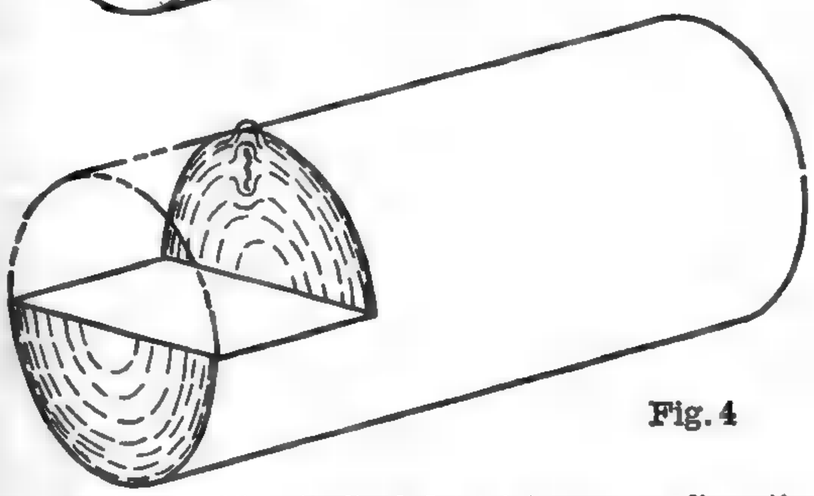


Fig. 4

Fig. 3 Distortion of longitudinal flux at transverse discontinuity
Fig. 4 Distortion of circular flux at longitudinal discontinuity

current is controlled by changing the location of the contacts, and the magnetizing field can be produced in almost any direction desired. In the prod method, the field is usually limited to about 12 in. in length and several inches in width for each passage of current, but by successive contacts, considerable area can be covered. Thus, magnetization can be produced in all directions by the circular method.

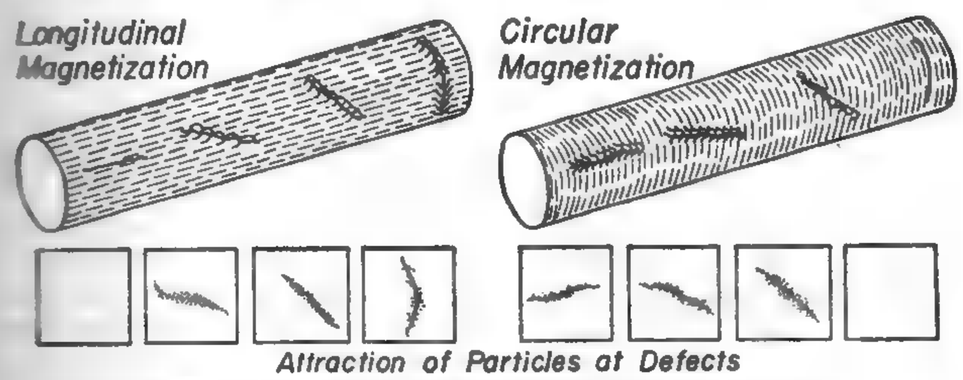


Fig. 5 Effect of direction of flux on strength of magnetic particle indication

Two variations in methods of applying the magnetizing current, relate to its timing with respect to the application of the indicating medium. In the *continuous* method, the indicating medium is applied to the work piece while the magnetizing current is acting. Under these conditions, the strength of the magnetic field induced in the work piece to attract the magnetic particles, is a direct function of the magnetizing current and the permeability of the iron or steel constituting the part. In the *residual* method, the indicating medium is applied after the magnetizing current has been cut off. Therefore, the useful magnetic field is determined by the residual magnetism remaining in the work (always less than that obtained by the continuous method) and depends on the retentivity of the metal, which varies with composition and hardness. Consequently, the residual method is less sensitive than the continuous method, when a particular part is magnetized by means of a given current.

Types of Magnetizing Current. Direct current, alternating current and rectified alternating current are all used for magnetizing. Direct current is more sensitive than alternating current for detecting discontinuities that are not open to the surface. Alternating current will detect discontinuities open to the surface and is used when the detection of this type of discontinuity is of exclusive interest. When alternating current is rectified, it provides a pulsating, surging force that increases the penetration of the magnetic field. In the magnetization of parts that are large in cross section, it has been shown that full-wave three-phase rectified current has greater penetrating effect than direct current from batteries. It is considered that half-wave single-phase rectified current has a penetrating effect at least as great as direct current from batteries. For special problems, permanent magnets of the alnico type have been used on welds and at locations where irregularities make more usual methods difficult.

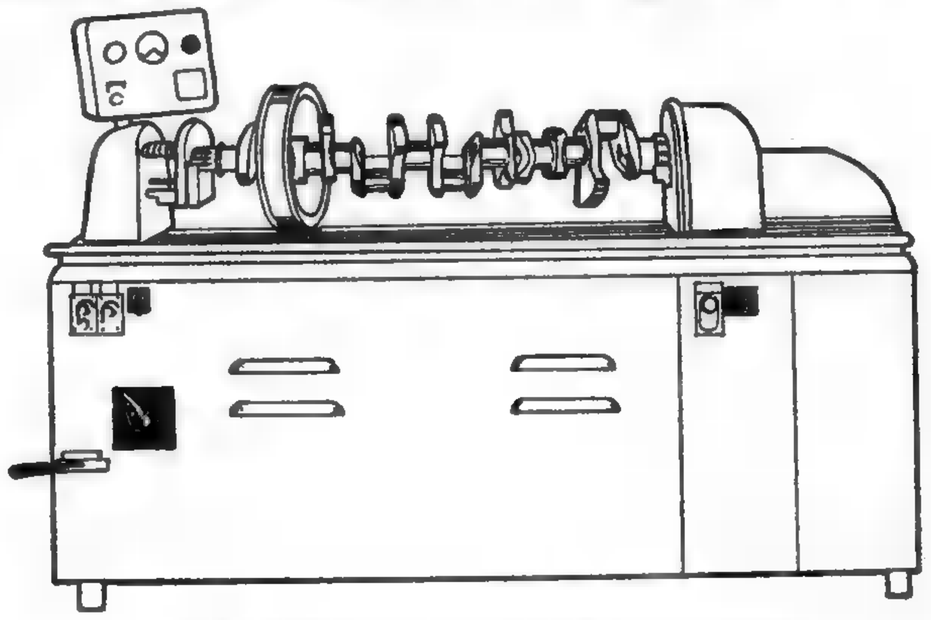


Fig. 6 Magnetizing a crankshaft longitudinally

Strength of Magnetizing Current. The sensitivity of magnetic particle inspection is affected by many factors, including strength of the indicating suspension, time in contact with the suspension, time allowed for indications to form, number of turns in the solenoid, time subject to the magnetizing current, and strength of the magnetizing

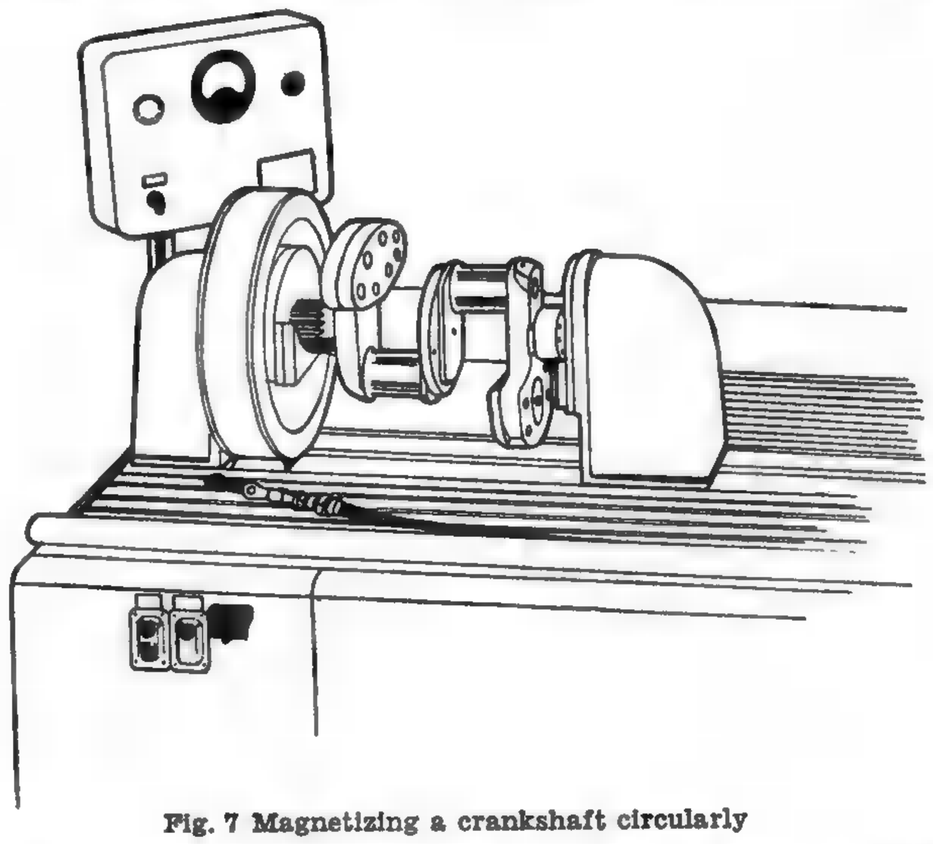


Fig. 7 Magnetizing a crankshaft circularly

current. The strength of the current can be adapted to provide a convenient, flexible control of sensitivity when other factors are kept constant. Therefore, most commercial magnetizing units are equipped with convenient means for adjusting the magnetizing current. The re-

quired current strength varies for different purposes. Usually a greater current strength is required for detecting discontinuities below the surface than for detecting those at the surface, and cracks open to the surface require less current strength than most other types of discontinuities. Cracks open to the surface can be detected with 500 to 800-amp residual circular magnetization in a 1-in. diam bar. If the inspector is interested only in cracks that are much deeper and wider than the smallest crack revealed by 800 amp, then a lower current strength should be used; but if he is interested in finer cracks or inclusions below the surface, a higher current strength should be used. Excessively high magnetizing currents should be avoided, because they cause the magnetic field to leave the metal at locations other than the ones desired. Where this occurs, the indicating powders will stand up in "whiskers", confusing the inspector.

Indicating Methods. One of the most widely used methods of indicating discontinuities is the wet method, in which the indicating medium is a liquid bath, consisting of a suspension of magnetic particles in a light petroleum distillate or a light oil. The liquid vehicle should have a flash point of not less than 140 F and a maximum kinematic viscosity of 3 centistokes at 100 F. The suspension is hosed over the part, or the part is immersed in the suspension, which serves to distribute the magnetic particles uniformly over the metal. The magnetic particles, treated to increase their dispersion and their ability to remain suspended in the liquid, are usually supplied in the form of a paste to be mixed in the liquid vehicle. The pastes are available in black and red colors and give indications of the same colors. The red paste improves visibility on dark surfaces. The usual concentration of solid particles in the suspension is about 1 oz per gal of liquid.

In the dry method, the indicating medium is a fine magnetic powder that is dusted uniformly over the work material by means of a cloth dusting bag, an atomizer or a special spray gun made for this purpose. The magnetic particles are available in black, red, and gray, and give indications in corresponding colors.

A third method often used is the fluorescent wet method, in which the magnetic particles are treated with fluorescent materials, causing them to glow or fluoresce under the action of part of a particular wave-length range of ultraviolet light called "black light". This is often referred to as "fluorescent magnetic particle inspection" and is performed in a manner similar to the wet method, except that the examination for indications is carried out under special lamps that emit "black light". This method is particularly valuable in locating discontinuities in corners, keyways, splines, deep holes and similar locations where illumination is poor. Also, the abrupt changes in cross section that are present in keyways, splines, shoulders, threads and such, cause the formation of nonrelevant or false indications heavy enough to mask the indications of true discontinuities. These heavy indications are developed by leakage from the magnetic field, under high magnetizing currents used to detect fine discontinuities. Fine discontinuities will develop more readily discernible indications when formed from fluorescent magnetic particles than when formed from nonfluorescent magnetic particles. Therefore, in such instances, the magnetizing current should be reduced below the point where nonrelevant indications form, and the fluorescent magnetic particles should be used for bringing out the fine discontinuities. The method is also of value when the color of the nonfluorescent magnetic particles available does not give satisfactory contrast against the surface of the parts being inspected. It is important for the oil vehicle to be nonfluorescent, because otherwise it will give off a confusing background glow, making the detection of indications difficult.

Effect of Protective Coatings. Primers, paints, enamels and similar nonmetallic coatings, as well as coatings of cadmium, copper, tin and zinc do not interfere with the satisfactory performance of magnetic particle inspection, unless the coatings are unusually heavy, or the discontinuities to be detected are unusually small. Chromium and nickel plating will not generally interfere with the formation of indications of cracks open to the surface of the base metal, but will prevent the formation of indications of fine discontinuities, such as inclusions. Because it is more strongly magnetic, nickel plating is more effective than chromium plating in preventing the formation of indications.

Interpretation of Indications. The principle features that distinguish among indications of different types of discontinuities, are shape, sharpness of outline, width, and the height to which the indication has piled up, known as "build-up". The particular value of these features is in distinguishing among different types of discontinuities, rather than in determining the significance of them.

Cracks open to the surface are distinguished by a well-defined sharp pattern, with a definite build-up produced by low magnetizing field strengths in residual.

Seams give indications that are straight, sharp, fine, and often intermittent, showing weaker build-up, and requiring higher magnetizing currents than cracks.

Indications of inclusions below the surface are broader and more fuzzy in outline than cracks or seams. They show minimum build-up, requiring high magnetizing field strength, and often require the use of the continuous method to develop indications.

False Indications. Interpretation of magnetic particle indications is often confused by particle patterns that simulate the appearance of indications of discontinuities when no discontinuities exist. When an internal keyway or spline is cut in a thin-wall shaft, or when a hole is drilled near a surface or edge, the magnetic field changes direction suddenly, in order to pass around the air gap formed by the opening. This causes magnetic field leakage that attracts the magnetic particles to form false indications on the surface behind the gap. When two materials with widely different magnetic properties are joined to form a composite part, an indication develops at the junction and is difficult to distinguish from that of a crack. This occurs when a low-alloy steel or carbon steel is resistance welded to an austenitic steel, and also when weld metal is deposited that has widely different magnetic properties from the base metal. If the structure of the steel contains a large proportion of retained austenite and is scratched or otherwise marked severely enough to cause local transformation, the transformation products display much greater susceptibility to magnetization than does the surrounding matrix. Consequently indications are developed that do not represent discontinuities. When a magnetized steel part is struck by another part, or another piece is dragged over it under pressure, leakages occur in the magnetic field at these places that have been cold worked, and cause indications to appear although no discontinuity exists. These conditions may occur while the parts are being handled or transported during inspection.

Demagnetization. Engine and machine parts that have been strongly magnetized to perform the inspection are usually put through a demagnetizing operation. Otherwise, during service operation, these parts will attract filings, grindings and chips that have not been cleaned out, and steel particles resulting from operational wear, with the result that these particles will cause scoring or galling of bearings and other wearing parts. In aircraft construction, steel parts in the proximity of the airplane compass must be demagnetized to eliminate any effect on the compass.

Demagnetization is usually accomplished by subjecting the work piece to a magnetizing force that is continually reversing in direction and gradually decreasing in strength, so that the hysteresis loop is reduced to virtually nothing. A simple and effective method of accomplishing this is to insert the piece in the field of an alternating current solenoid and gradually to withdraw it from the field. Complicated structures too large to be inserted in a solenoid can be demagnetized, one member at a time, by passing an alternating current through a member and gradually decreasing the strength of the current by means of a current controller. When large masses of iron or steel are involved, alternating current does not have sufficient penetration to demagnetize the piece thoroughly, so it becomes necessary to pass direct current through the metal and gradually to reduce the current to zero while it is undergoing cyclic reversals. Of course, total demagnetization can be accom-

plished by heating the work piece above the transformation temperature range, but this is rarely, if ever, feasible.

Equipment. Equipment for performing magnetic particle inspection is available in numerous types and arrangements. Some units serve only as a source of magnetizing current and are portable, while other units develop the magnetizing current, support the work pieces, contain the indicating medium and provide means for applying it to the work pieces.

Equipment of the latter type, suitable for relatively small parts for aircraft, automotive equipment and small machinery, is shown in Fig. 7, which illustrates a crankshaft supported between the electrical contact heads in position for passing the magnetizing current through the shaft, to produce circular magnetization. The heads are often equipped with different types of fixtures to support the various shapes of work pieces that may require testing. One of the heads is stationary; the other is free to slide in longitudinal guides to accommodate articles of different lengths. The source of the magnetizing current may be batteries, rectifiers, or transformers, located in the cabinet below the grill. The current is thrown on by a pushbutton, generally located on the front of the cabinet, and is cut off automatically after about ½ sec. The desired strength of the magnetizing current is set by using an autotransformer or other suitable means, before throwing on the magnetizing current. The amount of current passing through the part being inspected is indicated on an ammeter, on the instrument panel shown at left rear.

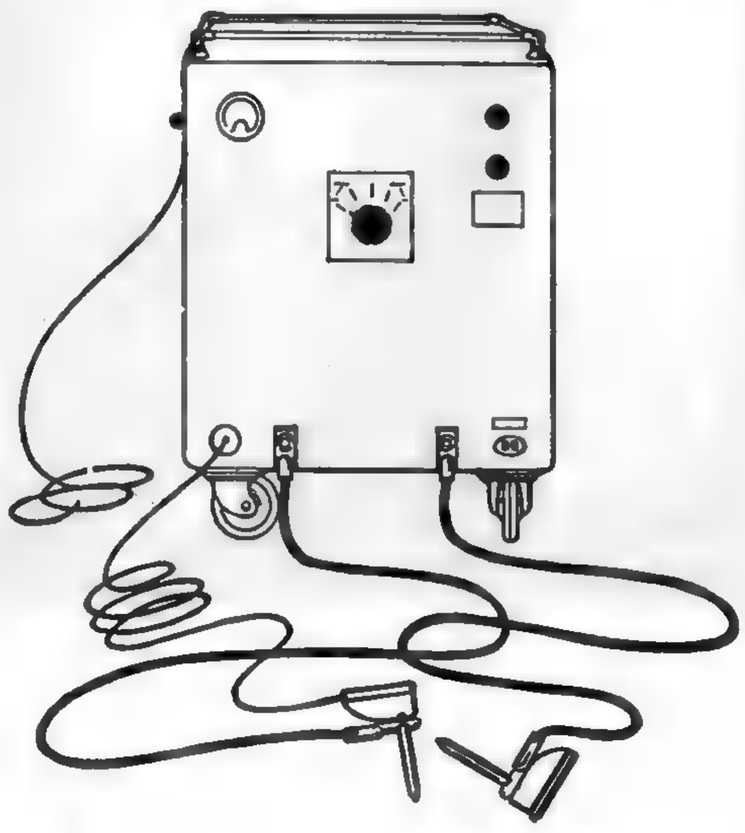


Fig. 8 Portable general-purpose equipment for magnetic particle inspection

The liquid indicating medium is contained in a collecting trough in the cabinet, and is circulated through a hose by means of a pump. The medium is directed over the surface of the work piece by a nozzle on the end of the hose shown lying on the grill in the foreground. The medium drains from the part and falls through the wooden grill into the collecting trough.

When it is desired to produce longitudinal magnetization, the work piece is supported in the coil, as illustrated in Fig. 6, and the magnetizing current is made to pass through the coil. Small parts that do not require the heads for support are simply held or laid in the coil.

The type of equipment described is suitable for general production inspection of the class of parts indicated. Other types of equipment, in which the magnetizing coil is arranged in a vertical position and contains the indicating bath, have been found of particular value for testing cylindrical and other special pieces. When production is intensive, and requires the inspection of thousands of pieces per day, as in the manufacture of bolts, studs, small projectiles, AP shot and such, automatic equipment is preferable. In such equipment, the parts are carried through the magnetizing coil on a conveyer belt, and the indicating medium is applied automatically.

Portable equipment that can be moved near the work pieces, is required for the inspection of large parts, such as railroad axles, crankpins, side rods, wheels, or large structural members, drums, or tanks. Equipment of this type ordinarily serves only as a source of magnetizing current, and carries rectifiers, transformers, or sometimes batteries for this purpose, as well as suitable current controls and meters. Flexible electrical cables carry the magnetizing current to the metal being tested, and are used to produce the magnetizing field by wrapping around the part (solenoid), or through and around drums and tanks; or the ends of the cable may contact the work material by means of prods, clamps, magnetic leeches or other devices, so that the magnetizing current can be passed through.

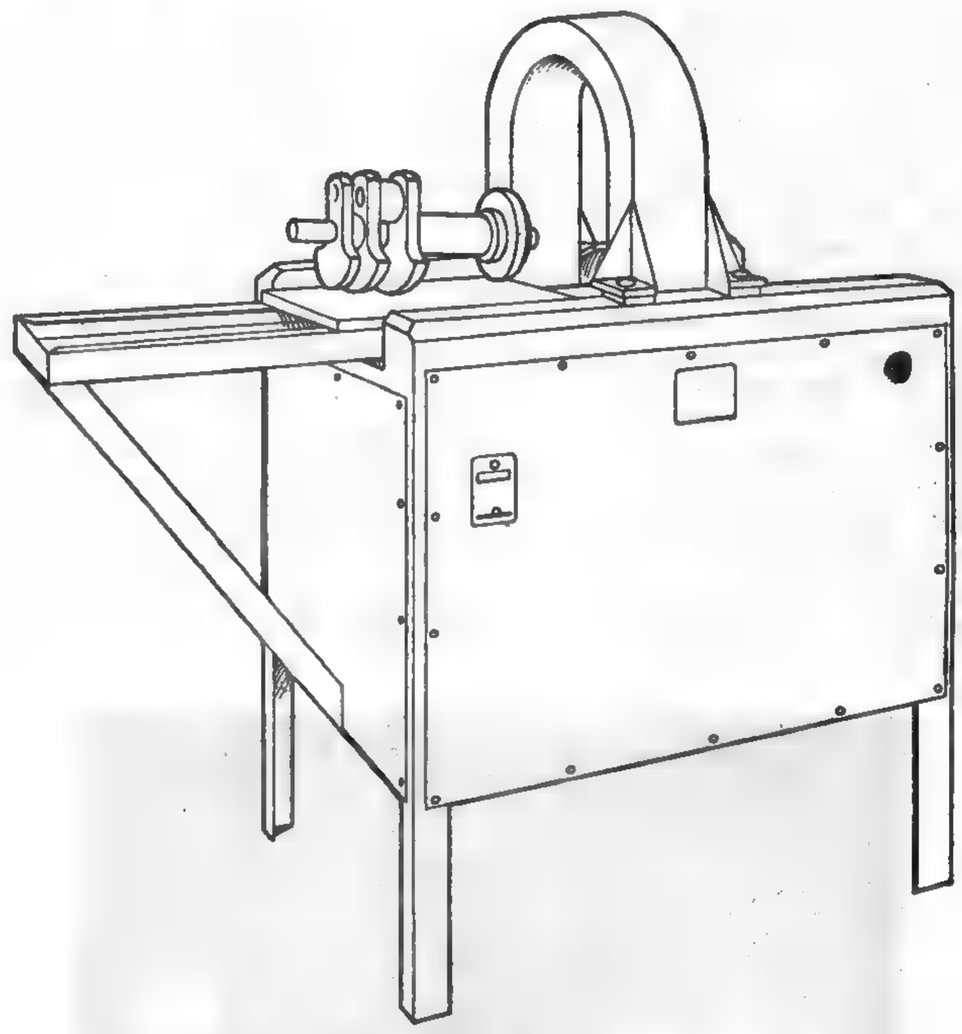


Fig. 9 Narrow-coil demagnetizer with carrier

Large welds are inspected with similar equipment, or the welding machine may be used as a source of magnetizing current. For weld inspection, the ends of the electrical cable are often fitted with prods, which are copper rods mounted in suitably insulated handles. They are used to contact the weld in order to pass the magnetizing current through it, producing circular magnetization. Equipment of this type is shown in Fig. 8.

Demagnetization of small parts is usually carried out by means of an a-c solenoid of suitable size. Figure 9 shows one type of construction. The truck and rails for carrying the part are convenient, although the part could be held in the hand as it is moved in and out of the solenoid. For large work pieces, many of the commercial magnetizing units are equipped to pass an alternating current through a piece and then gradually to reduce the current. This device serves to subject the piece to a reversing and gradually diminishing magnetic field. Other types of equipment, particularly suitable for heavy pieces, provide a reversing direct current that can be reduced gradually.

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Fluorescent Penetrant Inspection

By C. E. Betz* and Greer Ellis*

FLUORESCENT penetrant inspection* is a sensitive, nondestructive way of detecting minute discontinuities open to the surface, such as cracks, shrinkage and pores. The procedure consists of applying fluorescent liquid penetrant, which enters into discontinuities; removing excess penetrant remaining on the surface; and viewing, by fluorescence under near-ultraviolet radiation or black light, minute amounts seeping back out from discontinuities. Penetrant is often aided in re-emerging from discontinuities, by the application of a thin, powdery film of developer material, which acts as a blotter. Indications are brilliant under intense near-ultraviolet light. Lines indicate cracks and similar discontinuities; dots indicate pores. The spread of an indication away from a discontinuity gives a rough evaluation of the size of the discontinuity beneath the surface. Of necessity, inspection is confined to surfaces. Since discontinuities open to the surface are almost always more detrimental to the strength of parts than similar discontinuities not open to the surface, inspection is automatically limited to the most vulnerable regions.

Penetrant Materials. Materials most commonly used are oil-base, water-emulsifiable penetrant, which washes cleanly off surfaces of all types by a forced spray of water; and dry powder developer, dusted on parts after excess penetrant has been removed and the parts have been dried. Other penetrant materials include water-soluble, solvent-base penetrant, particularly useful on ceramics, and oil-base penetrant without emulsifier, the excess of which is removed by solvent action. Another type of developer is a colloidal suspension of powdery materials applied after the removal of excess penetrant and then dried in a film on the part, preferably by heat.

Fig. 1 Indication by fluorescent penetrant of a tight-lipped shrinkage in an aluminum permanent mold casting.

Methods of Inspection. In practice, small parts to be tested are usually briefly immersed in the penetrant and are allowed to drain for a period ranging from a few seconds to about 30 min before the removal of excess penetrant. The duration of this time for draining or penetration depends on the materials being inspected and on the character of the discontinuities being sought; tight fine discontinuities require more time for penetration than coarse open ones. Large objects may be painted or sprayed with penetrant. Local inspection (as of welds) may be made by applying penetrant with a brush to the areas in question.

When the best type of penetrants yet developed are used, no advantage is gained by heating parts or penetrant. The more penetrating components of the penetrant are volatilized with the increase in temperature, so the net gain in sensitivity is negligible.

After the draining, excess penetrant is removed from the surface by washing with water or using a solvent, depending on the type of penetrant employed. At this time and until final inspection is made, care must be taken to keep the cleansed surface uncontaminated by penetrant from the hands of the operator or any other source, in order to avoid confusing, irrelevant fluorescence, resulting from such contamination. Before inspection, parts should be cleaned of any fluorescent matter that might hold or absorb penetrant and result in pseudo indications.

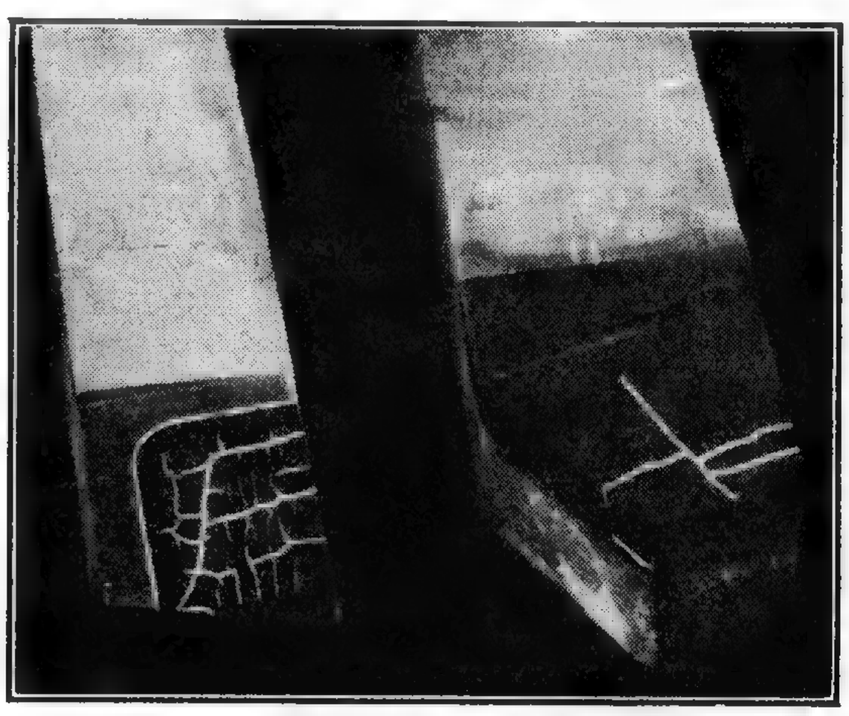

Fig. 2 Carbide-tipped tools with cracks identified positively under black light. Visual inspection, under high-power magnification, fails to disclose many such cracks and confuses scratches with cracks.

If developer of the colloidal suspension type is used, it may be applied to a water-washed wet surface before drying. If dry powder developer is used, parts washed in water are dried immediately after washing. Drying is accomplished preferably by heating, though wiping with a cloth is also satisfactory when dry developer is to be used. For some applications, where the discontinuities sought are rather large and wide open, no developer may be required. Developing time may be from a few seconds to several minutes, depending on the types of discontinuities.

Inspection under black light is carried out preferably with some exclusion of white or visible light. The more minute the discontinuities sought, the more darkness is required. In some applications it is desirable to conduct the inspection in almost complete darkness.

Sensitivity. When the best materials and equipment are being used on *clean* discontinuities open to the surface, the sensitivity of fluorescent penetrant inspection is comparable to that of magnetic particle inspection by the wet method. (*See* page 145.) Unlike magnetic particle inspection, however, fluorescent penetrant inspection is of no value in finding discontinuities that have no connection or opening to the surface. Since cleanliness of discontinuities determines the ease with which the penetrant can enter, it is essential that fluorescent penetrant inspection be used at a point in the manufacturing cycle when discontinuities would be expected to be clean. Otherwise ■ cleaning step must precede the inspection. For example, aluminum cast-

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ings merely cleaned of sand are found to respond very satisfactorily; whereas forgings, which may have die lubricant forced into discontinuities such as laps, may not give proper indications unless a previous cleaning or machining operation removes the included dirt or creates a void beside it.

Applications. Fluorescent penetrant inspection may be applied in locating cracks and shrinkage in castings made of aluminum, magnesium, brass, iron and other metals; cracks in the initial fabrication and regrinding of cemented carbide tools; cracks and pits in welded pressure vessels with nonmagnetic lining, during both fabrication and overhaul periods; cracks in steam and gas turbine blading, new and used; fatigue cracks in nonmagnetic parts of internal combustion engines; cracks in insulators for ceramic spark plugs during several stages in the fabrication of plugs; and seams in tungsten leads for vacuum tubes.

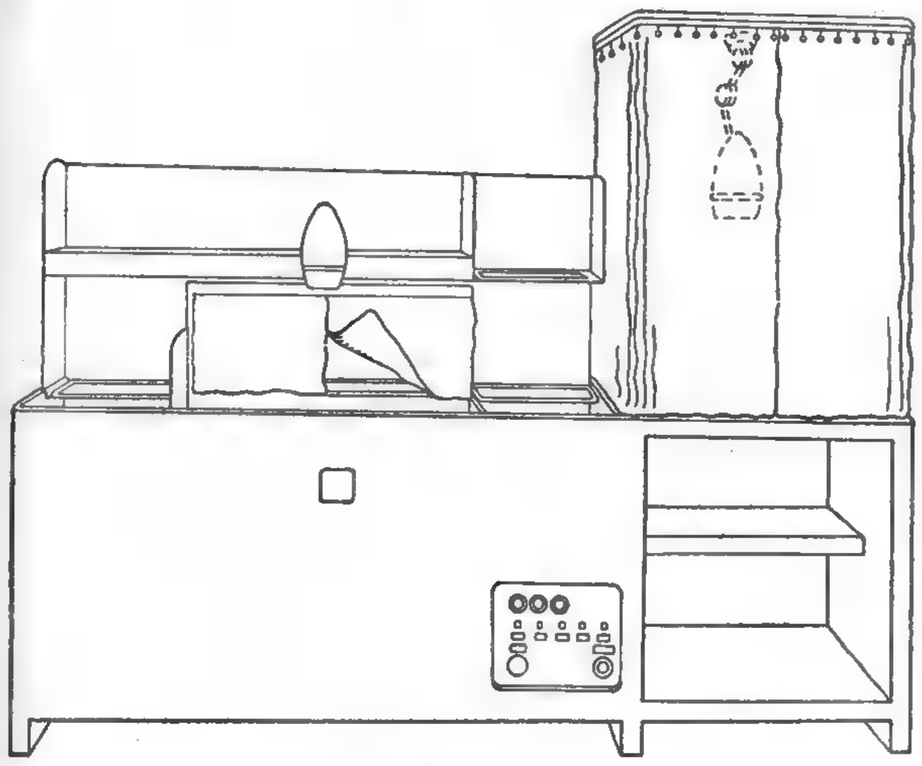

Fig. 3 Complete unit for inspection with fluorescent penetrant, to be used in laboratory work or in production inspection of small parts in moderate quantities. Penetrant dip station at left, drain above, water rinse in center, wet developer in tank at right, drier in rear, and inspection under black light in hood.

Fluorescent penetrant inspection is applicable to castings, particularly as a means to improve quality. For example, shrinkage, especially when it lies in a plane, is a serious defect difficult to locate visually, but immediately apparent when fluorescent penetrant is viewed under black light (*see* Fig. 1). Control of shrinkage is best started during setup experiments. Control should be continued during production, since an unobserved shift of any critical variable may start trouble without being noticed unless regular checks are made. Although light metals constitute the natural field for fluorescent penetrant inspection, simplicity of procedure has made this method useful for testing other materials, such as malleable iron.

Manufacturers and users of carbide-tipped tools have found an important application for fluorescent penetrant inspection, because carbides can be cracked without giving indication of the damage until the tools have failed in service. Although cracks occur most frequently during the grinding operations, their real origin is often traced to high residual stresses imposed by improper mounting. Figure 2 shows typical indications of grinding cracks.

Education of workmen is an important factor in eliminating trouble. One of the best systems is to have the workmen inspect their own work by the fluorescent penetrant method at locations convenient to them. Less time is required for this type of inspection than for a thorough visual examination, and results are much more positive. As an operator corrects his technique, he can taper off the amount of inspection and yet maintain the quality of his work.

Inspection of parts in service, such as pressure vessels and steam turbines, is relatively easy, because the only power needed is a 110-v a-c lighting circuit. Wet rags can be used for washing if water under pressure is not available. Penetrant is applied by spray or brush. Suitable portable sources of black light, such as pistol-grip lights, are powerful enough to allow inspection in daylight, if the operator simply uses his hand and body to shield the area being viewed. Smaller parts from service, such as those from aircraft engines, are inspected for fatigue cracks in permanent equipment.

Expensive parts can often be salvaged by grinding out discontinuities until no further indications appear. Much of the grinding can be done directly under black light, which causes the initial charge of penetrant in a discontinuity to continue glowing while new portions of the discontinuity are uncovered. A final retest through the penetrant cycle is customarily made to assure complete removal of the discontinuity.

The most fruitful use of any method for detecting defects comes during initial experiments, while setting up production procedures. If defects are observed, changes can be made until all troubles are remedied. The next most fruitful use is in continual sampling inspection to make certain that the quality is maintained during production runs. When defects do appear, it is important to be able to check back to the cause quickly and to correct it before much material of low quality is produced. During the emergency period of running down and remedying trouble, it is best to inspect all doubtful material 100%. Fluorescent penetrant inspection, within its scope, lends itself well to all these needs for inspection.

Inspection by Magnetic Analysis Using Measurements of Wave Form Distortion

By T. Zuschlag*

THE demand for better quality steel has stimulated the development of testing procedures that permit more efficient inspection at lower cost. This is particularly true of modern inspection by magnetic analysis to check ferromagnetic articles for uniformity and to detect flaws in steel bars and tubes.

Principles of Operation. Magnetic analysis, in its present state of development, relies on the fact that two specimens of identical composition, dimensions and physical properties possess the same magnetic characteristics and that this relationship makes it possible to ascertain the value of nonmagnetic conditions and properties by means of magnetic measurements. Alternating magnetic fields are utilized as sources of energy; corresponding sections of ferromagnetic materials are exposed to these fields and are systematically tested for changes in magnetic properties by comparative methods of measurement based on continuous procedures for wave analysis. The investigations are carried out with reference to electric standards of comparison that are representative either of a similar section of a standard specimen or of a different section of the same test specimen.

The essential requirement for this type of inspection is the existence of consistent correlations between the conditions of primary interest and the magnetic effects on which the inspection is based. To exploit such correlations successfully, the following circumstances are necessary:

1 The specific condition under examination must affect the magnetic characteristics of the material to be inspected.
2 The change in the magnetic characteristics must distort the alternating magnetic field that is used to investigate the material.
3 The resultant distortion of the alternating magnetic field or of any voltage induced by the field must be measurable and interpretable as an indicator of the condition that caused the deviation in the magnetic characteristics.

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A complete discussion of the first stipulation is found in Spooner, "Properties and Testing of Magnetic Materials", McGraw-Hill Book Co., 1927. The second stipulation is explained extensively in most textbooks on electrical engineering. No comparable references, however, are available for the third stipulation, since it relates to developments not yet adequately described in current technical literature.

Range of Application. Magnetic analysis is the nondestructive inspection by magnetic measurements of ferromagnetic articles for variations in nonmagnetic properties and conditions. This definition covers the testing of uniformly cross-sectioned material such as bars and tubes, as well as that of objects irregularly shaped but of like dimensions, such as small forgings, castings, machined parts and various other items.

The most important problem of inspection by magnetic analysis relates to the magnetic effect of the mechanical stresses normally present in ferromagnetic materials. These stresses change with the type of stress-forming operation and with the grade, heat, shape and dimensions of the material; and they are closely related to such factors as brittleness, case depth and machinability, as well as to the presence of defective sections in otherwise sound specimens. Representing the factual link between variations in mechanical conditions and magnetic characteristics, this relationship is the core of many magnetic test problems, since the efficiency of inspection by magnetic analysis depends largely on the level and the uniformity of the prevailing stress pattern. Thus, a magnetic inspection of annealed material, low in stress, is less efficient than a comparable inspection of material in a stressed state and, in fact, is limited to indicating the uniformity of such physical, chemical or mechanical factors as affect the magnetic characteristics directly. Test results of greater sensitivity are obtained for stressed material, because the inspection is normally concerned with conditions that change the prevailing stress distribution, thus affecting the magnetic characteristics both directly and indirectly. This is true of bars and tubes straightened by machine, and particularly of heat treated material. Cold drawn, stress relieved, hot rolled, and annealed stock, in that order, are less highly stressed and thus less sensitive to investigation of the following conditions and properties: uniformity of grade, heat, heat treatment, processing, cold working, hardness, structure, decarburization, case depth, stress distribution, and such flaws as cracks, seams, slivers, cupping, as well as defective welds in tubing.

The penetration of alternating magnetic fields into ferromagnetic materials is limited even for 60-cycle investigations. This fact makes testing by magnetic analysis a surface inspection method and, in general, prohibits the possibility of locating internal defects such as subsurface cracks and pipes, unless these flaws are linked to variations in the stress pattern at the surface. Similarly, the depth of flaws that can be located by these measurements is primarily a function of the magnitude of the disturbance in the normal distribution of surface stress caused by the defect, and the depth of perceptible flaws varies with the grade, size, shape and processing of the specimen. For cold drawn bars straightened by machine, the minimum depth of intermittent defects that can be detected by these methods is about 0.015 in. per in. diam for round bars and 0.012 in. per in. for hexagonal bars of comparable size.

Commercial inspections that can be carried out by methods of magnetic analysis vary with the type of materials, as indicated in Table I.

Table I. Types of Inspection by Magnetic Analysis

Type of Inspection	Material
Uniformity and *identification* of properties and conditions affecting magnetic characteristics directly	All shapes of ferromagnetic articles of like dimension and in annealed state
directly and indirectly	in stressed state
Detection of flaws	Machined — straightened bars of all shapes, including:
cracks	hot rolled, ground
seams	hot rolled, heat treated
slivers	cold drawn
cuppings	cold drawn, stress relieved
	cold drawn, heat treated
	Seamless tubes
	stress relieved
Welds	Electrically welded tubing
open and weak welds	Butt-welded tubing
burned areas	

Measurement of Distortion of Wave Form. During recent years the number of applications for magnetic analysis tests has been potentially increased by the introduction of investigation methods that possess greater sensitivity, selectivity and resolving power than many of the older test procedures formerly used for purposes of magnetic inspection. As employed in a majority of equipments for production testing, modern inspection by magnetic analysis relies primarily on measurements of wave form distortion to solve test problems.

The basis of these measurements relates to the fact that the wave form of any voltage induced by an alternating magnetic field is distorted by the introduction of ferromagnetic material into the field and that the type and strength of the distortion is characteristic of the inserted material. When different materials are exposed to the same alternating magnetic field, the resultant wave forms differ in many respects, including the properties and conditions mentioned. Although it is not generally possible to correlate a particular wave form with a specific property or condition, many chemical, physical, metallurgical or mechanical variations affect only limited sections of the basic wave cycle and therefore may be investigated by measurements that are restricted to the same, if relatively short, portions of successive wave cycles.

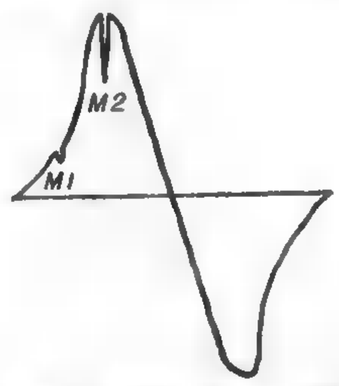

Fig. 1 Typical wave form of secondary voltage, showing superimposed electronic markers.

The utilization of these phenomena for test purposes requires inspection methods that are capable of a "point analysis" of the induced voltage wave. Although various types of laboratory methods suitable for such measurements have been known for some time, it was not until electronic circuits were developed for investigating cyclic distortions that these modern "point" methods proved their utility for commercial testing. (T. Zuschlag, Inspection by Magnetic Analysis, ASTM Bulletin, Aug 1939)

In their present form, electronic point methods are capable of measuring instantaneous amplitude at arbitrarily selected points of any induced voltage wave, by means of circuits with "gated" vacuum tubes. Adaptable for operation at any frequency, these methods are employed preferably for investigations at 60 cycles. The principle of these measurements can be visualized with the help of a cathode-ray oscilloscope pattern, as indicated in Fig. 1. Illustrating a single cycle of alternation, a typically distorted 60-cycle wave of induced or secondary voltage is shown as being inspected at two different phase locations identified by the electronic markers M1 and M2. The positions of the markers represent the locations where the measurements of instantaneous amplitude are carried out: these locations can be shifted to any portion of the voltage wave. When comparative measurements are employed even very slight variations from predetermined or standard voltage values are accurately determined by vacuum-tube voltmeters. This direct method of investigating wave amplitude is known as the "electronic standard method of point investigation" and is used primarily for separation of grades and problems of quality control involving bar and tube inspections.

A modification of this method is employed in connection

with the "mechanical standard" or "two-coil" method of magnetic comparison. Properly used, this arrangement permits the solving of test problems that would normally yield only to interpretation by the oscillograph. However, the most important application of electronic point inspection is for detecting flaws in bar stock and tubing. The method used for this purpose provides for the comparison of a section of the test specimen with another section of the same specimen spaced at some distance. The differential wave resulting from this comparison approximates a straight line with two 180-deg phase-displaced peaks that frequently show violent but meaningless fluctuations because of changes in the stress distribution of the material. The presence of minor flaws, such as shallow seams, does not affect this pattern greatly, even though it may change the shape of the peaks or result in the appearance of a slight additional distortion. Because the magnitude of this additional distortion is often smaller than that of the normal peaks, it would be difficult to detect such variations by means of standard methods of measurement. However, by using point inspection, it is quite feasible to avoid the regions of meaningless peak fluctuations and to investigate only such sections of the differential wave as contain pertinent or significant test information. The "null method" of point inspection is best suited to indicate the start and the end of intermittent defects and is used primarily for purposes of flaw detection.

Commercial Installations. Commercial equipment for magnetic analysis provides for the complete inspection of ferromagnetic articles, except for short sections at the ends. Practical speeds for inspection of bars and tubes range from 100 to 150 ft per min, depending on the diameter and shape of the material, the handling facilities, the standard of inspection and the ability of the operator. Under average conditions it is possible to test about 20 tons of 1-in. rounds in a single 8-hr shift.

Installations for production tests by magnetic analysis are either of the bar-and-tube tester type or of the comparator type. A typical installation for testing bars and tubes comprises a test-coil assembly, a combination indicator and control cabinet and auxiliary arrangements for operating and feeding. The material to be tested is passed through exchangeable secondaries capable of handling stock from ¼ in. to 3¼ in. in diam. The effect of the material on the primary energizing field is analyzed by several electronic point methods operating simultaneously, and the results of this analysis are individually presented for inspection by separate meters or high-speed indicators equipped with neon lights.

Comparator installations employ the mechanical standard method of magnetic comparison and consist of a two-coil assembly and a smaller combination indicator and control cabinet. The differential output wave of the two-coil units can be viewed directly by means of a cathode-ray oscilloscope or can be point analyzed and the result observed by means of a meter and a neon-light indicator.

Installed by a majority of leading steel companies and, during the war, by many plants manufacturing airplane engines, equipments for inspection have checked a large amount of material for flaws and for separation of grades by magnetic analysis, as well as for production and quality specifications. These results were obtained with equipment not incorporating the latest improvements in measuring distortion of wave form; therefore, it is reasonable to believe that the development of these methods will mean further advances in testing by magnetic instruments.

Nondestructive Inspection by Comparisons of High-Frequency Core Losses

By P. E. Cavanagh*

THE theoretical, experimental and practical establishment of useful correlations between the magnetic and electrical properties and the physical properties of metals has demonstrated the possibilities of developing nondestructive methods of comparing physical properties of metals. In particular, the agreement recently reached between fundamental magnetic theory and experimental results has allowed a theoretical explanation of many phenomena which formerly raised doubts as to the validity of using magnetic determinations in this manner.

Principles of Operation. If a metal sample is placed in the field of a test coil that is part of the tuned circuit of an oscillator, energy losses will occur in the metal sample, which will decrease the energy output of the oscillator. Both magnetic and eddy current losses will make up the total core losses in the coil. This principle offers a possible tool, with certain very definite limitations, for quick comparisons of physical properties of metals.

If such an oscillator is to provide useful information, it must be extremely sensitive and yet sufficiently stable for practical purposes. These objectives can best be realized in a frequency range from about 1,000 to 200,000 cycles per second. One commercially available instrument consists of a carefully constructed two-stage oscillator (Fig. 1). The test coil, which is part of the tuned circuit, is bifilarly wound to obtain maximum mutual inductance between the two sections of the oscillator, and to provide self-shielding from outside interference. This coil controls the operating frequency of the oscillator.

The oscillator is essentially a multivibrator. A sensitivity control governs the amount of regenerative feedback and allows adjustment of the initial energy output of the oscillator to any desired level. Core losses, occurring in the field of the test coil, decrease the output of the oscillator. The operating frequency remains constant within narrow limits. In order to stabilize the oscillator when it is operating near zero output, it is modulated by a much lower frequency, usually 330 cycles. The oscillator output is viewed on the screen of a cathode-ray tube. Descriptions of this instrument and its uses may be found in current technical literature.[1,2]

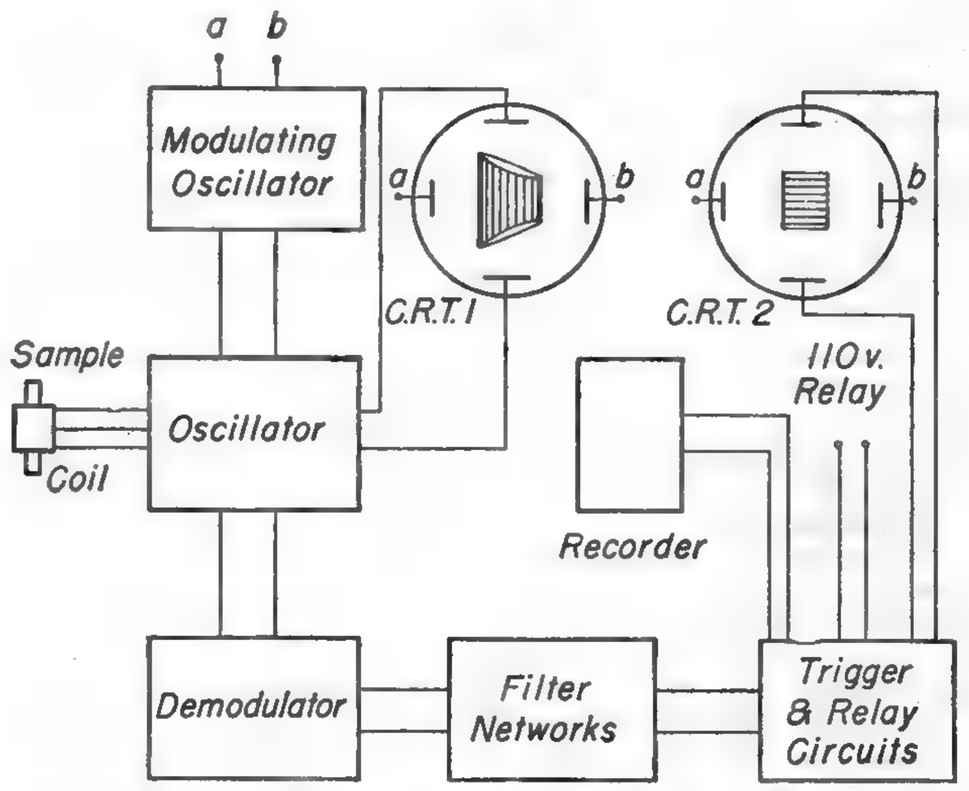

Fig. 1 Cyclograph block diagram

Many magnetic testing instruments in use today provide practical means for inspecting metals for one or more physical properties. The most serious limitation of magnetic testing is the fact that it is sometimes possible, on such an instrument, to obtain the same indication for two widely different pieces of metal. This is to be expected in a few instances, since an increase in one magnetic property may sometimes be exactly balanced by a decrease in

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others. A further complication is that small variations in unimportant physical properties may be accompanied by large changes in magnetic properties.

A major advantage gained by the use of high frequencies is the ease of performing multiple tests at several frequencies. Since it is obviously unreasonable to expect a single test always to evaluate a large number of variables correctly, multiple tests are required for reliable results when this type of testing instrument is used on production lots where many extraneous variables may affect the test.

Various physical properties affect the magnetic and electrical properties to different degrees. Since the proportions of magnetic and electrical losses which make up the total core losses vary with frequency, correlation can be obtained with different sets of physical properties by testing at different frequencies (Fig. 2).

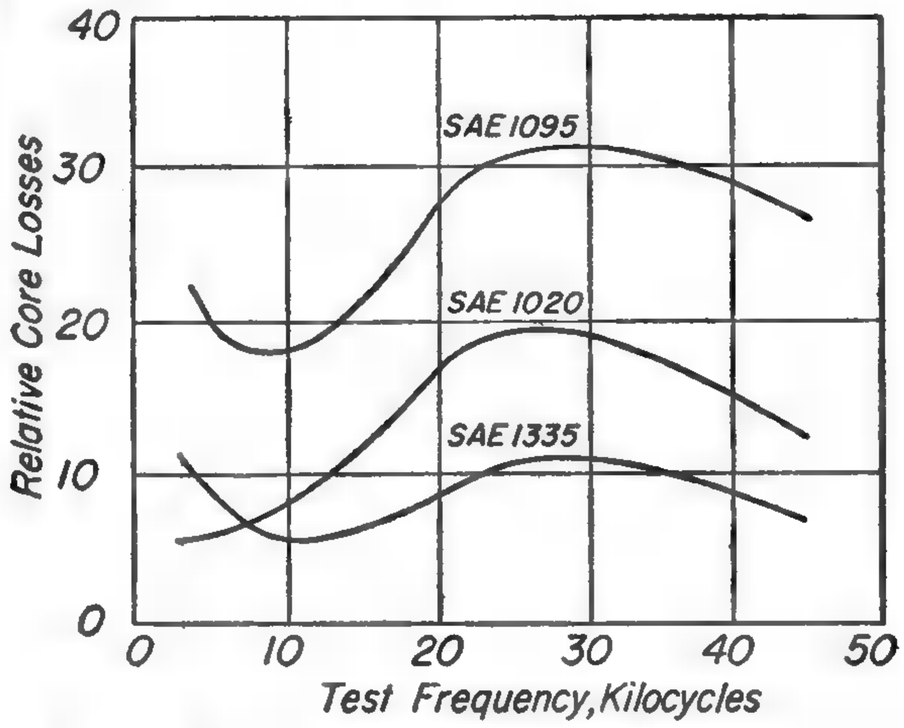

Fig. 2 Changes in relative core losses with test frequency. Excluding other factors 25 kc would be optimum test frequency; 7 kc would be entirely useless for separating these three steels.

Choice of Test Frequencies. In the lower range of test frequencies, from 1,000 to 10,000 cycles, the test flux penetrates a metal sample to a considerable distance and an average evaluation of the properties of the piece is obtained. At higher frequencies or with very large diameters, the test flux is confined to the material near the surface of the metal piece. This allows examination of the surface layers independent of the properties of the core material beneath the surface.

By use of auxiliary circuits, the output of the oscillator may be made to operate automatic rejection relays, which will throw out material not within specified limits. The rate of automatic inspection may be as high as five pieces per second for small metal parts.

Cracks and flaws do not affect the output of the instrument to any significant degree, except in certain instances. The test coil is designed to minimize the effect of discontinuities so that their presence does not influence the comparison of physical properties. Variations of approximately 10% in mass do not interfere with the results of the test.

Practical Uses. High-frequency core losses may be said to compare only two characteristics of metals. If the structure or stresses in a sample are different from those of a standard, this fact will be indicated by a change in the total core losses. The magnitude of change that is detectable depends on the sensitivity of the instrument used.

It follows that where this method is used to distinguish between metals that differ in chemical composition, the difference in composition, in order to be detectable, must produce some significant change in physical properties or structure. In general, a sufficiently sensitive instrument will readily distinguish among the commonly used grades of SAE and tool steels. On the other hand, the instrument would not be expected to distinguish between steels differing only by a small amount of sulfur. Furthermore, any change in composition is most easily detected in the stage of heat treating at which it produces the greatest difference in physical properties or structure. The same rules hold for ferrous and nonferrous metals.

Since a change in structure is usually accompanied by a difference in penetration hardness, it is sometimes possible to use high-frequency methods for acceptance tests of metal parts within certain limits of hardness. The test gives an over-all average for the metal within the test coil, so that good correlation with Rockwell hardness will be obtained only when the structure is extremely uniform or when Rockwell hardness measurements are integrated throughout the volume that is being inspected.

In order to obtain practical correlation with penetration hardness, extraneous variables must be reasonably constant. It is possible to conduct preliminary tests at a suitable test frequency; thus groups of pieces sufficiently alike in extraneous variables may be segregated from production so that inspection for hardness can be carried out successfully on each group at another test frequency. If too many extraneous variables are present, this procedure becomes too complicated to be practical and the instrument does not provide a suitable method for inspecting production.

These same comments apply to inspection of malleable castings for detection of an underannealed condition, and to all tests that have as their objective the selection of a certain desired structure which may be within certain limits of machinability, hardness or composition.

Inspection of Surface Layers. The use of tests at higher frequencies provides practical methods for comparing case depths and plating thicknesses. The test frequency is chosen so that the flux is confined to the area of the case or plating. Changes in case depth or plating thickness will affect the total core losses.

It is usually essential that preliminary tests be made on case-hardened parts to insure that all parts, in a group being compared for case depth, are sufficiently alike in extraneous variables to allow evaluation of case depth.

Since the relationship between case depth and core losses depends primarily on flux penetration, it will hold over only a certain range of case depth. In practice, this means that the high-frequency method of comparing case depths may be successful in grading parts within the range from 0.010 to 0.040 in., but that it will not segregate successfully parts with a greater case-depth range of 0.10 to 0.90 in.

The accuracy attained in comparing plating thicknesses is generally about 10% of the total plating thickness. A variation of 10% can be detected regardless of the total plating thickness, as long as the test frequency is properly chosen to penetrate just beyond the junction of plating metal and base material.

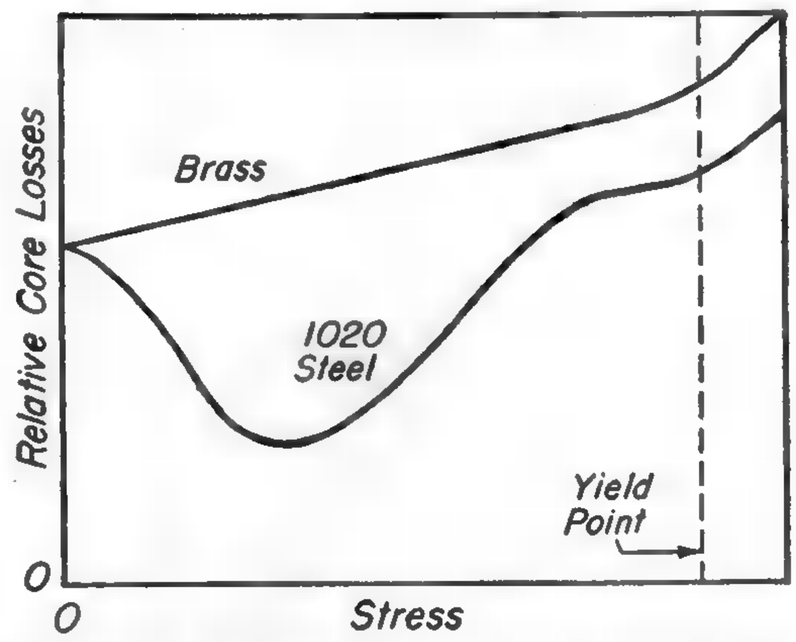

Fig. 3 Change in core losses in magnetic and nonmagnetic metals as tensional stress is increased. Tests on standard ½-in. diam tensile specimens mounted in tension test machine. Instrument reading decreases as core losses increase.

Stress Comparisons. Any distortion of the crystal structure in metal will produce some effect on the magnetic properties of a ferromagnetic material. Whether this change is measurable or not is a practical problem. The theoretical relationships between different types of stresses and magnetic properties have been established by several investigators.[3,4,5] Stresses in a nonmagnetic material will change the electrical resistivity. The manner in which total high-frequency core losses vary with stress is shown in Fig. 3. In this field of application, high-frequency core

losses may be used to compare stresses set up during quenching or cold working. Abnormally high residual stresses, which may cause cracking or premature failure, can be detected.

There are some interesting applications of this method for the detection of the beginning of plastic deformation. Practical use has been made of the fact that there will be a different relationship between an increase in applied stress and the resulting increase in core losses before and after a metal part has undergone plastic deformation.

Detection of Cracks and Flaws. As stated previously, circuits similar to that of Fig. 1 are not appreciably affected by cracks and flaws except in certain cases. If a radial crack extends completely through a ring-shaped sample, it can be detected easily by such an instrument.

Special testing arrangements have been used to locate cracks by designing eccentric test coils in which the sample is rotated. As a crack is brought into the field of the test coil, a sudden change in eddy-current losses will cause a large change in instrument reading. Several instruments use variations of this principle. In some instances, the sample may be rotated in a constant magnetic field. A small stationary pickup coil is placed beside the rotating sample and generates a surge of current each time a crack or flaw passes by. Tuned auxiliary circuits are used to emphasize this signal and give an indication of the presence of a crack or flaw.

Several types of radio-frequency crack detectors are also in use. These instruments depend on the large change in eddy-current losses caused by surface cracks in metal samples inserted in the test coil. The most successful type uses this change in core losses to change the frequency of one oscillator, which is then compared or "beat" against the standard oscillator.[6]

The only advantage of these methods is in the rapid inspection of great numbers of small parts. The results obtained are no better than those obtained by magnetic particle inspection or by low-frequency instruments for detecting cracks.

Applications. Practical uses of high-frequency test instruments are being made in many fields. The practical range of sample sizes is from a minimum of about $\frac{1}{16}$-in. diam to a maximum of 2 to 3 ft in some special instances. The portion of the samples within the field of the test coil must have the same dimensions within usual manufacturing limits. Since the portion of the sample that lies outside the field of the test coil does not influence the test, a bar 2 ft long might be compared with another bar 24 ft long, provided they have the same diameter.

Where irregularly shaped castings or forgings are tested, they must all be passed through a test coil in the same orientation. Local tests can be made by designing coils that will limit the test field to some portion of the specimen in exactly the way in which special coils are used for local induction heating.

Industrial uses of this type of equipment have included the following representative operations:

1 More than a million bolts were sorted that had been fabricated from two SAE steels, 1012 and 4037, because of an accidental mix-up. The proper steel was 4037. The hardened bolts were sorted automatically into the two types present, at the rate of 2 per sec.
2 About 12,000 lb of SAE 52100 in the form of ⅝-in. bar stock was inspected to segregate fully spheroidized from partially pearlitic stock.
3 Various sizes of ball bearing races made of SAE 52100 steel were tested to detect excessive grain growth caused by overheating in forging.
4 About 90,000 small copper cylinders were sorted into satisfactory soft specimens of Rockwell 15-T 80 and lower, and hard underannealed cylinders harder than Rockwell 15-T 80.
5 Extruded cylinder-head bolts were inspected to detect those having such high stresses in the heads that they would crack when tightened in the block.

Methods of Use. In industry, there are three general ways in which this method of inspection has been used.

Salvaging. Magnetic testing can very rapidly and cheaply salvage satisfactory parts from a mixture of large quantities of good and bad pieces.

Inspection. Magnetic testing can be used to inspect production 100%. Since this is a nondestructive test, it does not harm the pieces in any way and its high speed of operation makes feasible the inspection of enormous quantities of such articles as bolts, bearings, small castings and stampings.

Process Control. The most intelligent use of such instruments is for process control. The instrument can be installed immediately after some critical operation in the manufacturing process. Satisfactory pieces will give a reading within a certain specified range. If one piece is detected that does not give the expected reading, the manufacturing process can be immediately checked. This prevents the production of large quantities of unsatisfactory pieces that later would be rejected.

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Electric Inspection of Tubing and Bar Stock

By W. E. Habig*

THE objective of electric inspection of tubing and bar stock is to detect defects, such as seams, to the exclusion of all variables considered harmless. This testing is accomplished by inducing electric current to flow within the material and by measuring the degree and extent to which the current deviates from its normal path because of the presence of a defect.

The instrument to be described was designed to detect seams of various depths, without indicating variations either in chemical composition, metallurgical structure, stress concentrations or magnetic permeability.

Principle of Operation. *Excitation.* Figure 1 shows the basic principle of operation. Circumferential alternating currents are induced in the material placed within the coil, by the alternating flux within the exciter coil, which is energized by alternating current of selected frequency. These induced currents, distributed near the surface of the material, set up a magnetic field opposing the magnetic field of the exciter. The flux density at any point between the coil and the material is therefore a function of the resistance of the material and of the distance from the mean path of the current within the material.

Detection. The detection and measurement of the magnetic flux distortion are effected by means of search coils located within the magnetic flux and in close proximity to the material. The voltage induced in the search coil in an area of good material is compared with that induced in a coil in a defective area. For a searching unit it has been found most practical to use two or more coils in balanced opposition, so displaced that for the particular type of defect to be detected, one will be in a field of uniform flux while the other is adjacent to the defect. When both coils are adjacent to sound material, the voltages induced in them are equal, and since they are connected in electrical opposition, the output voltage is zero. A change of flux in one coil, because of a defect, unbalances the system, resulting in a differential output voltage, which is amplified and made to operate a signal lamp or other auxiliary equipment. The coils are so arranged that they compare the induced voltages around the bar circumferentially at numerous points and hence compare the soundness of the surface around the material rather than along it (a

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patented arrangement). Hence, a continuous and uniform defect, such as a long seam, would be detected by this arrangement as long as its depth does not exceed that of the current penetration, whereas it would be neglected by any system that compared conditions along the material.

Elimination of Indications Caused by Stress. Indications from symmetrically displaced stress concentrations are also eliminated by the patented arrangement for locating the search coils as partially described above.

Permeability Effects. False indications from permeability variations in ferrous materials are eliminated by another arrangement for saturating the material with d-c flux.

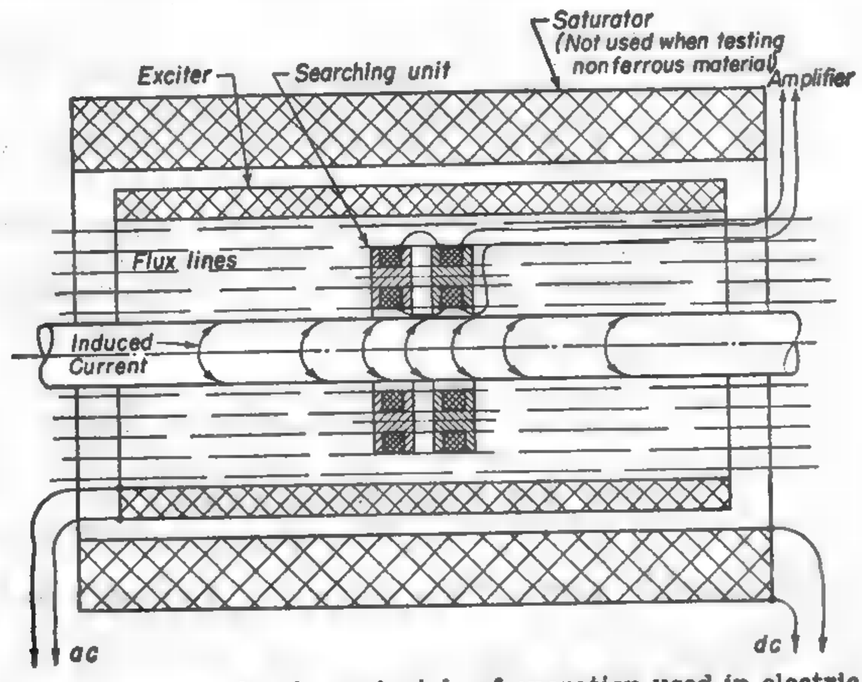

Fig. 1 Diagram showing principle of operation used in electric inspection of tubing and bar stock.

Depth of Penetration. The current induced in the material flows around it circumferentially in a thin layer near the surface, in accordance with the well-known phenomena of "skin effect". The current density varies exponentially from the surface to the center and is a function of the frequency of the exciting voltage. Since there is no clearly defined layer, the depth of penetration is considered to be the distance from the surface at which the current density drops to 37% of its value at the surface, as given by the formula:

$$D = 1400\sqrt{\frac{\rho}{\mu f}}$$

D = depth of penetration (inches)
ρ = resistivity (ohm-cm)
μ = magnetic permeability (for nonmagnetic materials = 1)
f = frequency (cycles per second)

The above formula is valid only as a first approximation, but will give reasonable results for the condition where the wall thickness is much greater than D. With d-c saturation as shown in Fig. 1, the permeability of such highly magnetic materials as magnetic steel, will be reduced to between 1 and 4. For practical purposes most magnetic materials will behave as nonmagnetic materials and the depth of current penetration can be calculated using $\mu = 1$. If the reader is interested in finding the penetration in magnetic material the permeability of which is known to be greater than 1 at saturation, he can use the data of Fig. 2 by merely dividing the result by the square root of the known permeability. It can be seen that as the resistance of the material increases, the frequency must be increased in order to maintain equivalent current density at the surface and, thereby, maximum sensitivity.

Conditions Affecting Electric Inspection. There are many conditions that cause variations in the magnetic flux around the material by currents flowing within it, namely: (*a*) defects consisting of seams, fissures or discontinuities with principal dimension perpendicular to the direction of flow of current; (*b*) stress concentrations within the material, caused by bending, cold working and similar operations; (*c*) variations in chemical composition, in successive pieces or lots; (*d*) permeability variations in ferrous materials, caused by variation in chemical composition, heat treatment or stress; (*e*) surface conditions, such as pitting, rust, checking and the like; (*f*) segregation, spheroidization, hardness and other metallurgical conditions.

All the above are measureable in the laboratory, but commercial equipment has been designed to reduce indications, from all causes except defects, to a negligible level. In order to measure any one of the conditions accurately, it is necessary either to isolate it or to eliminate all the others, employing electrical means or metallurgical treatment of the material. Seams, fissures and discontinuities,

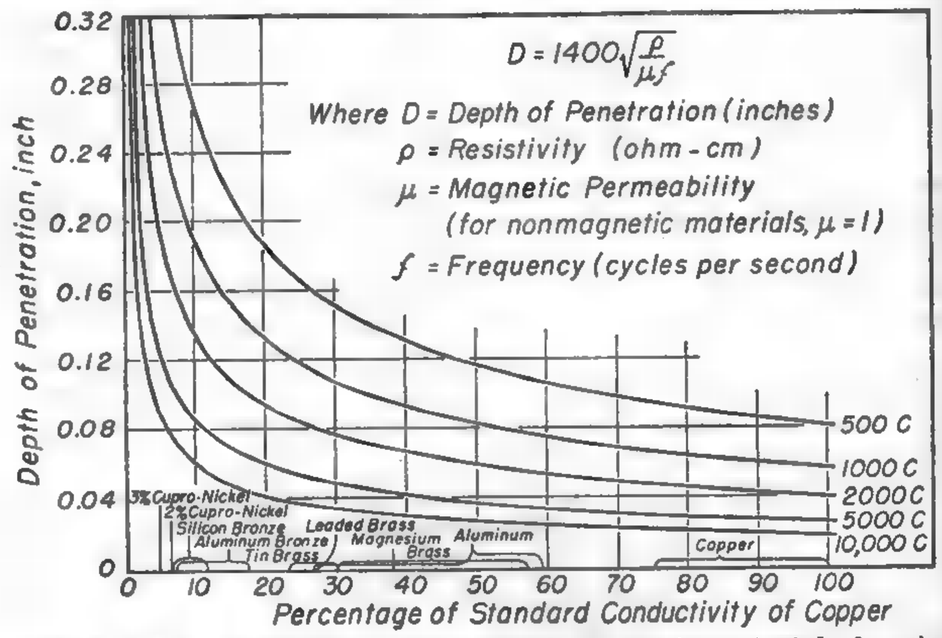

Fig. 2 Depth of penetration of induced current in material of various conductivities at 500, 1000, 2000, 5000 and 10,000-cycle exciting voltage frequencies.

as described, can readily be isolated electrically except for handling marks and dents, which are usually surrounded by nonsymmetrically displaced stress concentrations unless the material has been stress relieved after the introduction of the dents. Marks of this nature give large indications because of the extent of the stress condition. Therefore it is necessary to examine each indication, in order to insure against rejection of good material. There is naturally a limit to how near to the end of a given specimen testing can be accomplished before the end effects mark out any defect present. Experience has shown that good results can be obtained within 2½ in. of the end of a single bar or rod. With abutted ends, testing close to the junction depends on the ability of the operator to observe the flashing of the indicating light and the speed of travel of the material being tested. The junction at the ends of abutted material will cause the light to flash once. Assuming that the operator can distinguish an additional flash occurring 1/10 sec either earlier or later, testing would be continuous up to the following distances from the end of the material:

Speed, ft per min	160	120	80	40
Distance from end, in.	3.2	2.4	1.6	0.8

Size of Defect Detectable. The minimum depth of seam detachable in any given material depends on its surface condition. It has been found that several shallow seams or pits, displaced circumferentially about the material, may create signals equal to that from a single seam of greater depth. Therefore, if the material is badly pitted or checked over its entire length, the sensitivity must be reduced to the level at which signals from the pitting or checked condition are not indicated. This automatically limits the minimum depth of defect detectable in that material. In ground surface stock it is possible to detect seams of the order of 0.005 in. deep, whereas in most commercially finished stock an attempt to detect flaws less than 0.032 in. deep may result in excessive false indications caused by otherwise harmless surface conditions. Some special instances have been recorded where commercial testing has successfully revealed seams of a maximum depth from 0.010 to 0.020 in. without excessive indications. However, the smallest defect which experience has shown to be universally detectable is ⅛ in. long by 0.032 in. deep, lying within $\frac{1}{16}$ in. of the surface.

Supersonic Testing

By Floyd A. Firestone*

If a piece of metal is struck by a hammer, it will radiate certain audible notes of which the pitch and damping may be influenced by the presence of internal flaws. However, this ancient technique of hammering and listening is useful only for the determination of large flaws. A more refined technique consists in transmitting into the metal part to be inspected, sound waves with frequency so high (for example, 5,000,000 cycles per sec) and wave length so short (for example, $\frac{1}{16}$ in.) that a beam of sound waves can be sent through the piece, and will have properties similar to those of a beam of light. Large flaws will cast an acoustical shadow on the face of the piece opposite the face through which the waves entered. Small flaws can be detected by measuring the small amount of sound energy that they reflect back to the sending point. Distances to flaws, or to inaccessible faces, can be measured by measuring the time of flight of the waves, as in radar. Average grain size can be measured by measuring the attenuation or scattering of the waves. Practical equipment is now available for making such determinations in the production inspection of parts.

A supersonic wave is an elastic wave of higher than audible frequency. The properties of the wave that are useful for inspection and measurement derive not from the inaudibility but from the shortness of wave length. Air transmits only one type of sound wave (longitudinal) but a solid part will transmit three wave types if the wave length is short in comparison with the smallest dimension of the part. These types of wave are, namely: longitudinal waves, which have particle displacements in the direction of propagation (velocity in steel, 256,000 in. per sec); shear waves, which have particle displacements at right angles to the direction of propagation (velocity in steel, 128,000 in. per sec); Rayleigh waves, which travel only on the surface of the part and are somewhat similar to waves of short wave length on the surface of water, except that the particle displacement in Rayleigh waves penetrates beneath the surface for a distance approximately equal to the wave length (velocity in steel, 118,000 in. per sec).

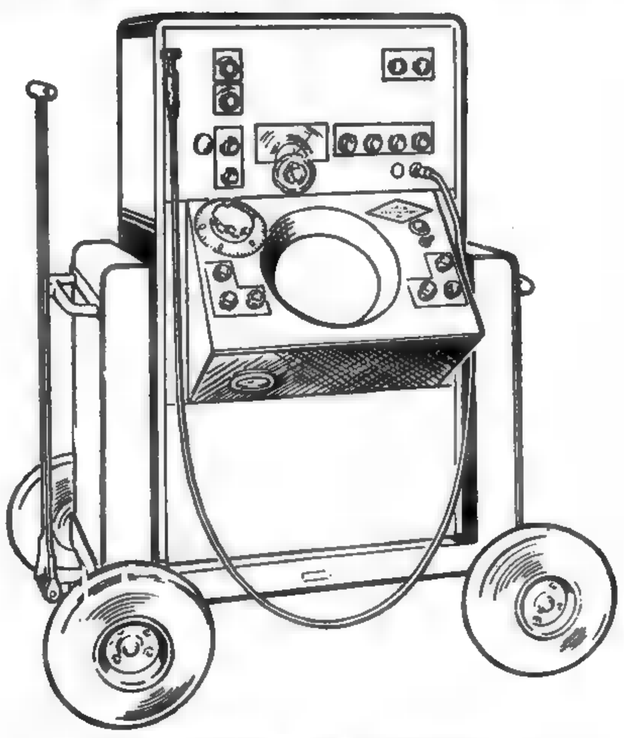

Fig. 1 Supersonic reflectoscope

If the wave length is comparable with some dimension of the part, still other wave types may be propagated, and in some instances may have useful properties. The longitudinal wave type first mentioned is the one generally used.

Supersonic waves of the desired type are radiated and detected by means of piezoelectric crystals—usually quartz of chosen cut and shape—which may be touched to the oiled surface of the part; or the sending and receiving crystals may be immersed in a tank of water, while the part to be inspected is placed in the sound beam in the water. Specific techniques are described in the references.

The simplest forms of supersonic equipment send a continuous stream of waves through the part under test. These can detect flaws large enough to cast a discernible acoustical shadow on the opposite face of the piece, or can measure accurately the thickness of sheet material by establishing resonance through it.

Another form of equipment (Fig. 1) sends into the part a wave train consisting of a few waves that are radiated in a few millionths of a second. Reflections of this train of waves from very small flaws or from the opposite side of the part are observed on a cathode-ray tube. This is the principle of the *supersonic reflectoscope*[1,2,3,8] (Fig. 2).

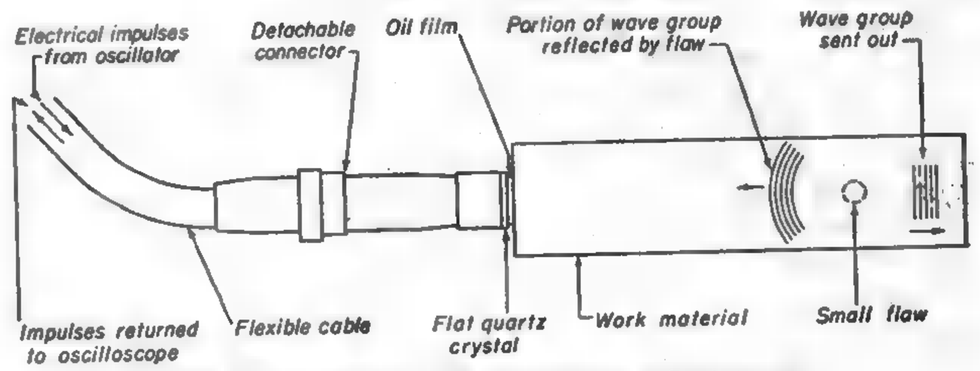

Fig. 2 Principle of the supersonic reflectoscope

Supersonic waves are interrupted wherever the solid material has a discontinuity, however thin; they are reflected from any abrupt change of density or elasticity. The velocity of propagation of the waves depends on average density and elasticity; the time of flight is proportional to the distance traversed; the attenuation of the waves (loss of amplitude with distance traveled) depends on grain size and composition. When the material has different elastic constants in different directions (that is, when it possesses elastic aeolotropy) longitudinal and Rayleigh waves have velocities of propagation that depend on the direction in which they travel through the part, while the velocity of shear waves further depends on the orientation of the plane of vibration around the direction of propagation. These are the basic physical facts utilized in supersonic determination of the condition of the interior of a metal part.

Possible Uses. *Determination and Location of Small Flaws.* When the supersonic reflectoscope is used, its crystal on the end of a flexible cable is touched to the surface of the part, and the presence and distance of the flaw from the surface are indicated at once on the screen of the cathode-ray tube. Approximately 20 ft of metal can be penetrated. Within a few inches from the contacting point, a spherical void 0.02 in. in diam can be detected, and at a distance of 10 ft, a sphere 0.2 in. in diam gives a plain indication, under average conditions. Under favorable conditions, with clean metal of small grain size, holes as small as 0.001 in. in diam have been detected, but dirty metal or unfavorable structure can yield a background of reflection that may reduce the sensitivity far below that mentioned in the previous sentence. Roughness of the surface at the contacting point also reduces the sensitivity. A rough casting should at least be touched to a grinding wheel at the contacting area; some users specify an F4 finish. Curved surfaces are contacted effectively by a crystal ground to fit the curve, although for radii greater than 3 in. a flat crystal may be used.

Determination of Large Flaws; Laminations in Rolled Plates. A beam of waves is sent into one surface of the part and is picked up on the opposite surface; a flaw large enough to occult the beam is indicated by decreased received energy. Continuous-wave equipment is simplest for this application, although the reflectoscope can also be used. Complete inspection of a rolled plate for laminations, by the aforementioned technique, requires the scanning of all parts of the plate by the supersonic beam. Another technique, which may be faster, consists in generating with the reflectoscope, near an edge of the plate,

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a beam of Lamb or surface waves[8] that will travel across the plate and be reflected from the opposite edge or from intervening laminations; it is then necessary only to scan along a single edge in order to inspect the entire sheet.

Inspection of Bond of Plated, Welded, or Soldered Surfaces. If both opposing surfaces are accessible, the same techniques may be used as for detecting laminations (explained above). If only one face is accessible, the reflectoscope is used normally to indicate a reflection from the opposite side of the piece, but will give also an earlier reflection from any places where there is no bond. Since the stresses in the supersonic waves are only a few pounds per square inch, they will not break a weak bond. The supersonic test indicates the presence or absence of bond, but does not test strength of bond, except where regions of no bond influence the over-all strength. If the bonded piece is in the form of a plate, the sonigage[5] may detect bad bond by its influence on the resonance that may be established through the plate thickness.

Measurement of Wall Thickness Where the Opposite Side Is Inaccessible. If the thickness to be measured is ⅛ in. or more, the reflectoscope may be used to indicate thickness directly, by indicating the time of round-trip flight of the waves. The accuracy is approximately 5%, increasing with the thickness, but decreasing if the opposing faces are not parallel. The thickness of parallel sheets can be measured with an accuracy of the order of 1%, by establishing resonance through the thickness; the simplest equipment for this purpose is the sonigage[5] although the reflectoscope can also be used to establish resonance.

Inspection of Tubes. Certain types of waves can be sent around the circumference of a tube so that the whole circumference, both inside and outside, can be inspected by making contact along a single element.[8]

Measurement of Average Grain Size. Since the attenuation or scattering of supersonic waves depends on the grain size, a long series of successive reflections can be shown with the reflectoscope if the grain size is small. However, the number of reflections decreases as the grain size increases. The method may be made sensitive in any range of grain size by choice of wave length. Once the wave length is chosen, the method is calibrated experimentally against microscopic determinations of grain size; the calibration must be repeated if the shape of the piece under test is changed.[1]

Inspection of Region Near Surface Only. Since Rayleigh waves travel on and just below the surface, they may be used for inspecting this region for flaws, grain size, or elasticity. Rayleigh waves are radiated by a crystal of suitable shape attached to the reflectoscope.[8] Depth of penetration is regulated by choice of wave length. Flaws on or beneath the surface produce reflections; grain size, in the region near the surface, influences attenuation and scattering; elasticity, or possibly residual stress in the surface region, influences velocity of propagation.

Measurement of Elastic Aeolotropy. When steel sheet is rolled, the crystals receive a preferred alignment relative to the direction of rolling, which results in a considerably different shearing modulus around axes along and across the direction of rolling. The difference is approximately 8% for cold rolled and 1% for hot rolled sheet. This elastic aeolotropy results in a different velocity of propagation of shear waves through the thickness of the sheet, depending on whether the plane of vibration of the wave is along or across the sheet. A technique[8] has been worked out whereby the reflectoscope can utilize shear waves to indicate directly the percentage of elastic aeolotropy of a sheet. The special crystal is touched to the sheet and an indication of the amount of aeolotropy appears at once on the oscilloscope screen. Forgings have also been found to be aeolotropic.

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METALLURGICAL EXAMINATION AND CONTROL

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Metallographic Polishing

By J. R. Vilella*

TO be of value a metallographic specimen, like any other sample, must be truly representative of the parent metal, both in chemical composition and in physical condition. If it is not, the finest polishing, etching and photomicrography are wasted effort. Ordinarily the purpose of the investigation and the shape and condition of the material suggest the position from which the specimen or specimens should be cut, but there are general rules which, if observed, help to obtain adequate specimens:

1 If the purpose of the investigation is to determine the cause of a failure, the specimen should be obtained from a position near where the failure was initiated. It is also advisable to obtain one or more specimens from a position at some distance from the failure, in order to compare the structure of sound metal with that of metal which has failed. Comparisons of this type usually yield valuable clues.
2 In rolled or forged materials, transverse and longitudinal sections should be examined. This is important whether the purpose of the examination is to study the nonmetallic inclusions or the structure. If the material has been cold reduced, specimens should be taken in the direction of working.
3 In wrought or wrought and heat treated materials, it is advisable to include in the specimen a portion of the outer skin, so that decarburization and other surface conditions may be noted.
4 If the metal is suspected of segregations, several specimens from different positions should be examined.

Cutting the Specimen. When the location most significant for examination has been selected, the specimen may be cut by a hack saw, a band saw, a cutting-off wheel, or in the sampling of hard and brittle materials, the specimen may be notched and fractured. Occasionally it is necessary to resort to flame cutting in order to obtain suitable specimens from large sections.

Regardless of the means employed, it is essential to avoid heating and dragging the metal at the cut surface. Heating hardened steel is particularly undesirable because the steel is likely to be tempered. To minimize heating during cutting, a hack saw should be used, with proper lubrication, for all specimens that can be cut by this means. Hard materials should be cut with cutting-off wheels operating under water. Dragging of the surface metal, a common defect encountered in specimens of soft materials, can be minimized by lubrication of the saw blade. The structure of a flame-cut surface is obviously not representative of the metal, and therefore not suitable for a metallographic specimen.

Specimen Size. Whenever possible, for convenience in subsequent handling, the size of the specimen should be from ⅜ to 1 in. sq (or diam) and somewhat less in thickness. Smaller specimens are not only difficult to handle but almost impossible to polish without rounding the edges excessively. Larger specimens are difficult to finish without scratching and without dislodging the nonmetallic inclusions. Specimens in which the height exceeds the linear dimensions of the face to be polished are difficult to grind with the necessary flatness. It is not always possible, however, to obtain specimens of comfortable size. Sheet metal, wire and a multitude of other small articles are too small in cross section to handle comfortably. Such specimens must be mounted either in clamps, in molding plastics or in fusible alloys.

Mounting of Specimens. The method to use depends on the purpose of the specimen, on its shape, on the maximum temperature it can stand without alteration of structure, and on the available equipment.

Steel clamps of adequate shape and dimensions are best adapted to rectangular and square specimens that have straight edges. These clamps constitute the most satisfactory means of preserving the flatness of the edges; in fact, they are almost indispensable, even when the specimens are large, if the edges are to be examined at intermediate or high magnification. In general, the degree of roundness of the edges is proportional to the difference in hardness (or abrasion resistance) between the specimen and the mounting material. For this reason, when maximum flatness is needed along the edges of hard specimens, even clamps, if made of soft metal, are not adequate. For such specimens, the clamp should be made of a material which approximates the hardness of the specimen. However, to obtain consistently satisfactory results, certain other precautions must be observed. In the first place, clamps often interfere with the etching of specimens of dissimilar composition—for example, stainless steel mounted in carbon steel clamps; secondly, their rigidity makes it difficult to obtain close contact between clamp and specimen, with the result that a trace of the etching reagent often creeps up and stains the edge it was desired to examine. A satisfactory way of overcoming these difficulties is to insert a strip of soft copper between clamp and specimen. Thus a tight contact is produced without damaging the edge in any way; and, at the same time, the interference with etching is overcome, for copper is hardly attacked by the usual etching solutions for steel.

Because of a tendency to smear and because of inability to prevent rounding of the edges, fusible alloys such as Woods metal have been largely superseded as mounting material by harder plastics, such as Bakelite, Lucite and Tenite, which have proved invaluable to those handling a large number of small specimens.[6] The chief merits of these plastics are: (1) adaptability to specimens of any shape; (2) close contact between specimen and mounting material, so that staining caused by seepage of the etching reagent is prevented; (3) relatively low molding tempera-

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ture, permitting the use of these plastics even for specimens subject to tempering; (4) inertness to the etching reagent; and (5) good, although not the best possible, preservation of the flatness of the edges.

Another practical and rapid method of mounting specimens, when optimum preservation of the flatness of the edges is not necessary, is the following: Place a brass ring of convenient size (preferably one made oval by compressing its sides) on a smooth steel plate and pour enough mercury inside the ring to form a pool ⅛ to ¼ in. deep. Turning downward the surface to be polished, push the specimen through the mercury and hold in contact with the plate. Pour molten sulfur over the mercury and specimen to fill the ring; then allow the sulfur to solidify, as it will rapidly. To recover the mercury, slide the assembly to the edge of the plate and collect the liquid in a convenient receptacle. In specimens mounted in this manner, the surface to be prepared is level with the walls of the ring but not in contact with it at any point, and also at a considerable distance from the level of the sulfur; thus the specimen can be polished without dragging the mounting material over the polished surface and without contaminating the wheels with sulfur. The low melting point of the sulfur, its rapid cooling and the fact that it never comes in contact with the immediate vicinity of the surface to be polished, minimize the danger of altering the surface structure as a result of heating.

Preliminary Facing. This may be accomplished by filing, by grinding on stones or prepared papers, or by machining. If filing is used, the best way to obtain a flat surface is to lay the file on the working bench and push the specimen against the cutting edges, preferably in one direction only, since rubbing back and forth tends to round the edges of the sample. More rapid and equally satisfactory results can be obtained with motor-driven belt surfacers. These are not restricted as files are to small specimens of soft materials, and when properely used, such surfacers produce satisfactory flatness. Grinding stones are perhaps the least satisfactory means of obtaining a flat surface; they tend to fill with metal, become dull in a comparatively short time, requiring frequent dressings, and eventually develop grooves which round the specimen. However, when a grinding stone is used by careful workers, these disadvantages can be largely overcome. Regardless of the means employed, care should be taken at this stage to keep the specimen cool and to avoid deep scratches, because a deep scratch may completely alter the structure of the underlying metal. This condition has often been observed in specimens of 18-8 stainless steel and other alloys susceptible to structural changes by slight cold working.

Grinding. Grinding consists of abrading the specimen by using a series of grits of increasing fineness, until a set of scratches is produced which are sufficiently fine to be totally eradicated in a reasonably short time by the finest polishing material available. There are several satisfactory ways of carrying out this step.

Grinding on Abrasive Papers. This method consists of abrading the specimen with papers coated with aluminum oxide (emery) or silicon carbide (Carborundum) of increasing fineness. The grades most commonly used are 100, 200, 320 and 400-mesh grit; or No. 2, 1, 0, 00 and 000. Abrading may be done either by hand or on power-driven wheels. In either method, on passing from coarser to finer paper, it is advisable to rotate the specimen 90 deg to facilitate recognizing when the coarser scratches have been entirely replaced by the finer ones.

The chief merits of this method are that the nonmetallic inclusions are not dislodged, that it is comparatively easy to master, and that the commercial papers available are well graded as to grit size and are of uniform high quality. The chief disadvantages are that in this method the structure of the surface metal is distorted, particularly when the papers are used after the grit has become dull; also there are tendencies to round the corners and edges of the specimen and to heat the specimen. However, these disadvantages can be greatly decreased by careful working.

Hand polishing is generally considered a slow and laborious process; for that reason it is seldom practiced in this country. The technique of those who still use it[1] consists of rubbing the specimen back and forth on abrasive papers stretched smoothly over a flat, hard wooden block or a metal surface. Advantages of hand polishing are that less heating and less distortion of the surface metal occur than in machine grinding.

In machine grinding, the speed of the wheels is of some importance. However, since the rate of cutting or abrasion depends on the linear velocity and not on the rpm, a higher rate of cutting is always obtained at the periphery than at the center; and likewise, the larger the disk, the faster the rate of cutting at the periphery. For these reasons, recommendations as to the best speed of grinding expressed in rpm are of little significance. High speeds are not conducive to the best results and do not appreciably expedite the process. A speed of 600 to 700 rpm for a 9-in. disk is satisfactory. With well constructed machines free from vertical vibrations, higher speeds can be used safely.

Grinding on Paraffin Wheels. Disks similar to those used for grinding with papers are covered with a layer of high-melting-point paraffin about ¼ in. thick, machined flat and having a spiral groove or a series of concentric circles 1/16 in. deep inscribed on the surface by means of a nail or some other pointed article. The function of the groove is to hold the water and abrasive on the disk. The abrasives consist of a series of emery powders, ranging in fineness from 200 to 600-mesh. These powders are suspended in a soap solution and are sprinkled over the revolving disks at frequent intervals. Natural emery is preferred.

An excellent modification of this method is to use canvas or billiard cloth previously impregnated with paraffin, instead of using a paraffined disk. The paraffin is melted in a suitable container and the cloth is immersed in it until it has absorbed all the paraffin it can hold. While the impregnated cloth is still warm and pliable, it is stretched smoothly over the disk and held in place by a ring that fits around the circumference of the wheel. Billiard cloth is preferable for the finer abrasives and 12-oz canvas for the coarser ones. At first the impregnated cloth will feel somewhat rough, but it will become smooth after grinding several specimens.

The merits of this method are: (1) satisfactory preservation of the nonmetallic inclusions, (2) good flatness of the edges of the specimens, (3) less distortion of the surface metal than is produced by grinding on papers and (4) negligible heating of the specimen during grinding.

Grinding on Lead Laps. Two methods[2, 3] involving the use of lead laps have been described. Both are based on the principle that grit held firmly by the carrying medium (that is, not free to roll during grinding) does not excavate the nonmetallic inclusions, nor widen any cracks or porosity which may be present in the metal. One of these methods, which originated in Sweden, is as follows: On each of three disks is deposited a layer of lead approximately ¼ in. thick and machined flat. The abrasive (emery or tungsten carbide) is applied and "fixed" to the lead lap with a fast-drying varnish previously thinned with benzene. The grinding procedure is carried out in three steps after preliminary "coarse" grinding to obtain a flat surface: (1) grinding with emery of 100 to 40 μ in grain size, (2) grinding with emery of 50 to 25 μ in size and (3) grinding with tungsten carbide having grain size less than 4 μ. It is important that the surface be as flat as possible after the preliminary grinding; if the surface is rounded, the process is greatly delayed in the subsequent step, because the lead lap cuts only in one plane. After the grit has become dull from grinding, it can be "resharpened" by simply passing over the disk a brush dipped in benzene; this softens the varnish and causes the abrasive grains to turn, thus presenting a new sharp face to the specimen. The varnish rehardens in about one minute.

The advantages claimed for this method are: (1) rapid preparation of the specimen, (2) a degree of flatness not obtainable by any of the usual metallographic polishing methods, (3) excellent preservation of the nonmetallic inclusions, (4) the possibility of using finer abrasives and hence shortening the time required for the final polish, and (5) lower operating cost than with abrasive papers.

The other method[3] utilizing lead laps was originated at the Bureau of Standards. It is carried out in two steps, but each step requires two disks, one for the actual grind-

ing, made of 50% Pb and 50% Sn alloy; and the other made of high-strength, fine-grain cast iron, used only for charging and maintaining the flatness of the lead-tin disk.

The cast-iron disk is ground in a precision surface grinder to a maximum deviation of 0.0001 in. from a plane over the entire surface. The disk contains grooves ½ in. apart, milled to a depth of 1/32 in. with a 60-deg milling cutter. This disk is somewhat larger than the lead-tin disk, which contains grooves similar but ¼ in. apart. The surface of the lead-tin disk should be faced flat in a lathe before milling.

Charging of the lead-tin laps is accomplished by mixing water with emery of the proper grades (American Optical Co. No. 302 and 303½), placing the mixture on the face of the cast-iron disk and rotating the lead-tin disk, face down, upon it for about 30 sec. The lead lap is then brushed and washed until free from loose grit.

During the grinding, water is used as a lubricant. Only a very gentle pressure is needed to obtain good cutting action. The advantages of this method are the same as those claimed for the Swedish method.

A widely used modification of this method consists in employing rotating laps instead of the stationary ones recommended by the Bureau of Standards. Three laps are generally used, one charged with coarse, one with medium and one with fine emery—ordinarily American Optical Co. Grades 302, 303½ and 305, respectively. The grit is fed to the laps in the form of a water suspension containing approximately one teaspoonful of grit per liter, from a bottle with a small nozzle. Grades 302 and 303½ can be used as received, but grade 305 should be levigated for approximately one minute before using.

To retain the abrasive and water on the disk during polishing, it is advisable to cut on it a spiral groove approximately 1/32 in. deep and 1/32 in. wide, with a pitch that may vary between ⅛ and 1/32 in. The pitch does not seem to be critical, but it is important that the spiral groove be cut so that it coils opposite to the rotation of the wheel. If the spiral and lap move in the same direction, the wheel tends to dry too quickly.

An automatic polishing method[4] employing cast-iron and lead laps was also recently described. It is not discussed here in detail because it requires specially built equipment.

Rough Polishing. Rough polishing is merely the last stage of grinding, but because it is the most important step in the entire process of metallographic polishing, it must be treated separately. On this step depend (1) the length of time required to finish the specimen, (2) the preservation or dislodgment of the nonmetallic inclusions, and (3) the thickness of the layer of distorted metal which must be removed before the true structure is revealed. This step can be carried out in several ways, of which the most frequently practiced are the following: (1) grinding on billiard cloth or canvas with powders such as 600 alundum, emery or tripoli; (2) grinding on fine abrasive papers such as No. 0000 or 600-grit emery or Carborundum; (3) grinding with 600 or finer emery on wax disks or billiard cloth impregnated with paraffin; or (4) grinding with 305 or finer emery or tungsten carbide powder on lead laps.

Loose Powders on Billiard Cloth or Canvas. These produce fine, even scratches, which disappear readily during the final polish and yield a surface with a minimum of disturbed metal. The main disadvantage is that the prepared surface is likely to be badly pitted as a result of the dislodgment of the nonmetallic inclusions. The method, therefore, is not recommended when the correct preservation of the inclusions is essential to the purpose of the examination.

Grinding Papers. Papers such as No. 0000 or 600 emery preserve the nonmetallic inclusions intact, but cause a considerable distortion of the surface metal and yield scratches of uneven depth, thus frequently retarding the final polish. Finer and more even scratches can be obtained by using a No. 000 or 600 paper which has been partly worn by use and glazed by polishing a piece of graphite on it.

Grinding With 600 Emery on Wax or Paraffined Cloth Disks. This kind of grinding preserves the nonmetallic inclusions quite well, yields fine, even scratches, which are removed easily during the final polish, and does not produce an excessive amount of disturbed metal. The method represents an excellent compromise between the two methods previously discussed.

Grinding With 305 or Finer Powders on Lead Laps. This is probably the best method of rough finishing so far developed. The inclusions are well preserved; the specimen exhibits a degree of flatness not attainable by any of the other methods; the scratches can be made fine and even by judicious selection of the powder and by care to avoid contamination with coarser grit; and distortion of the surface metal is not excessive. This method, however, is applicable only to specimens that have been ground very flat during the prior stages; otherwise the rounded parts of the specimen will not come in contact with the abrasive.

The Final Polish. Usually the specimen is finally polished on a soft cloth with either levigated alumina, rouge, magnesia or other equally fine finishing powders. The selection of the finishing powder is a matter of individual preference, since equally good results can be obtained with any of them, provided they have been properly levigated. Alumina is sometimes selected because it is the cleanest to handle and because an excellent grade can be purchased already levigated.

The type of cloth to use depends on the purpose for which the specimen is being prepared. If it is desired to obtain the best possible preservation of the nonmetallic inclusions, or the graphite flakes in cast iron, then it is advisable to use a hard, pileless fabric, such as the dull side of a heavy silk satin or a good grade of heavy cotton or linen cloth, because it has been observed by many experienced metallographers that the softer materials, such as broadcloth or "kitten's ear", exhibit a pronounced tendency to dislodge the inclusions. On the other hand, the soft fabrics are preferable when the structure of the specimen is to be examined or photographed at high magnification, since these fabrics produce fewer and smaller scratches.

It would be of little value to make precise recommendations concerning the optimum speed to use for the final polish, because experience has shown that satisfactory results are possible at a wide range of speeds. However, the consensus of experienced metallographers is that best results are obtained at low speeds; for instance, a speed of 280 rpm is used for a 9-in. disk.

Defects of Polished Surfaces. The defects most frequently found in metallographic specimens are: scratches, rounding of the corners and edges of the specimen, pits resulting from dislodgement of the nonmetallic inclusions, and distortion of the surface metal.

Avoiding Scratches. This is a question of cleanliness and careful levigation of the finishing powder. Some of the most common causes of scratches are dirty hands, grit under the finger nails, abrasive from the previous operations on the sides of the specimen, and contamination of the finishing fabric with flying grit from other wheels. The remedies suggest themselves: proper levigation of the finishing powder; careful washing of the specimen and hands, particularly before attempting to give the final polish; and keeping the wheels well covered when not in use.

Preserving Flatness of a Specimen. As was pointed out before, flatness depends on the method of polishing and on how the specimen is mounted.

Preventing Pits. Preventing pits that result from dislodgment of the inclusions has already been discussed. It will be well to state here, however, that a pitted surface gives an exaggerated impression of the amount of "dirt" in the steel, and that many a satisfactory heat of steel has been branded "too dirty" because of improper polishing. To rate a steel as dirty is unwise, unless one is sure that the inclusions are preserved intact.

Eliminating Distortion of Surface. Of all the defects of a polished surface, the most misleading, common and subtle is the inevitable distortion of the surface layer resulting when a malleable material is ground with a hard abrasive. It can be said without exaggerating that the greatest progress in metallographic polishing during the last 20 years has been recognition of the existence of this distorted layer and its elimination by the method of alternate polishing and etching to be described below. Although some methods of polishing produce less distortion than

others, none yields an undistorted surface. It is well to assume, therefore, that the structure revealed by etching a highly polished surface is not the true or undistorted structure of the metal. The question is how the true structure can be revealed. Probably the most dependable way of accomplishing this is the following: The polished surface is given a normal etch and its structure is noted under the microscope by using the dry objective that has the highest resolving power available. The surface is then repolished on the final wheel, etched and examined again. The process is repeated as long as changes in the appearance of the structure are noticed. As a rule, two or three repolishes suffice, but occasionally more may be necessary, particularly when working with soft metals. In general, the softer the metal, the greater the distortion, but even hard metals are never completely free from distortion after polishing. An attempt to cut the process short by deep etching usually results in pitting and obliteration of the finest details of the structure.

Summary. The *perfectly* or *ideally* prepared specimen must possess at least the following characteristics: (1) It must be truly representative of the metal in both chemical and physical condition. (2) It must be sufficiently flat, from edge to center, to permit examination at all points at all magnifications. (3) It must be free from scratches, stains and other imperfections which tend to mar its appearance. (4) It must contain intact all nonmetallic inclusions. (5) It must be free from all traces of disturbed metal.

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Photomicrography

By J. R. Vilella*

THE purpose of photomicrography is to procure permanent and accurate records of structures too fine for the unaided eye to see. To accomplish this a photomicrograph must meet certain minimum requirements: (1) It must represent the true structure of the metal. (2) The magnification and resolution must be sufficient to show clearly all significant detail. (3) It must be technically correct in a photographic sense.

The True Structure of a Metal. In the preparation of metallographic specimens it is important to bear in mind that the attainment of a specular finish free from scratches does not necessarily constitute a satisfactory polish for photomicrography. Frequently the structure that is revealed by etching a highly polished surface is not the true structure of the metal, but merely that of a layer of metal which has suffered considerable distortion as a result of polishing. The true structure lies below this layer and will not be seen until all traces of distorted metal have been eliminated. The softer the metal, the deeper the distortion; but even hard metals are susceptible to this effect. It is well, therefore, to expect distortion in all polished surfaces and to make certain that it has been eliminated before a photomicrograph is made. For a more detailed discussion of this subject, see the article on "Metallographic Polishing", page 159.

Likewise, a specimen is not ready to be photomicrographed until it has been correctly etched. Correct etching consists of (1) selecting the reagent best suited to the chemical composition and physical condition of the metal, and (2) etching to produce the proper degree of contrast, depending on the element of the structure that is to be emphasized and on the magnification at which it is to be photographed. Obviously, a surface exhibiting stains, etching pits or uneven attack, has not been correctly etched.

What reagent to use is entirely a matter of experience. If any doubt exists, several of the reagents tabulated in the articles on etching reagents should be tried and the photomicrograph should be made after etching with the reagent which most clearly reveals the true structure, since evidently that is the best reagent for the specimen at hand.

The depth of etching or degree of contrast produced in the structure is of great importance in photomicrography. Although it is not possible to give a set of instructions covering all problems, observance of the following will be found helpful:

1 Etch no more deeply than necessary to bring out the significant detail.
2 A degree of contrast satisfactory for low-power photomicrography is generally excessive for the best possible definition of the structure at high magnification.
3 If high contrast is desired, obtain it by photographic means rather than by deep etching, for deep etching obliterates the fine details of the structure.
4 If a specimen is insufficiently etched, thus affording too low contrast, repolish on the finishing wheel and re-etch, rather than to superimpose one etch on another.
5 Do not touch an etched surface with anything, and photograph soon after etching.

Magnification and Resolution. When a specimen has been properly polished and etched, the first question to decide is the magnification and the objective to use in making the photomicrograph. Concerning magnification, there are two rules which are sound but not inflexible:

1 Photograph at the lowest magnification which shows clearly all significant detail.
2 To obtain from a given objective the maximum amount of detail (resolution) and the sharpest image, maintain the magnification between the limits of 400 and 1000 times the numerical aperture (NA) of the objective.

A magnification of at least 400 NA is needed for a person of normal vision to distinguish all the detail resolved by the objective. This magnification, however, renders the finest detail hardly visible, and results in eyestrain and uncertainty. At higher magnification the detail becomes easier to see but, at the same time, the image loses sharpness. Therefore, it is necessary to arrive at a compromise. Experience has established 1000 NA as the highest magnification that will produce images of acceptable sharpness when achromatic objectives are used. With apochromatic objectives of the highest quality it is possible to make photomicrographs at more than 1500 NA which appear acceptably sharp when viewed at a distance of 10 in. from the eye. However, to produce a sharp photomicrograph even at 1000 NA, correct polishing and etching are essential and all other causes of defective images must be eliminated.

Beyond 1000 NA a considerable degree of empty magnification is necessarily involved, but it is justified when the photomicrograph is to be viewed from a distance, as by several observers simultaneously.

Resolving power is the property of a lens which enables it to show distinctly the separation between two elements of the structure that lie close together; for example, the lamellae of pearlite. The degree of fineness of detail which an objective can reveal, that is, the resolving power, increases directly with the NA; but the fact that an objective of high NA possesses high intrinsic resolving power does not necessarily mean that it will resolve a given fineness of detail under all conditions. It merely means that it will resolve that detail if properly used. It is important, therefore, to examine those factors under the control of the metallographer which affect the resolving power of the objective.

In the first place, the specimen must be correctly pol-

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ished and etched, because not even the objective of the highest NA will show clearly a structure in which the detail has been deformed or obliterated by poor polishing and etching. In addition, the following factors must be considered: (1) the proper adjustment of the illuminating system, (2) the optimum opening of the aperture diaphragm, (3) the wave length of the light used, and (4) the method employed to illuminate the specimen.

Proper Adjustment of the Illuminating System. Precise adjustment is essential because otherwise the image produced can be misleading. It is not possible, however, to make definite recommendations for the correct setting of the illuminating system, because of the varied design of the microscopes used in the metal industry. Failure to keep the illuminating system adjusted in strict accordance with the instructions given by the manufacturer of the instrument, invariably leads to some loss of resolving power.

Optimum Opening of the Aperture Diaphragm. Because the image produced by microscope objectives, particularly those of high NA, is not always so flat as would be desirable, many metallographers "stop down" the aperture diaphragm of the microscope in an effort to secure a larger area in focus, a practice which is equivalent to cutting down the NA of the objective, and therefore its resolving power. High power objectives cannot always be used at full aperture because of the interference of "flare", or internal reflections, but there is an optimum opening for every objective, at which flare is not objectionable, and which should be determined by the metallographer to enable him to use the objective at its highest practicable resolving power. The recent application of antireflection coating to microscope objectives has materially increased the maximum aperture at which objectives can be used without the interference of flare. Lack of flatness of field can be partly remedied by the use of negative oculars designed especially for that purpose, but resolution must not be sacrificed. A small field with maximum resolution is preferable to a large flat field lacking resolution.

Wave Length of the Light Used. The resolving power of an objective is higher, the shorter the wave length of the light illuminating the structure. For maximum resolution, therefore, the shortest wave length should be used for which the objective is adequately corrected; that is, yellow-green for achromatic and blue-violet for apochromatic objectives. Selection of wave length is the principal function of light filters in ferrous metallography, because the structures are seldom highly colored. However, in nonferrous metallography, where brightly colored structures are not uncommon, light filters are also used to bring about a more accurate tonal rendition of the colors. Since photographic emulsions are not equally sensitive to all colors, it is often necessary to filter out or partly suppress some of the wave lengths to which the emulsion is most sensitive, in order to reproduce photographically the correct relative brightness of the colors.

It is generally expected that the use of the electron microscope in metallurgical research will some day contribute greatly to our knowledge of the microstructure of metals. Photomicrographs exhibiting resolution beyond that attainable with the shortest wave length of the visible spectrum have been made from replicas of metallic structures but, chiefly because they are photographs of replicas, their interpretation is not free from uncertainties. As the technique of replica preparation improves, these uncertainties will decrease, and today it appears probable that in the not too distant future it may be possible to make direct electron photomicrographs of metallic structures.

Method Employed to Illuminate the Specimen. Modern metallurgical microscopes are generally equipped with a plane glass vertical illuminator, prism illuminator, dark field illuminator, polarized light, and adjustments designed to produce the effect known as "conical illumination". The plane glass vertical illuminator is the type generally used in photomicrography, because it permits obtaining all the resolving power of the objective. In most microscopes a plane glass illuminator is placed in a fixed position at the factory and requires no further adjustment.

The prism illuminator is supplied for two purposes—to obtain oblique lighting and to provide brilliant illumination for dark structures and for projection. Because prism illuminators utilize only one half of the pencil of light, they cut the resolution of the objective in half. This loss of resolution occurs only in the direction at a right angle to the axis of rotation of the prism. Such illuminators are intended only for low-power work.

Dark-field illumination is characterized by the fact that a reflecting surface, lying perpendicular to the axis of the objective and illuminated by converging rays, reflects no light into the microscope and consequently appears dark. Any part of the structure that is not perpendicular to the axis of the objective reflects into the microscope some of the light which strikes it; thus, such a part appears brightly illuminated. Dark-field illumination has several distinct advantages over ordinary bright-field illumination: (1) Since the objective is not used as a condenser, as in bright-field illumination, there is less "flare" or internal reflection and the objective can be used at full aperture. (2) Extreme contrast (black and white) can be obtained when desired. (3) Surfaces can be examined that are not so highly polished as is necessary for bright field. (4) Frequently detail is clarified that cannot be seen under bright-field illumination, either because of lack of contrast with the surrounding material or because of insufficient resolution. (5) Colored structures are shown in their natural colors.

The use of reflected polarized light in metallography is discussed in "Nonmetallic Inclusions in Steel", page 445.

Conical illumination is a means of illuminating the structure obliquely without sacrificing resolution, as happens when the prism illuminator is used for the same purpose. The relief that it produces imparts a natural appearance to the image, serves to differentiate between parts of the structure which appear identical under axial illumination, and makes fine detail easier to see. Conical illumination, if properly used, yields evenly illuminated micrographs, high in resolution and pleasing to the eye.

Most microscopes are provided with a second iris diaphragm, known as the "illuminated field diaphragm" and placed in the microscope so that the image of the diaphragm is focused on the surface of the specimen when the specimen is in focus. Because of its position, this iris does not affect the resolving power of the objective, but it will be observed that, as it is closed down, the fully illuminated field becomes smaller and the contrast and sharpness of the structure improve perceptibly. In photomicrography, whenever the size of the illuminated field is larger than the plate or film, the iris should be closed down until the diameter of the fully illuminated image is equal to, or less than, the diagonal of the photographic plate. This is especially important in high-power photomicrography.

Photographic Technique. For a photomicrograph to accomplish its purpose, it must show the structure clearly enough to convince the observer that it is a faithful reproduction of the structure. A photomicrograph lacking clearness, because of technical imperfections, generally defeats its purpose, inspiring doubt rather than conviction.

The photographic plates or films suited for photomicrography are those possessing the following characteristics:

1 High sensitivity to yellow and green light; that is, the plates or films must be orthochromatic. (All emulsions are sensitive to blue light; only panchromatic emulsions are sensitive to red light.)
2 Sufficient latitude to yield properly exposed negatives without the need for precise estimation of the exposure time. This latitude is necessary because the intensity of the arc light, generally used in photomicrography, fluctuates considerably even while the exposure is being made, and because the reflectivity of the various parts of the structure varies widely, depending on the polish, composition and amount of etching.
3 A fine-grain emulsion, able to record extremely fine details accurately. Photographic emulsions also possess resolving power; in general, the finer the grain, the smaller the detail that can be recorded in a photograph.
4 An effective antihalation backing. This is important since the presence of halation will shorten considerably the latitude within which the emulsion can accurately reproduce the finest details.

The correct exposure places the brightest and darkest portion of the structure within the limits of the latitude of the emulsion; that is, the brightest parts are not overexposed or the darkest, underexposed. Since the emulsions used in photomicrography are of the "short scale" type, the greater the degree of contrast produced by etching, the more accurate the exposure needs to be. Occa-

sionally such great contrast is produced in the structure through overetching that even though this contrast can be encompassed within the latitude of the negative, it exceeds the latitude of the printing paper, which is always less, and therefore a good print cannot be made. After all, a negative is only a means toward the achievement of a perfect print. For these reasons, care should be taken to avoid etching with excessive contrast.

Whenever there is doubt concerning the correct exposure, an exposure test can be made as follows: The entire plate is given a rather short exposure—for example, 2 sec—and then the dark slide is pushed in approximately one inch and another exposure made, of the same duration. The slide is then pushed in another inch and exposed again, but this time for 4 sec. The process is repeated until a set of exposures is obtained, each double the preceding one.

Standardization of developing practice helps to secure uniform negatives from day to day. The time-temperature method (tank development) lends itself to standardization better than the tray or inspection method, and should be preferred. The developer recommended by the manufacturer should always be used. The length of time required for developing a plate depends on the degree of contrast desired, because contrast increases with the developing time, if the temperature and agitation are constant.

Proper fixing and washing are also important. An active fixing bath containing an effective hardener is sufficient, if the temperature of the bath does not exceed 75 F. Above this temperature, there is danger that the emulsion will soften and reticulate. In hot weather, an advisable practice is to use a "short stop" hardening bath, consisting of 2% chrome alum and 2% sodium bisulfite. The hardener should be freshly prepared and used between development and fixing, and the plate should be left in it for 3 to 5 min with the light off. The negative should then be fixed for at least twice the time required to clear it and should be washed in running water for 30 to 60 min. Insufficiently washed negatives deteriorate in a short time.

In photomicrography, correct printing means reproducing on photographic paper all the detail that the negative was able to grasp, and recording this detail in the proper tonal relations. Two prerequisites are (1) choosing the grade of paper that will complement the contrast of the negative and (2) choosing the exposure that will print through the densest part of the negative where detail must be shown. To accomplish this, photographic papers are available in several grades of contrast. The "soft" papers, affording low contrast, are for use with negatives of high contrast and the "hard" or "contrasty" papers are used with "flat" or "soft" negatives. These various grades can be obtained in a variety of surfaces, but the glossy finish is generally used in photomicrography because the smoother the surface, the larger the scale of contrast reproduced by a photographic paper.

Summary. The aim in photomicrography is to reproduce the significant details and tones of the structure as faithfully as possible. This can be accomplished (1) by polishing the specimen in such a manner that the true structure will appear after etching; (2) by etching to ■ depth or degree of contrast that does not obliterate detail and can be reproduced photographically; (3) by adjusting the microscope correctly so that maximum resolution may be obtained; (4) by an exposure which produces an image within the latitude of the plate or film; (5) by developing this image to a contrast that fits the scale of the printing paper; (6) by using a paper that has the longest possible range of contrast.

For photomicrographic illustrations and a more detailed discussion of the various points emphasized in this article, see the ASM publication "Metallographic Technique for Steel", by J. R. Vilella.

X-Ray Diffraction

By Charles S. Barrett*

THE regular repetition of identical groups of atoms throughout a crystal forms a three-dimensional grating which diffracts a beam of X-rays in much the same way that an optical grating diffracts a light beam. When a small beam of X-rays is directed at a substance and the rays diffracted in different directions from it are photographed, the substance can be classified as amorphous, crystalline, or intermediate; the identity of the substance can often be established; the perfection of the crystal lattice can be determined; single crystals can be distinguished from polycrystalline substances, and the grain size can be estimated. From the X-ray pictures, supplemented by other data, the crystallographer determines space lattices, space groups, and positions of atoms in the unit cell. Diffraction also indicates the orientation of a single crystal and the preferred orientation in a polycrystalline specimen; the dimensions of the unit cell, to a high degree of precision; qualitative and, in some instances, quantitative measurements of residual and applied stresses; information concerning the effect on the lattice of plastic deformation, of heat treatments, or of the mechanism of deposition, crystallization, transformation, age hardening, and precipitation; and the constitution of organic and inorganic systems, minerals, and alloy systems.

Given a parallel set of planes of atoms repeating throughout a crystal and spaced at intervals of d, the condition for X-ray reflection from these planes is, by Bragg's law, $n\lambda = 2d \sin\theta$ where λ is the wave length of the X-rays, measured in the same units as d, n is the order of the reflection (always an integer), and θ is the angle of incidence of the beam on the planes, which is equal to the angle of reflection from the planes. This relation among the spacing of atomic planes, the wave length, and the diffraction angle, known as Bragg's law, and the analogous optical reflection relation are the basis for interpreting almost all practical applications of X-ray diffraction.

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Apparatus.[3, 9] X-ray tubes for diffraction operate on 30,000 to 60,000 v, rectified or unrectified. Both gas tubes and electron tubes are in common use, gas (or "ion") tubes operating at a critical gas pressure of about 0.01 mm Hg, with a cold cathode, and electron tubes operating at a high vacuum with a hot filament. Tubes of both types may be made demountable so that targets of various elements can be interchanged at will and cathodes replaced when necessary. Electron tubes, highly evacuated and sealed off from the vacuum pumps, are widely used. The sealed-off molybdenum target tubes are the nearest approach to a universal tube for commercial applications, for both monochromatic (characteristic) radiation and general radiation, of which a considerable quantity is emitted, so that the tube can be used with fair success in nearly all methods. Sealed-off tubes require the minimum amount of attention and skill in operating, but demountable tubes permit a greater variety of wave lengths and are advantageous in many research problems where extreme purity of the radiation is important. Complete units, with tubes, transformers and controls fully enclosed, and many types of cameras are available.

Laue Method.[1, 4, 9] The Laue method uses a beam of X-rays containing many wave lengths. A system of pinholes confines a beam to ■ narrow pencil of rays that fall upon a small crystal or penetrate a thin crystal. The usual arrangement is for a photographic film to be placed 4 or 5 cm beyond the crystal and perpendicular to the original X-ray beam, Film A in Fig. 1. (The film B is used only for the back-reflection method referred to below.) On the photographic film the diffracted rays make ■ pattern of spots, as in Fig. 2; each spot is the reflection of a certain

wave length from a certain crystal plane in one or more orders. The X-ray tube, best equipped with a target of tungsten and operated at 40,000 to 60,000 v, gives radiation with a broad band of wave lengths.

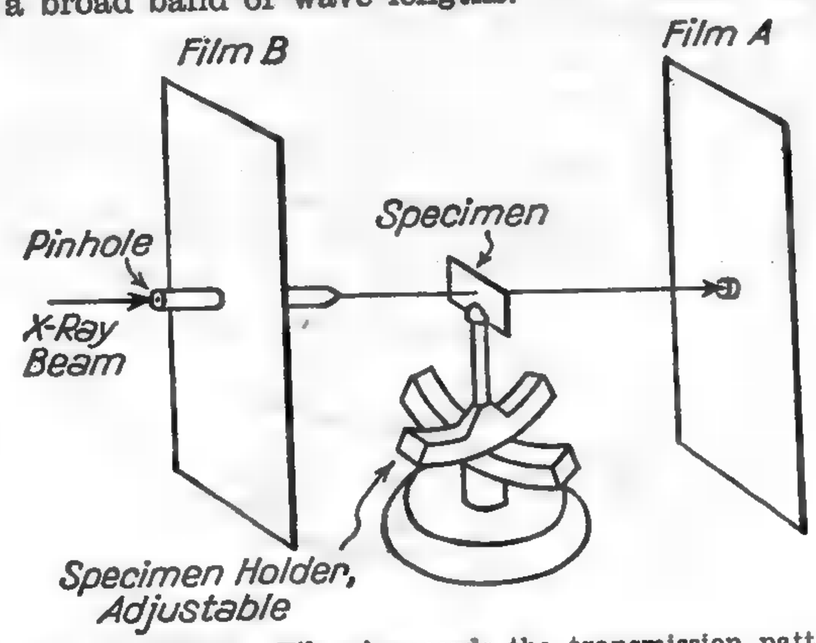

Fig. 1 Laue camera. Film A records the transmission pattern, film B the back-reflection pattern, usually not simultaneously.

Laue photographs show a pattern of spots that are reflections from the differently oriented planes of atoms in the crystal. Identification of the spots is generally accomplished by graphical methods. The Laue method is useful for the determination of the symmetry properties of a crystal. When an X-ray beam passes through the crystal parallel to a fourfold rotation axis, for example, the pattern will coincide with itself if given one quarter-turn about the center (Fig. 2). The elements of symmetry deduced from Laue patterns will always include a center of symmetry, whether or not the crystal possesses one. The Laue method is little used for determination of crystal structure but is often convenient for determining the orientation of crystals; this is done by the aid of stereographic or gnomonic projections of the spot patterns.

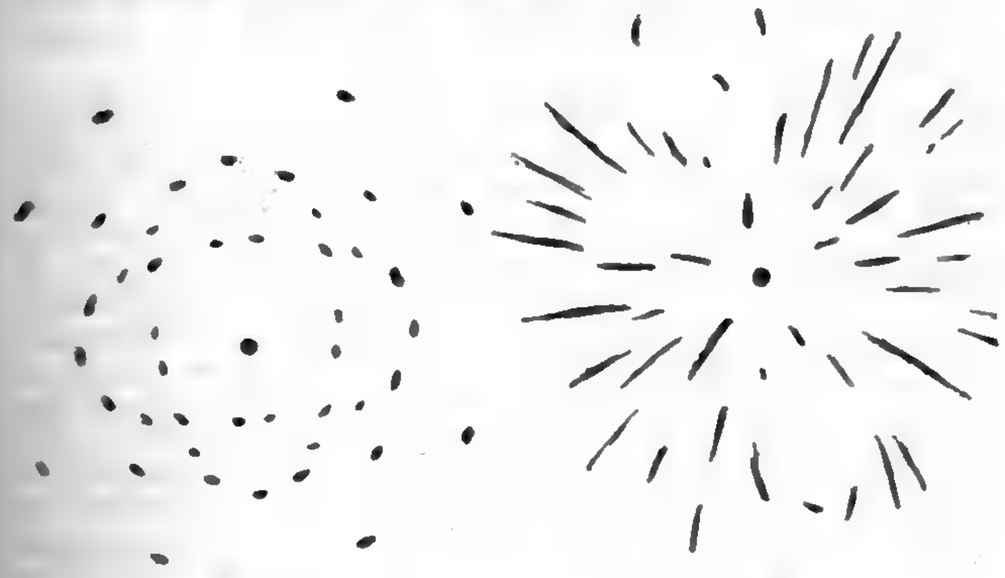

Fig. 2

Fig. 3

Fig. 2 Laue pattern (transmission type) with X-ray beam approximately parallel to a crystal axis of fourfold symmetry. Undistorted crystal.

Fig. 3 Laue pattern of a distorted crystal, showing asterism.

The Laue method reveals imperfections resulting from accidents of crystal growth or from deformation. The Laue spots from perfect crystals are sharp, as in Fig. 2; whereas imperfect crystals or plastically deformed crystals produce blurred images and spots elongated radially, as in Fig. 3, giving the appearance known as "asterism". An analysis of this can give the range of orientation of the reflection planes and can indicate the severity of the deformation received by the specimen, but does not provide a reliable means of measuring stresses quantitatively.

Back-Reflection Laue Method.[9] A convenient arrangement for orientation work is the back-reflection Laue camera, in which the film is mounted over the pinhole system, at B in Fig. 1. Back-reflection Laue patterns for single-crystal orientation are analyzed by stereographic projection. Crystals must be reasonably perfect for this method, because the spots overlap and become indistinguishable if imperfections amount to more than 2 or 3 deg.

The "Pinhole" Method. The "pinhole" method, sometimes called the "transmission method", as distinguished from a "reflection method" in which the rays strike a thick specimen at an angle, is a combined Laue and powder method that is often used in practical work. Because most practical applications of the pinhole method are simple and easily understood, they are presented before the powder method and will serve as an introduction to it. The apparatus is identical with that of the Laue method, except that the radiation used is not general, since it also contains strong monochromatic components. Molybdenum target tubes are used, operating at a voltage of 30,000 to 45,000 v and giving strong monochromatic (characteristic) lines at a wave length of 0.71 A (actually a close doublet of this average wave length) and a weaker line at 0.63 A—the Kα and Kβ lines, respectively. The specimens are polycrystalline materials—either wires or thin strips about 0.004 to 0.010 in. thick.

Patterns from coarse-grained materials contain many spots, as in Fig. 4. Throughout a series of exposures in a given camera, the size of the spots is proportional to the size of the grains and the number of spots is proportional to the number of grains per unit of volume of the specimen, provided the grains are smaller than the effective cross section of the X-ray beam. As the number of spots increases, circular diffraction rings appear (see following section). At first the rings are granular, but as the number of spots increases (that is, as the grain size decreases) the

Fig. 4

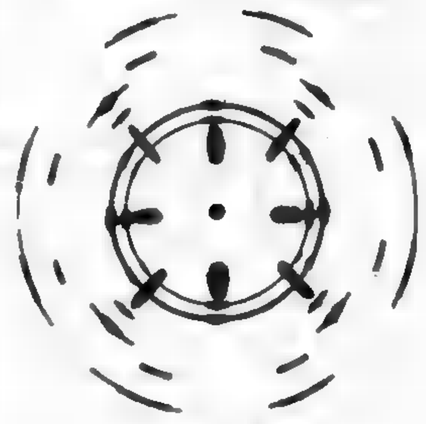

Fig. 5

Fig. 4 Pinhole pattern of undistorted polycrystalline material. Typical of recrystallized metal.

Fig. 5 Pinhole pattern (transmission) of sheet steel having a preferred orientation from cold rolling. (Rolling direction vertical, sheet surface perpendicular to the X-ray beam)

rings become continuous and smooth. Just as in the Laue method, a lengthening of the spots, "asterism", is caused by crystal imperfection or plastic deformation.[2,3]

The distribution of intensity around the diffraction rings reveals the presence or absence of a preferred orientation of the grains (fiber textures). Random orientations produce rings that are uniformly black all around; highly developed orientations give the appearance of Fig. 5, which is a tracing of a pattern from rolled steel. In the cold rolling of steel, preferred orientation begins to be detected at reductions of 20 to 40% in thickness and gradually increases in perfection until the pattern resembles Fig. 5 at 90 to 95% reduction.

Upon recrystallization, the rings break up into spots again and may or may not show the same maximums of intensity. The preferred orientations after recrystallization, analyzed from these patterns, are sometimes found to be the same as in the cold worked material, sometimes different, and frequently the recrystallization produces a random orientation. The presence or absence of preferred orientations can be determined only if there are many spots in the pattern—more than in Fig. 4, for example; with coarse-grained material it is often necessary to shift the specimen during the exposure in order to provide a sufficient number of spots.

If all orientations of the grains are to be studied, it is necessary to make a series of pinhole patterns, with different angular settings of the specimen in relation to the beam. It is customary to plot the data from a series of exposures of this type on a stereographic projection;[4,9] this plot is known as a pole figure.

For interpretation a pole figure is viewed as a stereographic map of a globe that has the sample at the center.

Perpendiculars to a single set of crystal planes—for example (100) planes—extend out radially and puncture the globe at various places; clustering of these punctures in certain areas of the globe indicates clustering of the crystal planes around a certain orientation. The density of the clusters is readily shown by the density of shading at corresponding areas on the stereographic map of the globe. The map must also show the principal directions in the sample. In a rolled sheet, for example, the rolling direction is plotted customarily at the north pole of the map; the cross direction in the sheet, at the right-hand end of the equator; and the sheet normal (which extends toward the observer) is plotted at the center. To facilitate reading angles on the pole figure, determining the areas of clusters and such, use is made of a stereographic projection of latitude and longitude lines of the globe (a Wulff net). Industrial problems can often be solved by taking one or two well-planned exposures without the labor necessary to plot a complete pole figure.

A convenient arrangement for determining the depth of cold work produced by machining is to have the beam strike the specimen at an oblique incidence and reflect from the surface of the specimen, rather than penetrate it. If the surface is cold worked, the spots will be blurred and may overlap into continuous rings, but after etching to a depth sufficient to remove the cold worked layer, the spots become sharp. Back reflection cameras, discussed in the following section, are also used for this purpose.

Powder Method.[1, 3, 4, 8, 9] *Radiation.* The powder method employs monochromatic radiation falling on a powdered crystal specimen or a fine-grained polycrystalline specimen. Radiation is obtained from X-ray targets of relatively low atomic number, giving weak general radiation and relatively strong characteristic radiation. Molybdenum targets may be used but are not satisfactory unless a zirconium filter is placed over the photographic film in the camera or a crystal is placed in front of the camera to serve as a monochromator. Best results are obtained by choosing targets of iron, cobalt, nickel, chromium or copper, or alloys of these. The target is chosen so that the characteristic Kα radiation is of longer wave length than the K absorption limit of the specimen, in order to avoid fogging of the film by fluorescent radiation originating in the specimen. See Table I, where elements listed in the sixth column and elements of lower atomic number than these fluoresce strongly to the Kα radiation listed.

Cameras. Powder cameras are of various types. The common Debye-Scherrer-Hull type (Fig. 6) consists of a cylinder on which is mounted the photographic film, a rod-shaped specimen on the axis of the cylinder, suitable slits or pinholes to direct the primary beam at the specimen, and a device to catch this undiffracted beam or conduct it out of the camera after it has penetrated the specimen, thus avoiding intense blackening where it strikes the film. Focusing cameras are also cylindrical but are designed so that the specimen, the slits, and the photographic film all lie on the circumference of the cylinder (Fig. 7). This arrangement causes diffracted rays from all parts of the specimen to come to a focus on the film and give sharp lines with relatively shorter exposure time. Back-reflection cameras employ large-angle diffracted rays only. They may be constructed with a cylindrical film, with a flat film, or with a photographic plate (see B, Fig. 1); a hole is provided in the film or plate for the passage of the primary X-ray beam. Any of these types may be modified to operate with the specimen at either high or low temperatures, and for use with large-grained samples, the cameras may be provided with devices to rotate, oscillate or shift the specimen, thus permitting more grains to reflect X-rays.

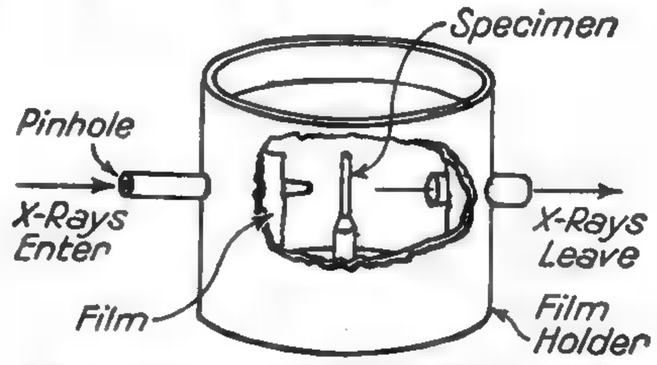

Fig. 6 Powder camera (Debye-Scherrer-Hull)

For studies of cold work and annealing, back-reflection cameras serve well. Cobalt and iron radiation may be used for steel and copper specimens, and copper radiation for aluminum specimens, to give a strong diffraction line at a large angle. The pinholes need not be so small as in cameras used for the precise determination of lattice constants. Cold work is shown by a blurring of the spots lying on the diffraction rings and a broadening of the rings, as indicated in Fig. 8 and 10. Recovery from the strained condition is indicated by a sharpening of the lines (compare Fig. 9, annealed, with Fig. 10), and may or may not go on simultaneously with recrystallization, which is indicated by a return of the spotty type of pattern, as in Fig. 11, indicative of large strain-free grains. This type of camera is not so useful for determining preferred orientations as the "pinhole" camera, which produces its pattern in the forward direction.

The Diffraction Pattern. When a primary beam of X-rays strikes a specimen, the diffracted beams leave the specimen along the generators of a number of cones; each of the cones is concentric with the primary beam. These cones fall on a flat film forming concentric circles, or on a cylindrical film forming curved lines, as indicated in Fig. 9. These circles or lines are frequently called "Debye rings". From the diameter of the circles or arcs on the pattern and the known dimensions of the camera, the apex angles of the cones are calculated, and from these are obtained the angles of reflection, θ, of the Bragg equation. In the camera sketched in Fig. 1, with the film at *A*, if x is the radius of a diffraction ring, and X is the perpendicular distance from specimen to film, then $\tan 2\theta = x/X$. In the camera of Fig. 1, with the film at *B*, $\tan (180 - 2\theta) = x/X$. In the

Table I. Useful Targets, Wave Lengths and β Filters[8, 10]

Target	Atomic Number	Kα_2[a]	Kα_1	Kβ_1	Kα Highly absorbed by elements listed below, also the elements of lower atomic number	Kβ[b]	Filter Material: Content, g per sq cm	Filter Material: Thickness, mm
Ti	22	2.74681	2.74317	2.5090	Sc			
V	23	2.50213	2.49835	2.2797	Sc	Ti		
Cr	24	2.28891	2.28503	2.0806	Ti	V	0.009	0.016
Mn	25	2.10149	2.09751	1.90620	V	Cr	0.011	0.016
Fe	26	1.936012	1.932076	1.753013	Cr	Mn	0.012	0.016
Co	27	1.78919	1.78529	1.61744	Mn	Fe	0.014	0.018
Ni	28	1.65835	1.65450	1.49705	Fe	Co	0.015	0.018
Cu	29	1.541232	1.537395	1.38935	Co	Ni	0.019	0.021
Zn	30	1.43603	1.43217	1.29255	Ni	Cu	0.019	0.021
Zr	40	0.78851	0.78430	0.70028	Ru	Y	0.053	0.210
Cb	41	0.74889	0.74465	0.66438	Sr	Zr		
Mo	42	0.712105	0.707831	0.630978	Y	Cb	0.069	0.108
Ag	47	0.56267	0.55828	0.49601	Mo	Pd	0.096	0.079

(a) When Kα_2 is not resolved from the stronger Kα_1, use the average value $(2\lambda\alpha_1 + \lambda\alpha_2)/3$. All wave lengths are kX units, used by Siegbahn and universally adopted for crystallographic work prior to 1947. To convert to angstroms multiply by 1.00202.

(b) Kβ filters should be made of elements listed in this column; thickness in last column reduces Kβ to 1/600 the intensity of Kα.

camera shown in Fig. 6, if s is the circumferential distance from the central undiffracted spot to an arc of the diffracted line, and R is the camera radius, θ is given in radians by the relation $\theta = s/2R$ (1 radian = 57.30 deg); in practice, measurement is best made of the distance $2s$, from arc to arc, rather than s, from arc to central spot. In the camera of Fig. 7 (and frequently in the others also) it is convenient to prepare a calibration chart for reading θ or d directly from the positions of diffracted lines. A sample the lines of which fall at accurately known angles provides the data for such a chart. Tables relating θ to d are available.[5]

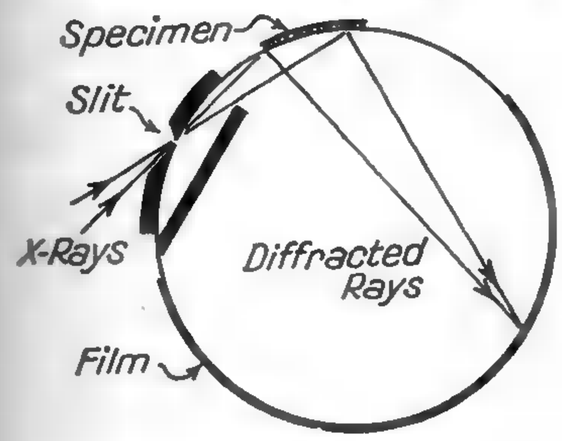

Fig. 7

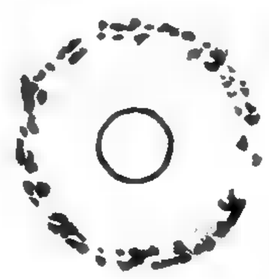

Fig. 8

Fig. 7 Focusing camera (Seeman-Bohlin, Phragmen)
Fig. 8 Pattern from distorted polycrystalline material in a back-reflection camera (Film B, Fig. 1). Blurred spots form a ring surrounding the central hole in the film.

Thus, from the position of the lines on the film, the spacing d of the corresponding atomic planes may be obtained. The sequence of lines on the film corresponds to the sequence of interplanar spacings in the crystal. The pattern in Fig. 9, for example, shows a sequence characteristic of body-centered cubic crystals. Large unit cells have all their interplanar spacings large, and thus their diffracted lines will lie at small angles from the direct beam, while small unit cells will have lines spread out at larger angles. It is the size and shape of the unit cell of a crystal that govern the "positions" of the diffracted rays, while the atomic arrangement within the unit cell controls the "intensities" of the rays. The determination of crystal structure from the powder diffraction patterns is a complex procedure that yields a reliable result in only the simplest cases; various tables, graphs, and other devices aid the investigator.[4,5,8]

Fig. 9

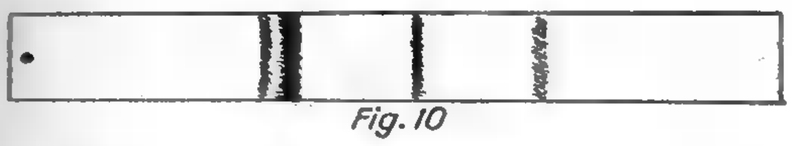

Fig. 10

Fig. 11

Fig. 9 Powder pattern of annealed iron, from camera of Fig. 6, with FeKα and FeKβ radiation. Increasing θ from left to right
Fig. 10 Pattern from cold worked iron. Lines widened and weakened by "microscopic" residual stresses.
Fig. 11 Pattern from recrystallized iron, the large unstrained grains forming spotty lines.

Strictly monochromatic radiation is not usually available; when radiation of two or more wave lengths is present in the beam, each wave length forms a diffraction pattern on the film independently. The Kα lines with closely similar wave lengths fall together and make a single line at low values of θ, but form a doublet at large values of θ (provided the specimen is able to yield sufficiently sharp lines). The Kβ radiation, if not filtered out, produces another superimposed spectrum, which is of single lines instead of doublets and is always weaker than the Kα spectrum. Its lines are recognized by these characteristics and by the fact that the ratio of $\sin\theta$ for Kα and Kβ radiations reflecting from a given atomic plane always equals the ratio of the corresponding wave lengths. The Kβ radiation may be removed by filtering, if desired, using the elements (or compounds containing the elements) listed in Table I under the heading of "Kβ highly absorbed by". The filters are best placed between the specimen and the film, but are also used at the window of the tube.

Precise Lattice Constants.[8,9] The accuracy of lattice dimension measurement with the Debye-Scherrer-Hull cameras and focusing cameras is from 0.1 to 0.02%, depending on the care taken and the operator's skill. Back-reflection cameras are more precise, for these will give from 0.02 to 0.003%. Corrections for errors have been carefully worked out and summarized.

Identification of Phases.[6] A great number of practical problems require no determination of crystal structure, but merely an identification of phases by their powder diffraction patterns, and this may be done without involved calculations, by simply comparing patterns of the unknown material with patterns of chemically or mineralogically identified material. The films are laid side by side or are superimposed, and the similarities are observed directly, or the patterns are compared with those listed in Hanawalt's tables (procurable in card index form from the ASTM). If the crystal structures are simple—for example, cubic—the unit cell dimensions can be computed easily and compared with tables of known structures. For this work large range cameras are required, so that many lines will be obtained. For identification to be certain, every line of the pattern must be accounted for. Important advantages of this X-ray method of identification are that only small quantities of material are required (a few mg), and that different compounds or states of combination of the same elements are distinguishable from each other, since they possess different crystal structures. Thus, chemical compounds are distinguishable from mixtures. The method is widely used for the identification of alloy phases; it is more direct and positive than metallographic methods, but is generally inapplicable when a phase constitutes less than 1 to 5% of the weight of the alloy. If more than one variety of crystal is present in any specimen, each will produce its spectrum independently, and the pattern will consist of superimposed spectra with relative intensities depending on the relative amounts of the two phases. Amorphous materials, glasses, liquids, and gases give only broad halos instead of sharp lines; better patterns are obtained when a crystal monochromator is used.

Solid Solutions. The presence of solute contracts or expands the dimensions of the unit cell of the pure solvent material. This change is registered on the powder photograms by a displacement of the lines to either greater or smaller diffraction angles, unless the effect is too small to be recorded. The effect is ordinarily proportional to the atomic percentage of the dissolved element (Vegard's law) or closely approximates this. The expansion or contraction comes to an abrupt halt at the solid solubility limit, and throughout the two-phase region beyond the limit the lattice dimensions remain constant in binary alloys. This behavior enables an accurate determination of the solubility limit (and its variation with temperature) provided certain precautions are taken. A thorough homogenization treatment is necessary and the surface must be free from sublimation, oxidation, or other reactions which would alter the surface concentration. If the specimen is to represent the condition of the alloy at the homogenization temperature, the quenching from this temperature must be sufficiently rapid to prevent changes; yet quenching stresses must not be introduced into the specimen. These stresses can best be avoided by quenching small wires or fine powders.

The interstitial or substitutional nature of the solid solution can be determined by comparing the measured density with the density calculated from the dimensions of the unit cell and the number and atomic weight of the atoms assumed to be in the cell. Solid solutions are ordinarily random arrangements of the different kinds of atoms on the lattice points. When one kind of atom migrates to a particular set of atomic positions in preference to others, a superlattice is formed. This is recognized in the diffraction pattern by the additional "superlattice lines" which appear after suitable low-temperature annealing of certain alloys.

Stress Measurement.[9] Residual and applied stresses in

metals may be studied with powder diffraction cameras. When an interplanar distance d is altered by stresses, the diffraction angle changes accordingly. If the elastic strain varies from grain to grain in a polycrystalline metal, the angle of diffraction will also vary, giving a widened diffraction line in the powder photograph, as in Fig. 10. The amount of widening beyond the normal width of an annealed stress-free material indicates the amount of variation of stress from point to point in the metal, the relative intensity of "microscopic" stresses. Other factors than stress, however, may contribute to the widening and must be considered in interpreting the photograph; namely, inhomogeneity in composition of the specimen and small size of the reflecting grains. If stresses are of equal intensity in all the reflecting grains, forming a homogeneous stress system, the diffracted rays from all grains will superimpose to produce sharp lines displaced from their normal unstressed positions. The diffraction pattern can then be used to calculate the homogeneous "macroscopic" stresses. Back-reflection powder cameras, arranged so that the X-ray beam falls perpendicularly on the surface of the specimen, give data from which is calculated the sum of the two principal stresses lying parallel to the surface; cameras providing oblique incidence of the rays are used to calculate the principal stresses individually. An accuracy in stress measurement by these methods of about 2,000 psi can be attained with annealed steel under laboratory conditions. Cold worked or quenched steels give diffuse lines which increase the errors to plus or minus 10,000 psi. The stresses measured are those in the surface layers of the specimen, for the radiation used does not penetrate deeply.

Rotating Crystal Method. *Photogoniometers.*[4,8] Types of cameras seldom used in practical work, but indispensable in determination of crystal structure, are those in which a single crystal is mounted so as to oscillate or rotate around a definite crystallographic axis. Monochromatic radiation is used, and the simpler cameras are similar to Fig. 6. Modifications of this are particularly helpful for solving complex crystals. Tne most common of these is the Weissenberg photogoniometer, which permits a photographic film to be shifted in synchronism with the oscillation of the crystal and is provided with a slit through which only selected rays from the crystal will pass. Spacings of the layers of spots in rotating crystal patterns give the distance between lattice points in the direction of the axis of rotation of the crystal. The orientation of single crystals may also be determined with these cameras.

Spectrometers.[1,2,3] The most accurate method of measuring the intensity of diffracted rays involves the use of an ionization chamber or a Geiger-Müller counter mounted on a spectrometer somewhat similar to an optical spectrometer. The current in the chamber, measured by an electrical device, is proportional to the intensity of the X-ray beam. The method is used in crystal structure determination and in quantitative analysis of mixed powders or mixed phases. Chemical analysis is accomplished by X-rays through the use of spectrometers that record the characteristic X-ray emission lines or absorption edges of the sample to be analyzed.[7] Favorable combinations of elements permit extreme sensitivity in the detection of small percentages of an element in a compound or mixture (independent of its state of chemical combination) and also, with care, permit fair precision in quantitative analysis.

X-Ray Diffraction Micrograph[11] A fine-grained photographic plate may be placed very close to a specimen irradiated by characteristic radiation. Images formed on the plate by diffraction of the characteristic radiation are micrographs that can be enlarged 25 to 250 diam, depending on the photographic emulsion. The images distinguish cold worked from recrystallized grains, and indicate microscopic imperfections and concentrations of strains over the surface of individual grains.

Summary of Applications and Methods Usually Employed

Preferred Orientations of Grains, Fiber Textures. Pinhole method, with beam transmitted through the specimen or reflected from the surface of the specimen, noting maximums of intensity around Debye rings (Fig. 5).

Cold Work; Recrystallization. Pinhole, Laue or powder method (Fig. 4, 8).

Identification of Phases. Powder method with cameras that have a wide range of reflection angles (Fig. 9).

Precision Lattice Dimensions; Boundaries of Regions in Phase Diagrams; Studies of Solid Solution and Aging. Powder method, back-reflection cameras.

Grain Size. If larger than 10^{-3} cm, pinhole method or powder method, noting size of spots (Fig. 4, 11). If smaller than 10^{-5} cm, powder method, noting line width (Fig. 10).

Perfection of Lattice in Grains. Pinhole, Laue, or back-reflection powder methods, noting sharpness of spots.

Residual Macroscopic Stresses or Applied Stresses. Back-reflection powder method, with measurement of lattice dimensions.

Residual Microscopic Stresses and Recovery. Back-reflection powder method, noting width of lines.

Orientation of Individual Grains. Laue, back-reflection Laue, or rotating crystal methods, or photogoniometer.

Determination of Crystal Structure. Powder method only in very simplest cases; rotating crystal or photogoniometer method.

Structure of Amorphous Solids, Glasses, Liquids, and Gases. Powder method or spectrometer.

Chemical Analysis. Spectrometer, registering emission lines or absorption edges.

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Dilatometry

By Peter Hidnert* and Wilmer Souder*

ONE of the most frequently measured physical properties of materials is thermal expansion. Virtually all materials undergo a change of dimensions when they are heated or cooled. In isotropic bodies, the expansion or contraction is the same in all directions, but in anisotropic bodies, the expansion or contraction is different in different directions. Allowances for differences in thermal expansion of various materials must be made in many scientific and industrial applications.

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If L_o is the length of a solid body at 0 C, then its length at any temperature $t°C$ may be represented by the following equation:

$$L_t = L_o (1 + at + bt^2 + \ldots) \qquad (1)$$

where a and b are constants depending on the material. Equations of this type are empirical. In most instances, these constants a and b are positive, because bodies usually expand at a more rapid rate as the temperature increases.

Similarly, if V_o is the volume of a liquid or solid at 0 C,

then its volume at any temperature t°C may be represented by the following empirical equation:

$$V_t = V_o (1 + \alpha t + \beta t^2 + \ldots) \qquad (2)$$

where α and β are constants depending on the material.

The average coefficient of linear expansion between any two temperatures t_1 and t_2 may be determined from equation (1) as follows:

$$_{t_1}a_{t_2} = \frac{L_{t_2} - L_{t_1}}{(t_2 - t_1) L_o} \qquad (3)$$

where $_{t_1}a_{t_2}$ is the average coefficient of linear expansion between t_1 and t_2, L_{t_1} and L_{t_2} are the lengths at t_1 and t_2, respectively, computed from equation (1), and L_o is the initial length (usually at 0 C or at room temperature). The lengths L_{t_1} and L_{t_2} may be obtained from the original data or plotted curve without using derived equation (1).

Similarly, the average coefficient of cubical expansion between any two temperatures t_1 and t_2 may be determined from equation (2) as follows:

$$_{t_1}\alpha_{t_2} = \frac{V_{t_2} - V_{t_1}}{(t_2 - t_1) V_o} \qquad (4)$$

where $_{t_1}\alpha_{t_2}$ is the average coefficient of cubical expansion between t_1 and t_2, V_{t_1} and V_{t_2} are the volumes at t_1 and t_2, respectively, and V_o is the initial volume. The average coefficient of cubical expansion of an isotropic solid may be considered equal to three times the average coefficient of linear expansion within a high degree of approximation.

The following equations were obtained by differentiation of equations (1) and (2):

$$a_t = a + 2bt + \ldots \qquad (5)$$

$$\alpha_t = \alpha + 2\beta t + \ldots \qquad (6)$$

In these equations a and α represent the instantaneous coefficients of linear expansion and cubical expansion, respectively, at 0 C, and a_t and α_t represent the instantaneous coefficients of linear expansion and cubical expansion, respectively, at any temperature t°C. Instantaneous coefficients of expansion at t°C may be designated simply as coefficients of expansion at t°C.

Dilatometric Methods. Determinations of dimensional changes of materials, of coefficients of linear and cubical expansion, and of the temperatures and magnitudes of dimensional changes during transformations at constant temperature and with slow or relatively rapid heating and cooling rates (including quenching), are important for progress in science and industry. Dilatometric methods have an advantage over the thermal method (temperature-time cooling curves) in investigating transformations, for the transformation temperatures may be passed through slowly or quickly, or the sample may be held at a given temperature for any length of time, in order to attain equilibrium, and the heating or cooling then resumed. Various types of dilatometers have been used for these determinations.

Eight dilatometric methods will be described. These methods give reliable results if they are used with an intelligent realization of their limitations.

Precision Micrometric Method. The National Bureau of Standards uses micrometric thermal-expansion apparatus for the most precise work on the linear thermal expansion of solids between minus 150 C and plus 1000 C. This apparatus is of two types: (1) the air-type heating chamber, shown at the left of Fig. 1, in which the sample is surrounded by air or a neutral gas; and (2) the stirred liquid bath, shown at the right of Fig. 1, in which the sample is surrounded by a suitable liquid.

In both types of apparatus, heating is effected by passing electric current through heating coils; likewise, both types are equipped with thermocouples and a potentiometer for measuring temperatures. Cooling, for determinations at low temperatures, is secured in the stirred liquid bath by expanding compressed air from a liquid air interchanger through coils immersed in the bath.

The positions of the ends of the sample in the air chamber are indicated by fine wires (0.001 or 0.002-in. diam) weighted and hanging vertically from the ends of the sample through slots in the bottom of the chamber. Two micrometer microscopes, mounted horizontally on a traveling comparator and separated by a lateral distance approximately equal to the length of the sample (10 to 50 cm), are used to measure the length changes of the sample, as indicated by the changes in separation of the two vertical wires hanging freely from the ends of the sample. In the stirred liquid bath, tungsten wires (0.001-in. diam) in contact with the ends of the sample, extend from a fixed horizontal bar above the sample to hinged fingers, inserted beneath the ends of the sample. Here the length changes of the sample are proportional to the changes in the distances between the wires in the plane of the microscopes.

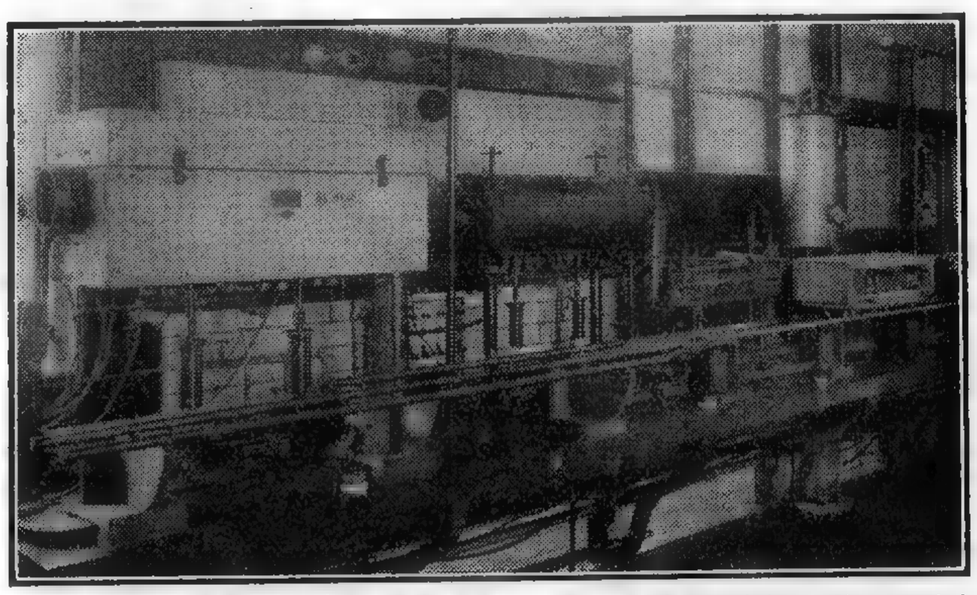

Fig. 1 Furnaces, standard bar and comparator of precision micrometric thermal-expansion apparatus

The sample is in the form of a straight rod or bar of uniform cross section. The usual length is 300 mm, and the diameter (or diagonal, if the rod has a rectangular cross section) is 5 to 10 mm. The sample is prepared with cylindrical ends that have radii of curvature equal to one-half the length of the sample. Provision has been made for handling samples of other lengths and diameters. The limits of length are the length of the furnace for long samples (50 cm) and the limit of contact approach of the two micrometer microscopes for the short samples (10 cm).

When a sample must be heated in the air furnace to a temperature at which oxidation or scaling is expected, the furnace may be filled with a neutral gas. When this gas is not available, it is possible to minimize the effects by placing the observation wires in sharp V grooves cut around the sample near each end.

A vane (5 to 25 g), attached to the bottom of each observation wire in the air-type heating chamber, is suspended in oil to damp out vibrations from the building and surroundings. The wires are annealed before observations are started, by passing sufficient electric current through the wires to heat them to a visible glow. For determinations below 700 C, chromel wires 0.001 or 0.002 in. in diam may be used. For determinations from 20 to 1000 C, platinum-osmium, platinum-rhodium or platinum-ruthenium wires 0.002 in. in diam may be used.

With the air furnace it is possible to make measurements between 20 and 1000 C. The stirred liquid bath is used for temperatures between minus 150 and plus 300 C. The stirred liquid bath, by reason of the circulation and intimate contact of the heated or cooled liquid, permits more rapid observations than the air furnace. Observations are recorded when the sample has reached the temperature of the furnace. This condition may be established by waiting until the observation wires show no movement in the microscopes. After readings are completed the heating current is adjusted for the next temperature. The immersion of samples in the liquid bath is limited to those samples not attacked by the liquids used. The general practice is to employ a light engine oil (Esstic 42) for the temperature range 20 to 300 C. For the range minus 65 to plus 60 C, Dow Corning Fluid No. 500 (kinematic viscosity 2.0 centistokes at 25 C) is used, and 2-methylpentane is used at low temperatures to about minus 150 C. A water

coil in the liquid bath is used to hasten cooling between 300 and 20 C.

The observation wires on which microscope settings are made are illuminated by 10-w Mazda frosted spherical lamp bulbs placed behind the wires. Resistances in the lamp circuit are used to reduce the illumination to a satisfactory intensity. An excellent arrangement for high-precision measurements is secured by the parallel spider lines on the reticle frames moved by the microscope micrometers.

The air furnace has control rheostats for each side and end of the heating chamber. The external heat loss from these rheostats is reduced by using a transformer for the lower temperatures.

With these types of apparatus it is essential that the position of the samples be maintained horizontal during the determinations. A further requirement for the stirred liquid bath is that the readings be made at a known distance above each end of the sample and that the ratio of distances (level of observation to upper supports of wires and ends of sample to upper supports of wires) be known and maintained.

The arrangement of the furnaces, standard bar and comparator is shown in Fig. 1. The air-type heating chamber or furnace is shown at the extreme left of the figure. A smaller air-type furnace is shown at the right of the large furnace. The standard bar of fused quartz and the micrometer comparator appear in front of the window. The interchanger and stirred liquid bath are partially visible near the right margin of Fig. 1. Vacuum bottles used in icing the thermocouple junctions appear at the right of the two furnaces in this figure. Connections to the potentiometer are made through lead-covered cables and a selector switch. Triple thermocouple junctions are placed in the air furnaces. A single thermocouple junction in the stirred liquid bath is sufficient. The forced circulation of the bath liquid by a motor and a propeller maintains uniformity of temperature. Platinum–platinum-rhodium thermocouples are used for the 1000 C air furnace. For the smaller air furnace (600 C), gold-palladium–platinum-rhodium thermocouples are used. A copper-constantan thermocouple is employed in the stirred liquid. The interchanger is of the regular air-liquefying type. The cooled air, compressed to about 2500 psi, is expanded through coils in the stirred liquid bath when temperatures between plus 20 and minus 150 C are required.

This method for determining linear thermal expansion is believed to be the most precise method known. Under most favorable conditions, coefficients of expansion accurate to 0.1% are possible with this apparatus.

Additional information about this equipment is given in publications by Hidnert[1] and Souder and Hidnert.[2] Blueprints giving details of construction are on file at the National Bureau of Standards and may be borrowed.

Interference Method. When only small samples of material (about 10 mm or less in length) are available, the Fizeau-Pulfrich interference method is especially useful for determinations of linear thermal expansion. The method is also useful for determinations of the linear thermal expansion of crystals or other solids in different directions. The sample is placed vertically between two transparent fused-quartz plates, each about 4 mm thick and free from bubbles and other imperfections. The surfaces of each plate should be flat within one-fifth of a fringe and should be inclined toward each other at an angle of about 20 minutes. The sample with the two fused-quartz plates is set in an electric furnace or cooling chamber for heating or cooling. When the plates are illuminated normally with monochromatic light, a set of interference fringes is produced by the interference of the light reflected between the lower surface of the upper plate and the upper surface of the lower plate, when the angle between these surfaces is slight. The fringes are observed by means of a viewing device. Changing the temperature of the sample, brings about a change in length, which causes the distance between the plates to change with a corresponding movement of the interference fringes past a reference mark on the lower surface of the upper plate. From the observed displacement of the fringes, the change in length or linear thermal expansion can be determined. The temperature of the sample may be determined with a thermocouple, resistance thermometer or interference thermometer.[3] This method may be used at low temperatures and at elevated temperatures to about 1000 C.

If the sample is maintained in a vacuum during the determinations, the linear thermal expansion for a given temperature interval may be computed from this equation:

$$\Delta L = \frac{\lambda N}{2L} \qquad (7)$$

where ΔL is the change in length or linear thermal expansion per unit length, λ is the wave length of monochromatic light, N is the number of fringes that passed the reference mark, and L is the initial length of the sample. However, if the sample is heated or cooled in air, a correction should be applied to the value of ΔL computed from equation (7). This correction, known as the "air correction", varies with the pressure and the temperature of the air. The average coefficient of expansion may be computed by dividing ΔL (corrected if necessary) by the change in temperature.

Austin[4] stated that the maximum errors of the interference method with his vacuum furnace should not be greater than 1% at 300 C or 0.7% at 600 C, and the probable error will be much less than this. When the sample is heated in an air furnace, the errors may be greater as a result of the uncertainty caused by the presence of an air film between the sample and the interferometer plate and the oxidation or scaling of the sample.

Additional information about the interference method has been published by Peters and Cragoe,[5] Merritt,[6] and Saunders.[7]

Trowbridge,[8] Arnulf,[9] Sinden,[10] Nix and MacNair,[11] and Saunders,[12] described methods of photographing interference fringes.

In 1916, Meggers[13] indicated how the determination of the exact order of interference or the optical measurement of length can be made with the aid of certain wave lengths of neon radiation. In 1919, Peters[14] described the use of the interferometer in the measurement of small dilations by observing fractional orders caused by several wave lengths, following the method described by Meggers. Willey and Fink[15] have recently used this method in determinations of coefficients of expansion of aluminum alloys. With this method, it is not necessary to count the interference fringes that pass the reference mark during heating or cooling. The method does not require the photographing of interference fringes nor the constant attention of the observer. The method has been used for many years at the National Bureau of Standards for determinations of the lengths of gage blocks at room temperature.

Fused-Quartz-Tube and Dial-Indicator Method. A fused-quartz-tube thermal-expansion apparatus may be used for determinations of linear thermal expansion for various temperature ranges between minus 190 and plus 1000 C. This type of apparatus, as improved by Hidnert and Sweeney[16] beyond a similar type used abroad, is recommended for commercial laboratories where data of the highest precision are not required. With this apparatus it is possible to obtain an accuracy of 2%.

Figure 2 shows a fused-quartz tube closed at the bottom, with a sample (20 cm) in the tube ready for heating or cooling. A movable fused-quartz rod rests on top of the sample and extends above the open end of the tube. The bottoms of the tube and the movable rod are ground concave and the ends of the sample, convex, in order to secure satisfactory contacts. The top of the movable rod, on which a dial indicator rests, is flat. Heating is effected by placing the tube containing the sample in a water or oil bath or in an electric furnace (Fig. 3) extending well above the top of the sample. Low temperatures are secured by using suitable cooling baths, such as: liquid air; solid carbon dioxide in a mixture of equal parts of carbon tetrachloride and chloroform; ice and sodium chloride; and melting ice. A thermocouple, placed inside the fused-quartz tube near the center of the sample, indicates the temperature. A dial indicator, fastened near the top of the tube, registers the differential expansion between the sample and an equivalent length (20 cm) of fused quartz. A small correction is made for the linear expansion of fused quartz. Prints showing details of this apparatus may be secured

from the National Bureau of Standards by persons interested in constructing this equipment.

Modifications of the fused-quartz-tube thermal-expansion apparatus, for use with shorter samples or with a load on the samples, have been described by Hidnert[17] and by Hidnert and Dickson.[18]

Walters and Gensamer[19] modified this type of apparatus so that the expansion of a sample can be determined in a vacuum or an inert gas between minus 200 and plus 1000 C. Kingston[20] modified the apparatus to a recording dilatometer by means of a contact mechanism, transmission shaft, recorder and electronic relay. He also made provision for the use of various atmospheres.

Autographic Optical-Lever Method. Souder, Hidnert and Fox[21] designed and constructed an autographic optical-lever thermal-expansion apparatus for use in commercial laboratories. It was found to give more accurate results than previous apparatus of similar type. With this apparatus it is possible to obtain expansion curves photographically or to observe points on the expansion curves of materials during the progress of the test.

A general view of the autographic expansion apparatus is shown in Fig. 4. The apparatus consists essentially of an adjustable furnace, *F*, mounted on a common base with a camera box, *C*, and an adjustable source of illumination, *I*. The back of the camera is provided with a hinged book-form plate holder for 8 by 10-in. photographic plates, films, sensitized paper, or ground-glass screen for photographic or visual observations. The over-all length of the apparatus is approximately 64 in., height 19 in., and width 14 in.

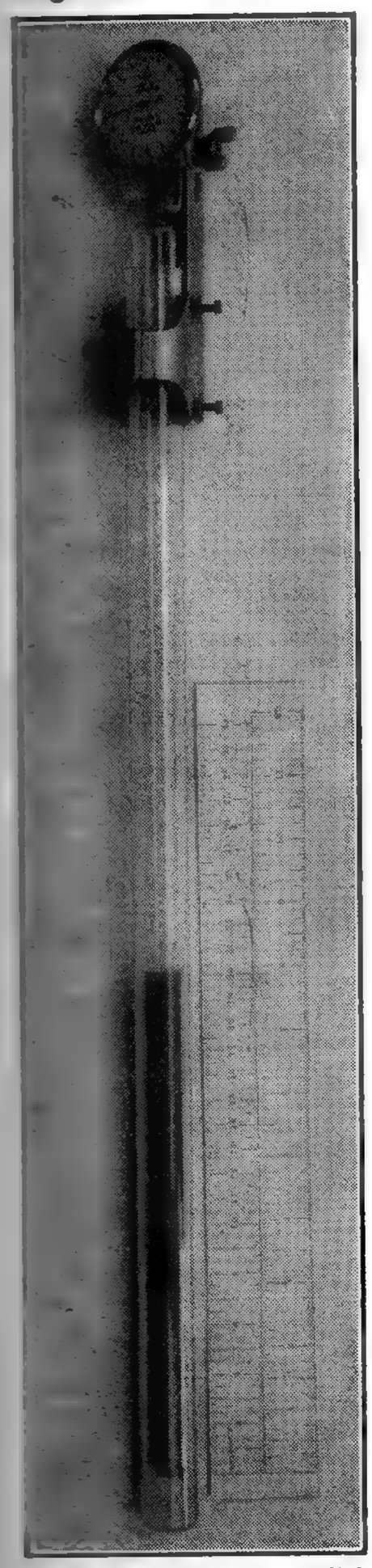

Fig. 2 Fused-quartz tube, dial indicator, and sample

The temperature-expansion relations are projected to the camera by a mirror (Fig. 5) held against three fused-quartz rods that extend from the end of the furnace. Lines joining the points of contact of these extensions against the mirror form a right-angled triangle. The extension which touches at the intersection of the two lines forming the right angle is from a fused-quartz rod in the furnace and is regarded as the "stationary" axis. The sample being tested is situated below this, and as it is heated, its expansion causes the mirror to deflect a spot of light vertically. The third rod, which has a regular rate of linear thermal expansion, causes the mirror to deflect the spot of light horizontally. The spot of light describes a curve, the resultant of these two expansions vertically and horizontally.

For materials having coefficients of expansion approximately equal to those for ordinary steel, the error of the autographic expansion apparatus is about 6% for the range from 20 to 100 C, and about 3% for the range from 20 to 500 C. The apparatus is not sufficiently sensitive for tests on low-expanding materials. It is not satisfactory at temperatures where softening occurs in the sample or for materials that bend at elevated temperatures. It is, however, a convenient, trustworthy, and efficient apparatus and fills a definite need.

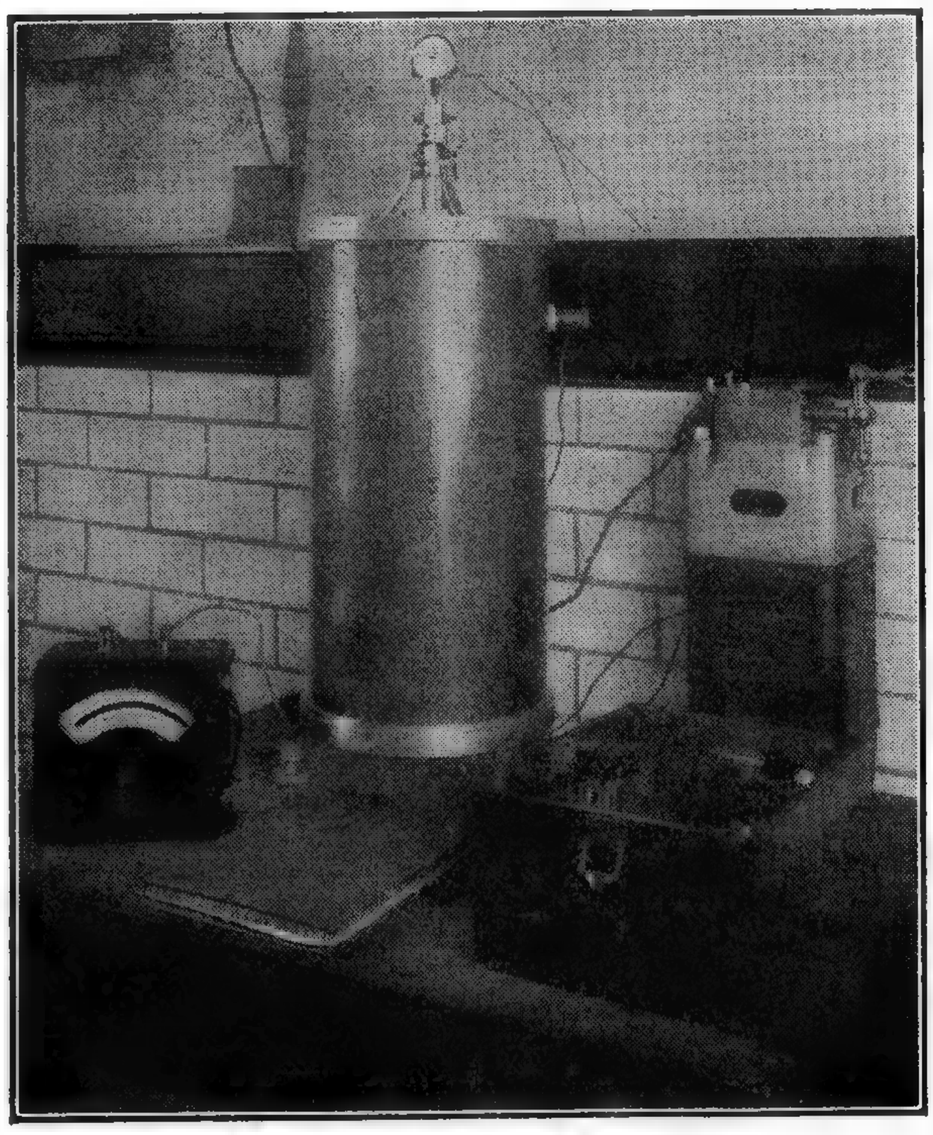

Fig. 3 Fused-quartz tube and dial-indicator thermal-expansion apparatus

Chevenard[22] and other investigators used other forms of the optical lever method for determinations of the linear thermal expansion of materials.

Liquid-Micrometer Method. A liquid-micrometer method for determining linear thermal expansion of solids has been described by Andrew, Rippon, Miller and Wragg.[23] The sample (in the form of a hollow cylinder, 2 in. long, ¾ in. in diam, with a ⅜-in. hole through the center) is placed horizontally in a silica tube of 1-in. internal diam.

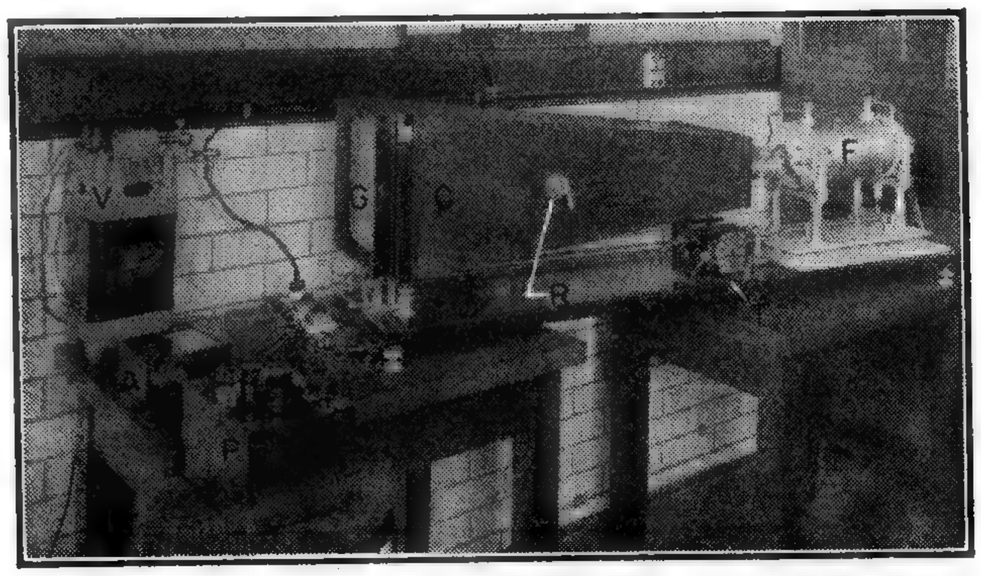

Fig. 4 Autographic expansion apparatus. *A*, ammeter; *C*, camera box; *F*, furnace; *G*, glass screen; *I*, illuminator; *P*, potentiometer indicator; *R*, internal reflecting mirror; *T*, transformer; *V*, induction voltage regulator.

The heating coil consists of a platinum wire wound around the silica tube over a length of 9 in. Two silica disks, accurately ground, are placed on the ends of the sample, which have been ground parallel and polished. These disks are pressed against the ends of the sample by means of two silica tubes, which transmit changes in the length

of the sample. One of the latter silica tubes is butted up against a heavy cast-iron block, and the other silica tube is pressed against a measuring device butted to a large lead block.

The relative movement of the silica tube is measured by a hydraulic device, consisting of a thick steel disk, 8 in. in diam, with a saucer-like depression on the face and a thin disk of saw steel clamped over this face. The space so enclosed is filled with colored water. A pipe runs through the back of the steel disk, connecting this liquid

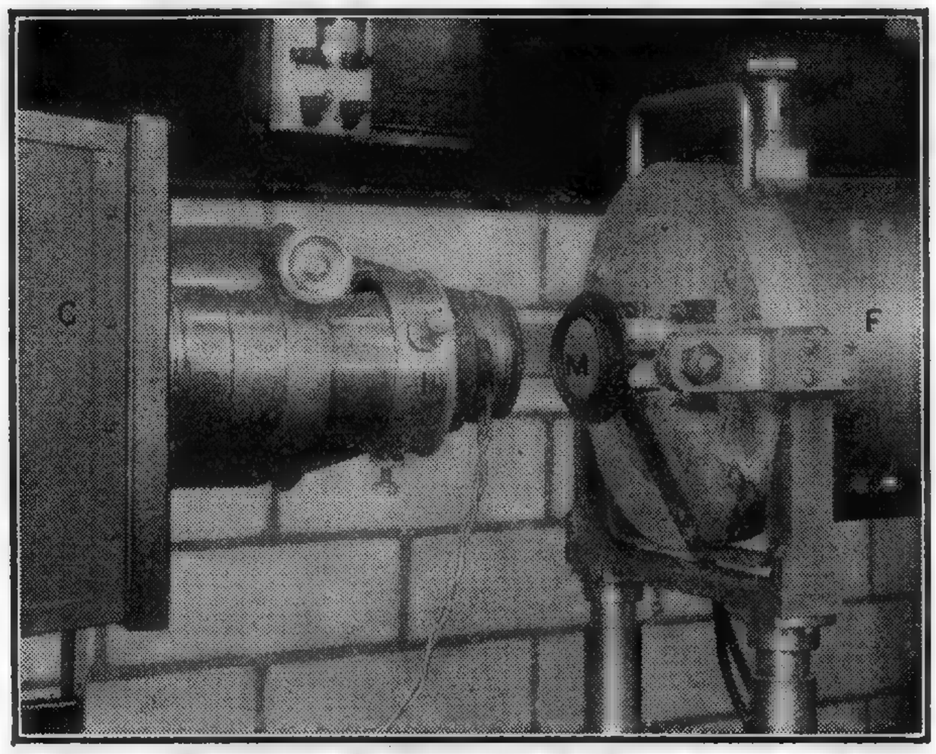

Fig. 5 Stellite mirror in contact with the fused-quartz rods and the "stationary" axis extending from the left face of the furnace. *C*, camera box; *F*, furnace; *I*, illuminator; *M*, optical lever mirror.

with a horizontal glass tube to which a scale is attached. A small reservoir with a stopcock is also fitted for adjusting the amount of liquid in the system. This liquid micrometer is bolted to the lead block, so that the thin steel disk is vertical. A steel disk with a flat surface 1 in. in diam, transmits the movement of the silica tube to the thin steel diaphragm. It was found that with a glass tube of about 2-mm bore, the movement of the meniscus magnifies the displacement of the silica tube two thousand times. The temperature of the sample is measured by means of a thermocouple placed at the center of the sample. Figure 6 shows a sketch of the apparatus.

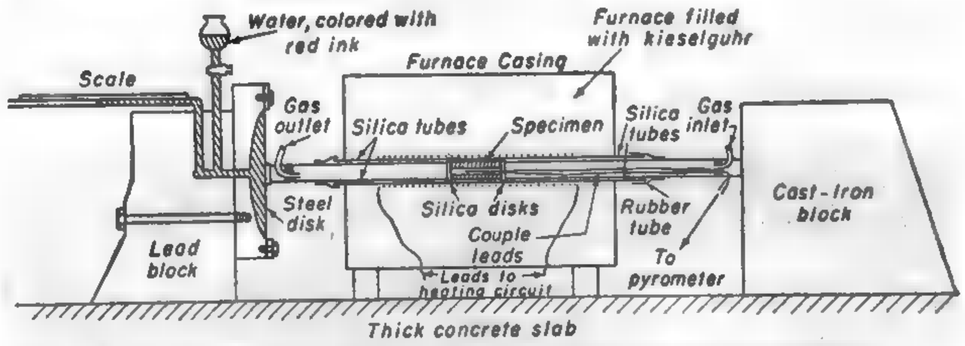

Fig. 6 Diagrammatic sketch of liquid-micrometer dilatometer

A flexible gastight joint is made by means of tubes of thin rubber fixed on the ends of the furnace tubes and then wired to the moving silica tubes. Through holes drilled in these two silica tubes, gas may be circulated around the sample to prevent oxidation.

It is necessary to calibrate this apparatus with samples of known expansion.

The apparatus was modified by Haughton and Griffiths,[24] the changes being the method of rendering the apparatus autographic, the method of mounting so as to enable adjustment of zero and resetting to be easily performed, and various minor modifications which, while by no means vital to the apparatus, simplify its arrangement and use. With this modified dilatometer, using a 2 in. sample, it is possible to record changes of the order of 10^{-6} in., though neither the sensitivity nor the accuracy is normally so high.

Because it is under pressure both in the original apparatus and in that modified by Haughton and Griffiths, the sample may become deformed at high temperatures.

Induction-Furnace and Dial-Indicator Method. A furnace of the high-frequency induction type was used by Heindl[25] for determinations of the linear thermal expansion of refractories between 20 and 1800 C. The heat was generated through the medium of a cylindrical graphite muffle, 12 in. long, 6 in. in diam, and having a wall ½ in. thick. A dial indicator, independent of the furnace, was supported by a framework with fused-quartz tubes for legs.

The setup of the sample (about 6 in. long) is indicated in Fig. 7. This setup formed a continuous system which expanded and contracted, independently of the furnace. Tungsten plates, ⅞ in. square and 0.015 in. thick, were placed between the sample and the graphite parts. The sample was placed within a muffle prepared from zirconium silicate.

Temperatures were measured with two platinum–platinum-rhodium thermocouples up to about 1500 C. Then the couples were removed from the apparatus and higher temperatures were observed with an optical pyrometer.

From a comparison of dial readings, with this apparatus, on a bar of artificial graphite between 20 and 1800 C and on a bar of fused quartz of known expansion between 20 and 1000 C, a curve was derived which gives corrections to be applied to the apparent expansion of a sample at various temperatures between 20 and 1800 C. The portion of the correction curve from 1000 to 1800 C was extrapolated, since the apparent expansion of artificial graphite showed no irregularities between 1000 and 1800 C.

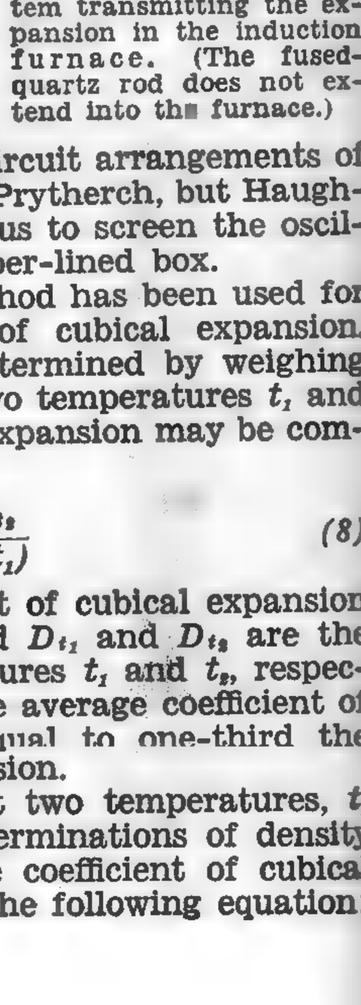

Fig. 7 Specimen, specimen support, and the system transmitting the expansion in the induction furnace. (The fused-quartz rod does not extend into the furnace.)

Capacitance Method. A capacitance dilatometer was developed by Prytherch[26] for use in the metallurgy department of the National Physical Laboratory. An oscillatory valve circuit is used and the sample (about 2 cm long) is made to actuate the moving plate of a small capacitor, which constitutes part of the series grid capacitance of the circuit. Small changes in this capacitance bring about relatively large changes in the mean steady anode current of the valve. A continuous record of the anode current of the valve is made on a thread recorder, which also simultaneously records the temperature of the sample. The changes in length of the sample can be correlated with temperature. Haughton and Adcock[27] altered this apparatus somewhat, in order to examine samples at temperatures as high as 1300 C in a controlled atmosphere. The circuit arrangements of the oscillator are those described by Prytherch, but Haughton and Adcock found it advantageous to screen the oscillator completely by means of a copper-lined box.

Density Method. The density method has been used for determinations of the coefficients of cubical expansion. If the densities of a sample are determined by weighing it in a liquid of known density at two temperatures t_1 and t_2, the average coefficient of cubical expansion may be computed from the following equation:

$$_{t_1}\alpha_{t_2} = \frac{D_{t_1} - D_{t_2}}{D_{t_2}(t_2 - t_1)} \qquad (8)$$

where $_{t_1}\alpha_{t_2}$ is the average coefficient of cubical expansion between temperatures t_1 and t_2, and D_{t_1} and D_{t_2} are the densities of the sample at temperatures t_1 and t_2, respectively. If the sample is isotropic, the average coefficient of linear expansion may be taken equal to one-third the average coefficient of cubical expansion.

If the volumes of the sample at two temperatures, t_1 and t_2, are obtained during the determinations of density or by another method, the average coefficient of cubical expansion may be calculated from the following equation:

$$t_1 \alpha\, t_2 = \frac{V_{t_2} - V_{t_1}}{V_{t_1}(t_2 - t_1)} \qquad (9)$$

where V_{t_1} and V_{t_2} are the volumes of the sample at temperatures t_1 and t_2, respectively.

The density method has been used previously by Matthiessen[28, 29] and Dewar[30] for determinations of the coefficients of cubical expansion of various materials. By this method it is possible to make determinations with small irregular pieces of materials.

Other Dilatometric Methods. Space will not permit descriptions of other methods for determining the thermal expansion of materials. References to publications describing various types and modifications of dilatometers are available at the National Bureau of Standards.

Relations Between Expansion, Temperature and Other Properties. From the data obtained on a sample by means of one of the dilatometric methods, it is possible to plot a curve that shows the relationship between expansion and temperature during heating and cooling. The curve during cooling may or may not coincide with the curve during heating, depending on the sample. From the expansion curve it is possible to compute average coefficients of expansion for various temperature ranges, or an empirical equation may be derived from the original data. For example, the linear expansion of tungsten may be represented by the following equation:

$$L_t = L_o\,[1 + (4.28\,t + 0.00058\,t^2)\,10^{-6}] \qquad (10)$$

where t is any temperature between minus 105 and plus 502 C. Coefficients of expansion may be calculated from this equation as indicated in the introduction.

Dilatometric methods permit the investigation of slow or rapid reactions and a quantitative description of transformations. These changes, observed during the heating and cooling of a sample, are caused by transformations of the constituents (allotropic phase transformations, anomalous transformations without change of phase, and decomposition of phases) and by the reactions between phases. Iron may be cited as an example of a metal which undergoes a transformation with change of phase. When alpha iron (body-centered cubic crystal structure) is heated, it undergoes an allotropic transformation $\alpha \rightarrow \gamma$ at about 910 C, with a contraction for several degrees higher. On being further heated above this temperature (Ac_3), gamma iron (face-centered cubic crystal structure) expands. On cooling, gamma iron undergoes an allotropic transformation $\gamma \rightarrow \alpha$ at about 900 C with an expansion. On further cooling below this temperature (Ar_3), alpha iron contracts.

Figure 8 shows the linear expansion of a carbon steel on heating and cooling between 20 and 900 C. This steel expanded regularly, while being heated to 729 C (Ac_1) and then contracted to 759 C (Ac_3). During heating through this range from 729 to 759 C, alpha iron transformed to gamma iron and iron carbide went into solution in gamma iron. At 759 C, the steel resumed its expansion at higher temperatures. On cooling, the steel contracted regularly to 685 C (Ar_3), when expansion started with a transformation to alpha iron. The expansion continued on cooling to 659 C (Ar_1). On further cooling to 20 C, the steel contracted in a normal manner.

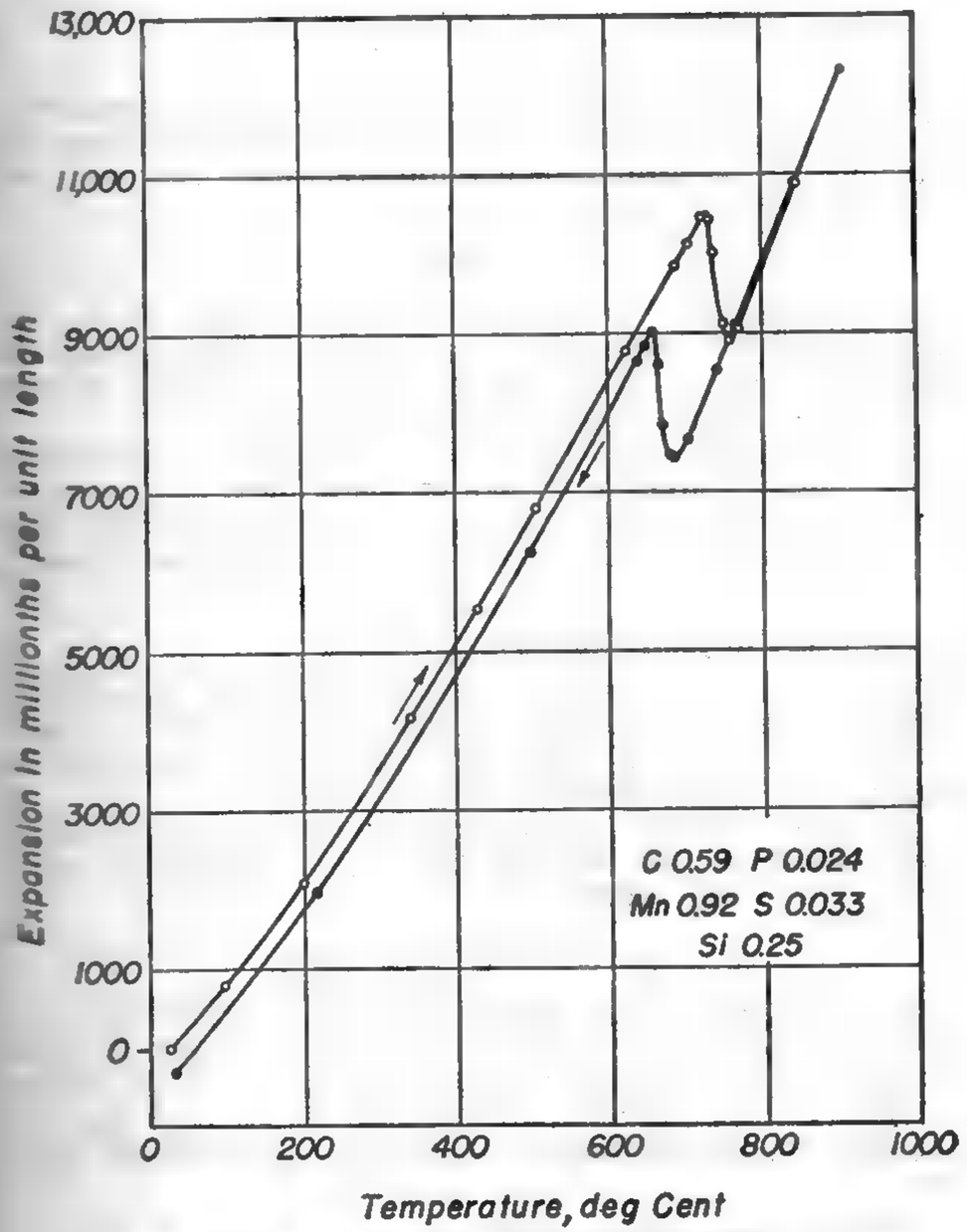

Fig. 8 Curve showing linear thermal expansion and transformations of steel

Dilatometric data may be used for obtaining relationships between thermal expansion and temperature; for investigations of the constitution of metals and alloys, investigations of dimensional changes in steels on hardening, aging phenomena of alloys and steels, kinetics of transformation of austenite during cooling of steels and during

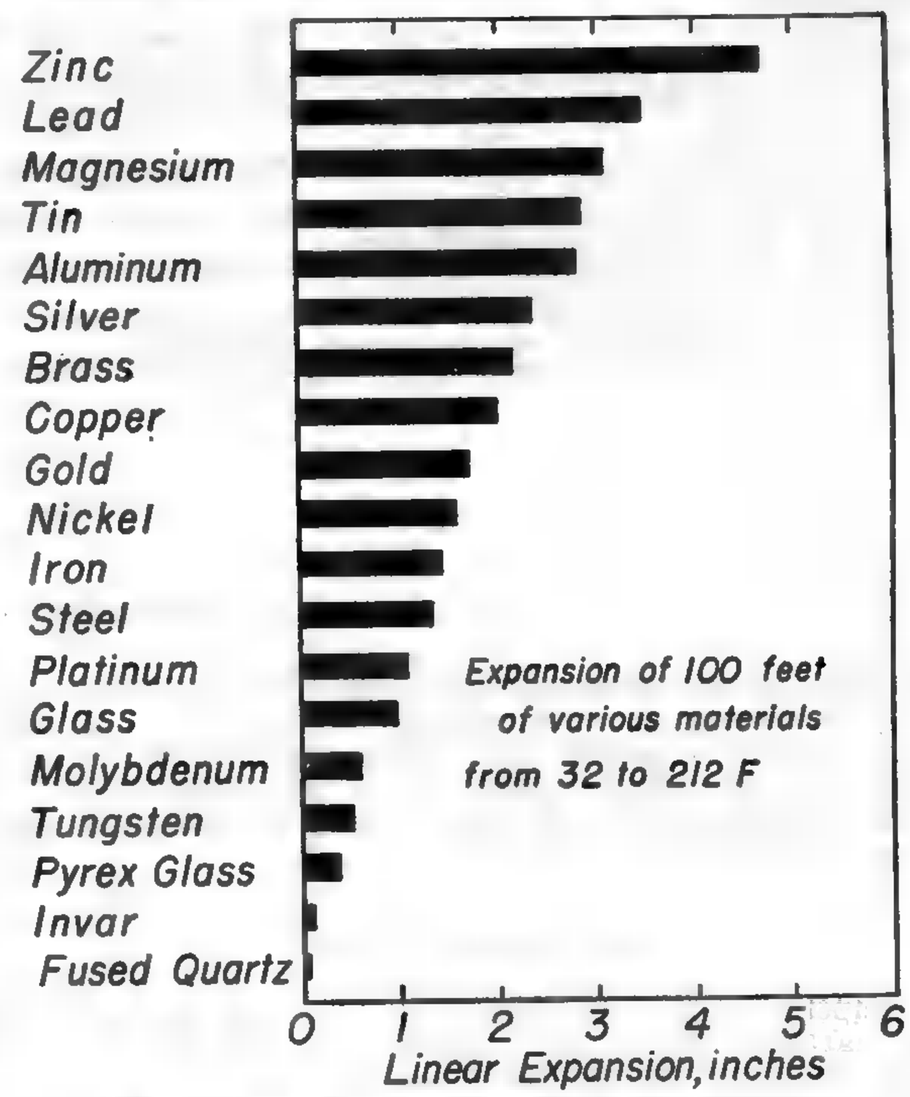

Fig. 9 Linear thermal expansion of 19 materials from 0 to 100 C (32 to 212 F)

isothermal holding below the eutectoid temperature, and of graphitization of cast iron; and for obtaining relationships between thermal expansion, chemical composition, thermal and mechanical treatments of materials, and the like. For example, the following equation shows the relationship between linear thermal expansion and chemical composition of cold rolled copper-zinc alloys:

$$a_{50} = (22.923 - 0.06833\,X + 0.0000695\,X^2)\,10^{-6} \qquad (11)$$

where a_{50} is the instantaneous coefficient of expansion at 50 C and X is the weight percentage of copper. This equation is based on measurements made on samples containing more than 62% Cu.

Grüneisen's law,[31] first deduced empirically in 1908, states that, for a metal, the ratio of the coefficient of linear expansion to its specific heat at constant pressure is constant at all temperatures. This law is a fairly good approximation but does not hold in all instances.

Data on Thermal Expansion. Data on thermal expansion of various materials may be found in the following

publications: International Critical Tables, Landolt-Börnstein Physikalisch-Chemische Tabellen, Smithsonian Physical Tables, Circular of the National Bureau of Standards C447, "Mechanical Properties of Metals and Alloys," and in this Handbook (see especially pages 25 and 309 to 312).

A chart indicating the linear thermal expansion of 19 materials on heating from 0 to 100 C (32 to 212 F) is shown in Fig. 9. Letter Circular LC679, "Thermal Expansion of Solids: Publications by Members of the Staff of the National Bureau of Standards", gives a list of publications that supply data on the thermal expansion of metals, alloys and other materials for various temperature ranges.

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Pyrometry

By the Subcommittee on Pyrometry*

PYROMETRY deals with the measurement of all temperatures higher than about 950 F or 500 C. The principal methods of pyrometry in industrial use are the thermoelectric, resistance, radiation and optical methods. All these, except the optical method, can be extended easily to temperatures below 950 F.

Temperature Scales

Temperature is now universally expressed either on the International Temperature Scale[1] or on a scale derived from this scale and hence in conformity with it.

On the International Scale, temperatures are designated as degrees Centigrade (deg Cent, C, °C). Other scales in general use are the Fahrenheit (deg Fahr, F, °F) and Kelvin (deg K, K, °K). These scales are related in the following way:

$$n°\text{C} = (n + 273.16)\ °\text{K} = (1.8n + 32)\ °\text{F}$$

The basis of the International Scale is as follows:

(*a*) From 0 to 660 C the temperature t is deduced from the resistance R_t of a standard platinum resistance thermometer by means of the equation

$$R_t = R_0\ (1 + At + Bt^2)$$

The constants R_0, A, and B are determined by measuring R_t at the ice point, steam point, and sulfur boiling point, which are defined as 0 C, 100 C, and 444.60 C, respectively.

(*b*) Below 0 C the temperature is also deduced from the resistance of a standard platinum resistance thermometer, but the equation used is

$$R_t = R_0\ (1 + At + Bt^2 + C(t - 100)\,t^3).$$

The constants R_0, A, and B are determined as in (*a*) above, and the constant C is then calculated from the measured value of the resistance at the normal boiling point of oxygen (defined as minus 182.97 C).

(*c*) From 660 to 1063 C, the temperature is deduced from the electromotive force e of a standard thermocouple made of pure platinum versus the alloy 90 Pt–10 Rh, with one junction at 0 C and the other at t, using the equation

$$e = a + bt + ct^2$$

The constants a, b, and c are calculated from measured values of e at the freezing points of antimony (determined with a standard resistance thermometer for the specimen actually used, about 630.5 C), pure silver (defined as 960.5 C), and pure gold (defined as 1063.0 C).

(*d*) Above 1063 C the temperature t is deduced from the Wien radiation law for the intensity J of light of wave length λ at temperature t:

$$J_{\lambda t} = c_1\lambda^{-5}e^{-\frac{c_2}{\lambda(t+273)}}$$

in which c_1 and c_2 are experimentally determinable constants. For the International Scale, c_2 is defined as 1.432 centimeter-degrees and the melting point of gold is defined as 1063 C. In practice, only ratios r of intensity are measured, which eliminates constant c_1. The working equation is:

$$\log_e r = \log_e \frac{J_{\lambda t}}{J_{\lambda 10 6 3}} = \frac{1.432}{\lambda}\left(\frac{1}{1063 + 273} - \frac{1}{t + 273}\right)$$

* All the material on pyrometry in the 1939 edition, including separate articles on temperature measurements of aluminum and brass, which are now incorporated in the present article, has been revised for this edition by the subcommittee consisting of R. B. Sosman, *Chairman* (United States Steel Corporation), G. T. Evans (The Bristol Company), C. O. Fairchild (Consulting Engineer), W. E. Forsythe (General Electric Company), T. R. Harrison (Brown Instrument Company), J. C. Peters (Leeds & Northrup Company), Wm. F. Roeser (National Bureau of Standards), H. T. Wensel (General Staff, War Department).

Thermoelectric Pyrometry

Thermoelectric pyrometers may be used satisfactorily for measuring temperatures up to about 3000 F.

Principle of the Thermoelectric Pyrometer. If two dissimilar wires are joined together at both ends and one junction is heated, an electromotive force (emf) or voltage is generated in the circuit. This discovery led to the development of the thermoelectric pyrometer, a simple form of which is illustrated in Fig. 1. It consists of a millivoltmeter connected to two wires of different metals, the other ends of which are joined together and placed in a furnace. These two wires constitute the *thermocouple;* one wire is the positive element and the other is the negative element. The millivoltmeter is an instrument to measure the emf or voltage generated.

Most thermocouples consist of two elements in the form of wires, but a few are made in the form of a wire element within a tubular element.

In the thermoelectric circuit shown in Fig. 1 there are three junctions, as follows: the junction of the two wires inside the furnace, often called the "hot junction", now generally referred to as the "measuring junction"; and the two junctions between the elements of the thermocouple and the copper wires connecting them to the millivoltmeter, A and A_1. Although there are two such junctions in the arrangement show in Fig. 1, the pair is commonly treated as a unit and is often called the "cold

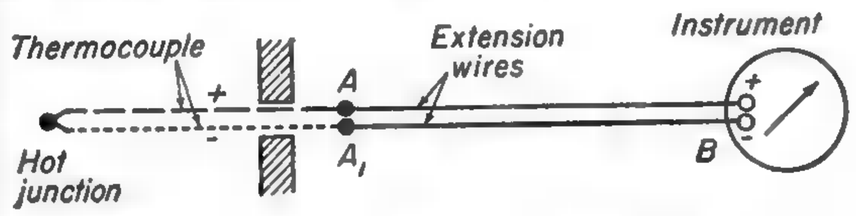

Fig. 1 Simple thermoelectric pyrometer circuit

junction", now more generally referred to as the "reference junction". Since this article concerns only high temperatures, it will be better to adhere to the terms "hot" and "cold", which can lead to no misunderstanding.

The total emf generated in a thermoelectric circuit, and measured as in Fig. 1, depends on the temperatures of all the junctions of dissimilar metals in the circuit. Consequently, if all the junctions but one (the hot junction) are maintained constant, then the resultant emf, as measured by the millivoltmeter, varies only with the temperature of the hot junction.

Thermocouple Materials. The number of metals and alloys suitable for commercial use in thermocouples is limited, because at high temperatures such materials must be resistant to oxidation, recrystallization, melting, and contamination; they must develop an emf high enough to be measured without the use of delicate apparatus; and finally, they must be reproducible and readily obtainable in uniform quality.

The following combinations of materials are in common commercial use for thermocouples: platinum versus the alloy 87% Pt plus 13% Rh; platinum versus the alloy 90% Pt plus 10% Rh; Chromel versus Alumel; iron versus constantan; and copper versus constantan. The last three pairs are commonly referred to as "base-metal couples".

The useful life of a thermocouple depends not only on the maximum temperature to which it will be subjected, but also on the atmospheric conditions.

Platinum versus platinum-rhodium thermocouples may be used at temperatures as high as 3000 F, but they are easily contaminated and must be protected suitably at all times. Continuous subjection to temperatures above 2800 F is not recommended.

There is no completely satisfactory material for long service in the presence of reducing gases. Stainless steel (iron-chromium-nickel alloy) is being used to a limited extent paired with Chromel, but the couple has not been standardized by the instrument companies.

The Chromel-Alumel thermocouple will generally be more satisfactory than the iron-constantan when used in oxidizing atmospheres at 1200 to 2200 F. Chromel-Alumel may be used intermittently up to a temperature of 2400 F. The emf of this couple is subject to change when the wires are exposed to a reducing atmosphere.

The iron-constantan thermocouple is not recommended for continuous use in air at temperatures above 1400 F. At this temperature, No. 8 gage wire of either element of the couple will last about 1000 hr in air. Ordinarily the iron-constantan couple will have a longer life and be more satisfactory than Chromel-Alumel in a reducing atmosphere up to 1800 F.

The copper-constantan thermocouple is satisfactory for continuous use as high as 700 F and for intermittent use as high as 1000 F.

The life of any base-metal thermocouple will be relatively short when exposed continuously to temperatures above 2200 F. Alternately reducing and oxidizing conditions are especially detrimental to any base-metal couple.

Construction of Couples. The hot junctions of all thermocouples should be welded; however, they may be silver soldered in base-metal thermocouples for use at comparatively low temperatures (below 1000 F). Borax is a satisfactory flux for silver soldering any base-metal thermocouples or for welding iron-constantan. Fluorspar is better for Chromel-Alumel thermocouples. Plenty of flux should be used. No flux is required for welding platinum thermocouples. Greater mechanical strength can be obtained at the hot junctions of base-metal thermocouples by twisting the two wires together for about two turns before making the weld.

When base-metal thermocouples have burned out or have become so contaminated that they give incorrect readings, they should be destroyed to prevent accidental reuse.

When platinum thermocouples have become contaminated and give incorrect readings, it is sometimes possible to prolong their usefulness by annealing them with an electric current in air and cleaning with fused borax. However, it has not been demonstrated conclusively that platinum-rhodium thermocouples, after contamination, can be greatly improved in homogeneity by prolonged heating in air, although it is logical to suppose that certain impurities can be driven off or, through oxidation, rendered less detrimental.

Cold Junctions. Every thermoelectric pyrometer is calibrated for a particular cold-junction temperature, generally 0 F, 32 F or 75 F. During subsequent use the cold junction need not necessarily be maintained at that particular temperature, as long as the actual temperature is known, because it is possible to compensate for the difference between the actual cold-junction temperature and that for which the instrument was calibrated.

It is generally more feasible to compensate instrumentally for different cold-junction temperatures than to maintain them at the particular temperature for which the pyrometer was calibrated. However, it is highly desirable to eliminate rapid variations in the cold-junction temperature.

Extension Wires. Unless the two wires forming the thermocouple are long, the cold junctions will be so close to the furnace that they will be subject to extensive temperature variations. Since it is desirable to place the measuring instrument some distance away from the furnace, and since it is often impracticable to make the thermocouple long enough to reach to the instrument, "extension wires" are used to connect the thermocouple to the instrument.

If in Fig. 1 the wires are of copper, the cold junction is close to the furnace at A. If, on the other hand, the extension wires consist of a pair made of the same materials as the thermocouple, or of some less expensive pair made of materials that have the same thermoelectric characteristics as the thermocouple pair, the cold junction will be located not at the furnace but at the binding posts of the instrument B, a position of more nearly constant temperature.

The extension wires of base-metal thermocouples are usually made of the same materials as the thermocouple wires. Sometimes copper-constantan extensions having suitable characteristics are used with Chromel-Alumel couples. With platinum – platinum-rhodium thermocouples, a copper extension wire is connected to the platinum-rhodium and a special copper-nickel extension wire to the platinum. Although the temperature-emf relation of

the copper–copper-nickel extension wires is virtually the same as that of platinum–platinum-rhodium thermocouples, the individual extension wires are not identical thermoelectrically with the thermocouple wires to which they are attached and, therefore, the two junctions where the extensions are attached to the thermocouple should be kept at the same temperature. This means that special care must be taken that this pair of junctions is not heated unsymmetrically. Such precautions are unnecessary for base-metal thermocouples where the thermocouple wire and the extension wire attached to it are of the same material. The temperature of the points of connection between the extension wires and the thermocouple should be limited to that at which the calibration of the extension pair departs from the couple calibration by the maximum amount permissible for the purpose at hand.

In general, extension wires intended for a thermocouple made of one pair of materials should not be used with a thermocouple made of a different pair of materials.

The positive and negative extension wires, identified by color of insulation or otherwise, must always be connected respectively to the positive and negative elements of the thermocouple. If there is doubt as to the identity of the positive and negative wires of extensions, the wires should be tested with a millivoltmeter or potentiometer. It is possible to have the extension wires wrongly connected to the thermocouple and also wrongly connected to the instrument, so that the instrument will read up-scale, yet read wrong. An up-scale reading is no guarantee of correctness in the setup. A safe way to connect the circuit is first to connect the extension wires alone to the instrument; then to twist the other end of the extensions together and heat the junction with a match. The instrument should read up-scale. Then the extensions should be connected with the thermocouple, the terminals should be allowed to cool, and the couple junction should be heated. The instrument must again read up-scale; if it reads down-scale, the extensions should be reversed at the couple, not at the instrument.

There are a few simple methods of using extension wires to remove the cold junction to a position of constant temperature, and of making one cold junction serve several thermocouples.

The arrangement shown in Fig. 1, with extension wires to remove the cold junction to the indicator, is the simplest, but the cold junction is still subject to variations in room temperature, which will introduce errors into the reading unless the indicator is equipped with an automatic cold-junction compensator.

Cold-Junction Compensation. If the temperature at the cold junction is not maintained constant, but is allowed to assume the temperature of the air, as in most pyrometer installations, correction or compensation must be made for this fluctuating temperature.

If the measuring instrument (*see* later paragraphs for description) has no manual or automatic device for compensating for the cold-junction temperature, the correction can be made with the aid of tables of emf versus temperature for the thermocouple that is being used. It is wrong simply to add an air-temperature correction to the reading of the instrument without regard to the temperature-emf curve.

When a millivoltmeter is used with no automatic cold-junction compensation but with a scale reading in degrees, variations in the temperature of the cold junction can be compensated for by making the zero or open-circuit position of the instrument pointer on the scale agree with the actual temperature of the cold junction. This can be done by means of the "zero adjustment" provided. This adjustment should be checked at frequent intervals because the cold-junction temperature may have changed, or the zero setting of the pointer may have been disturbed accidentally.

When a millivoltmeter is used that is equipped with an automatic cold-junction compensator, the zero position of the pointer should agree with a specified temperature on the scale or with the actual cold-junction temperature, depending on whether the compensator is operated electrically or mechanically, as when a bimetallic spring, "Breguet Spiral", is attached to the moving coil. For either type of compensator the manufacturer's instructions should be followed.

With a potentiometer, a cold-junction compensator, operated either manually or automatically, is generally provided. If this compensator is manually operated, the dial should be adjusted at frequent intervals to agree with the actual temperature of the cold junction.

The element of the compensator that is sensitive to temperature should be kept close to the cold junction of the thermocouple and the two should be shielded or wrapped so that the temperature of the one will always be the same as that of the other. The reader is referred to the manufacturers for detailed descriptions of the different types of compensators in common use.

Figure 2 illustrates the use of extension wires when a number of thermocouples are connected to a distant instrument equipped with an automatic cold-junction compensator. Instead of being extended from each thermocouple all the way to the instrument, the extension wires are extended only to a centrally located common zone box and a single auxiliary couple is extended from the common zone box to the element of the automatic cold-junction compensator that is sensitive to temperature. The cold junction for the system is at *B*.

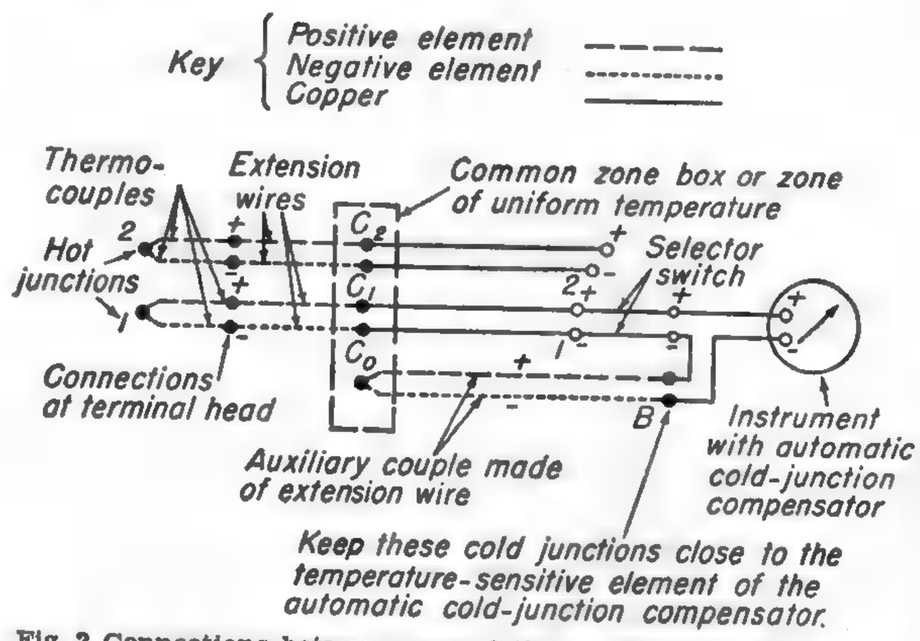

Fig. 2 Connections between several thermocouples and a distant instrument equipped with an automatic cold-junction compensator

This arrangement is solely for the purpose of reducing the length of the extension wires required and is advantageous only when it results in a reduction in the total cost of installation.

Relation of Emf and Temperature. Until recent years each manufacturer of thermoelectric pyrometers had his own source for thermocouple alloys and his own curve for the relation of emf to temperature. The platinum metal thermocouples were the first to be standardized, and the tables of emf versus temperature for both the 10% Rh and the 13% Rh couples have been determined accurately by the National Bureau of Standards. These tables are now accepted as standard by most if not all of the manufacturers of pyrometers in the United States.

Next came Chromel-Alumel. The composition and properties of these two trademarked nickel alloys can be kept under good technical control. Having found that the alloys can be reproduced to specifications, the Bureau of Standards has published a standard table that is now in general use by the manufacturers of pyrometers.

Constantan is no longer a trademarked name, but applies to a limited range of copper-nickel alloys containing a little manganese. Since the several alloys of this type differ somewhat in thermoelectric power, there are no "standard" tables for iron-constantan and copper-constantan couples. A range of thermoelectric characteristics is obtained by varying the composition suitably.

There is no difficulty in obtaining reproducible pure copper. At the National Bureau of Standards it has been found that constantan is regularly available which, when used with pure copper, conforms to L. H. Adams' table (1914, 1920, 1926).

Pure iron is difficult to make, and the wire actually used in thermocouples contains from 99.5% to 99.9% Fe,

with small amounts of various elements that influence the thermal emf. The National Bureau of Standards has published a table for a thermocouple consisting of the more nearly pure iron and the same constantan as that used with copper to reproduce the L. H. Adams table. Most manufacturers of pyrometers use iron having principally a higher manganese content in conjunction with constantan of a composition somewhat different from that required for the Adams table.

Table I contains the accepted data for platinum–platinum-rhodium and Chromel-Alumel thermocouples, together with the data published by the National Bureau of Standards for iron-constantan and copper-constantan couples, and the data for the iron-constantan couples supplied by most manufacturers of pyrometers. At the head of each column, in the name of the couple, the positive element is named first. Many other combinations have been used in thermoelectric pyrometry, but none has been accepted as generally as those listed in Table I.

Table I. Representative Tables of Emf versus Temperature for Principal Commercial Thermocouple Combinations

Emf is in millivolts. Cold junction, 32 F

Temp, deg Fahr	90 Pt. 10 Rh versus Platinum[a]	87 Pt, 13 Rh versus Platinum[a]	Chromel versus Alumel[b]	Iron versus Constantan A[c]	Iron versus Constantan B[d]	Copper versus Constantan[c]
32	0	0	0	0	0	0
100	0.221	0.220	1.52	2.00	1.96	1.52
200	0.594	0.596	3.82	5.03	4.92	3.97
300	1.016	1.030	6.09	8.12	7.95	6.64
400	1.473	1.503	8.31	11.24	11.02	9.52
500	1.956	2.012	10.56	14.35	14.09	12.57
600	2.457	2.546	12.85	17.43	17.16	15.77
700	2.975	3.102	15.18	20.48	20.23	19.09
800	3.505	3.675	17.52	23.53	23.31	22.53
900	4.044	4.263	19.88	26.59	26.41	26.06
1000	4.594	4.867	22.25	29.70	29.54	29.67
1100	5.155	5.486	24.62	32.88	32.74	....
1200	5.725	6.122	26.98	36.17	36.04	....
1300	6.307	6.773	29.33	39.58	39.46	....
1400	6.898	7.438	31.65	43.12	42.96	....
1500	7.500	8.118	33.94	46.74	46.48	....
1600	8.112	8.810	36.20	50.39	50.00	....
1700	8.734	9.518	38.43	53.87	53.52	....
1800	9.365	10.237	40.62	57.16	57.04	....
1900	10.006	10.970	42.77	....	....	....
2000	10.657	11.720	44.89	....	....	....
2100	11.315	12.478	46 97	....	....	....
2200	11.977	13.242	49.01	....	....	....
2300	12.642	14.010	51.00	....	....	....
2400	13.305	14.777	52.95	....	....	....
2500	13.968	15.543	54.85	....	....	....
2600	14.629	16.308	....	....	....	....
2700	15.288	17.073	....	....	....	....
2800	15.943	17.833	....	....	....	....
2900	16.596	18.588	....	....	....	....
3000	17.246	19.342	....	....	....	....

(a) Bur Standards RP 530 (1933). (b) Bur Standards RP 767 (1935). (c) Bur Standards RP 1080 (1938). (d) Data applicable to much of the wire supplied by pyrometer manufacturers.

For accurate temperature readings (better than 1% of scale) reliance should not be placed on Table I, but the individual thermocouple and instrument should be calibrated. (*See* page 180.)

Protection Tubes. One of the reasons why certain materials have come into common use for thermocouples is that they are reasonably stable thermoelectrically when heated in a clean oxidizing atmosphere. The standards of performance generally accepted for the various combinations of thermocouple materials are based on the behavior of these combinations in air. Although it has not been shown that a reducing atmosphere, in itself, necessarily contaminates or alters the thermoelectric properties of all thermocouple materials, it is nevertheless generally observed that exposure of thermocouples to such atmospheres is accompanied by contamination or change in the chemical composition, which seriously alters the readings of thermoelectric emf. Consequently, in order to obtain the best performance of thermocouples, it appears necessary to maintain them in an atmosphere having essentially the same oxygen content as air. The selection of a proper tube for protecting the thermocouple from vapors, fumes or furnace gases is sometimes as important as the selection of the thermocouple materials.

Contamination results from such causes as the following:

1 Metals (solid, liquid or vapor) coming into contact with the thermocouple materials and altering their chemical composition.
2 Furnace gases and fumes coming into contact with the thermocouple materials. Sulfur and sulfur compounds are particularly deleterious.
3 Materials normally stable in an oxidizing atmosphere coming into contact with the thermocouple material in a reducing atmosphere. One common cause of contamination, which is serious in rare-metal thermocouples, is the reduction of silica (usually present in insulating and ceramic protection tubes) to silicon, which readily combines with the thermocouple materials.
4 Preferential oxidation and reduction of base-metal alloys, when these are exposed alternately to oxidizing and reducing atmospheres. This results in a gradual change in chemical composition, because all the elements that comprise an alloy cannot be expected to oxidize and reduce at the same rates under all conditions.

Many types of protection tubes are required in order to meet all needs. Often the conditions under which thermocouples are used are such that two tubes are necessary to provide the desired protection. For instance, a primary tube of porcelain or fused silica may be placed inside a secondary tube of metal, silicon carbide or fire clay. The primary tube of low volatility is intended to provide the imperviousness to gases at high temperatures, and the secondary tube provides the resistance to thermal and mechanical shocks and to corrosion.

However, in thus providing protection for the thermocouple, it is important to remember that a thermocouple can perform its function only when the conditions of heat transfer are such that the measuring junction will attain or at least approximate the temperature to be measured. When a tube of large cross section or more than one tube is used, particularly if the tubes have high thermal conductivity, it should be considered carefully whether the depth of immersion is sufficient to insure that the temperature of the thermocouple junction is reasonably close to the temperature to be measured. Short heavy tubes may cool the junction so much that indications will be comparatively worthless.

Platinum to platinum-rhodium thermocouples are particularly susceptible to contamination and should be protected by ceramic tubes that are impervious to gases and vapors at all operating temperatures. If furnace gases are not present, metal tubes usually provide sufficient protection for base-metal thermocouples. The oxide coatings on the thermocouple wires are fairly effective in protecting the wires from contamination by metallic vapors. Metal tubes that provide sufficient protection in an oxidizing atmosphere may be entirely unsatisfactory if large amounts of furnace gases are present.

Primary ceramic tubes that meet most requirements of stability and imperviousness to gases are made of the following materials: highly refractory porcelain, sometimes called "Sillimanite" or "Mullite", for temperatures up to 2800 F; vitreous silica (fused quartz) to 1900 F and Vycor glass, to 1800 F, both in an oxidizing atmosphere; Pyrex glass, to 1100 F.

The secondary or metal tube most suitable for a particular application depends to a large extent on the type of corrosion encountered. Nickel tubes are useful above 2100 F. Tubes of nonscaling alloys such as nickel-chromium and nickel-chromium-iron are suitable for many applications at temperatures up to 2000 F. Tubes of iron and steel are suitable for numerous applications up to 1500 F. Calorized wrought iron is impervious to certain gases and meets certain needs up to 1800 F. Fire clay, silicon carbide and graphite meet certain requirements of secondary tubes at temperatures above the useful limit of metal tubes.

Numerous other types of secondary tubes have been developed for specific purposes. Information regarding the best type of tube for any particular purpose is usually available from the pyrometer manufacturer.

Insulators. Except at the hot junction where the two wires should be welded together, the two elements of a thermocouple must be electrically insulated from each other. Fire clay or porcelain beads, and even asbestos for low temperatures, are satisfactory for base-metal thermo-

couples. However, for platinum thermocouples, *clean* porcelain beads or tubing should be used.

The insulation on the thermocouples should be kept intact, because if the wires come in contact with each other, another junction may be formed, causing the indicator to register some temperature other than that of the intended hot junction of the thermocouple.

Terminal Heads. Terminal heads for thermocouples are not absolutely necessary because the extension wires can be soldered, brazed or welded directly to the elements of the thermocouple, but they serve to simplify installation and replacement of thermocouples as well as to keep contaminating dirt and dust out of the protection tube and to provide a good connection between thermocouple and extension wire. Therefore terminal heads are recommended.

Measuring Instruments

The electrical instruments used with thermocouples as well as with radiation pyrometers (*see* page 181) may be classified for present purposes as indicators, recorders, controllers, indicating controllers and recording controllers. They are all characterized by the high sensitivity required in electrical pyrometry, in which the voltages to be measured or detected range from a few microvolts (millionths of a volt) to about 60 mv (60 thousandths of a volt), and hence differ essentially from electrical power instruments. Accordingly, they should be treated with some care, kept reasonably clean and cool, and not subjected to severe vibration.

Indicators. These may be defined as instruments for showing the magnitude of a measurable variable, such as temperature or voltage, by the coincidence of a pointer or reference line with a point on a calibrated scale. The two main classes are millivoltmeters and potentiometers, either of which can be portable or designed primarily for mounting on a wall or panel. Portable instruments are particularly useful in experimental tests or investigations, and for the checking of permanently mounted instruments. Indicating potentiometers (particularly those for permanent mounting) may be balanced either manually or automatically.

Millivoltmeter Indicators. The common form of millivoltmeter consists of a moving coil mounted with pivots to turn in jewel bearings between the pole pieces of a permanent magnet, and constrained by two spiral springs to turn through an angle proportional to the current through the coil. A long pointer is attached to the coil and moves over a scale usually graduated in degrees. Many such instruments are provided to advantage with automatic cold-junction compensation; ordinarily this is simply a bimetallic spring to move the pointer in correspondence with the temperature of the cold junctions, which are preferably housed in the case of the instrument so that junctions and bimetallic device are at the same temperature. The indicator should not be subjected to rapid changes in temperature while in use.

Since the deflection of this type of indicator depends on the *current* through the coil, and the temperature of a thermocouple is measured by its *emf*, it follows that any change in the *resistance* of the circuit of the thermocouple, extension wires and indicator will be accompanied by a corresponding error. For this reason millivoltmeter indicators are preferably provided with a series resistor of manganin, 10 to 500 ohms or more, to reduce the percentage change in resistance resulting from a change in temperature of the couple or extension wires, or in contacts of connections. The calibration is good for only one value of the external resistance (extensions plus thermocouple), and it is considered good practice for the maker to mark the instrument with both the value of the internal resistance, and that of the external resistance for which the calibration is correct.

Potentiometer Indicators. A simplified potentiometer circuit is shown in Fig. 3. With this circuit, the emf of a thermocouple can be balanced against the IR drop in the slide-wire resistor by moving the contact along the wire until the galvanometer connected through the *TC* switch shows no current flowing through it, by standing at no deflection from its open-circuit position. Before a measurement is made, the current through the slide-wire is adjusted to a standard value corresponding with the scale of the instrument (millivolts or degrees), by connecting the galvanometer and standard cell in series across the resistor marked *"SC coil"* and turning the rheostat until the galvanometer stands at "zero", that is, no deflection. The IR drop across this coil now equals the voltage of the standard cell (approximately 1.019 v), and the current I has a selected value—for example, 2 ma—when the resistance of the standard coil is 509.5 ohms. The resistance of the slide-wire for the 60-mv scale is then 30 ohms.

The galvanometer, or other form of detector used with a potentiometer, serves only to detect unbalances of emf. It need not be calibrated but must be sufficiently sensitive and have good zero stability. The potentiometer is relatively free from errors caused by changes in resistance of the thermocouple circuit. In explanation of this, assume an internal potentiometer resistance of 40 ohms, plus 10 ohms external resistance, making a total of 50 ohms, and assume that an unbalance of 1 °F can be detected. If the external resistance is now increased from 10 to 60 ohms, doubling the total, the minimum detectable change will merely be increased from 1 to 2 °F.

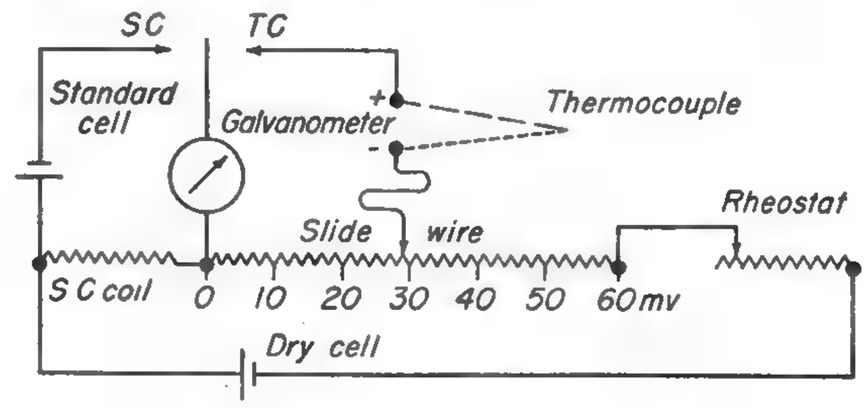

Fig. 3 Diagram of potentiometer circuit

The circuit shown in Fig. 3 is in many instruments modified to take care of the emf of the cold junctions, either manually by the setting of an auxiliary dial, or automatically by the change in resistance with temperature of a cold-junction compensating resistor suitably arranged in ■ branch circuit. If there is no compensation for the cold-junction temperature, the proper correction must be applied to the reading after measuring the cold-junction temperature with a thermometer or by other means. If the compensation is by manual adjustment of a dial, then again the cold-junction temperature must be measured and the dial must be set accordingly. If the compensation is automatic, it applies to one particular type of couple only.

Each circuit has special advantages and limitations. Automatic compensation and a scale graduated in *temperature* are usually preferable for a permanent installation. For a portable indicator that is to be used for general checking, including other potentiometers, it may be preferable to use an instrument without automatic compensation with the scale calibrated in *millivolts*. This type of instrument may have provision for manual cold-junction compensation by setting of an auxiliary dial, calibrated in millivolts.

The accuracy of a potentiometer, aside from that attained by the maker in the original calibration, depends primarily on the constancy of the voltage of the standard cell. Although this deteriorates at the rate of only one or two hundredths of a per cent per year under average circumstances, it should be checked occasionally. This checking can be done directly by measuring the cell voltage with a potentiometer suitable for the value of approximately 1.019 v, or indirectly by comparing results obtained before and after substituting a standard cell known to be of correct voltage. A voltmeter must not be connected to a standard cell, and appreciable current should not be drawn from it by any other means.

Potentiometers for permanent installation are frequently of the self-balancing type in which the emf of the thermocouple is automatically balanced against that of the potentiometer, particularly when they serve also as automatic controllers. With some instruments, standardization of the potentiometer by comparison with a standard cell is also automatic.

Self-balancing means may be broadly classified as (1) mechanical, or (2) electronic. In the mechanical type, deflection of a galvanometer is mechanically detected, and power for balancing is obtained through mechanical means of amplification.

The electronic type may or may not involve a galvanometer, but in any case, it uses electronic devices in the scheme for rebalancing. In one arrangement a light beam from a galvanometer mirror is caused to fall upon a photocell to an extent that depends on the degree of emf unbalance. The photocell current is electronically amplified to operate relays that start and stop a balancing motor. In another scheme there is no galvanometer; the unbalanced voltage is converted to alternating current, which is amplified and used directly to operate a motor that moves the slide-wire in the direction required to restore the balance.

An automatically balanced potentiometer may be of the multiple-point type with an automatically operated switch for the purpose of connecting the same instrument to two or more thermocouples in turn. Multipoint instruments will be further discussed in the next section, on Recorders.

Recorders. Recorders generally retain the indicating feature, and have the added feature of a moving chart on which the temperature is recorded by suitable means, either intermittently or continuously.

Millivoltmeter recorders are available in which a record is produced by a mechanism that depresses the pointer at regular intervals, causing an intervening inked tape to make contact with a strip chart at the pointer position. With multipoint instruments, arranged for the connection in turn of several thermocouples, different colors of ink are often used for purposes of identification.

Recording potentiometers are made with either round or strip charts. Because there is ample power to overcome friction between a pen and the chart, continuous ink records are usual with single-point instruments. With multipoint instruments the printwheel type of marker is commonly supplied; the connected couple is usually identified by a number and sometimes also by color of ink.

Multipoint recorders are practical when the interval between successive records of a given temperature is not too long. The advent of electronic potentiometer recorders with their higher balancing speeds has made it practical to switch from one thermocouple to another every several seconds, whereas previous recorders required as much as one minute per point. Several manufacturers have offered recorders in which switching takes place upon balance on a given point, not on a uniform time-interval basis.

An important application of high-speed potentiometers is in connection with the measurement of the temperatures of moving objects such as rails and billets, with the radiation pyrometer. In this application both the radiation pyrometer and the recorder must respond rapidly.

Instruments for Automatic Control.* Both millivoltmeters and potentiometers, in the form of either indicators or recorders, may be obtained with added signaling and automatic control features. With millivoltmeters, suitable actuating contacts may be made through the action of a depressor bar that presses the pointer against contact-operating members; or the required action may be obtained without mechanical contact with the pointer, through change of inductance or capacitance as the pointer approaches the operating position.

With potentiometers of the self-balancing type, control actions may be initiated through the making and breaking of suitably arranged contacts, movement of contacts over slide-wires, or by a combination of the two methods. If a control valve is to be pneumatically operated, control actions are usually initiated by movement in the instrument of a small "pilot valve", which is frequently of the flapper-and-nozzle type.

If automatic control only is desired, a simple potentiometer instrument without the self-balancing feature may be used. A dial is set for the desired control point. The balance indicator (usually a galvanometer) then shows no unbalance when the temperature is correct, and appropriate control actions are initiated in accordance with deviations.

Program controllers are available to carry automatically the temperature of a particular operation through a predetermined temperature-time cycle. Additional features are frequently applied in adapting instruments to particular control problems.

Installation and Use of Thermoelectric Pyrometers

Installation. *Instruments.* The selection of a place for the instruments is very important. A few precautions observed at the time of installation will reduce maintenance to a minimum and prolong the life of the instruments. They should be placed where they will be (1) free from excessively high or low temperatures, (2) free from excessive vibration or shock, (3) free from mechanical damage, (4) free from dirt or dust.

Thermocouples. Place the hot junction of the thermocouple as close to the work as practicable. The opening around the well or tube protecting the thermocouple should be sealed. It is desirable but not essential that provision be made to insert a second thermocouple alongside the furnace thermocouple for purposes of checking and possible calibrating; consequently, a suitable opening should be provided and kept sealed when not in use.

Extension Wires. A thermoelectric circuit operates in the range of microvolts to millivolts, voltages far too low to break down the contact resistance of oxidized, corroded or loose connections. Hence all connections in the thermocouple circuit, except where electrical connectors are provided, should be soldered (using none but a nonacid soldering flux). It is vitally important to respect polarity markings and color code of extension wires, since this is a d-c circuit. Also the circuit must be well insulated from high-voltage power circuits, and protected against overheating and wetting.

It is essential to disconnect all instruments before checking out the circuit. Checking may be done by using a magneto, dry cell and bell, or the like. Pyrometer measuring circuits are not rated electrically to stand power-line voltages.

If a thermocouple must be grounded, all other sections of the circuit *must* be well insulated, including the battery for the potentiometer.

Thermoelectric Pyrometer Troubles. Pyrometer troubles are either external or within the measuring instrument. The details of design of instruments in use today are so varied that it would be futile to attempt a discussion of troubles possible in the instruments themselves. Therefore it is recommended that the manufacturer's manual be consulted in regard to maintenance of the instrument. Some manufacturers conduct brief courses of instruction in maintenance and repair for users of their instruments.

Circuit Troubles. If the pyrometer reading is erratic or obviously wrong, the first suspicion is that one wire of the thermocouple may be completely oxidized or broken. This should be, but is not always, apparent during examination. Visual examination of the extension wires and connections to binding posts and such, may disclose a poor connection or open circuit. If, by visual inspection, the trouble is not apparent, it is recommended that a complete check be made of the external electrical circuit with the aid of a magneto or dry cell and bell, but before such a check begins, it is imperative to disconnect all instruments. Short circuits occur also, and can be detected in the same way. The difficulty is sometimes caused by a faulty selector switch. Grounding of both the thermocouple and the instrument can cause large errors, since there are often large differences of ground potential at different points in an industrial plant using electrical power. If both must be grounded (as is possible with electronic recorders) a ground wire should be run so that only a single connection to "earth" is used.

Incorrect and erratic readings on instruments may have other causes; for example, a deteriorated thermocouple, wrong thermocouple, increased resistance of extension wire or a cross circuit through a high resistance. For a complete explanation of these troubles and their correction, the best source is the maintenance manual prepared by the manufacturer of the instrument.

* *See also* section on **Principles of Automatic Control, page 185.**

Recalibration of a Thermoelectric Pyrometer. *Comparison Method.* A very satisfactory and practical method of checking the calibration of a thermoelectric pyrometer is by comparison with another thermoelectric pyrometer of known accuracy, such as a portable indicating potentiometer of tested quality, in conjunction with a calibrated thermocouple. It is well to have two calibrated thermocouples, one to be kept as a primary standard and used only for rechecking the calibration of the second, which is used for checking the calibration of the furnace pyrometer. It should be remembered that the complete pyrometer includes a thermocouple and an indicating or recording instrument, and that there are chances of error in both.

During the calibration, the hot junction of the standard thermocouple should be kept in intimate contact with the hot junction of the furnace thermocouple to insure that they will be at the same temperature. It is often advisable to bind base-metal thermocouples together with wire of a material that will not contaminate the couples and will resist the furnace temperature. Both thermocouples should be inserted in the same protection well for satisfactory results. Platinum–platinum-rhodium thermocouples should never be inserted in a furnace unless they have a protection tube—not even during a calibration.

It is important to maintain the furnace temperature nearly constant at the various check points before taking any reading, and always to take at least three readings at each point. Both thermocouples should be at the same depth of immersion in the furnace.

If the pyrometer being checked or calibrated is found to be in error, it may be for one of the reasons mentioned under Pyrometer Troubles. All the possibilities should be investigated before concluding that the calibration has changed.

Potentiometric or Pyrometer Test-Set. Several manufacturers of instruments market a pyrometer test-set, which is a special potentiometer having extra units and electrical circuits capable of making a complete check or calibration of a pyrometer, or of the installation in general. This test-set is a valuable instrument in locating troubles in pyrometer installations and is indispensable if a plan of routine service is in effect for maintaining pyrometers and their accessories. Whatever standard is used in the recalibrating or checking of pyrometers, the accuracy of the standard must be assured in advance. This applies to the portable indicating potentiometer, the pyrometer test-set, or the portable indicating pyrometer, which is used quite frequently for checking.

It is always a good practice to immerse the thermocouple hot junction in crushed ice when everything is ready for operation. If the instrument does not read 0 C or 32 F, it is evident that something is wrong.

Calibration by the Freezing-Point Method. This is the method used by the National Bureau of Standards and a few well-equipped laboratories for making primary calibrations of thermocouples. The proper procedure requires considerable expertness and careful attention to details and, except in a few limited instances, is not recommended for the majority of pyrometer users.[2]

Measurement of Temperature with Thermocouples. A thermoelectric pyrometer measures only the temperature of the hot junction of its thermocouple. Therefore it is essential to know what difference of temperature exists between the junction and the object or material of which the temperature is to be measured. In some instances, as with a gas that is cooler or hotter than its enclosing walls, the difference can be much larger than is suspected.

When a solid metal with a dull or rough surface is concerned, the temperature of the work material in a furnace can sometimes be estimated by comparing the brightness of the material with that of the hot end of the thermocouple, which must be as close to the work as practicable, and in such a position that both can be observed through a small hole in the furnace wall or door. It is necessary to ascertain that neither work metal nor thermocouple is licked by any flame, and that reflected light from a hot surface licked by flames or from a combustion chamber does not cause either to appear hotter than it really is. When the work metal and the hot junction are of equal brightness, as nearly as can be determined by eye, the temperatures of the two will be the same for all practical purposes, at least within plus or minus 15 to 25 F.

The heads or terminal ends of rare-metal and Chromel-Alumel couples must be kept relatively cool, because the extension wires are a thermoelectric fit for these couples only over a limited range of temperature.

Thermocouples for Measuring the Temperature of Molten Metals. In measuring the temperature of molten aluminum-base and copper-base alloys in pouring ladles, it is often necessary that the readings be obtained easily and quickly. This precludes the use of heavy protection tubes. In many installations a bare Chromel-Alumel thermocouple, about No. ■ gage, has been found satisfactory. The junction may be welded or left open. If the junction is left open, the thermoelectric circuit is completed through the molten metal. A slightly steadier reading is obtained if the junction is welded, but the cost of maintenance is higher. The effect of slags and of the cooler metal at the surface is minimized by immersing the tips of the thermocouple wires 4 to 6 in. in the metal and, after several seconds, quickly raising the wires until only the tips are in the metal. The maximum reading obtained in this process is taken as the temperature of the metal.[3]

With aluminum-base alloys, the surface effects can be virtually eliminated by insulating both of the thermocouple wires with a continuous felted layer of asbestos. The asbestos becomes brittle and rubs off but, with reasonable care, the rate of loss of insulation approximately equals the rate of solution of the wires.[4]

With copper-base alloys, the surface effects can be eliminated completely by enclosing the thermocouple wires and junction in a metallic protecting tip. The manufacturers of different types of tips state the advantages obtained with their particular design but, in general, the most desirable is the one that gives the quickest reading. Protective tips made of ferrous alloys containing a high percentage of chromium usually have a longer life in brasses than tips made of ferrous or nonferrous alloys containing nickel.[5]

For research work and special melts, the temperature of molten cast iron can be measured with a platinum–platinum-rhodium thermocouple in a porcelain and graphite protection tube.[6] The temperature of molten steel can be measured satisfactorily with a platinum–platinum-rhodium thermocouple encased in a protection tube made of vitreous silica (fused quartz).[7] Special types of thermocouple, such as the graphite versus silicon carbide couple,[8] have also been used in liquid metals.

Resistance Thermometry

The operation of a resistance thermometer depends on the variation with temperature of the resistance of an electrical conductor. A high temperature coefficient of resistivity might, accordingly, appear of primary importance. Certain oxides possess this property, having a resistance at room temperature from a hundred thousand to a million times that at 800 F. However, the resistance of a suitably mounted material can be determined easily and accurately, so a high temperature coefficient is rarely, if ever, the deciding factor in the choice of the material. The fundamentally important property is reproducibility and constancy of resistance. A further desirable feature is a simple and convenient relation between temperature and resistance.

For industrial purposes, resistance thermometers are made usually of copper, platinum or nickel; nickel is the most satisfactory for temperatures below 600 F. Although the resistance thermometer is of great importance in the laboratory, for work of extremely high precision, its employment for industrial processes requires many precautions easily overlooked. Bad contacts in the line, a broken strand in a flexible cable, or such, may cause large errors. The thermometer is fragile and the calibration of it may be altered by severe handling, by the slightest contamination, or by volatilization of the wire that forms the coil.

In most industrial processes carried out above 600 F, the thermoelectric pyrometer is to be preferred. When very small changes or intervals of temperature must be meas-

ured with high precision, the resistance thermometer may be employed effectively. In certain processes where an integrated or average temperature is required over the entire bulb, the resistance thermometer is highly desirable. A homogeneous thermocouple indicates the temperature of its hot junction, while a resistance thermometer indicates the average temperature of the entire coil or bulb, which may be constructed to be as long as desired. There are no cold-junction corrections for the resistance thermometer, a decided advantage over the thermocouple, but one that is offset by the disadvantages mentioned. A more complete treatise on resistance thermometry is given elsewhere.[9]

Temperature and Radiation*

Some other type of pyrometer must be used when the temperature becomes too high, or the object is too inaccessible, to permit use of a thermocouple. Since all bodies emit radiant energy with intensity dependent on the temperature, the temperature can be determined by measuring this radiant energy. The total radiant energy from any temperature-excited radiator increases about four times as fast as the temperature, while the spectral radiant energy in the red part of the spectrum increases about 18 times as fast as the temperature at 1832 F, and about 10 times as fast at 3632 F. Thus, the percentage error in measuring the temperature is much smaller than in measuring the energy.

Principles. *The Blackbody and the Blackbody Laws.* The standard radiator is the "blackbody", which is defined as a body that absorbs all the radiant energy that falls upon it. From this simple definition and some very plausible assumptions, it can be shown that the radiancy (total radiant flux density) increases with the fourth power of the absolute temperature, that is,

$$W = \sigma T^4$$

which is known as the Stefan-Boltzmann Law. σ is one of the fundamental physical constants. It can also be shown that the spectral radiancy for any interval of wave length is given quite accurately, for not too high a temperature and not too long a wave length, by the Wien equation on page 174. This equation holds with all the accuracy needed for industrial optical and radiation pyrometry. Thus the temperature of the blackbody can be obtained from measured values of either the total radiancy or the spectral radiancy of it for a definite interval of wave length.

The Practical Blackbody. The name "blackbody" was chosen for the standard radiator because at room temperature it is actually black. No material exists in nature that is a blackbody for all wave lengths, but some forms of carbon and some finely divided metals may be very nearly black. A cavity with opaque walls of uniform temperature contains blackbody radiation, corresponding to the temperature of the walls. If an opening, small compared with the area of the walls, is made into the cavity, the radiation escaping from the opening will be blackbody radiation of this temperature. Thus, to construct a working blackbody, it is necessary only to make a small opening into a cavity having walls that can be heated to a uniform temperature. From the definition, it can be shown that the blackbody will emit more energy, both total and spectral, than any other temperature-excited radiator at the same temperature.

Emissivity. The ratio of the energy emitted by any radiator not a blackbody to that from the blackbody at the same temperature is called the "emissivity" of the material studied. Emissivity depends both on the composition of the material and on the condition of its surface; the emissivity is smaller for well-polished than for dull metallic surfaces. The total emissivity of different materials covers a wide range; for example, that of polished silver is about 0.02 to 0.05, while carbon may have an emissivity of 0.95. Furthermore, the spectral emissivity of a given material may vary over a wide range for different intervals of wave length, and it may also change with the temperature.

* Revised with the collaboration of E. Q. Adams

Types of Pyrometer. Three types of pyrometer are used industrially to determine the temperature of blackbodies from measurement of their "steradiancy" (areal radiant intensity of the source): (1) the *total radiation pyrometer,* which determines the temperature from a measurement of the intensity of the radiant energy at a distant point, utilizing nearly all the wave lengths radiated by the source; (2) the *partial radiation pyrometer,* which measures this same intensity of radiant energy, but only in a selected part of the spectrum, by some such device as a photoelectric cell or a thermoelectric radiation pyrometer having a glass lens (*see* page 183); (3) the *optical pyrometer,* which determines temperature by measuring the brightness of the source in a selected part of the spectrum, generally the red, utilizing the human eye as a part of the instrument and consequently reading temperatures only above approximately 1100 F.

Radiation Pyrometry*

Principle of the Instrument. The basis of radiation pyrometry is the Stefan-Boltzmann Law ($W = \sigma T^4$). Most radiation pyrometers are more strongly influenced by certain bands of wave length than by others; hence their response never exactly follows this law.

The usual radiation pyrometer includes (1) a blackened receiver that absorbs and is heated by incident radiation from a source of which the temperature is to be measured; (2) a housing that has a fixed aperture or apertures to limit the cone throughout which the receiver can be irradiated by the source; (3) in most instances, a lens or a mirror by means of which this cone is completely filled with rays emanating from a relatively small area of the source. To measure the rise in temperature of the receiver, use is made of a thermocouple or thermopile, a bolometer or some other device sensitive to temperature. The thermopile, which is most widely used for the purpose, may have its hot junctions attached to a receiver made of a separate thin metal disk, or the hot junctions may be made flat and suitably blackened to serve directly as the receiver.

When the pyrometer is sighted on a blackbody at elevated temperature T_1, the receiver will be heated quickly to a temperature T_2, such that the radiant energy absorbed in unit time by the receiver, both from the blackbody and from the surrounding housing at temperature T_3, equals the energy radiated by the receiver plus that conducted away from it through the wires of the thermopile and, unless in vacuo, through the air.

In the measurement of high temperatures, the temperature attained by the receiver is much lower than that of the source, and the relation between these temperatures is then given by the equation

$$T_2 - T_3 = \frac{X_1 T_1^4}{A}.$$

The emf developed by the thermopile is more or less directly proportional to the rise in temperature of the hot junction above the pyrometer housing temperature T_3, that is, to $T_2 - T_3$ as given in the above equation. If the housing temperature T_3 rises, T_2 must also rise; hence no "cold-junction compensation" in the usual sense is required for the thermopile. However, the term A increases when the housing temperature increases, so when T_3 rises, as by ambient temperature change, T_2 rises by a smaller amount. This causes a small decrease in the emf developed in response to a given source temperature, T_1. Therefore, where the pyrometer is to be used under conditions of considerably varying ambient temperature, it is advisable either to take steps to minimize the variations in the temperature of the pyrometer housing, or to provide the pyrometer with automatic ambient-temperature compensation of some kind.

The term X_1 in the above equation represents the fraction to which the radiant energy received from the source at temperature T_1 is reduced, as a result of reflection and

* The term "radiation pyrometer" is commonly used in referring to the total radiation pyrometer and to other heat-absorbing radiation instruments having windows and lenses that absorb enough of the energy in certain parts of the spectrum to render them actually partial radiation pyrometers.

absorption by the lens or protecting window (and absorption by the mirror when one is used), as well as by reflection from the receiver itself. For a pyrometer equally sensitive to radiant energy of all wave lengths, X_1 would be a constant and the energy absorbed by the receiver would vary as the fourth power of the temperature of the source sighted upon. Such a pyrometer would be a true *total* radiation pyrometer.

Because of their resistance to heat shock, fused silica and Pyrex glass are used to a considerable extent as lenses for radiation pyrometers. These materials are relatively opaque to wave lengths longer than approximately 3.8μ and 2.6μ respectively. In consequence, when lenses of these materials are used, the term X_1 increases rather rapidly (and at different rates for the two materials) as T_1 increases. Thus, with increase in T_1, the product $X_1T_1^4$ increases at a rate higher than that of the fourth power of T_1, causing a correspondingly higher rate of increase in pyrometer emf. On the other hand, most mirror materials exhibit greater reflectivity at long than at short wave lengths; consequently, unless reflection and absorption by a window affect it otherwise, X_1 for a mirror pyrometer decreases as T_1 increases, so when T_1 changes, $X_1T_1^4$ varies at a rate lower than that of T_1^4.

Emissivity Corrections. When sighted on an object in the open at absolute temperature T_a and having an emissivity ϵ that is less than unity, the pyrometer will read the same as if sighted on a blackbody at temperature T_1 where

$$\epsilon X_a T_a^4 = X_1 T_1^4$$

Here X_a applies for a blackbody temperature T_a in the same way that X_1 applies for T_1, and emissivity ϵ applies for the limited range of wave lengths that is absorbed by the receiver. By means of this relation, the true temperature T_a can be deduced, if the values of the other terms are known.

In certain instances, e may differ somewhat from total emissivity e_t. However, the values given for total emissivity that are available from various tables,[10,11,12,13] may be used with reasonable accuracy for a radiation pyrometer equipped with either a fused silica or a Pyrex lens, as well as for a true total radiation pyrometer.

The ratio of X_a to X_1 in the above expression depends on the material of the lens; therefore the correction to be added will differ for pyrometers having lenses of different types. In a recent article[11] tables and curves are given for the determination of emissivity corrections for radiation pyrometers that have fused silica and Pyrex glass lenses. Corrections for total radiation pyrometers, for which $X_a = X_1 =$ constant, are published elsewhere.[10]

Table II illustrates the magnitude of the emissivity corrections that may be required with a radiation pyrometer sighted on different substances in the open. These values, condensed from the previous issue of this Handbook, apply for the *total* radiation pyrometer. Smaller corrections are required with radiation pyrometers that have fused silica or Pyrex glass lenses.

Table II. Emissivity Corrections for a Total Radiation Pyrometer

(To be added to observed temperatures)

Observed Temperature, deg Fahr	Corrections in degrees Fahrenheit: Iron Oxide	Nickel Oxide	Copper Oxide	Molten Iron	Molten Copper	Platinum
1000	60	210	200	...	890	970
1400	75	170	250	695	1130	1100
1800	90	135	300	835	....	1235
2200	105	100	...	...	....	....

When the object sighted upon is surrounded by walls at the same temperature as itself, energy radiated by the walls is reflected by the object, thus augmenting the energy emitted by the object, so that the total equals blackbody radiation and no correction is needed. When the walls are at a higher or lower temperature than the object, special treatment is required. Some examples are discussed in an article[11] referred to above.

In many industrial applications where uniformity and reproducibility of conditions are the principal objectives in view, it is often unnecessary to determine actual temperatures; hence corrections for emissivity are not required.

Checking Radiation Pyrometers. It may be desirable to check a radiation pyrometer, either to ascertain the physical condition of it or to determine the accuracy of the readings as installed, taking into account emissivity and other factors.

For ascertaining the physical condition of a radiation pyrometer, comparative readings are taken between the pyrometer under test and a suitably located thermocouple, an optical pyrometer, or another (standard) radiation pyrometer. The radiation pyrometer under test should be sighted into a uniformly heated enclosure through an adequate opening. If the pyrometer is sighted into a closed ceramic tube, the closed end should be heated uniformly over a length four or five times the internal diameter.

To check the effect of emissivity and the like, on the apparent temperature of an object as read by a radiation pyrometer, it is desirable to compare the readings of the radiation pyrometer with the readings of a thermocouple in good thermal contact with the object in question, or with readings of an optical pyrometer sighted into a crack or crevice in the object. If no such crack or crevice is in view, and the object is surrounded by walls no hotter than itself, the readings of an optical pyrometer will usually be more nearly correct than those of the radiation pyrometer, and the use of an inexact value of emissivity in deducing the true temperature will lead to a smaller error with the optical pyrometer than with the radiation pyrometer. The full correction for emissivity should never be applied unless the walls are much colder than the object or unless the object is in the open; no correction is required when walls and object are at the same temperature. If the walls are hotter than the object, the reading taken on the surface by the optical pyrometer may be in greater error, because of low emissivity (high reflectivity) of the object, than the readings of the radiation pyrometer.

Relative Dimensions in the Pyrometer System. Radiation pyrometers are arranged for the receiver to be irradiated through a cone of fixed dimensions limited by a suitable aperture. The area irradiated is either the total area of the receiver, or it is fixed by a second aperture, sometimes a small one, immediately in front of the receiver. Frequently extra diaphragms are employed to prevent stray radiation from reaching the receiver by internal reflection.

The calibration is substantially independent of the size of the source of radiant flux or its distance from the pyrometer (in the absence of absorbing mediums in the path of the rays), provided the area of the source is large enough that its radiation fills the above-mentioned cone.

When no condensing lens or mirror is used, the area of the source must be sufficient to fill the entire cone. In this instance, each point on the receiver will receive radiant energy from the entire area of the source lying within the cone. The use of a condensing lens or mirror reduces the area of the source required to fill the cone, and each point on the receiver will be irradiated by energy emanating from a smaller area of the source. If the lens or mirror is located so that the source and receiver are at conjugate focuses, each point on the receiver will receive all its irradiation from a corresponding point on the source and an image of the source will be formed on the receiver. This is the condition requiring the minimum area for the source. However, for purposes of temperature measurement, it is not necessary for an image of the source to be formed on the receiver, since the heating effect is the same regardless of whether or not the source is focused on the receiver, as long as the cone to the receiver is filled with radiant energy emanating from the source.

Radiation pyrometers with adjustable focus are arranged to provide for such focusing without altering the dimensions of the cone subtended from the receiver by the limiting aperture, in order to permit adjustment of focus without altering the calibration of the pyrometer.

The fixed-focus types, illustrated here, are widely used industrially. The focus is set suitably for the majority of industrial applications and the manufacturers supply tables showing the minimum diameter of source required for different distances.

A fixed-focus mirror type of radiation pyrometer is shown in Fig. 4. The cone determining the sensitivity is the cone α subtended by the mirror M, at points on the

receiver *R*. The receiver and the end of the pyrometer shield tube *B*, are at conjugate focuses of the mirror. The tube serves to prevent stray rays from beyond limiting lines *AA* from reaching the receiver or the adjacent thermocouple wires. When the tube is in use, care must be taken to avoid heating the end, because it would then become a source of extra radiant energy and would affect the reading. The source must fill the angle β as defined by limiting lines *AA*.

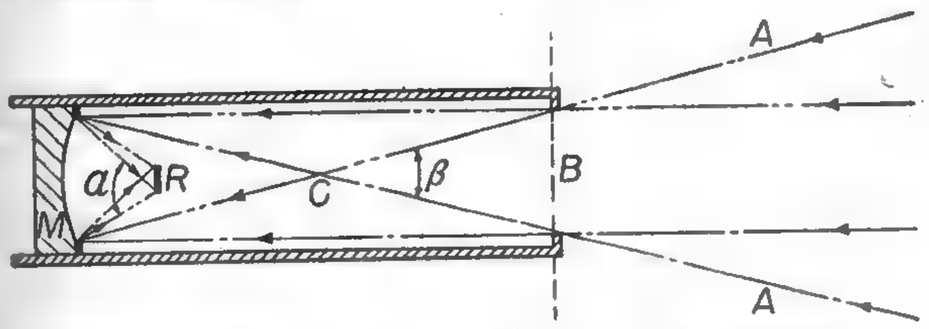

Fig. 4 Diagrammatic section of a radiation pyrometer; fixed focus, mirror type

A type of fixed-focus radiation pyrometer having a lens is shown in Fig. 5. The cone a at points in the small aperture in D_1 in front of receiver *R*, subtended by the aperture in diaphragm *D*, determines the sensitivity of the pyrometer. The conjugate focal plane of the lens *L*, with respect to the position of the aperture in diaphragm D_1, is at *B*, which lies at some position in space in front of the lens. The source may be at *B* or at some position in front of or behind *B*. The source must be large enough to include either the limiting lines *AA*, diverging at angle β, or the lines *A'A'*, whichever are outside at the position of the source. Diaphragm D_1 prevents irradiation of the receiver or thermopile wires by external sources outside of limiting lines *AA* or *A'A'*, thus limiting the area of source required.

The index of refraction of the lens material varies with the wave length; hence the lens gives rise to a family of limiting lines *AA* and *A'A'*. The source must be large enough to include the outermost of these limiting lines corresponding to the wave lengths transmitted by the lens.

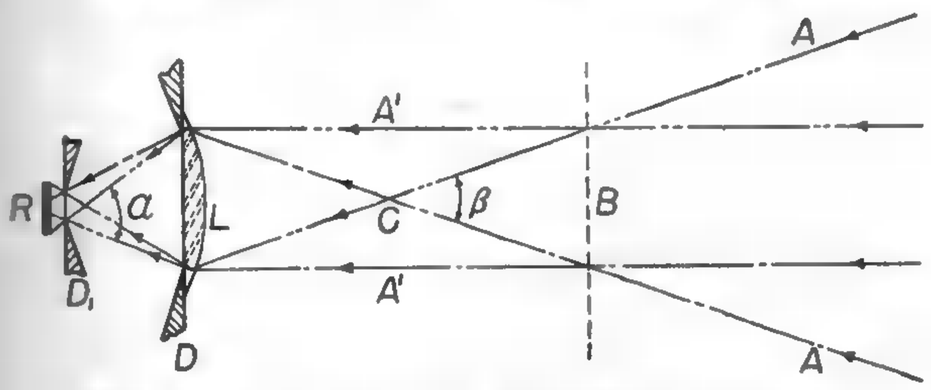

Fig. 5 Diagrammatic section of a radiation pyrometer; fixed focus, lens type

In practice, dimensions of apertures and focal length of mirror or lens are selected to meet the requirements of the application for which the pyrometer is designed.

Photoelectric Pyrometry[14]

In principle, a photoelectric pyrometer may be regarded as another variety of radiation pyrometer, from which the more familiar variety just described might be differentiated by calling it a "thermoelectric radiation pyrometer". In accordance with common usage, however, these instruments will be designated here as "photoelectric pyrometers" and "radiation pyrometers", respectively. The difference between the two is that either a photoemissive surface or a photovoltaic surface is substituted for the receiver of the thermopile used in the conventional radiation pyrometer.

The optical arrangements may be much the same as those illustrated in Fig. 4 and 5, though since the photoelectric surfaces are usually of relatively large area, the mirror of Fig. 4 can be replaced directly by such a surface, while in Fig. 5 the photosensitive surface might be located far enough to the left of diaphragm D_1 to receive the energy passing through the aperture in D_1, over a rather large area.

One type of photovoltaic cell that has been used in a pyrometer,[14,15] the Weston Photronic cell, responds to a band of wave lengths closely similar to that to which the human eye responds (approximately 0.3 to 0.7μ). Spectral emissivities and emissivity corrections that apply to the optical pyrometer* should be reasonably applicable to a Photronic pyrometer. This cell generates its own current, at an emf of the same order of magnitude as that of industrial thermocouples. The cell responds within about 98% almost instantaneously to changes in temperature, so that the time lag encountered is usually determined by the lag of the measuring instrument.

The vacuum type of photoelectric cell (photoemissive) employs a battery or other source of energy so that large changes in voltage may be produced by variations in the amount of radiation received by it. Thus the cell is adapted to the direct operation of vacuum-tube amplifiers for operating recording or controlling instruments.[8] Such a cell is even more rapid than the Photronic cell. The cesium+cesium oxide + silver photoelectric cell has its important response in the wave-length band 0.5 to 1.0μ, and

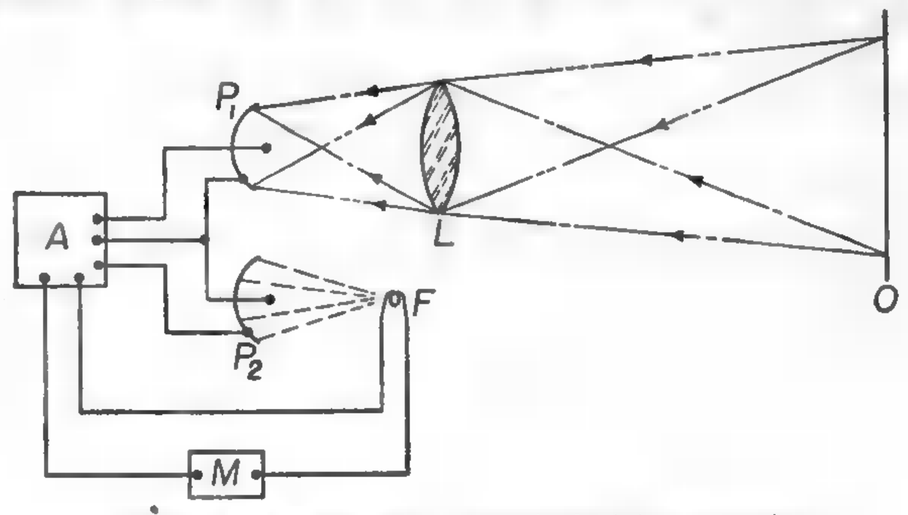

Fig. 6 Comparison type of photoelectric pyrometer

is thus most responsive in the near-infrared band of wave lengths where the radiant energy from a blackbody at the usual industrial temperatures is much more intense than it is within the band of wave lengths to which the Photronic cell responds. Emissivity corrections applying for the band of wave lengths from 0.5 to 1.0μ are not available, though the optical pyrometer corrections might be employed with moderate accuracy.

Because of the shortness of the wave lengths to which the photoelectric and Photronic cells respond, their response varies according to a high power of the temperature. Consequently the scale is compressed to insignificance in the low-temperature range and expands rapidly with increasing temperature. The Photronic scale is even more extreme in this respect than is the cesium photocell, a characteristic advantageous for measuring or controlling high temperatures over a relatively small range, and disadvantageous where operation over a wide range of temperature is desired.

A photoelectric pyrometer that utilizes a comparison principle is illustrated in Fig. 6. An electric lamp *F* irradiates P_2, one of two photoelectric cells, P_1 and P_2, connected in series. The other cell, P_1, is irradiated by the source *O*, the temperature of which is to be measured. The amplifier *A* adjusts the current continuously through the lamp to keep the response of the two cells in balance, so that the temperature of the lamp varies approximately in direct proportion to the temperature of the source. A recording d-c milliammeter *M*, responding to the current through the lamp, may be calibrated to read in degrees of temperature. Because of the relation between the current through the lamp and the corresponding filament temperature, the resulting scale tends to approach linearity, with the result that a wide range of temperatures may be read or recorded on the same scale.

Precautions. Water jackets and protective glasses must be used to prevent heating the photosensitive surfaces above 140 F. The surface of the Photronic cell and cer-

* See Table III, page 185.

tain parts of the circuit of a photoelectric cell must not be exposed to excessive humidity. Since the currents involved are extremely small, special care must be taken to avoid electrical leakage.

Optical Pyrometry

For the general principles on which optical pyrometry is based, the reader may refer to page 181. Several forms of optical pyrometer have been developed, but the form most widely used in industry is the "disappearing-filament" type.

The Disappearing-Filament Optical Pyrometer. This pyrometer has the form of a telescope that is sighted on the object of which the temperature is to be measured. Figure 7 is a diagram of the arrangement of the pyrometer parts. The objective lens *L* is focused to form an image of the object in the plane of the filament of a small tungsten-filament pyrometer lamp *F*. The eyepiece *E* is focused on the filament of the pyrometer lamp and on this image; both are simultaneously in focus, with the pyrometer filament crossing the image of the source.

In making settings, a photometric match is brought about either by varying the temperature of the filament in the pyrometer lamp or by keeping the filament at a definite temperature and varying the apparent brightness of the hot body by means of an absorbing screen. To make the light approximately monochromatic, which simplifies obtaining the photometric balance, a red glass filter that transmits only a narrow band of the visible spectrum, is mounted in the eyepiece of the telescope. The value of the wave length to be used in the equation on page 174 is the "effective" wave length of the light transmitted by the red glass filter. The red glass filters used with most optical pyrometers have an effective wave length centering at about 0.65μ.

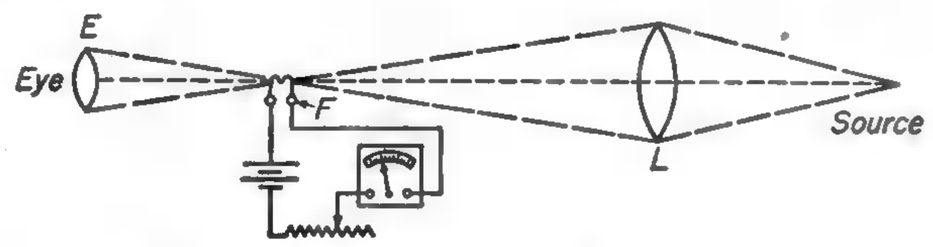

Fig. 7 Optical pyrometer of the disappearing-filament, variable-current type

In an observation with the first type of optical pyrometer, the current through the pyrometer filament is adjusted until the tip, or some other predetermined part of this filament, as observed through the eyepiece, has the same apparent brightness as the source being viewed. When this condition is reached, the comparison portion of the filament is indistinguishable from the portion of the image of the hot body that it crosses. The value of the current in the lamp at disappearance of filament is read by means of a milliammeter or potentiometer; the corresponding temperature is then read from a table or directly from the scale of the current-measuring instrument. In order to avoid deterioration of the filament and blackening of the bulb, the lamp should not be operated at temperatures above 2700 F. For higher temperatures, standardized absorption glasses are placed between the lamp and the objective, so as to diminish the intensity of the light from the object under observation. The amount by which this filter increases the range of the pyrometer may be ascertained by calculation, using the Wien equation (page 174) and the measured transmission of the filter. This increase in range for different temperatures may also be made a part of the calibration.

In the type of optical pyrometer that has a disappearing filament of constant intensity, the filament operates at a definite brightness obtained by setting the current through the lamp at a standard value. A semicircular wedge of black absorbing filter, which can be rotated through any desired angle, is mounted just in front of the pyrometer lamp. By varying the angular position of this wedge, a thicker or thinner portion is brought into the line of sight and the brightness of the image of the source viewed may be matched with the brightness of the filament. A scale attached to the wedge may be calibrated directly in degrees Fahrenheit for both high and low range. For temperatures above the range of the wedge, an additional absorbing filter is used in front of the lamp or the objective lens.

A check of the disappearing-filament pyrometer should include a check of the milliammeter calibration. This check is at least as important as that of the lamp.

Calibration of the Optical Pyrometer. The standard method of calibrating is by direct comparison with a blackbody at certain definite temperatures. The Wien radiation law is the basis for the calibration. However, an optical pyrometer can be calibrated without a knowledge of this law, by the use of a blackbody that can be heated to known temperatures through the entire range of the calibration. For checking the calibration where a blackbody is not available, the pyrometer may be compared with a tungsten-ribbon filament lamp so calibrated that its brightness, through the same or a similar red filter, for certain currents, corresponds to that of a blackbody at certain temperatures. This filament should be about 3 mm wide to enable making a good match of brightness and should be about 3 cm long to obtain a uniform area. A small notch shows where the match should be made.

The National Bureau of Standards will certify the readings of commercial types of disappearing-filament, variable-current optical pyrometers in good condition, to an accuracy ranging from ± 9 F to ± 6 F at 2000 F and to $\pm$ 0.3% at higher temperatures. Readings with the same instrument, under shop conditions, can be repeated by a practiced operator within about one-half these limits.

Precautions. When the optical pyrometer is adopted for a particular use, the limitations imposed by the laws of radiation must be carefully considered; either blackbody conditions must exist, or correction for the lack must be made, since this pyrometer determines the true temperature only for a blackbody. Under some conditions, the radiation emitted from a furnace, or from an object within it, is so nearly that of a blackbody that true temperatures are determined by a measurement of the brightness of radiation. If, however, the temperature of the furnace walls differs considerably from that of an object, within the furnace, on which the pyrometer is sighted, or if flames are present, or if it is possible for bright daylight or artificial light to enter the furnace and be reflected back to the pyrometer, a considerable error may result.

Large errors that occur because of departures of a furnace from blackbody conditions, usually result from lack of uniformity of temperature within the furnace. When a mass of cold material is to be inserted into a hot furnace, before the mass has been heated appreciably, the radiant energy reflected from it will give a false indication of its temperature. If the material reflects all or nearly all the light that falls on it, it will appear as bright as the furnace appeared previously, and an optical pyrometer will indicate that it is at the temperature of the furnace. On the other hand, if the mass of material has an emissivity of nearly 1, the material will absorb all the light falling on it, and consequently no light will be received from it until it has been heated to the point at about 1100 F where it begins to emit light of its own.

One method of reducing stray reflections in a heat treating furnace is to sight into a deep cavity in the metal being heated. Temperatures of closed furnaces can be read by the use of a refractory tube, closed at one end and so placed that the pyrometer can be sighted through the open end on the closed end, which is inserted in the furnace. Before the tube can be used in making temperature readings, it must be burned out thoroughly in order to remove any tendency to produce smoke.

Care should be taken not to sight through smoke or visible fumes. A considerable depth of clear, nonluminous flame may be sighted through without introducing an important error, but it is safer to turn off the flame while reading, or to sight to one side of it.

For taking temperatures of bodies outside a furnace, blackbody conditions will not exist, generally, unless a closed-end tube is used, or its equivalent, such as a deep cavity in the body. The radiation from surfaces of carbon and of a few oxides in the solid condition, such as iron oxide, closely approximates the radiation from a blackbody,

so the optical pyrometer gives temperatures that are accurate for practical purposes on such surfaces in the open. The temperature of steel billets or of sheet free from loose scale, can be measured successfully in the open with the optical pyrometer.

The emissivity of molten metal surfaces free from oxide is low, and there is a characteristic emissivity for each material, which must be known so that the corresponding correction can be applied to the apparent or brightness temperature to get the true temperature. When it is desired merely to repeat conditions on a given material, and there are no complicating factors, such as the changeable film on cast iron (Table III), apparent temperature will serve as well as true temperature and the correction for emissivity need not be known. Since liquid metal surfaces are good reflectors, readings should be made from such a position that reflections from flames, lights or windows

Table III. Optical Pyrometer Emissivity Corrections

Readings made with red pyrometer glass of effective wave length 0.65μ
(To be added to observed temperature)

Observed Temp, deg Fahr	Corrections in deg Fahr: Molten Cast Iron[a], [c]	Molten Cast Iron[b], [c] and Carbon Steel	Molten Alloy 27 Cr, 73 Fe[d]	Solid Iron[e]	Iron Oxide[f]	Molten Copper[f]	Solid Copper[g]
1400	..	...	...	90	1	...	214
1500	..	...	...	99	2	...	240
1600	..	...	...	112	3	...	267
1700	..	...	...	122	5	...	294
1800	..	...	...	133	7	263	...
1900	..	...	...	148	9	288	...
2000	..	...	...	162	11	311	...
2100	60	...	...	175	14	342	...
2250	65	...	...	...	18	369	...
2300	70	189	...	...	..	402	...
2400	75	202	...	...	..	432	...
2500	80	217	...	...	..	...	...
2600	86	234	...	...	..	...	...
2700	93	249	108	...	..	...	...
2800	..	266	100	...	..	...	...
2900	..	283	89	...	..	...	...

(a) Below transformation point in surface brightness

(b) Above transformation point in surface brightness. Based on emissivity 0.40, the value which is now in general industrial use for iron and steel. Recent measurements indicate that the emissivity of molten pure iron, plain carbon steel and cast iron, increases with temperature; the corrections are therefore smaller than shown in the table.

(c) Wensel and Roeser, Trans AFA, 36, 191–212, 837 (1928)

(d) G. N. Goller, Trans ASM, 32, 239–254 (1944). Corrections for various other chromium-nickel steels fall between these values and those for molten cast iron and plain carbon steel (column 3).

(e) Computed from emissivity 0.37. Burgess and Waltenberg, Bull Bur Standards, Sci Paper 242, 11, 591–605 (1915)

(f) Bur Standards Technol Paper 170, 1921

(g) Computed from emissivity 0.11. Bur Standards Technol Paper 170, 1921

do not enter the pyrometer. Table III gives the corrections in °F to be applied to readings made with an optical pyrometer employing a red filter glass that transmits a mean wave length of 0.65μ.

A tapping or pouring stream of steel usually shows a set of bright streaks on a darker background. The dark surface is the flat or convex clean metal to which the emissivity of 0.40 is applicable, on which are based the corrections in column 3 of Table III. It is known that certain alloying elements, such as chromium and manganese, increase the emissivity above 0.40 and consequently lead to high readings of the temperature if the customary scale based on 0.40 is employed.

Size of Object. In order to determine sharply the disappearance of the filament, the image of the hot body, as seen in the telescope, should be at least four times as wide as the image of the filament. In practice, using instruments generally available, the smallest object that can be sighted on with convenience and certainty must have a diameter not less than 0.1 in. In principle, however, there is no objection to measuring the temperature of much smaller objects by the comparison of brightness.

To measure the temperature of a furnace in which blackbody conditions are approximated, the pyrometer may be sighted on an opening in the furnace from a position that receives direct radiation from the interior.

Advantages and Disadvantages of the Optical Pyrometer. Some of the advantages of the optical pyrometer have been brought out in the preceding discussion. These include its utility for measurement of high temperatures; for measurements, at both high and low temperatures, on inaccessible bodies, moving bodies and small bodies, the temperature of which would be affected by the attachment of a thermocouple; and for occasional readings when the installation of a thermocouple would not be economical or feasible. Other advantages are that no part of the instrument is exposed to the destructive effects of heating; and that the indicated temperature derives directly from the temperature of the heated body under test and not from the temperature of some adjacent body (for example, a thermocouple) that can only be assumed to be at the same temperature as the test material.

The principal disadvantages are the ease with which errors may be introduced by absorbent screens of smoke or by incandescent gases between the observer and the object under test; and the fact that with most instruments, each reading is the result of a photometric match made by an individual observer, thus affording an opportunity for accidental errors and biased judgment. Errors introduced by uncertainty as to both the amount and the constancy of the departure from blackbody conditions, have been pointed out in the discussion of the instrument.

Principles of Automatic Control

Elements of an Automatic Controller. Figure 8 is a diagrammatic representation of an *automatic controller** applied to a fuel-heated furnace. For convenience, the

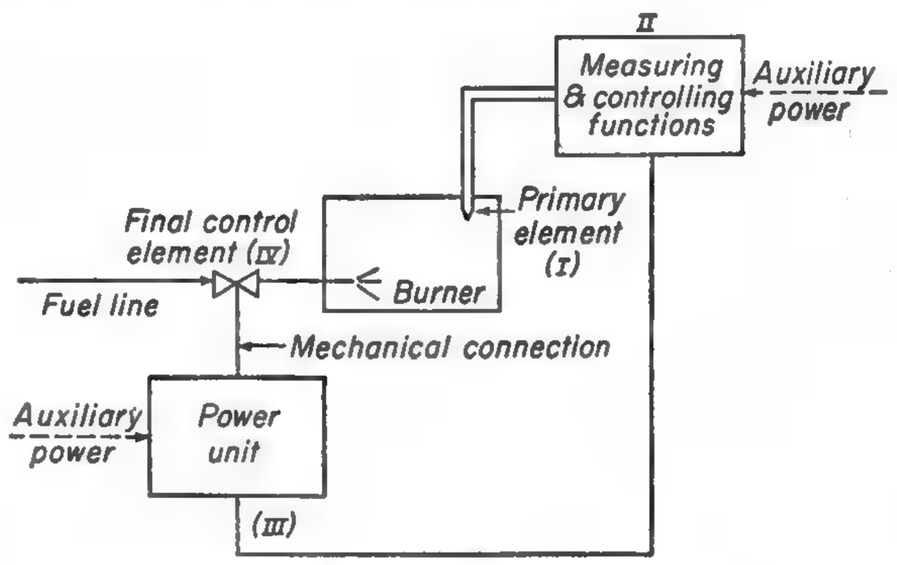

Fig. 8 Diagrammatic representation of a controller applied to a furnace

controller has been broken down into four units (marked I to IV), designated by general terms. The *primary element* is shown as a thermocouple with emf (representative of the temperature) transmitted to unit II, which has both measuring and controlling functions. Through suitable mechanism, the voltage of the thermocouple is interpreted to the control elements to initiate control actions. The control elements of unit II may be extremely simple or fairly complex. Through them the operation of a *power unit* (III) is directed to position the fuel valve (IV) in accordance with predetermined relationships, to be discussed later.

Depending on the requirements of the particular application and on personal preference, the primary element may be a resistance thermometer, a radiation or photoelectric pyrometer, a liquid expansion thermometer, a vapor or gas pressure thermometer, or a bimetallic strip or other metallic differential-expansion element.

The power unit may be electric, pneumatic or hydraulic.

The *final control element* may be a valve (as shown), a variable speed pump, a rheostat, a variable-voltage transformer, a saturable core reactor, or simply the contacts of an electrical contactor.

Lack of space prevents discussion of other than gen-

* Italicized terms are defined in "Automatic-Control Terms", a report by the Terminology Committee, Industrial Instruments and Regulators Division, American Society of Mechanical Engineers, published in Mechanical Engineering, 68, 134–138 (1946) and reprinted as a 16-page pamphlet.

eral details of mechanisms. In the simplest *self-operated* controllers, the final control element is supplied with power directly from the primary element and there is no indication of temperature on a scale. On the other hand, many control instruments provide both an indication and a record of the temperature.

Types of Action of Automatic Controllers. Upon receiving indications of temperature from the measuring part of the controller, the controlling mechanism may introduce valve motion in accordance with various laws. The most commonly applied types of controller action are: *two-position* (with or without differential gap), *proportional-position, floating, proportional-plus-reset, proportional-plus-reset-plus-rate.* In the field of temperature control, floating controller action is seldom used alone, but is important in that it provides the "reset" action in proportional-plus-reset control.

Two-Position Control. This has also been known as "open-and-shut" and "on-and-off" control. With two-position control the heat is supplied alternately at two different rates, one of which is too low and the other too high to meet the average demand. In the simplest instance a temperature record like that in Fig. 9*a* is obtained. As the temperature decreases to value *L*, full heat is applied. The temperature immediately starts to rise and continues until temperature *H* is reached, when the heat supply is suddenly changed to the lower rate and the temperature again begins to fall. This repeated rise and fall continues indefinitely. In general, decreasing the *differential gap* $(H - L)$ increases the frequency of controller operation and decreases the magnitude of temperature variations.

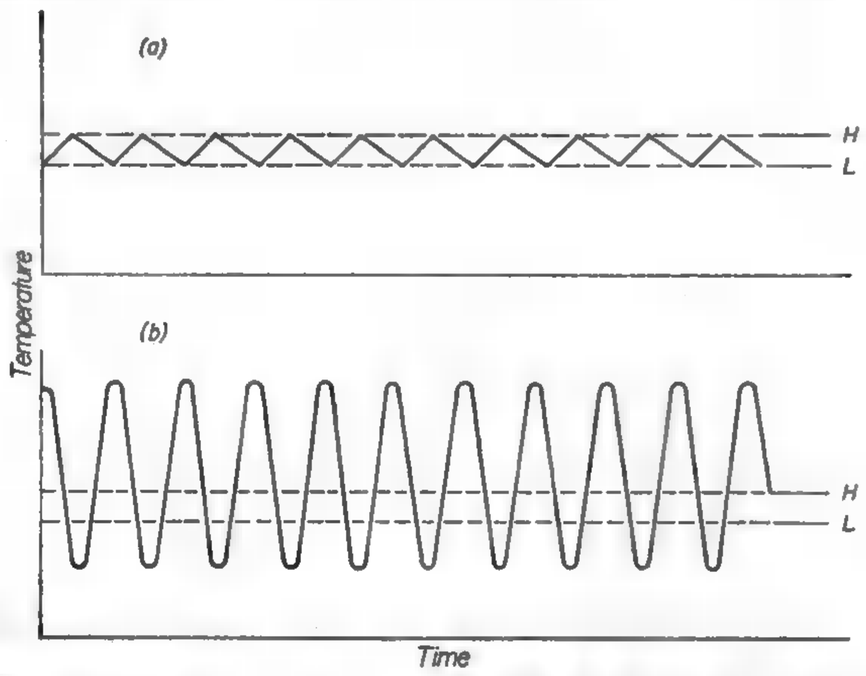

Fig. 9 Two-position control records, (*a*) as obtained under highly favorable conditions; (*b*) as obtained under very unfavorable conditions.

A record similar to that of Fig. 9*a* is obtained only when no unfavorable lags exist in the furnace and in the measuring and controlling means. Mainly because of the effects of heat-storage capacity and thermal resistance, the form of the record is more likely to be represented by Fig. 9*b*. The differential gap $(H - L)$ is the same as before, but the temperature trend does not change suddenly when the rate of fuel supply to the burner is changed. Reducing the differential gap will, in general, reduce somewhat the magnitude of oscillations, but even with zero gap the range of temperature variation may be so great as to be objectionable.

Proportional-Position Control. This is one of a number of types capable of positioning the valve with any degree of opening, and allowing the temperature to remain steady when the requirement for heat is steady. The simple valve action involved is that which would be obtained if the pointer of a powerful temperature indicator could be connected to move the valve directly. Valve movement is proportional to temperature change and in the proper direction to counteract it.

The range of temperature change required to full-stroke the valve (the *proportional band*) must be adjustable to suit the application. The optimum width of the proportional band may be 2° of temperature in one instance and 20° in another. Figure 10 shows the effect of the same sudden change in heat requirement when, for successive tests (*b*, *c* and *d*), the proportional band settings were in the ratio of 4, 2 and 1. It is characteristic of this type of control that the control point moves within the proportional band when the heat requirement changes. The shift from the desired value, caused by this phenomenon, is called *offset*. Offset can be reduced by narrowing

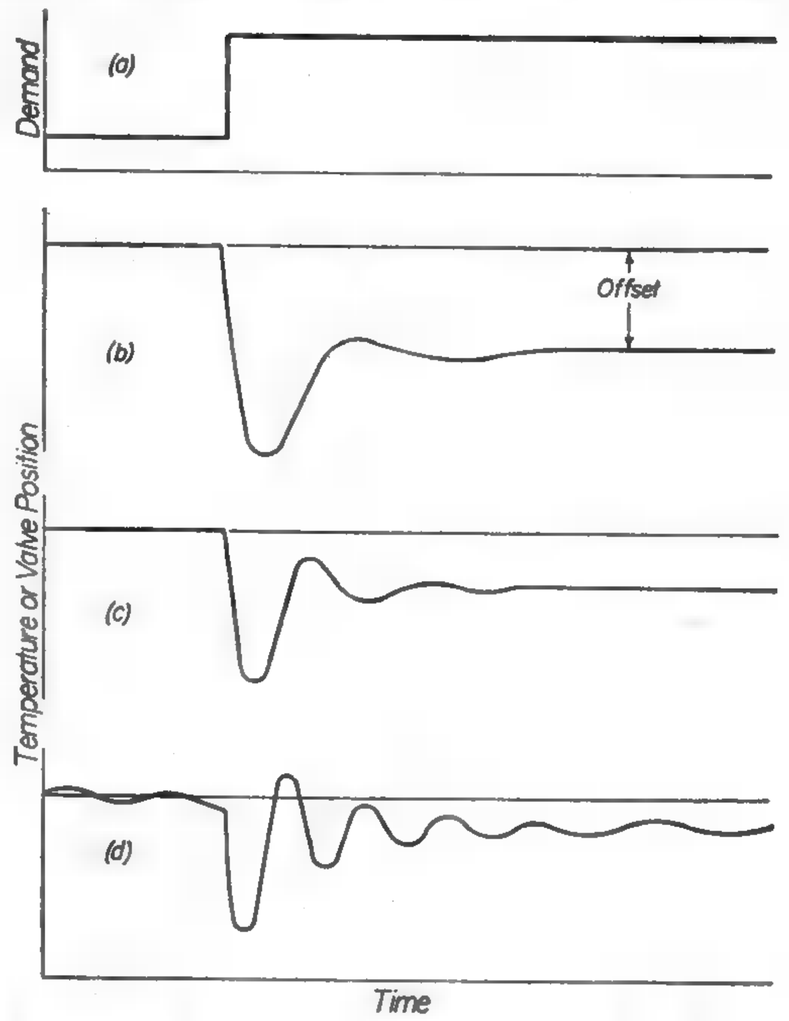

Fig. 10 Responses of a proportional-position controller to change in demand, with successive reduction in proportional band from 4 to 2 to 1 (curves *b*, *c* and *d*)

the proportional band to the point where undesirable oscillations appear, as noted by their progressive increase in Fig. 10 (*b*, *c* and *d*).

Floating Control. The chief use of *floating controller* action in temperature control is in combination with proportional-position action. By adding the actions of the two types, stable control without offset is obtained.

Three types of floating action are illustrated in Fig. 11. In each, the valve is moved continuously in the closed direction when the temperature is high, and in the opposite direction when the temperature is low. The graphs

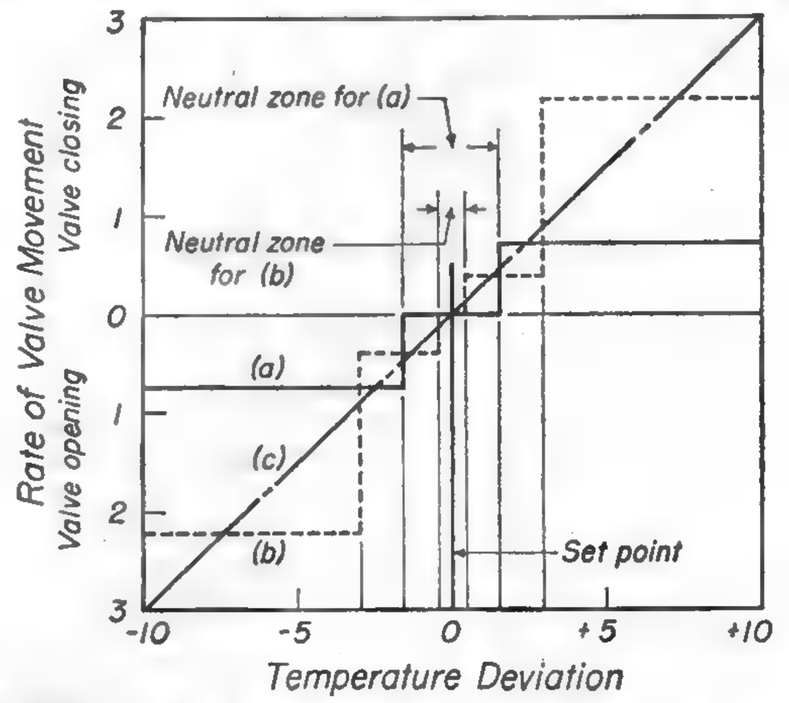

Fig. 11 Responses of valve movement to changes in temperature for floating controllers with a single speed, two speeds and proportional speed

are of rate-of-valve-movement versus temperature. When the temperature is at the control point, no valve movement occurs. Curve *c* illustrates *proportional-speed floating* control in which the rate of valve movement is proportional

to deviation from the *set point*. In *single-speed floating action* (curve *a*) the valve moves at the same speed regardless of the deviation, provided the deviation exceeds the limits of a *neutral zone* within which no valve motion takes place. Two-speed floating action (curve *b*) provides a second fixed higher rate of valve motion when the deviation exceeds a predetermined value.

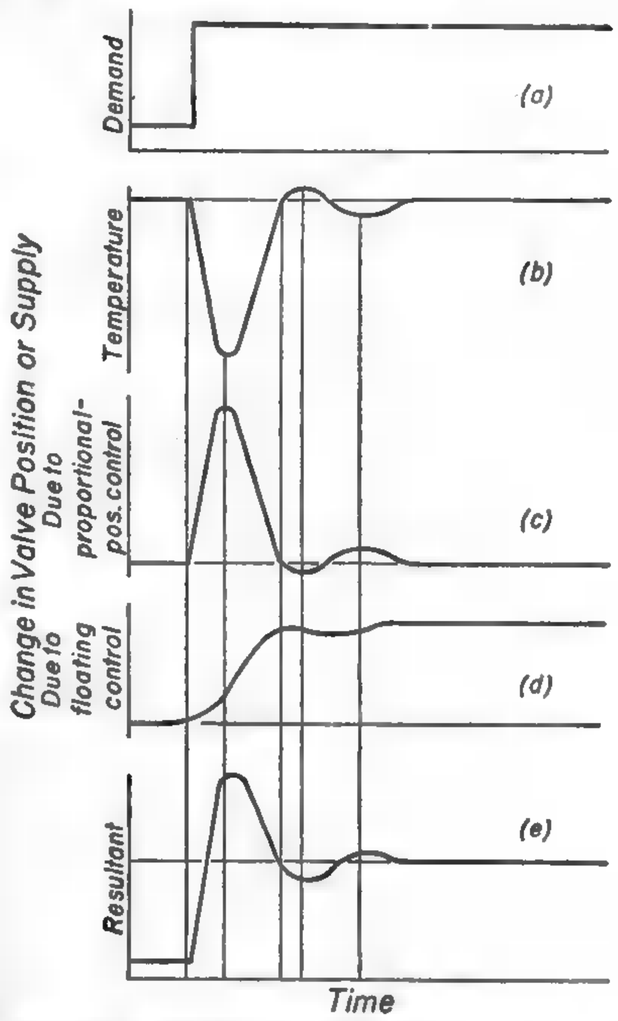

Fig. 12 Responses of temperature and valve movement to change in demand with a proportional-plus-reset controller, showing effect of individual components

Proportional-Plus-Reset Control. When proportional-position and proportional-speed floating actions operate simultaneously to determine the valve position, the resultant action is known as *proportional-plus-reset control*, analyzed in Fig. 12. A sudden change in demand (curve *a*) results in temperature deviation as shown in *b*; the return to the set point is accomplished through valve movement as indicated in *e*. Curve *c* shows the component of the valve movement caused by proportional-position action, to which is added the proportional-speed floating component *d*. It will be noted that the algebraic addition of *c* and *d* gives the resultant curve *e*.

Rate Action. This action is sometimes applied to supplement proportional-position and proportional-plus-reset control. It reduces deviations by moving the valve by additional amounts with variations in the rate of change of temperature.

Average-Position Action. This refers to a method for obtaining the effects of those previously discussed control actions that require the rate of heating to be continuously variable, even though only two instantaneous heating rates are possible. By alternating between the two instantaneous values with suitable timing, any intermediate average rate of heating may be obtained. If the frequency of alteration is made great enough, the effect of the average, rather than the instantaneous, heating rate appears in the temperature record.

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Statistical Methods as a Guide in Control of Operations and of Quality of Product

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MODERN statistical methods are as well suited to problems of quality in the metallurgical industries as the methods of calculus are suited to the study of mechanics or electricity. Under conditions of plant operation, when attempts are made to follow the same procedure repeatedly in order to achieve a given final result, sameness is not obtained. Instead, results vary within a range of values, and the frequency of occurrence within the range varies from one extreme to the other with more or less well-defined mathematical regularity. These conditions arise because observed results depend on a multiplicity of factors. If the influential factors are constantly present, the observed results are distributed according to some law of chance, and occur as a result of the chance combinations

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of the influencing factors whose magnitudes always vary from time to time. Sometimes certain of the influencing factors cease operating altogether, or new factors of influence may enter the system, making the observed results a combination of chance and assignable causes. The same situations exist even under the "controlled" conditions of a research laboratory, although the observed results are generally confined to much narrower ranges of reproducibility. Modern statistical techniques are appropriate for industry because they are designed scientifically to cope with problems of variation and to distinguish between chance variations and variations that result from assignable causes.

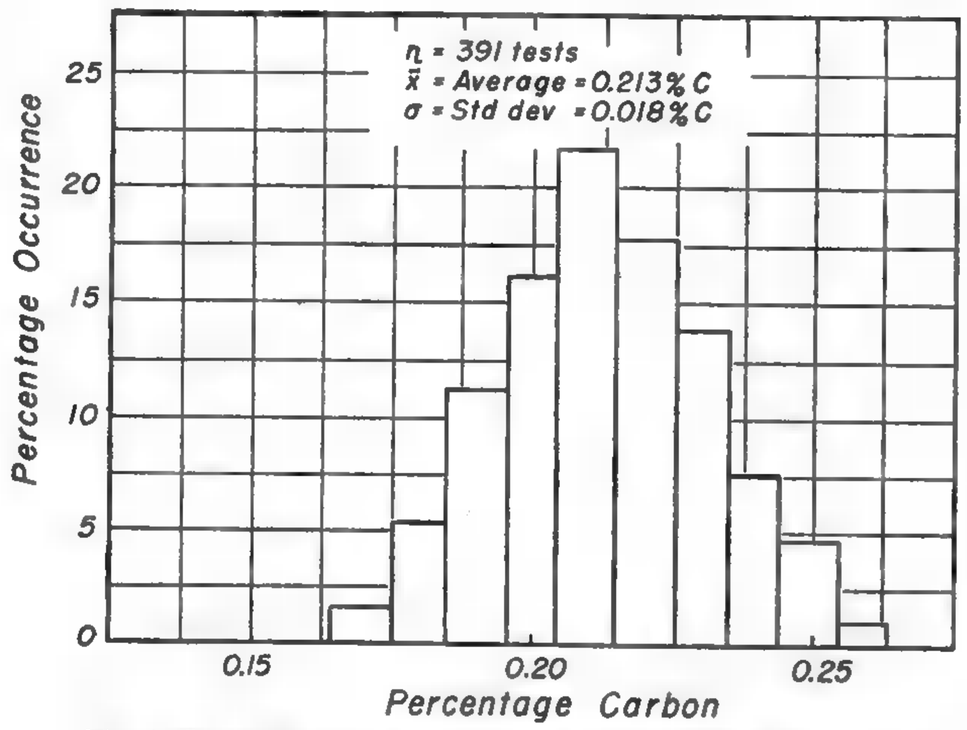

Fig. 1 Frequency histogram showing distribution of carbon in a given grade of hot rolled open hearth steel

In order to describe the quality of a process, a distribution of observed results must be shown. Simple averages or statements of the percentage defective are not sufficient. The references[1-4] give detailed descriptions of typical ways of assembling the data and presenting it effectively. Typical distributions of a quality characteristic are shown in Fig. 1 and 2.

From these distributions, the following important features of quality are evident: mode (most common value), median (middle value), minimum, maximum and percentage of values within any range. The average and the standard deviation (measure of degree of dispersion) can be calculated readily, as can other parameters such as those relating to skewness (lopsidedness) or kurtosis (flatness), which portray other characteristics of the distribution.

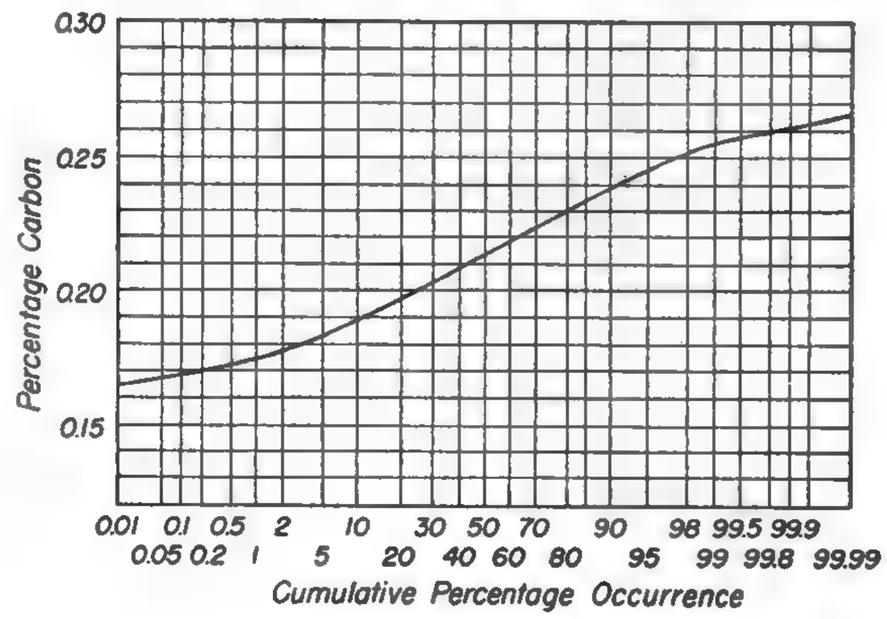

Fig. 2 Cumulative distribution for the frequency histogram of Fig. 1

Two processes may have the same average, yet may vary widely in quality because of differences in uniformity or standard deviation. If such variations exist, when it is desired merely to meet a minimum specification and when it costs appreciably more to obtain higher values, frequently considerable amounts can be saved by taking advantage of the greater uniformity and producing work at a lower average *(see* Fig. 3).

In order to tell, from samples or small-scale tests, which of two or more compared conditions or methods of procedure is superior, the differences observed must be greater than can be attributed to chance. In evaluating such differences, difficulties arise since, even when samples are

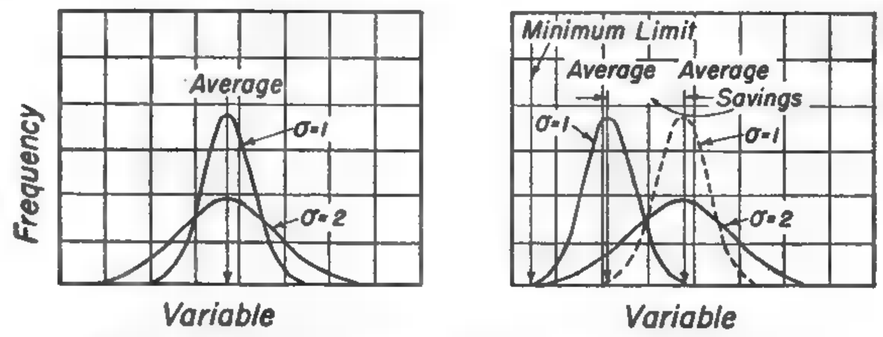

Fig. 3 Frequency curves showing differences in uniformity or standard deviation

taken from a distribution resulting from the operation of a constant system of chance causes, considerable variation in the characteristics of small samples is to be expected because of chance, as illustrated in the following:

Universe	Sample Size, N	Anticipated Variation in Sample: Average, $\bar{X}$	Anticipated Variation in Sample: Standard Deviation, σ
$\bar{\bar{X}}$ = Average = 60,000	5	55,980 to 64,020	0 to 5370
σ = Std Deviation = 3000	25	58,200 to 61,800	1636 to 4182
	100	59,100 to 60,900	2363 to 3637

It will be noted that the expected variation in the averages and the variability of samples decreases with increasing sample size. Therefore, many tests may be necessary in order to arrive at a satisfactory decision concerning a better method or device, especially if it is desired to estimate how much better; and the degree of testing necessary increases as the variability of the material or process increases. In the past, the above situation has been responsible many times for the acceptance of devices or methods no better than those in current use and the rejection of those distinctly superior. It is also partly responsible for conflicting results when tests are duplicated at various places or times. The

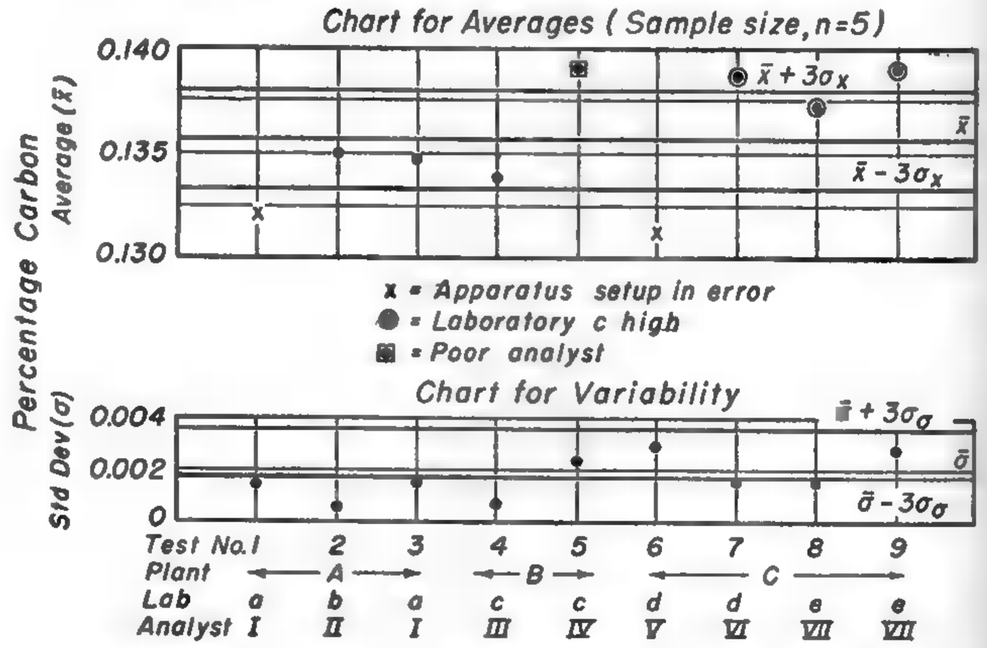

Fig. 4 Control chart for carbon content of five groups of identical drillings submitted to laboratories of three plants

same problem exists in acceptance or rejection of material when samples are tested for specified properties. Many statistical tools are available to solve such problems.[5,6,7]

In industrial processes, distributions that depend on the operation of a constant system of chance causes are the exception rather than the rule. Assignable causes usually enter and leave the system from time to time, and periods when such causes are operating can be located most effectively by employing techniques such as Shewhart control charts[1,2,8,9,10] or the analysis of runs.[11,12] A typical Shewhart control chart is shown in Fig. 4.

Such methods should be used when it is desired to interpret effectively industrial data on a quality characteristic or on factors important in the control of quality. Through the use of these methods needless investigations are avoided; trouble is expected only when the chart indi-

cates that an assignable cause is operating. The chart will not tell the cause of trouble; it merely signals that an assignable cause has entered, that something definite has gone wrong. Proper search should lead to the isolation of the trouble. The control chart method has proved to be an effective way of controlling quality during production.[9,13,14,15] It may be beneficial to shut down a machine when its product is out of control and to eliminate the assignable cause before producing more material.

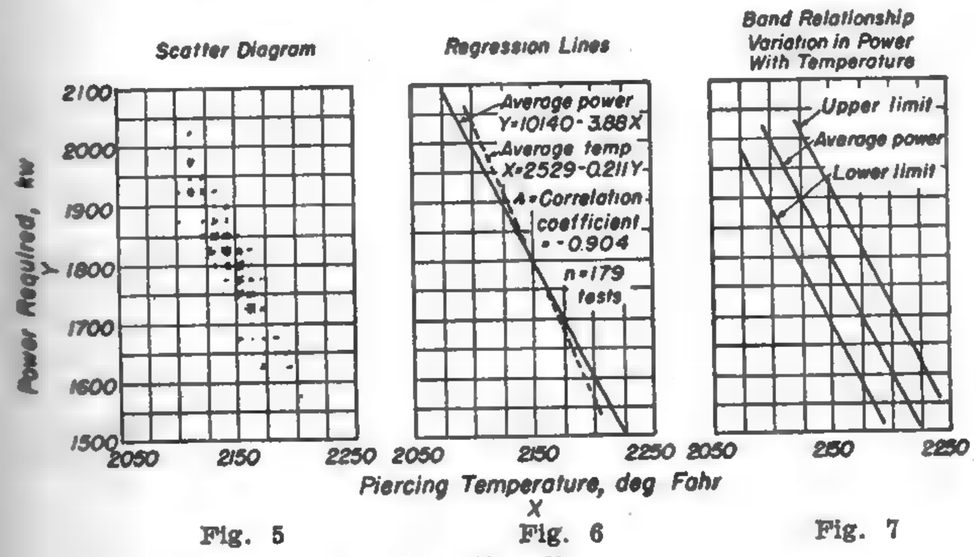

Fig. 5 Fig. 6 Fig. 7

Fig. 5 Scatter diagram
Fig. 6 Regression lines
Fig. 7 Band relationship. Variation in power with temperature

The inherent variability of materials and processes complicates the problem of determining relationships among variables. Functional relationships (where one value of Y and one only is obtained for a given X) do not exist; instead a *range* of Y's is found for a given value of X; yet average Y, or minimum and maximum Y, varies with varying X. Statistical relationships may be linear or curvilinear, just as are the ordinary functional relations. A typical statistical relation is shown in Fig. 5, 6 and 7.

Important problems arise here: Is the observed relation caused by chance? How does Y vary on the average with varying X? Within what limits can Y be predicted if X is known? An extension of this problem involves determining the simultaneous relation between a number of independent variables—Y_1, Y_2, Y_3, Y_4, ...Y_n—and X. Predicting equations may be developed, of the form $X = a + bY_1 + cY_2 + dY_3 + eY_4 + ...zY_n$, where b depicts the relation between X and Y for constant values of Y_2, Y_3, Y_4, and c, the relation between X and Y_2 for constant Y_1, Y_3, Y_4 and so on. Good descriptions of the necessary techniques[4,7,16,17,18] and examples of their industrial application will be found in technical publications.[19,20–25]

In spite of strong evidence in favor of the statistical approach, there is considerable skepticism as to the utility and results, probably because of the common interpretation of "statistical methods" as meaning a tabulation of averages or percentages. These may be misleading because of the small size of samples, and failure to classify the data properly. In the hands of a person familiar with the field and able to make proper hypotheses and classifications of data, the various statistical tools available have proved extremely helpful in the control of quality throughout industry. It must be remembered, however, that in the last analysis, statistical techniques are only a means of judging whether or not the observed data are fulfilling a hypothesis; if irrational hypotheses are contemplated, irrational results will probably be obtained.

The most useful statistical tools now available in quality control work are the following:

Frequency Curves. In addition to the uses of the frequency curve that have already been described, this device has had wide application in the isolation of factors influencing quality, particularly when large quantities of data must be considered.[23,26,27,28] Tabulating equipment and punch cards may be particularly valuable in performing an analysis of this type.

The analytical procedure here consists in sorting various factors and comparing frequency distributions of the quality variable, or comparing frequency distributions of the factors of possible influence for materials from the good and bad thirds or halves of the distribution of the quality variable. Other classifications of data may also be desirable. Examples of effective and ineffective factors determined in this manner are shown in Fig. 8.

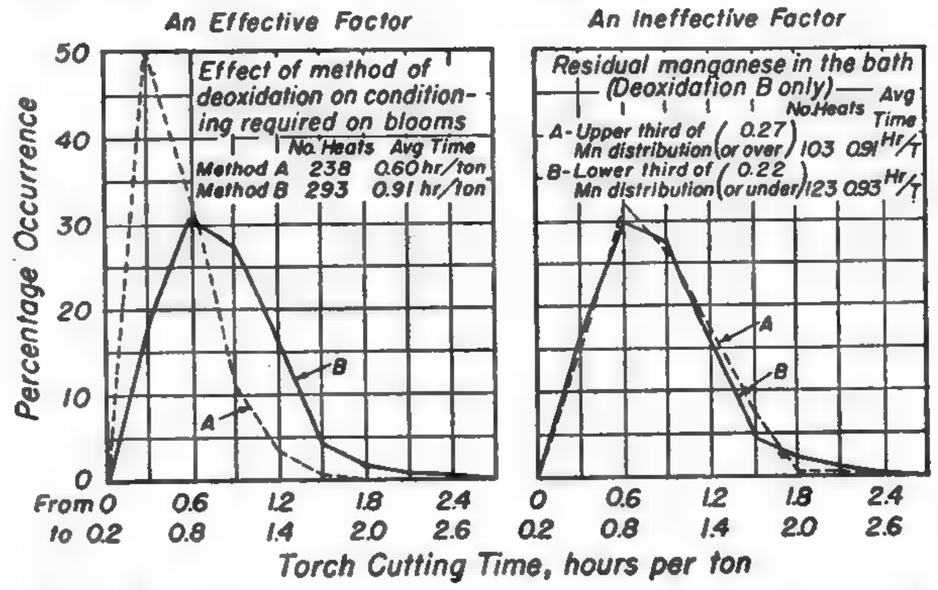

Fig. 8 Effective and ineffective factors determined by the use of frequency curves

Tests of Significance for various statistics of data, such as average, standard deviation, or chi-squared. These are important when relatively small samples are used to compare two conditions. [23] Table I illustrates the use of a test of this type for the difference between averages.

Table I. Significance Test for Differences in Averages of Two Conditions

Quality of Bloom Surface (as Measured by Time-to-Condition) for Two Methods of Deoxidation

Deoxidation A			Deoxidation B	
3.38	2.36	2:30	2.41	
3.84	2.41	3.38	2.53	
0.95	3.58	1.52	2.29	
2.37	3.61	3.36	3.29	
2.16	2.46	2.18	3.49	
1.73	3.39	0.88	4.03	
1.81	2.65	3.64	1.52	
2.18	3.10	0.49	0.86	Difference Between Methods A and B
2.38	3.21		2.03	
2.45	1.18			
Total Samples		28	9	
Average conditioning time		2.46	2.72	0.26
Maximum difference expected because of chance (2σ limits)*				0.67

The observed difference should be interpreted as attributable to chance, since it is less than the 2σ level, and method B should be considered as good as method A.

* See reference 3 or 7 for method of calculation. The limits depend both on the dispersion of individual observations under each condition and on the number of tests involved.

Tests of significance should also be used for comparing frequency distributions, discussed above, when the number of samples is relatively small.

Simple Regression and Correlation. When a large number of data are available, another method of isolating effective factors and determining their quantitative effect on an observed result, is to obtain average values of the quality characteristic in question for various small ranges of the factors being investigated. Because of the operation of the law of large numbers,[26] effects of other factors influencing individual observations will compensate, and the true relation between the factor under investigation and the quality characteristic will be developed. Averages for effective factors will vary in some systematic way with increasing values of the factors; those for ineffective factors will exhibit no trend and the averages will vary more or less at random. Examples of an effective and an ineffective factor and a description of the quantitative relationship in the effective factor are shown in Fig. 9.

It should be noted that the quantitative relations developed under operating conditions in the shop, can be expected to be maintained under these conditions and are therefore of more practical consequence than many relationships developed in the laboratory, where all variables are kept constant except the one being investigated. Calculations made in the laboratory may not hold under operating conditions because of countereffects not foreseen.

When few observations are available, least-squares methods must be resorted to and Pearsonian correlation coefficients must be calculated, in order to establish relationship and distinguish between true and chance association. At times association can be established with a surprisingly small number of samples.

Least-squares methods should also be utilized when it is desired to establish the quantitative method of variation of one dependent variable with another, based on relatively small samples; here tests of significance of regressions and accuracy of slopes should be calculated. When it is desired to develop the complete band type of relationship—linear or curved—least-squares methods should be used.

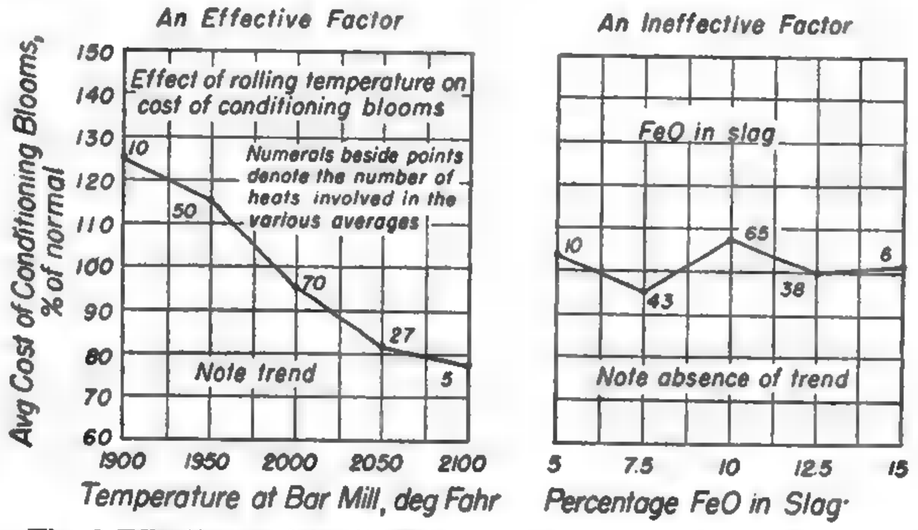

Fig. 9 Effective and ineffective factors determined by the use of simple regression and correlation

The determination of correlation by least-squares or regression using either averages or least-squares, can be greatly expedited by using tabulating equipment.[29,30]

Multiple Regression and Correlation. Probably the best method of isolating effective factors from routine data is that of the simultaneous consideration of their effect on the quality characteristic in question, by using least-squares methods of multiple correlation.[16,17,19–22,24] Effects of the various factors as developed, will differ from those of simple regression and correlation (*see* above) in that the results shown for any particular factor are the results for constant values of other factors of influence.

An equation may be developed in which all the effective factors are included, and the value of the dependent variable can be calculated in any given instance. An expression may be developed for the accuracy of the predicting equation. The total variation in the dependent variable, explained by all the effective factors, can be determined so that it can be seen at once whether or not it is worth while to search for effects of other factors not included in the study. The contribution of each effective factor to the total explained variation can also be determined roughly. It is emphasized, however, that factors for use in regression equations should be selected on the basis of some definite hypothesis, and that large quantities of data should be used if it is desired to develop regression equations for predicting future results. It may be desired to include some factors as reciprocals, some as squares, and so on, if the theoretical evaluation of the problem indicates that such should be done. Table II gives an example of the use of this technique. Many other examples are discussed in the literature.[19–22,24] Use of tabulating equipment will be found indispensable here.

Analysis of Variance and Design of Experiments. These techniques should be applied when special tests are conducted in either mill or laboratory to determine the effect of variables. The experiment should be designed and calculation sheets prepared before any testing is done. When designed so that the technique of analysis of variance can be applied to results, experiments have the following advantages:

1 Correct reproducible answers are obtained with a minimum of testing.
2 The effect of each factor and of combinations of the several factors included are determined as distinguished from chance. Factors and their combinations are classed as "effective" or "ineffective".
3 The reliability of experimental technique is evaluated.

Use of this device should eliminate reversals of test results during repetition. After effective factors have been isolated, they or their combinations can be expressed conveniently as a multiple regression equation, and a predicting equation can be evolved with little additional work. Books describing techniques and articles describing industrial applications are included in the references.[3,7,22,31–35] An example of such an analysis, taken from a laboratory investigation of the effects of nickel, manganese and vanadium on a property of a steel, is shown in Table III.

Control Charts. As mentioned previously, it is important to use control charts as a matter of routine in order to interpret variations in the quality characteristics of a part being produced on a rolling mill, drawbench or machine, so that no deliberate changes will be made as long as the process is under control, and so that operators will search for trouble immediately when an assignable cause results in an observation beyond control limits. It is also im-

Table II. Example of the Isolation of Effective Factors and Determination of Their Quantitative Effects Through the Use of Multiple Correlation

FeO in Metal. From the results on 65 tests on open hearth heats for C, Mn, and FeO in the bath, MnO, FeO, Fe_2O_3, R $\left(=\frac{CaO}{SiO_2 + 0.634\ P_2O_5}\right)$ and temperature, the following regression equations and evaluations of the effects of these factors on [FeO] were developed:

$$[FeO] = -0.322 + \frac{0.0092}{[C]} + 0.0798\,[Mn] + 0.0011\,(MnO) + 0.0019\,(FeO) + 0.0034\,(Fe_2O_3) - 0.0067\,(R) + 0.00013\,T \quad (1)$$

$$[FeO] = -0.299 + \frac{0.0092}{[C]} + 0.1188\,[Mn] + 0.0003\,(MnO) + 0.0035\,(Fe) - 0.0082\,(R) + 0.00012\,T \quad (2)$$

$$[FeO] = -0.296 + \frac{0.0092}{[C]} + 0.1280\,[Mn] + 0.0035\,(Fe) - 0.0082\,(R) + 0.0012\,T \quad (3)$$

Total variation in FeO unaccounted for after considering factors in: Equation 1=10.0%[a], Equation 2=10.8%[a], Equation 3=10.6%

Factor	Significance (Probability that the effect is caused by chance)	Independent Quantitative Effect on [FeO][d] (Most probable values from equation 3)
[C]	Less than 1 in 1 billion	From 0.05 to 0.06 C, FeO decreases 0.031% 0.10 0.11 0.008 0.30 0.31 0.001 0.60 0.61 0.0005
[Mn]	2 out of 5[e]	For 0.05% increase in [Mn], (FeO) increases 0.006%
(MnO)	9 out of 10[b]	
(Fe)	1 out of 50	For 1% increase in (Fe), (FeO) increases 0.0035%
(R)	1 out of 4[c]	For 0.05% increase in (R), (FeO) decreases 0.004%
T	1 out of 4[c]	For 100° F increase in T, (FeO) increases 0.012%

Standard deviation of error $\overline{(S)}$ considering all variables from Equation 3 = 0.025%; from duplicate tests = 0.018%.[e]

(a) Comparison of unaccounted-for variations from Equations 1 and 2 indicates that little is to be gained by considering iron oxide as FeO and Fe_2O_3. Total Fe tells the story as well.
(b) Ineffective factor.
(c) Effective, as a result of previous knowledge. Generally a level of 1 in 20 is taken as a lower limit for considering a factor effective.
(d) Quantitative effects of the factors.
(e) Use of equation 3 permits evaluation of [FeO] almost as precisely as chemical analysis.

Table III. Example of Analysis of Variance Applied to a Research Problem

Effect of 1 to 2% Mn, 0 to 3% Ni, and 0.0 to 0.1% V on a physical property of an aluminum-killed steel with 0.30% C, 0.30% Mo, 0.25% Si

1 *Data* consisted of 24 experimental melts with:
(a) 0 V, 1% Mn, and 0, 1, 2 and 3% Ni; same with 1.5% Mn; same with 2.0% Mn
(b) 0.10% V, 1% Mn, and 0, 1, 2 and 3% Ni; same with 1.5% Mn; same with 2.0% Mn
Tests run in triplicate (72 tests)

2 *Analysis of Variance.* Significance of test results:

Factor	Degrees of[a] Freedom	Sum of[b] Squares	Variance (Mean Sum of Squares)	F[c] Data	Limits of F[d] 5% Chance Level	Limits of F[d] 1% Chance Level	Remarks
Mn	2	30720.08	15360.04	44.65	5.14	10.92	Highly significant
Ni	3	9690.89	3230.30	9.39	4.76	9.78	Significant
V	1	6272.00	6272.00	18.23	5.99	13.74	Highly significant
Mn, Ni	6	4385.36	730.89	2.13	4.28	8.47	Not significant
Mn, V	2	735.59	367.80	1.07	5.14	10.92	Not significant
Ni, V	3	235.11	78.37	0.23	8.94	27.91	Not significant
Mn, Ni, V	6	2064.31					
Without group	48	58.67	344.05 = Estimate of error				
Total	71	54162.00	1.22 = Estimate of reliability of test[e]				

Notes:
(a) From the design of the experiment. *See* references 3, 5, 7, 31.
(b) Evaluated from the data. *See* references 3, 5, 7, 31.
(c) Variance for factor divided by estimate of error.
(d) Limits of chance variation for F. If the observed F exceeds the 5%-chance level, the factor is significant; if it exceeds the 1% level it is highly significant.
(e) If the variable here exceeds the estimate of error, the experiment has not been conducted in a reliable manner and other factors that may be very important are operating to affect the results.

3 *Quantitative Effects.* The regression equation.
Property = 18.258 + 45.83 (% Mn) + 10.49 (% Ni) + 234.84 (% V)
$R^2 = 0.85$; 85% of the variation in the property is explained by the manganese, nickel and vanadium contents in these steels, in these tests.

portant to use control charts for variables affecting final quality, such as open hearth variables affecting surface quality in conditioning or final working. Control charts are the usual criteria for statistical control, and when it is desired to take fullest advantage of various plans for sampling inspection, statistical control must be obtained first.

Analysis of Runs. This technique may be used likewise to distinguish between real and chance variation and probably represents some advance beyond the control chart in that it distinguishes between causes producing trends and those producing discontinuous and erratic effects. Observations are listed or plotted in order of time or position taken, and the sequence is examined for existence of runs up or down and those above or below the median. A "run down" is the interval between a maximal number and the next succeeding minimal one, and the length of run down is the number of numbers involved, including maximal and minimal numbers. Runs up and runs above or below the average are similarly defined. The exact mathematical formulation of this problem is somewhat complex,[21, 22] but for practical purposes it may be said that a run of seven or more, either up or down or above or below median, is significant evidence for entry of an assignable cause. This technique is illustrated in Fig. 10.

Sampling Inspection. Statistical sampling inspection plans may be applied whenever the purchaser is willing to take a slight risk of accepting a small proportion of product considered defective. Even with 100% inspection, however, it is usually found that a small proportion of defective product is shipped, as proved by reinspection of material that had been inspected 100% and accepted. Sampling inspection can never guarantee an accepted product that is entirely free from defects, such as might be required in parts used in critical positions; however, neither can 100% inspection. A product inspected 100% twice is required here. Sampling inspection has been found very useful in controlling the flow of good products from department to department within a plant, as well as for final inspection, and should be used where the cost of 100% inspection cannot be justified or where tests are destructive and 100% inspection is impossible.

Statistical sampling inspection will function most economically after statistical control has been attained, as indicated by the control chart. Consequently, installation of these procedures generally results not only in decreased cost of inspection but also in increased production and greatly decreased rejections. After the sample inspection procedure is in operation, the entrance of an unfavorable assignable cause results in reversion to 100% inspection in some types of plan or to the use of a more stringent plan with greater rejection of complete lots in other types of plan. In either instance, strong pressure is brought to bear on the operator, and diligent effort is expended to eliminate the assignable cause, resulting on the whole in greatly decreased rejections.

Plans for statistical sampling inspection are built on a detection feature and are designed to reject when the quality becomes unusually bad. If quality becomes unusually good, sampling can be further reduced. It is never possible to estimate the quality of the lot from a relatively small sample. The plans operate so as to give the customer reasonable assurance that he is receiving a product of satisfactory quality and to give him protection against the acceptance of inferior lots or the acceptance of a substandard product in the long run. The plans also operate so as to give the producer reasonable assurance that good material will not be rejected too frequently.

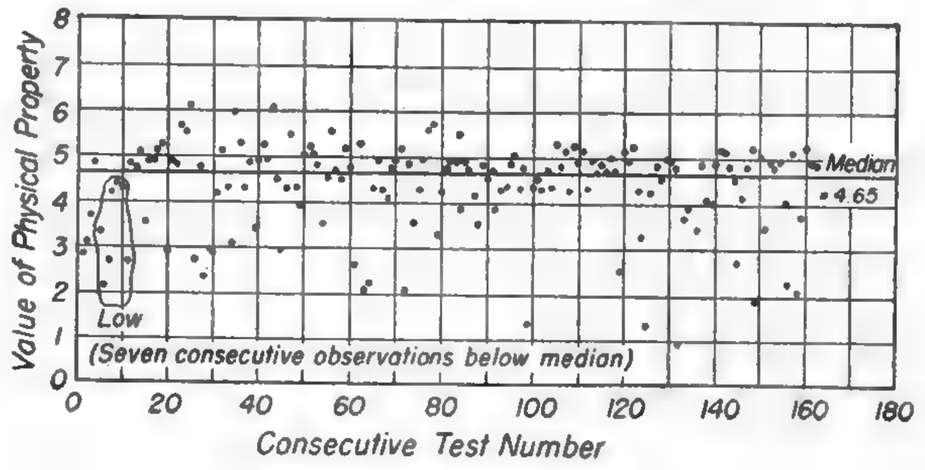

Fig. 10 Analysis of runs

When inspection with "go or no go" gages is carried out and material is classified as good or bad, a variety of plans is available, any of which will operate so as to guarantee that, independent of the quality of the material to be inspected, the material accepted or rejected will conform to the consumer's risk of accepting bad material and to the producer's risk of rejecting good material. Good and bad materials are defined by agreement as containing certain specified quantities of rejects. The following are the popular plans in use at present for this type of inspection.

The Dodge-Romig Plans.[36] These plans, of both single and double sampling types, are designed to guarantee either a maximum percentage defective in accepted lots,

or a maximum average outgoing quality limit. The consumer's risk is fixed at 10% and the producer's risk is about 5%. The plans assume that rejected lots will be inspected in detail 100%. When the size of lot and process average for defects is known, the plans list the size of sample to be taken, along with the number of rejections permissible in the sample for acceptance, reinspection (double-type plan), or rejection. The plans are designed to give a minimum of inspection if incoming material is at the process average. Examples of the application of these plans are discussed in reference 37. It should be noted that economies obtained in inspection are greater, the larger the lot size, but that lots must be homogeneous or misleading results may be obtained. Double sampling tables are used mainly for the psychology of a second choice; there is actually not much greater chance for acceptance, and these plans will not necessarily pass the greatest proportion of lots without inspection.

Army Ordnance Plans.[38] These plans are also of either the single or double sampling type and were designed mainly to keep the rejection of satisfactory goods at a minimum. After the acceptable quality limit for defects has been decided, the "normal" tables show the necessary samples to take and the defects permitted for various sizes of lots. Inspection results are also checked cumulatively. If the producer's quality becomes bad, inspection is automatically made more stringent; if the quality improves, the "reduced" inspection tables may be used with consequent greater savings in inspection costs.

Sequential Plans.[39] Based on assumed or negotiated values for good and bad quality, and the consumer's and producer's risks, limits for acceptance or rejection in samples ranging in number from one to as many as several hundred, are calculated from a simplified formula presented in reference 39. Successive samples are then taken until a decision is reached, and the material is either accepted or rejected. On material unquestionably good or bad, these plans give a decision quickly, but extensive testing may be required on borderline material.

Each of the foregoing types of plan has advantages and disadvantages, both practical and theoretical in nature. Single-sampling plans are simple to understand and it is not necessary to hold the lot for reinspection; but ordinarily somewhat more inspection is required than for double or sequential sampling. Double-sampling plans offer the second choice and are psychologically good. An effective reduced inspection plan is available in the double-sampling Army Ordnance Table. Sequential-sampling plans may not be convenient from a practical viewpoint because of the necessity of holding the lot until the samples are inspected piece by piece. As a rule, sequential plans will result in somewhat reduced inspection, but on certain lots a long time may be required for a decision.

Shewhart's control chart technique can also be applied to give a variety of plans for acceptance-rejection. However, this work requires a competent statistician, co-operating with the engineering staff.

When inspection involves actual measurements of the quality characteristic in question, the two most popular plans are Shewhart's control chart technique[10,12,23] and sequential-sampling plans for variables.[39] The previous remarks relating to these techniques, as applied to "go or no go" gage inspection, also apply here. When actual measurements are made, either of these techniques should be used and the actual measurements should be taken into account. This is a more reasonable way than to consider the material good or bad, if conforming or nonconforming to specified tolerance limits, since the degree of goodness or badness, as evident from the actual measurements, appreciably reduces the sampling required for making a decision concerning the lot.

The foregoing principles of statistical sampling inspection should eventually find wide application in the field of specifications, particularly when tests are destructive or expensive. After painstaking and expensive physical and chemical tests have been made on samples taken from the product, most present-day specifications are written so that it is still uncertain whether or not the material is suitable for the actual requirements of the user. There has been a decided lack of application of knowledge of the relationship of a sample to the whole. Today, most sampling inspection in specifications leads to acceptance or rejection on the basis of chance, and the customer usually gets a product that is precisely what the manufacturer offers for inspection. Technical publications[40,41,42] contain examples of the need and utility of modern statistical techniques in the development of satisfactory specifications.

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STRUCTURE AND PROPERTIES OF METALS

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The Crystal Structure of Metals and Alloys

By Kent R. Van Horn*

THE various elements crystallize according to a definite pattern or symmetrical arrangement of atoms that is repeated at regular intervals to form a section of any size. The three-dimensional latticework of imaginary lines connecting the atoms is called a space lattice. The smallest prism which possesses the full symmetry of the crystal is termed the unit cell. Each unit cell in a space lattice is identical in shape and orientation with every other. The type and dimensions* of the unit cells of most elements have been determined and tabulated in X-ray books[1,2,3,4,5] and are summarized on pages 20 and 21 of this Handbook.

Only 14 types of space lattice are possible (Fig. 1) and they fall into the seven crystal systems, each possessing certain characteristics as to equality of angles and lengths of the co-ordinate axes. The features that typify the seven crystal systems are:

1 *Cubic* (sometimes called isometric or regular). Three equal axes mutually perpendicular.
2 *Tetragonal.* Two equal axes perpendicular to each other and to a third (unequal) axis.
3 *Hexagonal.* Three equal axes inclined at an angle of 120 deg and a fourth (unequal) axis perpendicular to their plane.
4 *Rhombohedral.* Three equal axes mutually inclined at an angle not equal to 90 deg.
5 *Orthorhombic.* Three unequal axes mutually perpendicular.
6 *Monoclinic.* Three unequal axes, only one of which is perpendicular to the other two.
7 *Triclinic.* Three unequal axes, no two of which are perpendicular.

It is necessary to have a method for describing the faces of a crystal or the atomic planes within a crystal or a space lattice. The Miller indices are generally used to show the relationship of the planes with respect to the co-ordinate axes. These indices, *hkl,* are simply the reciprocals of the intercepts of a plane on the three crystal axes, *X Y Z* (edges of unit cell). The intercepts are measured in unit distances along the three axes, and not in centimeters. Thus, if a plane intersects the *X* axis at a positive unit distance and is parallel to the *Y* and *Z* axes, the intercepts are 1 ∞ ∞ and the indices (100). A plane cutting each of the three axes at unity on the positive side of the origin would be the (111) plane. If a plane cuts any axis on the negative side of the origin, the corresponding index would be negative and is designated by a minus sign above the number ($\bar{1}12$). A specific plane is enclosed by parentheses (100); a family of planes of similar form in curved brackets {100}, meaning (100) + (010) + (001) + ($\bar{1}$00) + (0$\bar{1}$0) + (00$\bar{1}$); and a direction or line in a crystal by a square bracket [100]. The indices of a direction are the smallest integers proportional to the co-ordinate differences, in terms of the parameters, between equivalent points lying on a crystal line. Therefore, reciprocals are not used in determining the indices of a direction. A full

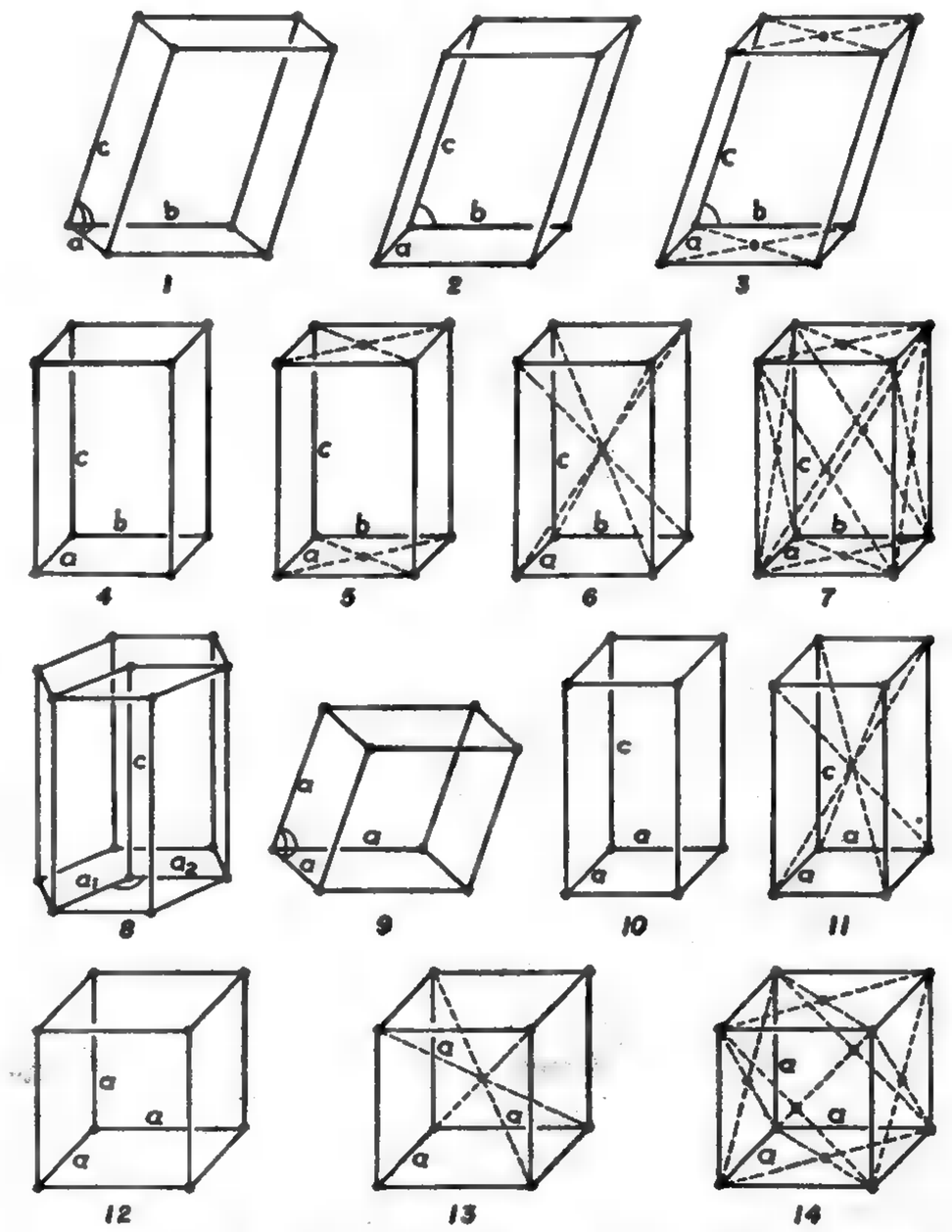

Fig. 1 The 14 space lattices illustrated by a unit cell of each: (1) triclinic, simple; (2) monoclinic, simple; (3) monoclinic, base-centered; (4) orthorhombic, simple; (5) orthorhombic, base-centered; (6) orthorhombic, body-centered; (7) orthorhombic, face-centered; (8) hexagonal; (9) rhombohedral; (10) tetragonal, simple; (11) tetragonal, body-centered; (12) cubic, simple; (13) cubic, body-centered; (14) cubic, face-centered. (C. S. Barrett[4])

set of equivalent directions (similar form) are indicated by carets <100>, representing [100] + [010] + [001] + [$\bar{1}$00] + [0$\bar{1}$0] + [00$\bar{1}$]. The cubic system is the only one

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* The characteristic magnitude for defining the unit cell or a point in the cell is called the parameter. The edges of the unit cube *a, b, c* and the angles α (between *b* and *c*), β (between *c* and *a*) and γ between *a* and *b*) are its parameters.

in which each direction is perpendicular to a plane of the same indices.

Two methods are in common use for identifying planes and directions in the hexagonal system: one with indices consisting of three and the other, of four numbers. Only three axes a_1, a_2, and c are considered in the first method while four axes a_1, a_2, a_3, and c are in the other method (Fig. 1). The reciprocals of the intercepts of a plane on the axes are reduced to the smallest integers in the same manner as for other crystal systems.

A periodic table of the elements is reproduced in Fig. 2, with the inert gases and the metals beryllium and magnesium appearing twice to complete the symmetry of the arrangement. The number in the periodic system is indicated above each member of Group I and above the last element occurring on any horizontal line. The large majority of the metals crystallize according to three of the fourteen space lattices—the face-centered and body-centered of the cubic, and the close-packed type of the hexagonal system—and are enclosed by characteristic designations. All polymorphic modifications having any of these three atomic arrangements are represented by additional outlines (Fe, Co, Tl, and others). The complex lattices are not indicated. The majority of the metals, which generally have one (or more when there are polymorphic modifications) of the three lattices of high symmetry, appear at the left and the central part of the table. The nonmetallic elements, excepting the inert gases of Group VIII, are located at the extreme right of the table and have more complicated unit cells.

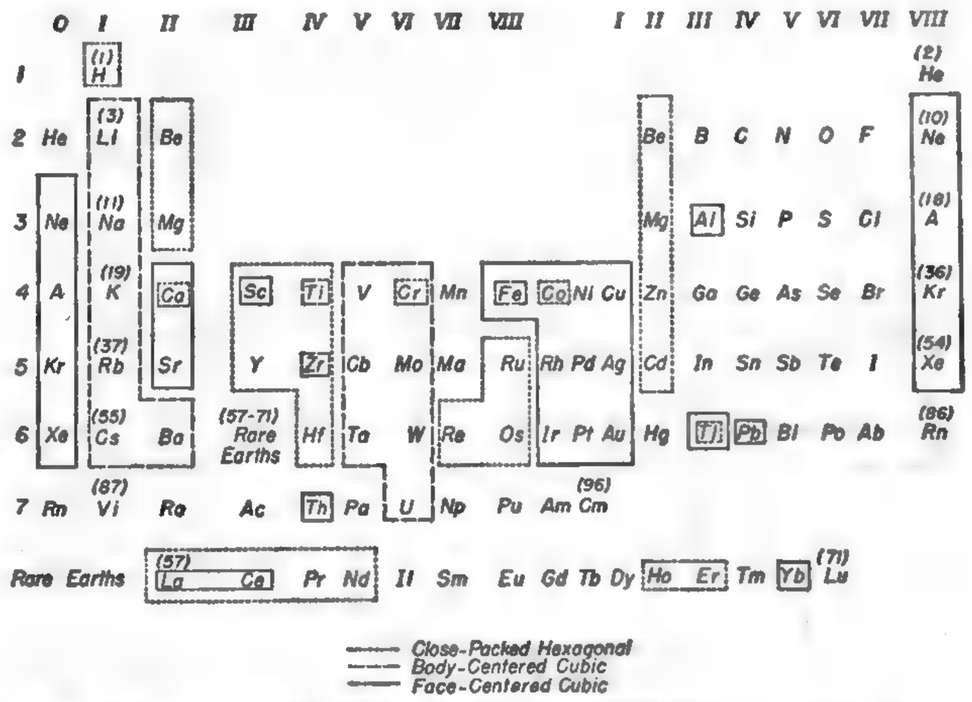

Fig. 2 Periodic table showing the chemical elements that have crystal structures of high symmetry

Since a high degree of crystalline symmetry (for example, face-centered cubic, body-centered cubic, and close-packed hexagonal arrangements) is responsible for many of the important properties of metals, these types of lattice will be described briefly. The plasticity of metals is generally attributed to movements along specific crystallographic planes in certain directions, all the atoms in one series of planes moving as a block relative to a similar series of parallel planes. The planes of easiest slip generally have the greatest atomic concentration and the associated characteristic of a large distance between the intervening planes (interplanar distance). The latter feature implies that the restraining forces acting between consecutive planes will be a minimum. Also, slip within the favorite planes proceeds most easily along the atomic rows of highest density. It is the flowing or gliding movement along these planes of atoms which permits a solid metal to alter its external form. The three lattices of high atomic symmetry have more densely populated planes and lines of atoms than the complex structures. The three simple atomic arrangements also exhibit different degrees of plasticity; for example, metals crystallizing in the close-packed hexagonal lattice are generally less ductile than those of the face-centered cubic type.

Face-Centered Cubic Lattice. A more concrete picture of the common metal crystal structures can be obtained from Fig. 3, 4 and 5, which were reproduced from Hume-Rothery's treatise on alloys.[6] Figure 3a shows the face-centered cubic unit cell with an atom located in each corner and center of each face of the cube. Figure 3b illustrates the same configuration repeated for a number of cells, but the atoms are represented by spheres in contact. This type of lattice is termed "close-packed" because the most intimate possible association of the spheres results. Although

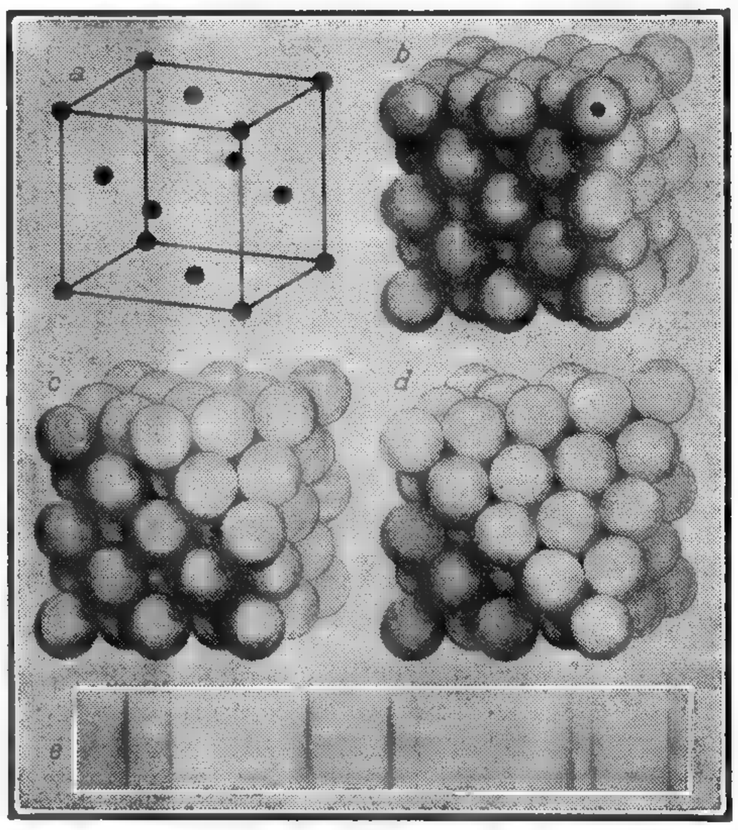

Fig. 3 Face-centered cubic structure. (*a*) Face-centered cubic unit cell. (*b*), (*c*), (*d*) Face-centered cubic packing of spheres in contact.[6] (*e*) X-ray photogram of face-centered cubic copper. Mo-K*a* radiation.

Fig. 3b typifies the manner in which the atoms exist in metals more nearly than do the voids suggested by Fig. 3a, it should not be inferred that an atom is a hard ball of specific dimensions. If the sphere marked with a dot is removed from a corner of a cube Fig. 3b, the arrangement of Fig. 3c is obtained, exposing a plane of six spheres (appearing lighter in the illustration). Lines through the centers of the spheres form an equilateral triangle. Figure 3d shows the arrangement on this plane more clearly after these six spheres are extracted. The same operation could be initiated from any of the corners of a cube, thereby uncovering eight similar close-packed planes, in which each atom is at the center of a hexagon formed by lines through the centers of its six equidistant neighbors. Because the eight planes, if extended, would form the faces of an octahedron, they are called the octahedral or {111} planes. There are only four series of {111} planes, since the opposite faces of the octahedron are parallel. The three rows of close atom packing on the {111} planes are the sides of the equilateral triangles or <110> directions, which are the normals to the faces of the regular dodecahedron. The face-centered cubic lattice has, therefore, four close-packed planes {111} and twelve close-packed directions <110>, amounting to the highest degree of atomic concentration and symmetry encountered in any lattice. Consequently, the metals of this type (such as aluminum, copper and silver) are ductile, easily deformed, and good as conductors of heat or electricity. The X-ray pattern characteristic of this space lattice is included as Fig. 3e.

Body-Centered Cubic Lattice. The body-centered cubic unit cell has an atom at each corner and one in the center of the cube, as illustrated in Fig. 4a and represented by spheres in contact in Fig. 4b.[6] If the two dot-marked spheres of the nearest cube edge of Fig. 4b are removed, the result is shown in Fig. 4c. The plane exposed is that containing the most atoms for this space lattice, namely, the face diagonal or dodecahedral (110) of which there are six sets. The large voids or interstices between the atoms suggest that this plane is not one of close packing compared with the face-centered cubic {111} planes. Therefore, the body-centered cubic metals do not have a well-defined slip plane, but deform by movement along various planes {110}, {112}, {123}, depending on the relations of

stress and the important directions <111>. Figure 4c exhibits close-packed lines of atoms, the diagonal <111> rows, which are normal to the four sets of octahedral {111} planes. With no close-packed planes and only four close-packed directions, this condition does not permit a high degree of plasticity and the metals of this type (such as *a* iron, molybdenum, or tungsten) have great strength and medium ductility. The X-ray pattern characteristic of this lattice is illustrated in Fig. 4d.

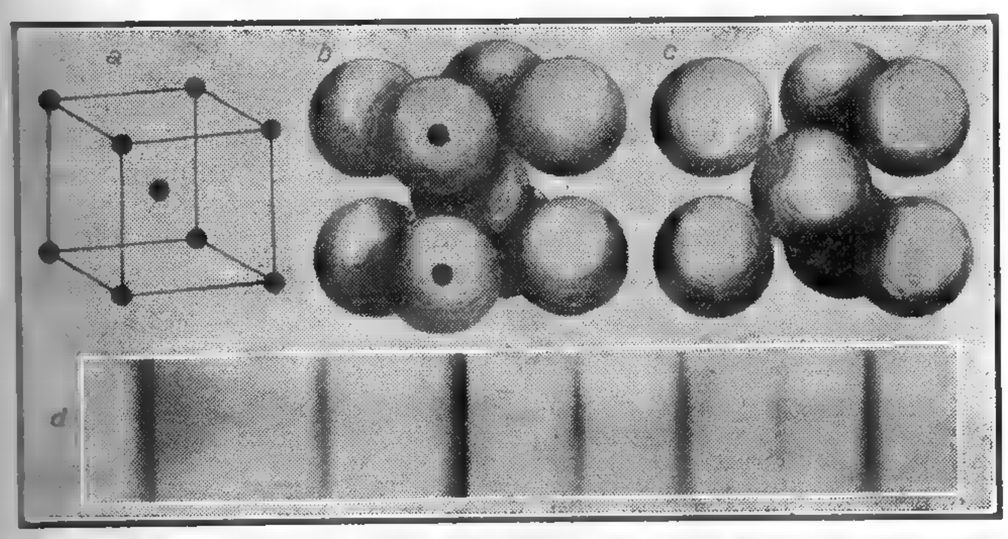

Fig. 4 Body-centered cubic structure. (*a*) Body-centered cubic unit cell. (*b*), (*c*) Body-centered cubic packing of spheres in contact.[6] (*d*) X-ray photogram of body-centered cubic iron. Mo-K*a* radiation

Close-Packed Hexagonal Lattice. The close-packed hexagonal unit cell is represented in Fig. 5a and is also illustrated by spheres in contact in Fig. 5b. The close packing of spheres approaches that of Fig. 3b. The upper and lower horizontal planes of spheres exhibit the hexagonal grouping of one atom intimately surrounded by six neighbors. These planes of high atomic concentration are the basal faces {001} or {0001}, *see* Fig. 5, and the lines of close-packing on these planes are parallel to the edges of the first-order prism faces <210>. Since the opposite faces of the hexagon are parallel, there is one close-packed series of planes {001} and three important rows <210>. Consequently, it is to be expected that slip may proceed along specific planes in certain directions in this structure, but not with the freedom of the face-centered cubic lattice (four planes, twelve directions). The hexagonal elements (such as cadmium, magnesium and zinc) can accommodate their structure to stresses by another mechanism, twinning, which alteration generates new additional slip planes {001}, thereby approximating the plasticity possessed by the face-centered cubic metals and surpassing that of the body-centered cubic metals. The X-ray pattern characteristic of the close-packed hexagonal cells is reproduced in Fig. 5c. Metals crystallizing with lower symmetry than the face-centered cubic, body-centered cubic and close-packed hexagonal arrangements, such as orthorhombic, monoclinic, or triclinic, do not have the close-packed planes and directions for slip or deformation. They are, therefore, relatively brittle and are used less extensively than the more plastic metals.

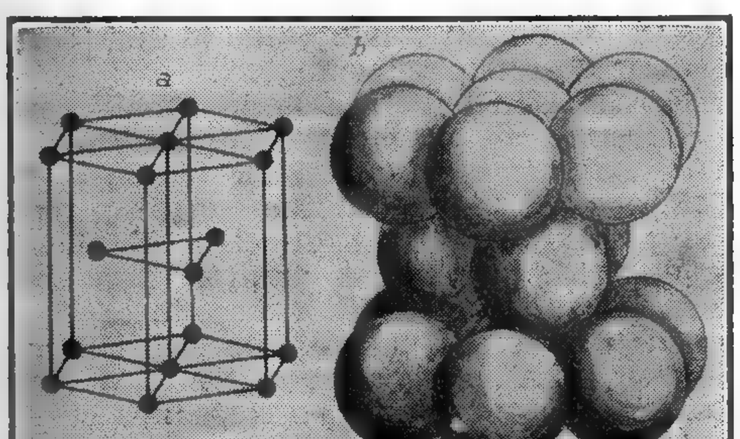

Fig. 5 Close-packed hexagonal structure. (*a*), (*b*) Close-packed hexagonal unit cell and packing of spheres in contact.[6] (*c*) X-ray photogram of close-packed hexagonal zinc. Mo-K*a* radiation

Polymorphic Modifications of Metals. When a mineral crystallizes in two or more different forms, it is termed polymorphic. The prefixes "di" or "tri" are employed to denote the number of modifications, if there are two or three. Metals that occur in two or more forms, characterized by either different crystal structures or marked differences in energy content, or both, are generally called "allotropic". The terminology has been the source of confusion, because allotropy has been interpreted by some to represent a reversible change of a physical property, while others consider allotropy to be equivalent to polymorphism, involving only an alteration in the crystallinity. The disturbing effects of impurities frequently cause a variation in some physical property, which has been erroneously interpreted as a significant allotropic change. Although allotropy may be considered by some to denote a crystal structure transformation, it seems advisable to use the term "polymorphism", so that there will be no doubt as to the nature implied.

Precision X-ray investigations of the elements have disclosed that at least fifteen metals (calcium, cerium, chromium, cobalt, iron, lanthanum, manganese, rhodium, scandium, thallium, tin, titanium, tungsten, uranium and zirconium) exist in two or more different crystal forms. The names of the polymorphs, the types of crystal structure and the temperature ranges of stability have been tabulated.[4,5,6,7] In addition to the metals, carbon, nitrogen, oxygen, phosphorus, selenium and sulfur have polymorphic modifications. The elements arsenic, barium, beryllium, erbium, hafnium, neodymium, praseodymium, ruthenium and strontium may possibly be polymorphic.

The classic example of polymorphism is the transition, at 13 C, of metallic white tin to the gray powder frequently called "tin pest". White tin is tetragonal and the gray variety, diamond cubic.

The much discussed phase change from α to γ iron, on heating, is the basis of heat treating steel. For a considerable period of time there were supposed to be four crystalline forms, namely, α, β, γ and δ iron. However, the nature of the transformations was established by the X-ray analysis of pure electrolytic iron at elevated temperatures.[8] The so-called "β" iron was found not to be a polymorphic modification and pure iron exists in only two different crystalline forms corresponding to the two transformations, $\alpha \rightleftarrows \gamma$ at A_3, and $\gamma \rightleftarrows \delta$ at A_4. Both α and δ iron are body-centered cubic; the γ form is face-centered cubic.

Alloy Structures. When two metals are melted together and then solidified, a number of different structures may result. The various types are derived from the degree of mutual solubility of the component metals, their ability to combine or form intermediate phases, and the effect of temperature on these tendencies. The structural types which the elements may assume in the solid are represented by phase diagrams, and are characterized by (1) elements, (2) solid solutions and (3) intermediate phases.

There is at least some solid solubility of any two metals. However, the solid solubility of one metal in another may be indeterminately small. In this instance, the metal is considered to exist in the binary system and if the metal is not polymorphic, the same crystal lattice will exist up to the melting point.

A solid solution of two or more elements is defined as a phase in which the crystal lattice of only one component is retained. This includes complete solid solubility and restricted solubility, such as the end (terminal) phases of systems exhibiting immiscible regions (eutectic and peritectic) and intermediate phases. Solid solutions, representing either complete or restricted solubility, may be divided into two types—the substitutional class, and the interstitial group. When the solute atoms replace or are substituted for some of the atoms of the solvent lattice, the solution is termed "substitutional". Substitutional solutions contract or expand the dimensions of the solvent metal cell, depending on the size of the replacing solute atoms. In the second, or interstitial type, the solute atoms are dispersed in the vacant spaces between the solvent atoms; that is, they are introduced into the lattice in addition to the solvent atoms. An interstitial solute always enlarges the solvent lattice. The interstitial solutions occur infrequently and are confined to systems where the diame-

ter of the solute atom is appreciably smaller than that of the solvent atom. Boron, carbon, and nitrogen are prone to form interstitial solutions with the transition elements—for example, carbon in γ iron (austenite). The crystal structures of continuous or extended terminal solid solutions are generally of high symmetry (Fig. 3 to 5).

Intermediate phases are frequently referred to as intermetallic compounds or solid solutions, depending on certain phenomena and preferences of definitions. With the older methods of determining phase diagrams, it has been difficult to define the limits where a solid solution begins or a compound terminates. No satisfactory classification of intermediate phases was evolved until the advent of X-ray analysis. The term "intermediate phase" is used in this Handbook to denote those reaction products of two or more elements having a crystal structure different from that of any of the components.* An intermediate phase may have a restricted or extended range of homogeneity. A variable composition is obtained by a change in the numerical atomic ratios of the elements composing the phase, effected generally by atomic substitutions and infrequently by interstitial additions. In several instances, two atoms or a chain of atoms replace a single atom in a substitutional region of an intermediate phase. The crystal structures of some intermediate phases are of high symmetry (Fig. 3 to 5) but most are complex arrangements.

A substitutional solid solution ordinarily exhibits a random or disordered distribution of the solute and solvent atoms in the solvent cells. However, some solid solutions, when slowly cooled or annealed at low temperatures, possess definite ordered positions of both types of atom in the solvent space lattice (superstructure). This re-sorting of atoms may occur in a solid solution when two elements, A and B, exist in concentrations approximately represented by the formulas AB and A_3B, such as AuCu, $AuCu_3$, $PdCu_3$. Also intermediate phases, having a variable composition in the range of the same atomic proportions as above, may experience an order-disorder change, as the β phase, CuZn.

It would appear that the ordered distribution is the stable condition at low temperatures in the susceptible composition. At high temperatures, where the alloy is less rigid, thermal movements tend to shuffle the atoms into random positions. The transition is not so abrupt as transformations involving a lattice change, but is gradual, so that many intermediate stages may be encountered. X-ray methods can follow the process accurately in either direction, since the ordered atoms give diffraction effects in addition to the reflections from the parent lattice.

* In a few systems, intermediate phases have the same type of structure as a component but appreciably different parameters.

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The Interconversion of Atomic and Weight Percentages

By Cyril Stanley Smith*

THOUGH alloys are compounded and analyzed by weight, the research metallurgist frequently needs to know the relative proportion of atoms in an alloy. The conversion for binary alloys is done by means of the following formulas:

$$y = \frac{100\,\frac{x}{A}}{\frac{x}{A} + \frac{100 - x}{B}}; \qquad x = \frac{100\,yA}{yA + (100 - y)B}, \qquad (1)$$

where x and y are the percentages by weight and by atoms, respectively, of the element that has atomic weight A in a binary alloy with another element that has atomic weight B. The following rearrangement of these equations is easier to use:

$$y = \frac{100x}{x + \frac{A}{B}(100 - x)}; \qquad x = \frac{100y}{y + \frac{B}{A}(100 - y)}. \qquad (2)$$

The relation can be expressed also as a function of the ratio of the amounts of the two elements, because the ratio by weight is merely the ratio by atoms multiplied by the ratio of atomic weights, that is

$$\frac{x}{100 - x} = \frac{A}{B}\left(\frac{y}{100 - y}\right). \qquad (3)$$

By the use of a table of $f(x) = \log\left(\frac{x}{100 - x}\right) + 10$ and a table of log (A/B), the multiplication becomes simple addition just as in the use of ordinary logarithm tables. Such tables are given herewith.*

Use of the Tables.

1 First look up in Table I the value of log $\frac{\text{at. wt } A}{\text{at. wt } B}$ for the two components concerned. A is the element whose percentage is to be converted; B is the other, usually major, component. If the system is not represented in Table I, compute the figure from known atomic weights.

2 Find from Table II or III the value of $f(x)$ corresponding to the percentage figure (either atomic or weight per cent) that it is desired to convert.

3 If conversion is from *atomic* to weight per cent, *add* the two values. The resulting value of $f(x)$ corresponds to the desired weight percentage, which is found by consulting Table II or III again.

4 If conversion is from *weight* to atomic per cent, *subtract* log (A/B) to obtain a new value of $f(x)$ corresponding to the desired atomic percentage.

Conversion of Small Percentages. Small percentages may be converted by using the approximate formula $y = (B/A)x$. Sometimes it is simpler to use a correction factor $x[(B/A) - 1]$ to add to the weight percentage to obtain the atomic equivalent directly. Neither method should be used for percentages greater than about 0.3% except when the value of (A/B) is close to 1.

Conversions When Components Do Not Differ Greatly in Atomic Weight. A simple method due to Marsh [Metals and Alloys, 5, 48 (1934)] employs a correction curve to give a number to be added to the weight percentage to obtain the atomic percentage directly without multiplication. This is useful when the elements concerned do not differ much in atomic weight, systems such as Fe-V, Fe-Cr, Fe-Mn, Fe-Co, Fe-Ni, Cu-Zn, Ag-Cd, Pt-Au, Pt-Ir or Pb-Bi.

Conversions in Ternary Systems. Tables I, II and III cannot be used for ternary systems. Where great accuracy

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* Tables I and II and Fig. 1 are reprinted by permission of the American Institute of Mining and Metallurgical Engineers. Table III was prepared by the Computation Section of the Los Alamos Laboratory, Manhattan District. Further discussion of the principles involved in the conversions, will be found in AIME Contribution 60 (1933).

is not required, the graphical method described below may be used. On the triangle representing the composition of the system in the usual way, draw two lines from the corner representing the element of highest atomic weight (point C, Fig. 1) to two points (B', A') on the opposite side, located accurately so that, in Fig. 1, $\frac{AB'}{AB} = \frac{\text{at. wt } B}{\text{at. wt } C}$ and $\frac{BA'}{BA} = \frac{\text{at. wt } A}{\text{at. wt } C}$.

A line from point A then divides CB and CB' each into parts the ratio of which differs in the ratio of the distance of the intercepts from point A, and hence represents graphically equation 3 above.* This is true regardless of the relation among points C, B and A, but it is convenient to select these as the corners of the equilateral composition triangle.

A line $Apde$ (Fig. 1) passing through point p on the weight percentage scale, represents all binary alloys whose ratio of B to C is the same as at point p, and is given by point e on the binary side, BC. Point d represents the atomic ratio corresponding to this (more correctly, Cd/dB' is the desired ratio but the co-ordinates of the point d are exactly proportional to this). This is transferred to the

* This construction is useful in binary systems, but the accuracy obtainable is far less than by the use of the tables.

Table I. Values of Log Atomic Weight Ratios*

	Element B*																	
At. No.	12	13	24	25	26	27	28	29	30	47	48	50	51	78	79	80	82	83
Symbol	Mg	Al	Cr	Mn	Fe	Co	Ni	Cu*	Zn	Ag	Cd	Sn	Sb	Pt	Au	Hg	Pb	Bi
At. Wt.	24.32	26.97	52.01	54.93	55.84	58.94	58.69	63.57	65.38	107.88	112.41	118.70	121.76	195.23	197.2	200.61	207.22	209.00
Log At. Wt.....	1.3860	1.4309	1.7161	1.7398	1.7470	1.7704	1.7686	1.8033	1.8154	2.0329	2.0508	2.0745	2.0855	2.2905	2.2949	2.3024	2.3164	2.3202
Element A* At. No.	Symbol																	
1	H	$\bar{2}$.6174	$\bar{2}$.5725	$\bar{2}$.2873	$\bar{2}$.2636	$\bar{2}$.2564	$\bar{2}$.2330	$\bar{2}$.2348	$\bar{2}$.2001	$\bar{2}$.1888	$\bar{3}$.9704	$\bar{3}$.9526	$\bar{3}$.9289	$\bar{3}$.9179	$\bar{3}$.7128	$\bar{3}$.7085	$\bar{3}$.7010	$\bar{3}$.6869	$\bar{3}$.6832
3	Li	$\bar{1}$.4554	$\bar{1}$.4105	$\bar{1}$.1353	$\bar{1}$.1016	$\bar{1}$.0944	$\bar{1}$.0710	$\bar{1}$.0728	$\bar{1}$.0388	$\bar{1}$.0259	$\bar{2}$.8984	$\bar{2}$.7906	$\bar{2}$.7669	$\bar{2}$.7559	$\bar{2}$.5508	$\bar{2}$.5465	$\bar{2}$.5390	$\bar{2}$.5249	$\bar{2}$.5212
4	Be	5693	5243	2391	2154	2083	1848	1867	1520	1398	9223	9044	8808	8697	6647	6603	6529	6388	6351
5	B	$\bar{1}$.6483	$\bar{1}$.6034	$\bar{1}$.3181	$\bar{1}$.2944	$\bar{1}$.2873	$\bar{1}$.2638	$\bar{1}$.2657	$\bar{1}$.2310	$\bar{1}$.2188	$\bar{1}$.0013	$\bar{2}$.9834	$\bar{2}$.9598	$\bar{2}$.9487	$\bar{2}$.7437	$\bar{2}$.7393	$\bar{2}$.7319	$\bar{2}$.7178	$\bar{2}$.7141
6	C	6932	6483	3631	3394	3322	3088	3106	2759	2637	0462	1.0284	1.0047	9937	7886	7843	7768	7628	7590
7	N	7604	7155	4303	4066	3994	3760	3778	3431	3309	1134	0956	0719	$\bar{1}$.0609	8558	8515	8440	8300	8262
8	O	$\bar{1}$.8182	$\bar{1}$.7732	$\bar{1}$.4880	$\bar{1}$.4643	$\bar{1}$.4572	$\bar{1}$.4337	$\bar{1}$.4356	$\bar{1}$.4009	$\bar{1}$.3887	$\bar{1}$.1712	$\bar{1}$.1533	$\bar{1}$.1297	$\bar{1}$.1186	$\bar{2}$.9136	$\bar{2}$.9092	$\bar{2}$.9018	$\bar{2}$.8877	$\bar{2}$.8840
11	Na	9757	9308	6456	6219	6147	5913	5931	5584	5462	3287	3109	2872	2762	1.0711	1.0668	1.0593	1.0452	1.0415
12	Mg	0.0000	9551	6799	6462	6390	6156	6174	5827	5705	3530	3352	3115	3005	0955	0911	0836	0695	0658
13	Al	0.0449	0.0000	$\bar{1}$.7248	$\bar{1}$.6911	$\bar{1}$.6839	$\bar{1}$.6605	$\bar{1}$.6623	$\bar{1}$.6276	$\bar{1}$.6154	$\bar{1}$.3979	$\bar{1}$.3801	$\bar{1}$.3564	$\bar{1}$.3454	$\bar{1}$.1403	$\bar{1}$.1360	$\bar{1}$.1285	$\bar{1}$.1145	$\bar{1}$.1107
14	Si	0621	0172	7320	7083	7011	6777	6795	6448	6327	4152	3973	3736	3626	1576	1532	1457	1317	1279
15	P	1057	0608	7756	7518	7447	7212	7231	6884	6762	4587	4408	4172	4061	2011	1967	1893	1752	1715
16	S	0.1200	0.0751	$\bar{1}$.7899	$\bar{1}$.7662	$\bar{1}$.7590	$\bar{1}$.7356	$\bar{1}$.7374	$\bar{1}$.7027	$\bar{1}$.6905	$\bar{1}$.4730	$\bar{1}$.4552	$\bar{1}$.4315	$\bar{1}$.4205	$\bar{1}$.2154	$\bar{1}$.2111	$\bar{1}$.2036	$\bar{1}$.1895	$\bar{1}$.1858
20	Ca	2170	1721	8868	8631	8560	8325	8344	7997	7875	5700	5521	5285	5174	3124	3080	3006	2865	2828
22	Ti	2944	2495	9643	9405	9334	9099	9118	8771	8649	6474	6295	6059	5948	3898	3854	3780	3639	3602
23	V	0.3212	0.2763	$\bar{1}$.9911	$\bar{1}$.9673	$\bar{1}$.9602	$\bar{1}$.9367	$\bar{1}$.9386	$\bar{1}$.9039	$\bar{1}$.8917	$\bar{1}$.6742	$\bar{1}$.6563	$\bar{1}$.6327	$\bar{1}$.6216	$\bar{1}$.4166	$\bar{1}$.4122	$\bar{1}$.4048	$\bar{1}$.3907	$\bar{1}$.3870
24	Cr	3301	2852	0.0000	9763	9691	9457	9475	9128	9007	6832	6653	6416	6306	4256	4212	4137	3997	3959
25	Mn	3539	3089	0237	0.0000	9929	9694	9713	9366	9244	7069	6890	6654	6543	4493	4450	4375	4234	4197
26	Fe	0.3610	0.3161	0.0309	0.0071	0.0000	$\bar{1}$.9765	$\bar{1}$.9784	$\bar{1}$.9437	$\bar{1}$.9315	$\bar{1}$.7140	$\bar{1}$.6961	$\bar{1}$.6725	$\bar{1}$.6614	$\bar{1}$.4564	$\bar{1}$.4520	$\bar{1}$.4446	$\bar{1}$.4305	$\bar{1}$.4268
27	Co	3845	3395	0543	0306	0235	0.0000	0.0019	9672	9550	7375	7196	6960	6849	4798	4755	4681	4540	4503
28	Ni	3826	3377	0525	0288	0216	$\bar{1}$.9982	0000	9653	9531	7356	7178	6941	6831	4780	4337	4662	4521	4484
29	Cu*	0.4173	0.3724	0.0872	0.0634	0.0563	0.0328	0.0347	0.0000	$\bar{1}$.9878	$\bar{1}$.7703	$\bar{1}$.7524	$\bar{1}$.7288	$\bar{1}$.7177	$\bar{1}$.5127	$\bar{1}$.5083	$\bar{1}$.5009	$\bar{1}$.4868	$\bar{1}$.4831
30	Zn	4295	3846	0994	0756	0685	0450	0469	0122	0.0000	7825	7646	7410	7299	5249	5205	5131	4990	4953
33	As	4887	4438	1586	1349	1277	1043	1061	0714	0592	8417	8239	8002	7892	5841	5798	5723	5582	5545
34	Se	0.5128	0.4679	0.1826	0.1589	0.1518	0.1283	0.1302	0.0955	0.0833	$\bar{1}$.8658	$\bar{1}$.8479	$\bar{1}$.8243	$\bar{1}$.8132	$\bar{1}$.6082	$\bar{1}$.6038	$\bar{1}$.5964	$\bar{1}$.5823	$\bar{1}$.5786
40	Zr	5741	5292	2440	2203	2131	1897	1915	1568	1447	9272	9093	8856	8746	6696	6652	6577	6437	6399
42	Mo	5963	5514	2662	2425	2353	2119	2137	1790	1668	9493	9315	9078	8968	6917	6874	6799	6658	6621
45	Rh	0.6265	0.5816	0.3024	0.2727	0.2655	0.2421	0.2439	0.2092	0.1970	$\bar{1}$.9795	$\bar{1}$.9617	$\bar{1}$.9380	$\bar{1}$.9270	$\bar{1}$.7219	$\bar{1}$.7176	$\bar{1}$.7101	$\bar{1}$.6960	$\bar{1}$.6923
46	Pd	6422	5973	3121	2884	2812	2578	2596	2249	2127	9952	9774	9537	9427	7376	7333	7258	7117	7080
47	Ag	6470	6021	3169	2931	2860	2625	2644	2297	2175	0.0000	9821	9585	9474	7424	7380	7306	7165	7128
48	Cd	0.6649	0.6199	0.3347	0.3110	0.3039	0.2804	0.2823	0.2476	0.2354	0.0179	0.0000	$\bar{1}$.9764	$\bar{1}$.9653	$\bar{1}$.7603	$\bar{1}$.7559	$\bar{1}$.7485	$\bar{1}$.7344	$\bar{1}$.7307
50	Sn	6885	6436	3584	3346	3275	3040	3059	2712	2590	0415	0236	0.0000	9889	7839	7795	7721	7580	7543
51	Sb	6996	6546	3694	3457	3386	3151	3170	2823	2701	0526	0347	0111	0.0000	7950	7906	7832	7691	7654
52	Te	0.7196	0.6746	0.3894	0.3657	0.3586	0.3351	0.3370	0.3023	0.2901	0.0726	0.0547	0.0311	0.0200	$\bar{1}$.8150	$\bar{1}$.8106	$\bar{1}$.8032	$\bar{1}$.7891	$\bar{1}$.7854
56	Ba	7519	7070	4218	3981	3909	3675	3693	3346	3224	1049	0871	0634	0524	8473	8430	8355	8214	8177
58	Ce	7606	7157	4304	4067	3996	3761	3780	3433	3311	1136	0957	0721	0610	8560	8516	8442	8301	8264
73	Ta	0.8727	0.8278	0.5426	0.5188	0.5117	0.4882	0.4901	0.4554	0.4432	0.2257	0.2078	0.1842	0.1731	$\bar{1}$.9681	$\bar{1}$.9637	$\bar{1}$.9563	$\bar{1}$.9422	$\bar{1}$.9385
74	W	8789	8339	5487	5250	5179	4944	4963	4616	4494	2319	2140	1904	1793	9743	9699	9625	9484	9447
77	Ir	8998	8549	5697	5460	5388	5154	5172	4825	4703	2528	2350	2113	2003	9952	9909	9834	9694	9656
78	Pt	0.9046	0.8597	0.5745	0.5507	0.5436	0.5201	0.5220	0.4873	0.4751	0.2576	0.2397	0.2161	0.2050	0.0000	$\bar{1}$.9956	$\bar{1}$.9882	$\bar{1}$.9741	$\bar{1}$.9704
79	Au	9090	8640	5788	5551	5480	5245	5264	4817	4795	2620	2441	2205	2094	0044	0.0000	9926	9785	9748
80	Hg	9164	8715	5863	5625	5554	5319	5338	4991	4869	2694	2515	2279	2168	0118	0074	0.0000	9859	9822
82	Pb	0.9305	0.8856	0.6003	0.5766	0.5695	0.5460	0.5479	0.5132	0.5010	0.2835	0.2656	0.2420	0.2309	0.0259	0.0215	0.0141	0.0000	$\bar{1}$.9963
83	Bi	9342	8893	6041	5803	5732	5497	5516	5169	5047	2872	2693	2457	2346	0296	0252	0178	0037	0.0000

*A is the element whose percentage, either weight or atomic, is being converted; B is the other component, usually the major one.

*Editor's Note: Since the proof of this article was read, the Committee on Atomic Weights of the International Union of Chemistry has accepted 63.54 as the atomic weight of copper [J Am Chem Soc, 69, 731 (1947)]. The values in this table are based on the previously accepted atomic weight of 63.57 for copper. This can be corrected for by adding 0.0003 to all values in the copper column of the table.

Table II. Values of Log $\frac{x}{100-x} + 10$

x	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
See Table III for $x = 0.01$ to 4.99.										
5	8.7212	7303	7392	7479	7565	7649	7732	7814	7894	7973
6	8050	8127	8202	8276	8349	8421	8492	8562	8631	8699
7	8766	8832	8898	8962	9026	9089	9151	9213	9274	9334
8	9393	9452	9510	9567	9624	9680	9736	9791	9845	9899
9	9952	0005	0057	0109	0160	0211	0261	0311	0360	0409
10	9.0458	0506	0553	0600	0647	0694	0740	0785	0831	0876
11	0920	0964	1008	1052	1095	1138	1180	1222	1264	1306
12	1347	1388	1429	1469	1509	1549	1589	1628	1667	1706
13	1744	1783	1821	1858	1896	1933	1970	2007	2044	2080
14	2116	2152	2188	2224	2259	2294	2329	2364	2398	2433
15	9.2467	2501	2534	2568	2602	2635	2668	2701	2734	2766
16	2798	2831	2863	2895	2926	2958	2989	3021	3052	3083
17	3114	3145	3175	3205	3236	3266	3296	3326	3356	3385
18	3415	3444	3473	3502	3531	3560	3589	3618	3646	3674
19	3703	3731	3759	3787	3815	3842	3870	3898	3925	3952
20	9.3979	4007	4034	4060	4087	4114	4141	4167	4193	4220
21	4246	4272	4298	4324	4350	4376	4401	4427	4453	4478
22	4503	4529	4554	4579	4604	4629	4654	4679	4703	4728
23	4752	4777	4801	4826	4850	4874	4898	4922	4946	4970
24	4994	5018	5042	5065	5089	5112	5136	5159	5182	5206
25	9.5229	5252	5275	5298	5321	5344	5367	5389	5412	5435
26	5457	5480	5502	5525	5547	5570	5592	5614	5636	5658
27	5680	5702	5724	5746	5768	5790	5812	5833	5855	5877
28	5898	5920	5941	5963	5984	6005	6027	6048	6069	6090
29	6111	6132	6154	6175	6196	6216	6237	6258	6279	6300
30	9.6320	6341	6362	6382	6403	6423	6444	6464	6484	6505
31	6525	6545	6566	6586	6606	6626	6646	6666	6686	6706
32	6726	6746	6766	6786	6806	6826	6846	6865	6885	6905
33	6924	6944	6964	6983	7003	7022	7042	7061	7081	7100
34	7119	7139	7158	7177	7197	7216	7235	7254	7273	7293
35	9.7312	7331	7350	7369	7388	7407	7426	7445	7463	7482
36	7501	7520	7539	7558	7576	7595	7614	7633	7651	7670
37	7689	7707	7726	7744	7763	7781	7800	7819	7837	7856
38	7874	7892	7911	7929	7948	7966	7984	8003	8021	8039
39	8057	8076	8094	8112	8130	8148	8167	8185	8203	8221
40	9.8239	8257	8275	8293	8311	8329	8347	8365	8383	8401
41	8419	8437	8455	8473	8491	8509	8527	8545	8563	8580
42	8598	8616	8634	8652	8670	8687	8705	8723	8741	8758
43	8776	8794	8811	8829	8847	8864	8882	8900	8917	8935
44	8953	8970	8988	9005	9023	9041	9058	9076	9093	9111
45	9.9129	9146	9164	9181	9199	9216	9234	9251	9269	9286
46	9304	9321	9339	9356	9374	9391	9409	9426	9443	9461
47	9478	9496	9513	9531	9548	9565	9583	9600	9618	9635
48	9652	9670	9687	9705	9722	9739	9757	9774	9792	9809
49	9826	9844	9861	9878	9896	9913	9931	9948	9965	9983

x	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
50	10.0000	0017	0035	0052	0070	0087	0104	0122	0139	0156
51	0174	0191	0209	0226	0243	0261	0278	0295	0313	0330
52	0348	0365	0382	0400	0417	0435	0452	0470	0487	0504
53	0522	0539	0557	0574	0592	0609	0626	0644	0661	0679
54	0696	0714	0731	0749	0766	0784	0801	0819	0836	0854
55	10.0872	0889	0907	0924	0942	0959	0977	0995	1012	1030
56	1047	1065	1083	1100	1118	1136	1153	1171	1189	1206
57	1224	1242	1260	1277	1295	1313	1331	1348	1366	1384
58	1402	1420	1437	1455	1473	1491	1509	1527	1545	1563
59	1581	1599	1617	1635	1653	1671	1689	1707	1725	1743
60	10.1761	1779	1797	1815	1833	1852	1870	1888	1906	1924
61	1943	1961	1979	1998	2016	2034	2053	2071	2089	2108
62	2126	2145	2163	2182	2200	2219	2237	2256	2274	2293
63	2311	2330	2349	2367	2386	2405	2424	2442	2461	2480
64	2499	2518	2537	2555	2574	2593	2612	2631	2650	2669
65	10.2688	2708	2727	2746	2765	2784	2803	2823	2842	2861
66	2881	2900	2919	2939	2958	2978	2997	3017	3036	3056
67	3076	3095	3115	3135	3154	3174	3194	3214	3234	3254
68	3274	3294	3314	3334	3354	3374	3394	3414	3434	3455
69	3475	3495	3516	3536	3556	3577	3597	3618	3639	3659
70	10.3680	3701	3721	3742	3763	3784	3805	3826	3847	3868
71	3889	3910	3931	3952	3973	3995	4016	4037	4059	4080
72	4102	4123	4145	4167	4188	4210	4232	4254	4276	4298
73	4320	4342	4364	4386	4408	4430	4453	4475	4498	4520
74	4543	4565	4588	4611	4633	4656	4679	4702	4725	4748
75	10.4771	4794	4818	4841	4864	4888	4911	4935	4959	4982
76	5006	5030	5054	5078	5102	5126	5150	5174	5199	5223
77	5248	5272	5297	5322	5346	5371	5396	5421	5446	5472
78	5497	5522	5548	5573	5599	5624	5650	5676	5702	5728
79	5754	5780	5807	5833	5860	5886	5913	5940	5967	5994
80	10.6021	6048	6075	6103	6130	6158	6185	6213	6241	6269
81	6297	6326	6354	6383	6411	6440	6469	6498	6527	6556
82	6585	6615	6645	6674	6704	6734	6764	6795	6825	6856
83	6886	6917	6948	6979	7011	7042	7074	7105	7137	7169
84	7202	7234	7267	7299	7332	7365	7398	7432	7466	7499
85	10.7533	7567	7602	7636	7671	7706	7741	7776	7812	7848
86	7884	7920	7956	7993	8030	8067	8104	8142	8180	8218
87	8256	8294	8333	8372	8411	8451	8491	8531	8571	8612
88	8653	8694	8736	8778	8820	8862	8905	8948	8992	9036
89	9080	9124	9169	9215	9260	9306	9353	9400	9447	9494
90	10.9542	9591	9640	9689	9739	9789	9840	9891	9943	9995
91	11.0048	0101	0155	0210	0265	0320	0376	0433	0490	0548
92	0607	0666	0726	0787	0849	0911	0974	1038	1102	1168
93	1234	1301	1369	1438	1508	1579	1651	1724	1798	1873
94	1950	2027	2106	2186	2268	2351	2435	2521	2608	2697

Subtract value of log (A/B) when converting from weight to atomic percentage.
Add value of log (A/B) when converting from atomic to weight percentage.

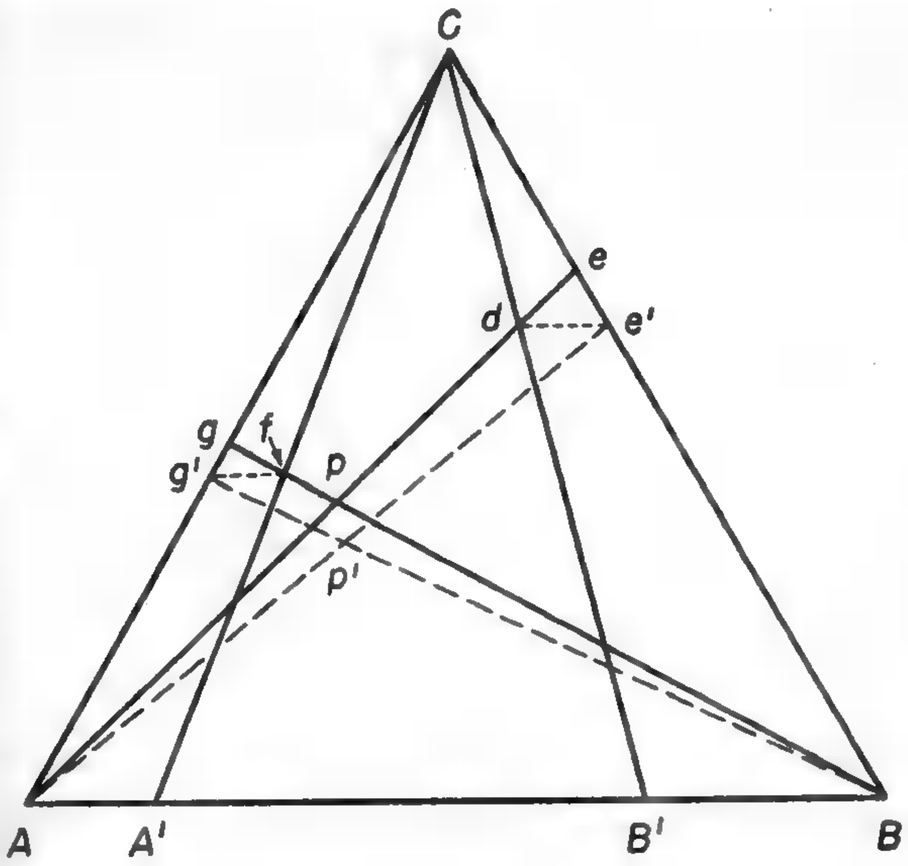
Table III. Values of Log $\frac{x}{100-x} + 10$

x	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	∞	6.0000	3011	4772	6022	6992	7784	8454	9034	9546
.1	7.0004	7.0419	0797	1145	1467	1767	2048	2312	2560	2796
.2	3019	3231	3434	3627	3812	3990	4161	4325	4484	4637
.3	4784	4927	5065	5200	5330	5456	5579	5698	5814	5928
.4	6038	6146	6251	6353	6454	6552	6648	6742	6833	6923
0.5	7.7012	7.7098	7183	7266	7347	7428	7506	7584	7660	7734
.6	7808	7880	7951	8021	8090	8157	8224	8290	8355	8419
.7	8482	8544	8605	8665	8725	8783	8841	8899	8955	9011
.8	9066	9120	9174	9227	9279	9331	9382	9433	9483	9534
.9	9582	9630	9678	9725	9772	9819	9865	9910	9955	0000
1.0	8.0044	8.0087	0130	0173	0216	0258	0299	0340	0371	0422
.1	0462	0502	0541	0580	0619	0657	0695	0733	0770	0808
.2	0844	0881	0917	0953	0988	1024	1059	1094	1128	1162
.3	1196	1230	1263	1297	1330	1362	1395	1427	1459	1491
.4	1522	1554	1585	1616	1647	1677	1707	1738	1767	1797
1.5	8.1826	8.1856	1885	1914	1943	1971	2000	2028	2056	2084
.6	2111	2139	2166	2193	2220	2247	2274	2300	2327	2353
.7	2379	2405	2431	2456	2482	2507	2532	2557	2582	2607
.8	2632	2656	2680	2705	2729	2753	2777	2800	2824	2848
.9	2871	2894	2917	2940	2963	2986	3009	3031	3054	3076
2.0	8.3098	8.3120	3142	3164	3186	3208	3229	3250	3272	3293
.1	3314	3335	3356	3377	3398	3419	3439	3460	3480	3501
.2	3521	3541	3561	3581	3601	3621	3640	3660	3680	3699
.3	3718	3738	3757	3776	3795	3814	3833	3852	3870	3889
.4	3908	3926	3945	3963	3981	3999	4018	4036	4054	4072

x	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
2.5	8.4089	8.4107	4125	4142	4160	4178	4195	4212	4230	4247
.6	4264	4281	4298	4315	4332	4349	4366	4383	4399	4416
.7	4432	4449	4466	4482	4498	4514	4531	4547	4563	4579
.8	4595	4611	4627	4643	4658	4674	4690	4705	4721	4736
.9	4752	4767	4782	4798	4813	4828	4843	4858	4874	4888
3.0	8.4904	8.4918	4933	4948	4963	4978	4992	5007	5021	5036
.1	5050	5065	5079	5094	5108	5122	5136	5150	5165	5179
.2	5193	5207	5221	5235	5248	5262	5276	5290	5304	5317
.3	5331	5344	5358	5372	5385	5398	5402	5425	5438	5452
.4	5465	5478	5491	5504	5518	5531	5544	5557	5570	5583
3.5	8.5595	8.56■8	5621	5634	5646	5659	5672	5685	5697	5710
.6	5722	5735	5747	5760	5772	5784	5797	5809	5821	5834
.7	5846	5858	5870	5882	5894	5906	5918	5930	5942	5954
.8	5966	5978	5990	6002	6013	6025	6037	6048	6060	6072
.9	6083	6095	6107	6118	6130	6141	6152	6164	6175	6186
4.0	8.6198	8.6209	6220	6232	6243	6254	6265	6276	6288	6299
.1	6310	6321	6332	6343	6354	6365	6375	6386	6397	6408
.2	6419	6430	6440	6451	6462	6472	6483	6494	6504	6515
.3	6526	6536	6547	6557	6568	6578	6588	6599	6609	6620
.4	6630	6640	6650	6661	6671	6681	6691	6702	6712	6722
4.5	8.6732	8.6742	6752	6762	6772	6782	6792	6802	6812	6822
.6	6832	6842	6852	6862	6872	6881	6891	6901	6911	6920
.7	6930	6940	6949	6959	6969	6978	6988	6998	7007	7017
.8	7026	7036	7045	7054	7064	7073	7083	7092	7102	7111
.9	7120	7130	7139	7148	7157	7167	7176	7185	7194	7203

side of the standard equilateral triangle as point e' by drawing a line parallel to the triangle base. A new line joining e' to A then represents all alloys of the correct ratio of atoms B and C. A similar construction on the opposite side, using CA and CA', converts the line $Bpfg$ to the corresponding line $Bp'g'$ representing the atomic ratio, and the intersection, p', is the desired point corresponding to p, but in atomic instead of weight percentage.

In practice, using triangular co-ordinate paper, the lines CB' and CA' are established and drawn once and for all, while point d is found by a straight edge and transferred by eye to e', where a point is marked. Enough of the line $ap'e'$ is drawn to ensure an intersection. Similarly point g'



is found and marked; then p' is found and finally marked.

Though Fig. 1 shows the conversion in an equilateral triangle, and operation with an element common to both ratio lines, it is equally satisfactory to have points A' and B' *outside* the triangle, to use point A or B in place of C for one or both of the ratio lines, and to use an isosceles triangle where a larger scale is needed for one component. Just the base of such a triangle may be used and only the requisite portion of the lines CA' and CB' need be drawn.

Conversions of Volume Percentages. All the above methods are applicable for conversion from or to volume percentage of any elements or phases whose density is known. This is most useful in two-phase mixtures where the weight and densities of the component phases, not the elements, are used. In binary mixtures, compute the value of $\log \frac{\text{density } A}{\text{density } B}$ and use it in conjunction with Table II in exactly the same manner as the value of log (A/B) when converting between atomic and weight percentages—*subtracting* from the appropriate value of $f(x)$ if converting from weight to volume percentage, and *adding* if converting from volume to weight percentage.

Fig. 1 Conventional equilateral triangle of composition for a ternary system, showing constructions necessary for the graphical interconversion of atomic and weight percentages. See text for explanation.

Fluidity of Metals

By Charles W. Briggs*

THE term "fluidity" refers to the property of a metal which allows it to flow freely and evenly into a mold and fill it before such freezing occurs as would offer an obstruction to its further flow. This property is sometimes referred to as "castability", "runnability", "flowing power" or "fluid life". In the past, "fluidity", the word often preferred, had a specific physical meaning; namely, the reciprocal of the coefficient of viscosity. However, in recent literature the term "coefficient of liquidity" is preferred for this constant, thus allowing the broader field to be covered by "fluidity". Many have not yet accepted the term in its new sense, believing that old associations stand in the way of its adoption; hence the terms given above are often preferred.

When fluidity is considered in its broader aspects, it should not in any sense be identified with viscosity. The viscosity of a fluid in the physical sense is concerned with movements in the interior of the liquid; thus, at a given temperature it is a definite physical constant. The viscosity test, which is rather simple and accurate at relatively low temperatures, is exceedingly difficult to perform at the higher temperatures required by molten iron and steel. Therefore it has been necessary for foundrymen to devise a simpler method for the study of fluidity. In general, this test consists of pouring molten metal into sand molds that contain a cavity in the form of a channel. The test is concerned primarily with the fluid life of the metal, and measurements refer both to the metal and to the mold.

The fluidity of metal depends on two major factors: (1) properties of the metal and (2) variables of testing. The factors relating to the metal are those of viscosity, surface tension, surface films, gas content, suspended inclusions, and the mode of solidification and crystallization. The second set of factors includes the form of the test piece, the casting head, the properties of the mold, the rate of pouring and the degree of superheat.

Properties of the Metal. *Viscosity.* There is a general belief that molten metals differ widely in viscosity and that metals that flow poorly have high viscosity. In reality the viscosity of metals is very low; the kinematic viscosity is less than that of water in all metals investigated.[2] Also, since viscosity changes only slightly with change of temperature, it is really a negligible factor in casting. Two main methods are employed in measuring viscosity. In one method liquid metal is allowed to flow under a constant head through a capillary tube; in the other, some form of torsional pendulum is used. The first method can be applied only to metals of low melting point, since the capillary tube is constructed from glass or quartz. The second method may be used at relatively high temperatures with a fair degree of success, since the apparatus consists essentially of refractory cylinders or disks suspended in the molten metal and operating in torsional oscillations. Studies of tin and lead,[3] various brasses, bronzes, copper,[4] and cast iron[5] have been undertaken by the torsional pendulum method.

A critical review of the published data on viscosity was prepared by Andrade.[6] In this he developed a new theory of the inner mechanism of the viscosity of liquids, which has enabled him to calculate η with close approximation of the experimental values for a number of metals. These are listed in Table I.

Table I. Viscosity of Certain Liquids[6]

Substance	η, poise
At atmospheric temperature	
Water	0.0105
Just above the melting point	
Mercury	0.021
Lead	0.028
Tin	0.020
Copper	0.038
Iron	0.040

It may be concluded, therefore, that the viscosity of metals is only a small multiple of that of water; and that the kinematic viscosity (or viscosity divided by density), on the basis of which may be compared the effects of stresses resulting from viscosity in modifying the existing motion of a fluid, is considerably lower than that of water. Evidently the viscosity of metals is not closely related with casting behavior, and the effects that have been attributed to viscosity are mainly from other causes.

Surface Tension. When molten metals are poured into a sand mold, the mold surface is not wetted.[7,8] The rise of steel in a narrow channel is impeded by the surface tension of the liquid metal. This effect becomes less marked as the diameter of the passage is increased.

Bircumshaw[9] has tabulated values of the surface tensions

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of some of the common metals, at temperatures not much higher than their melting points (Table II).

Table II. Surface Tension of Some Common Metals[9]

Metal	Temperature, deg Cent	Surface Tension, dynes per cm
Antimony	640	350
Bismuth	269	378
Lead	327	452
Mercury	20	465
Tin	232	526
Cadmium	320	630
Zinc	419	758
Silver	998	923
Copper	1131	1103
Gold	1120	1128
Iron (2.2% C)	1420	1500
Iron (3.9% C)	1300	1150

The deductions that may be drawn from the table above are these: (1) the surface tension of metals increases as the melting point increases; (2) from the figures for the two alloys of iron and carbon, steel has a higher surface tension than cast iron; and (3) since the surface tension of water at 20 C is only 81, the values for metals are relatively high. It has also been determined that surface tension generally diminishes as temperature increases.

A high value of surface tension has the effect of increasing the pressure required to cause the metal to enter and flow along a narrow channel, but the direct effect of the true surface tension of many metals is almost overshadowed by the effect of surface films which exert an influence equivalent to that of greatly increased surface tension.

Surface Oxide Films. It has been found that surface films affect the flowing power, especially of nonferrous alloys. In a study made on brass ingots, Genders and Bailey[10] showed that the oxidation of a stream of molten brass by contact with air creates a surface film of zinc oxide which raises the apparent surface tension of the metal, restricts the flow, and is an inevitable cause of defects in ingots.

Determinations of the apparent surface tension of oxidized and clean molten aluminum have been described by Portevin and Bastien.[11] They show that the effect of the oxide film is to increase the value nearly three times. This surface film property of aluminum also affects alloys in which it is present. According to Desch,[2] the difficulty of casting aluminum bronze is caused by the formation of a skin so tough that it hinders pouring and, when broken into fragments, is entangled in the metal, making a dirty casting. When the oxide is soluble in the molten metal, no film is formed, so copper, cast iron and nickel pour in a clean stream.

According to Greaves[12] there is evidence that strongly suggests the existence of films in an overoxidized steel killed with aluminum. Such a surface film would reduce the fluidity. A chromium-rich oxide skin is also thought to have a marked effect on the fluidity of steels.

Gas Content. In the application of data relating to the effect of surface tension in a metal flowing in a channel, one difficulty arises from the fact that the metal is often not in actual contact with the mold, but is separated from it by a thin layer of gas, either issuing from the metal or arising from the material of the mold. Gases that are given off from metal during its flow through a casting, probably increase the resistance to flow. It is also probable, however, that gas issuing from the metal tends to break up oxide films or prevent the formation of them, thus improving fluidity.

Suspended Inclusions. Solid matter in suspension causes a rapid rise in the apparent viscosity of a liquid, since suspended particles hinder flow. A liquid in which more than a small portion of particles is suspended will give a higher value than the same liquid free from particles.

Many steel foundrymen have attributed fluidity to the effect of dissolved oxides. There is no evidence to suggest that oxide in solution would in itself improve the fluidity of cast steel. It may, however, alter the surface tension or produce some effect on surface oxide films.

Solidification and Form of Crystallization. Tests on binary alloys led Portevin and Bastien[13] to formulate two laws: (1) Fluidity varies inversely with the interval of solidification. It will be greatest when the melt is homogeneous (as in pure metals, or eutectics) and least for the saturated solid solutions. (2) Fluidity depends on the crystal form of solidification and is relatively much greater when the liquid forms crystals with convex faces than when it forms dendrites. The above principles have been confirmed by other investigators.

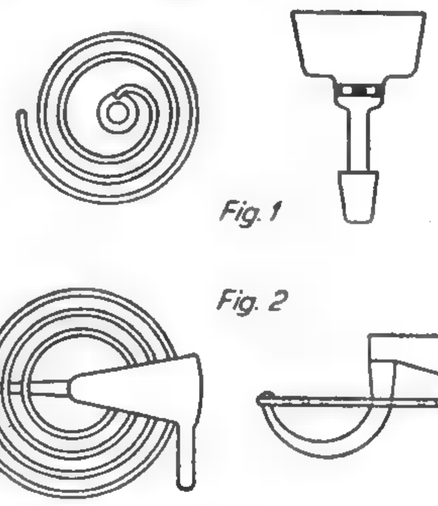


Fig. 1 European type of fluidity mold (Cury)
Fig. 2 Bureau of Standards type of fluidity mold (Saeger and Krynitsky)

Variables of Testing. *Form of the Test Specimen.* Various types of test specimens have been used to measure fluidity in the past. Unfortunately many of the investigators have adopted totally new specimens or have so altered specimens previously used that it is not possible to compare data. It appears desirable that a standard test specimen and testing procedure be devised, so that fluidity values will be more comparable.

In nearly all the tests that have been used to evaluate fluidity of molten metals, a channel of small cross-sectional area is provided, through which the molten metal is caused to flow. The channel is long enough to extract sufficient heat to cause solidification of the metal and to stop movement of the stream. The length of flow is regarded as the measure of fluidity. If a test specimen is to develop good sensitivity, it must be designed with a definite relationship among (1) the factors of force acting to drive the metal through the flow-channel, (2) the dimensions of the flow-channel, and (3) the thermal characteristics of the mold material. The flow-channel of most of the test specimens

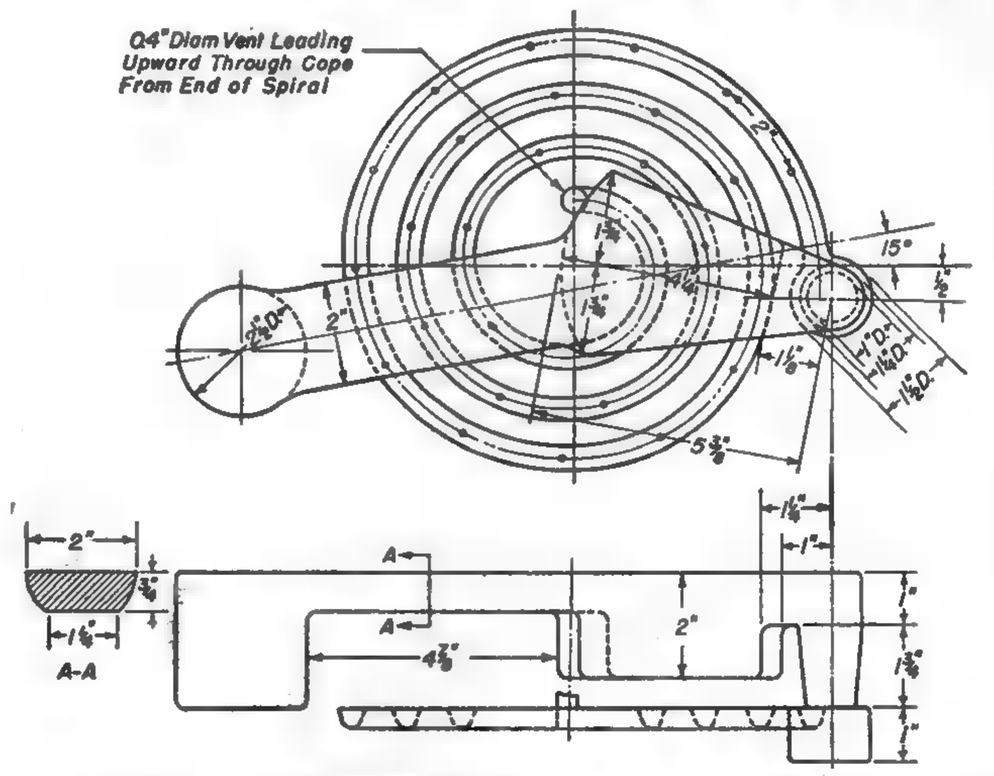


Fig. 3 Spiral piece for testing fluidity, used in U. S. Naval Research Laboratory (Taylor, Rominski and Briggs)

has been constructed in the form of a spiral (Fig. 1, 2 and 3). A straight flow-channel of short length (Ruff type,[21] Fig. 4) is also used. Studies concerning the shape and dimensions of the flow-channel indicate that the circular or half-circular and trapezoidal sections are the preferred types, since in these types a minimum surface of contact exists between the metal and mold. The cross-sectional area of the flow-channel is usually from 1/12 to 1/7 sq in.[20]

Gating Methods. The system of gating should be designed so that metal is available at the entry of the flow-channel under a constant pressure-head and without

appreciable inertia. These ideal conditions are virtually unattainable, but they must be approached as nearly as possible. Although a horngate has been used successfully in testing the fluidity of cast iron, a straight down gate is prescribed for steel and magnesium. The cross-sectional area of the sprue must be considerably larger than that of the flow-channel. A six-to-one ratio is recommended. The sprue should be short and must be filled as rapidly as possible after pouring is started.

Casting Head. One of the essential parts of the mold is the casting head and the metal reservoir. The height of these above the flow-channel affects the length of the spirals run. A reservoir must be provided to break the fall of the metal from the ladle and to supply an even flow of metal to the down gate of the mold.

Properties of the Mold. Important data have been recorded, especially for alloys melting at a low temperature; in these investigations permanent molds have been used. However, in the last few years sand molds have been used almost entirely, since for reasons of sensitivity, a mold should have the least possible tendency to chill.

Slight variations in the temperature of the mold and the state of dryness of the mold do not affect the length of the spiral obtained. The permeability of the sand should be sufficient to insure an easy escape for the gas produced by the contact of the liquid metal with the mold. The molding sand should be so bonded that the permeability is not less than 75 by the AFA permeability test.

To insure an easy escape of gas or air from the mold, the end of the spiral should be well vented. The bond strength of the sand should be sufficient to avoid erosion of the sand by the liquid metal. Mold surfaces may cause variations in the length of spiral obtained. Factors that influence the character of the results are (1) grain size of the sand, (2) mold washes and (3) surface coatings.

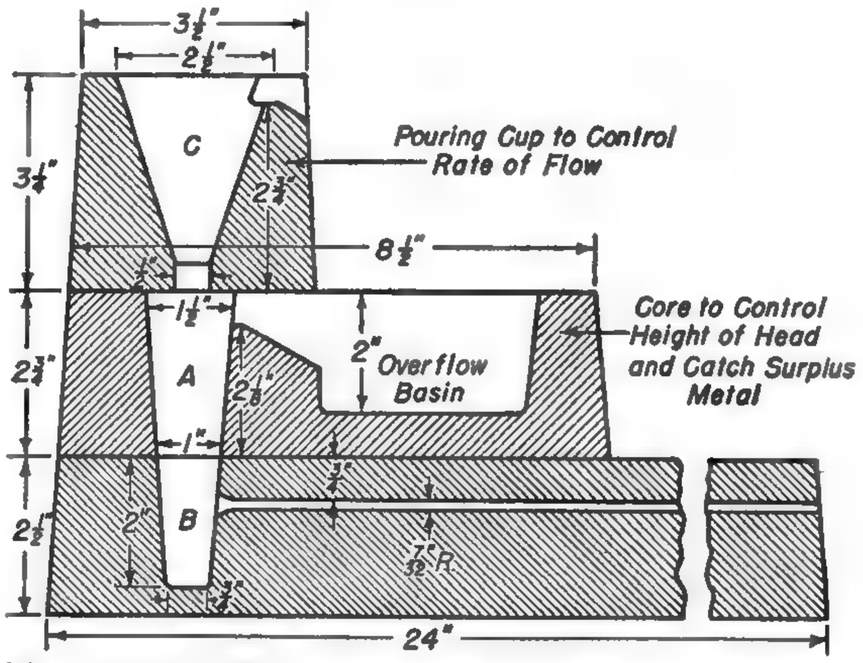


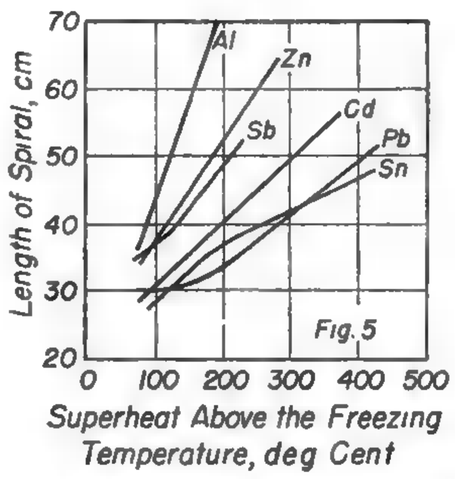
Fig. 4 Ruff's fluidity test mold having a straight flow-channel

Rate of Pouring. The length of the test specimen depends also on the speed of running the metal in the flow-channel. This speed depends, in turn, on the rate at which the mold is poured. If the pouring rate varies between one test and another, the length will vary in the same way. Therefore, exceptional care must be taken to pour all molds at the same rate (preferably a fast rate) and to insure that the pouring height above the mold is always the same.

Degree of Superheat. As the temperature of the molten metal is raised, the length of the resulting cast flow-channel is increased. An increased length of flow-channel with increase of casting temperature does not necessarily imply that the metal is more fluid at the higher temperatures, since the additional spiral length may result entirely from the increased ranges of temperature, through which the metal cools while it is flowing in the flow-channel. It should also be emphasized, however, that the degree of superheat may alter the composition of the metal or increase surface oxide films or gas content so much that the channel length is affected.

There is some tentative evidence[22] which indicates that many alloys have approximately equal fluidity when heated an equal amount above their liquidus temperatures.

Accuracy of Test Methods. Before proceeding to the results that have been obtained by testing methods, it is necessary to emphasize that it is difficult to establish a correlation between these tests and actual foundry experience unless numerous tests are made under foundry conditions. In fact, little correlation has been established to date. The probable reason for not establishing better correlation is that the test methods are inadequate, involving so many factors that it is impossible to avoid erratic and meaningless results unless extreme care is used. Also there is no one standard test method.



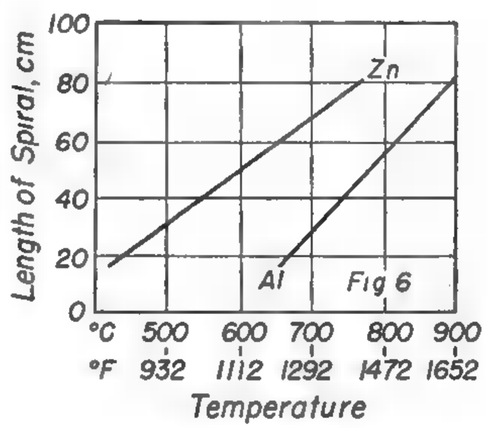
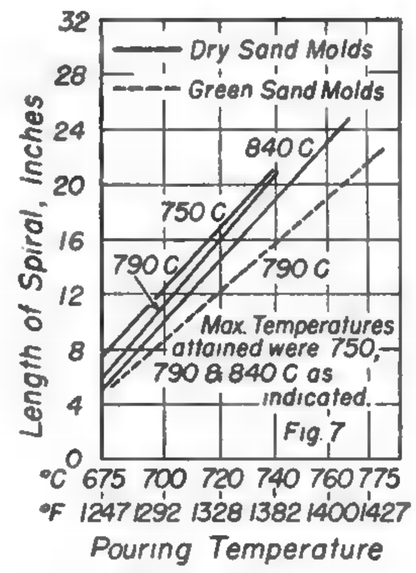


Fig. 5 Fluidity of metals that have low melting points; cast in permanent molds; spiral cross-section area, 0.170 sq in. (Portevin and Bastien)
Fig. 6 Fluidity of zinc and aluminum cast in permanent molds (Portevin)

Fluidity of Metals With Low Melting Temperature. Most of the experimental work on the fluidity of metals with low melting temperature has been carried on by Portevin and Bastien,[13] using a permanent mold. The data, as set forth in Fig. 5, are complete and are plotted so that fluidity values can be correctly evaluated. In Fig. 6 the curves for zinc and aluminum are plotted directly against the temperature and offer conditions comparable with those set forth in Fig. 5.

A few studies have been carried on, using aluminum in sand molds. The results of Saeger and Krynitsky[14] (Fig. 7) are typical of what may be expected of commercial aluminum. These authors studied the effect of various maximum temperatures on the fluidity and explain the decrease in fluidity, accompanying increase in heating temperature, as caused by absorbed gas.



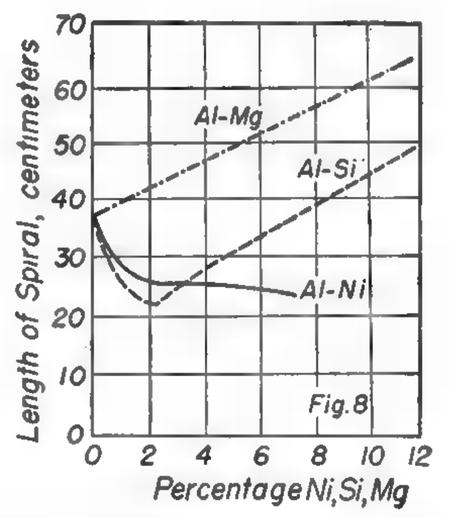


Fig. 7 Fluidity of commercial aluminum cast in a sand mold—spiral cross section, 0.066 sq in. (Saeger and Krynitsky)
Fig. 8 Effect of alloying elements on the fluidity of aluminum cast in permanent mold (Portevin)

The effect that alloy additions have on the fluidity of aluminum is shown in Fig. 8. It may be noted from this

Table III. Relative Fluidity of Some Aluminum Alloys[23]

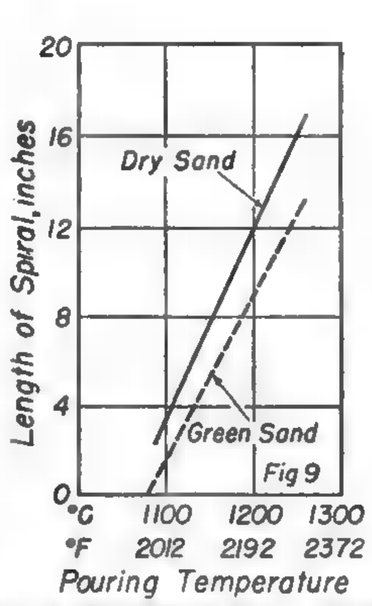
Alloying Element, percentage		Relative Fluidity[a] At 1350 F	At 1450 F
5	Si	100	100
10	Cu	103	103
3.75	Mg	77	92
3.75	Mg, 1.0 Si	93	99
4.3	Cu	87	92
6	Mg, 1 Mn, 1.5 Ni	103	110

(a) The 5% Si alloy is generally recognized as a fluid alloy and its fluidity was taken as 100. Cross section of spiral flow-channel, 0.11 sq in.

figure that the addition of some metals—for instance, nickel—brings about a drop in the fluidity; others may act as magnesium does to increase fluidity; and still others, such as silicon, may first decrease and then increase the fluidity.

Other information on the effect of alloying elements on the fluidity of aluminum is shown in Table III.

The Fluidity of Brass and Bronze. Using the Bureau of Standards mold that they had devised, with a spiral cross section of 0.066 sq in., Saeger and Krynitsky[14] studied the fluidity of brass, Fig. 9. They obtained a straight-line



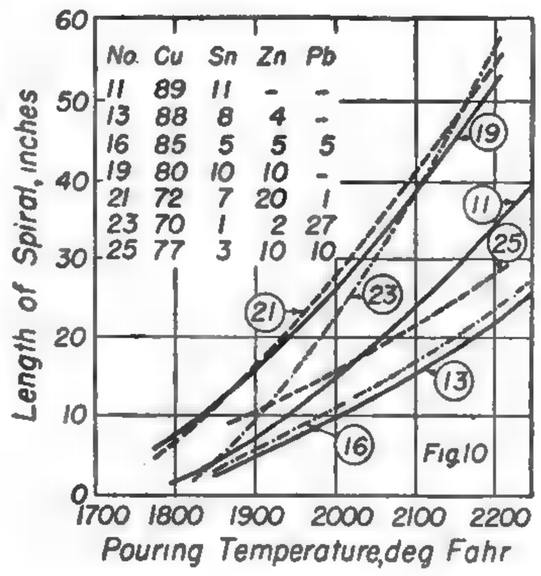
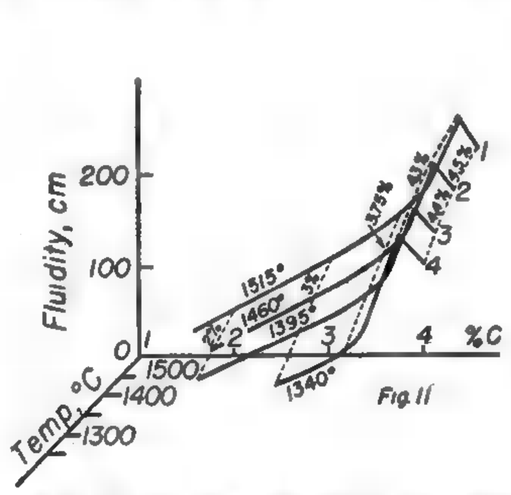


Fig. 9 Fluidity of brass, virgin metal containing 85% Cu, 5% Zn, 5% Sn, 5% Pb. Spiral cross section 0.066 sq in. (Saeger and Krynitsky)

Fig. 10 Fluidity of bronzes cast in green sand mold; spiral cross section 0.098 sq in. (Pilling and Kihlgren)

relation, whereas Pilling and Kihlgren,[15] using a modification of the Bureau of Standards mold with a spiral cross section of 0.098 sq in., obtained a slight curve for a comparable alloy, Fig. 10. The effect of aluminum and of antimony on the fluidity of cast red brass (85-5-5-5) was studied[24] in green sand molds. Aluminum was added in increments up to 0.1%. It was observed that quantities of 0.025% Al increased the fluidity the most at 1065 C (1949 F) and 1150 C (2102 F), whereas at 1230 C (2246 F) an addition of 0.05% Al produced the longest flows. Antimony additions up to 0.25% indicated that adding from 0.15 to 0.20% Sb increased the fluidity of red brass considerably at all testing temperatures.

The Fluidity of Cast Iron. Studies concerning the fluidity of cast iron have been carried on by various investigators,[1] using permanent molds and sand molds. The most nearly complete set of data, however, has been prepared by Perin and Berger.[16] In Fig. 11, the relations among



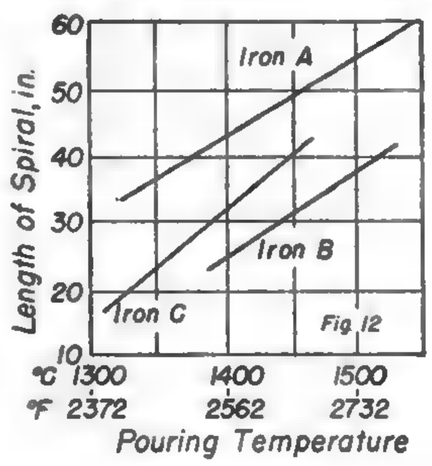


Fig. 11 Diagram showing the relations among temperature °C, fluidity and carbon content; cast in sand mold; spiral cross section, 0.078 sq in. (R. Berger)

Fig. 12 Fluidity of cast iron; sand mold, spiral cross section 0.066 sq in. (Saeger and Ash)

	TC	GC	CC	Si	■	Mn	P	Liquidus °C
Iron A	3.56	2.85	0.71	2.62	0.016	0.21	0.85	1170
Iron B	2.91	2.05	0.91	2.07	0.023	0.17	0.68	1240
Iron C	3.71	2.81	0.90	1.16	0.054	0.58	0.10	1200

temperature, fluidity, and carbon content are indicated. It may be seen from this diagram that if the casting temperature is kept constant, the fluidity increases with the carbon content until the eutectic concentration (4.3% C) is reached, and then decreases at higher carbon contents. Also, in the hypoeutectic region, there is a sudden increase in fluidity around 4.0% C.

Of course there are several elements in cast iron other than iron and carbon. Berger has investigated the influence of these elements, also, on the fluidity of cast iron. Because the additions of phosphorus and silicon influence the temperature of the liquidus, the fluidity comparisons are rather complicated, and for exact information the reader should turn to Berger's original work. However, for those interested in the study of irons, a general law may be formulated as follows: the eutectic mixtures are those which possess the greatest fluidity. The hypoeutectic alloys are the only ones of practical importance. In these the element regulating fluidity is carbon, next is phosphorus, and in a certain measure (under 1%) silicon. As for manganese, its influence on fluidity is of little importance. The amount and direction of its influence are essentially a function of the composition of the metal considered. Since, however, the modern commercial trend is toward the low-carbon metals, the fluidity of cast iron would depend more on the increment in temperature above the liquidus than on the other recognized controllable factors.

Three commercial cast irons investigated by Saeger and Ash[17] are shown in Fig. 12. These authors state that the running qualities of the irons depended on the liquidus temperature and apparently were not influenced by any previous maximum heating temperature prior to the pouring of the fluidity test at a lower temperature. For a chosen pouring temperature, the heats of iron having the lower liquidus temperature have superior running qualities.

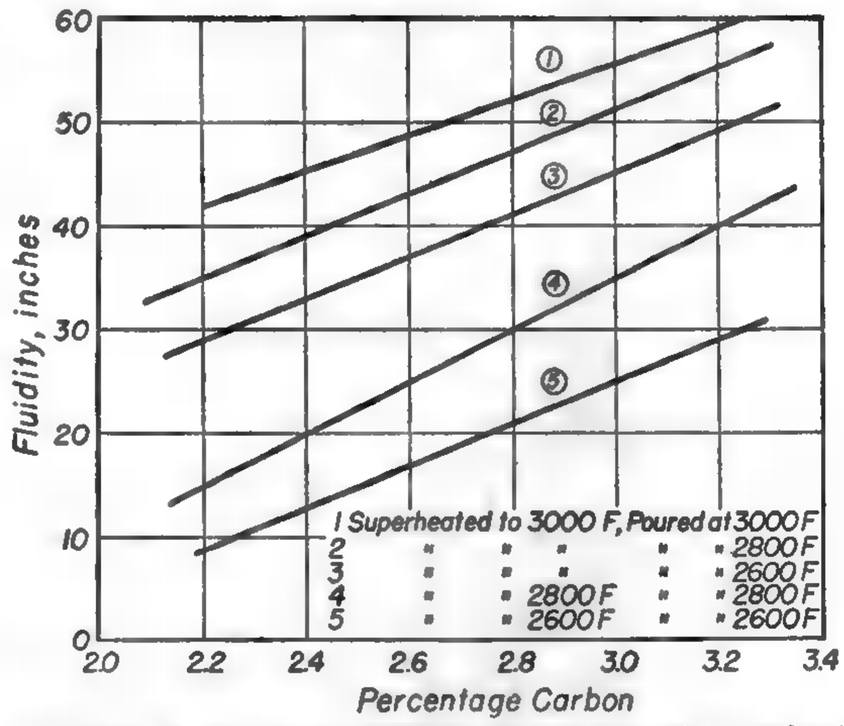


Fig. 13 Fluidity of cast iron of different carbon contents superheated at various temperatures (Zeigler and Northrup)

These results are not entirely substantiated by the work of Zeigler and Northrup.[25] Their studies of standard gray irons indicate, as shown by Fig. 13, that the influence of carbon content on fluidity is a straight-line relationship and that fluidity is affected not only by the pouring temperature but also by the degree of superheat. Thus fluidity of cast iron is increased by increasing the carbon content, the pouring temperature and the temperature of superheat.

It has been pointed out previously that the surface characteristics influence the fluidity. This has been demonstrated in a practical way by Courty.[18] He found that when cast iron was poured into a steel spiral mold, the length of the spiral could be increased from 51 to 81 cm by varying the mold coatings. The order of progressive increase was (1) linseed oil, (2) iron oxide, (3) graphite, (4) black lead and (5) a thin layer of soot from an acetylene flame.

The Fluidity of Steel. A number of studies concerning the fluidity of steel have been made in recent years. For steel, Ruff[26] devised the fluidity test specimen having a straight flow-channel. Andrews and co-workers,[19,27] using a special specimen, found that variations in carbon content up to 0.90% increased the fluidity of cast steel only slightly. Additions of silicon, manganese, copper, chromium, nickel and phosphorus were found to improve fluidity in proportion to the amount added. Walker[28] compiled results from practical foundry trials, using the straight flow-channel.

His results were inconclusive, chiefly because of the lack of adequate means for measuring steel temperatures. Sarjant and Middleham,[29] using a test specimen having a straight channel, indicated that the method has the necessary simplicity and convenience for use in plants. Their studies showed that carbon contents of 0.15, 0.43 and 0.83% progressively increase fluidity; that small additions of aluminum up to 0.30% increase fluidity of low-carbon steels; that copper up to 2% improves the fluidity of cast steel; and that high-manganese steels do not possess good fluidity at high temperatures.

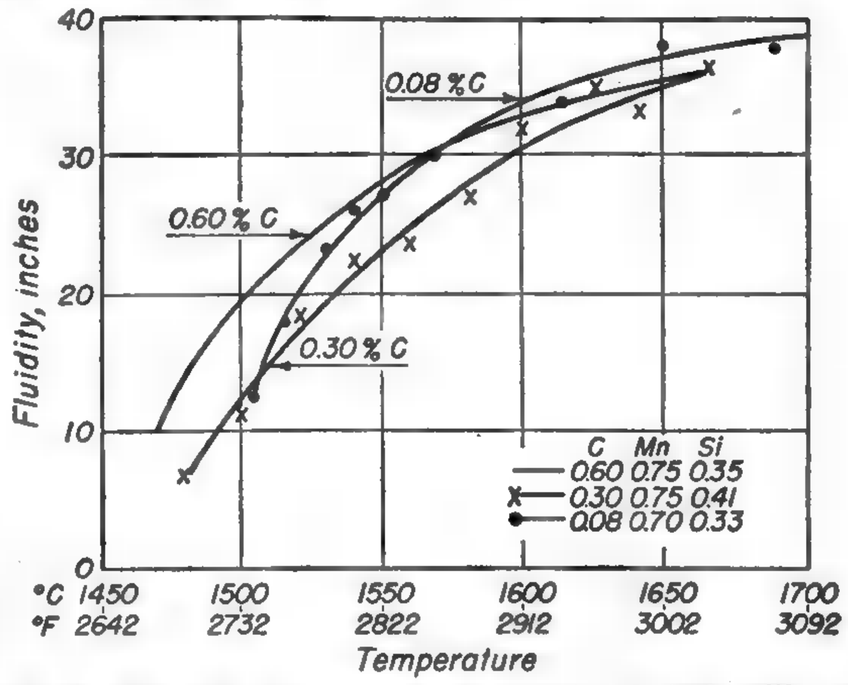


Fig. 14 The influence of carbon on the fluidity of steels with average manganese and silicon contents (Taylor, Rominski and Briggs)

Kron and Lorig[30] studied relationships among fluidity, temperature and composition in cast steels of several compositions, using the straight flow-channel. Their studies indicated that the flowing qualities of carbon steel were improved moderately by increased amounts of manganese, silicon and copper.

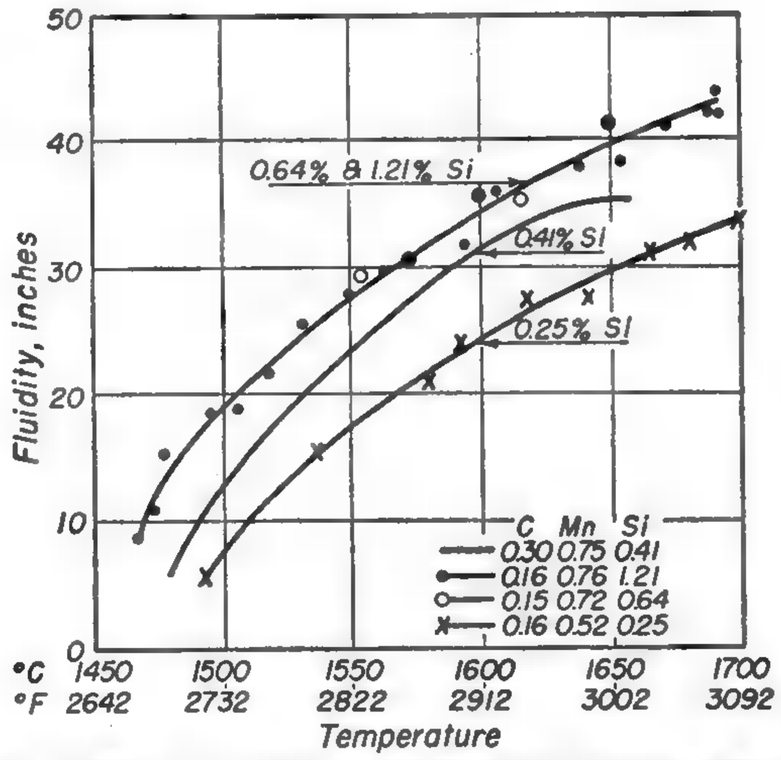


Fig. 15 The influence of silicon on the fluidity of steels having commercial compositions (Taylor, Rominski and Briggs)

The most nearly complete studies of the fluidity of steel have been made by Taylor, Rominski and Briggs.[31] Figure 14 shows that carbon has only a slight influence on fluidity of steel, whereas silicon has a marked effect on fluidity, as shown in Fig. 15. A notable change toward greater fluidity is found in the medium-carbon steels when silicon is increased from 0.25 to 0.45%. Presumably this change is not an effect of silicon addition as such, but rather of the state of deoxidation of the steel. Nickel improves the fluidity of steel progressively up to 3.25% as shown in Fig. 16. Higher concentrations as great as 5% Ni result in a decrease in fluidity.

An increase of manganese to 2% has virtually no greater effect on the fluidity of the alloy than that found in a regular grade carbon steel of about 0.75% Mn. Steels containing more maganese (approximately 2 to 14%) will exhibit improved fluidity at low temperatures (2650 to 2800 F) as the manganese content increases, whereas at temperatures 2900 F and above, the manganese-rich steels are inferior to plain carbon steels in fluidity.

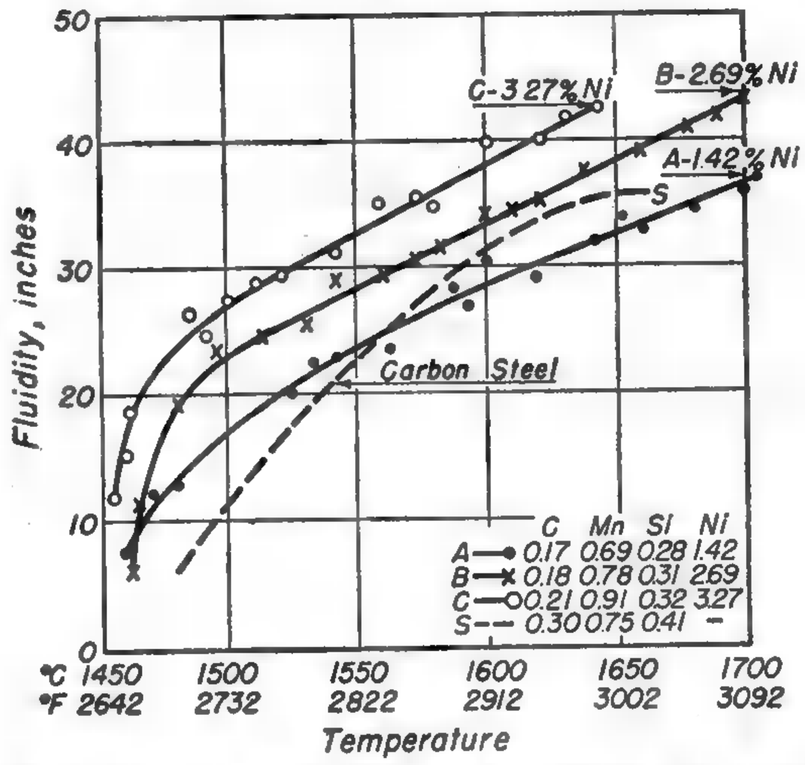


Fig. 16 The influence of nickel on the fluidity of cast steel (Taylor, Rominski and Briggs)

Additions of copper to plain carbon steel increase fluidity progressively as the concentration increases to about 4% Cu. Substantial additions of chromium to steel decrease the fluidity as compared with plain carbon steel. Small additions, less than 1.5% Cr, have no effect on the fluidity characteristics. Molybdenum and vanadium, when added to a normal plain carbon steel in amounts between 0.25 and 1%, cause a reduction in fluidity from that ordinarily obtained with no molybdenum or vanadium.

Aluminum is more effective than silicon in promoting fluidity, especially at the lower temperatures and when small quantities of aluminum are used. As aluminum is added beyond 0.2%, or that amount required for deoxidation control, fluidity is progressively decreased to low values at 1.2% Al. This indicates that the amount of aluminum for maximum fluidity is somewhat critical. The threshold value depends on the state of oxidation of the bath prior to the addition of the element. In order to have good fluidity, steel must be well made and thoroughly deoxidized. Rimming steels have fluidity inferior to that of dead-killed steels. Also, dead-killed steels that are excessively high in deoxidizers, such as aluminum and silicon, have fluidity inferior to that of steels killed with just sufficient silicon and aluminum.

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Properties of Metals at Low Temperature

By Russell Franks*

IT is well known in the field of metallurgy that temperature has a marked influence on the properties of the metals—both cast and wrought—that are widely utilized for constructional purposes. The data presented here deal with the effects of temperature on metals, in the range from room temperature (70 to 75 F) to minus 300 F and lower.

All the common metals are considered here, such as steels of both high and low alloy content, nickel and nickel alloys, copper and copper alloys, aluminum and aluminum alloys, magnesium and magnesium alloys. The mechanical properties that are considered include toughness, strength, ductility and hardness. Other data are presented concerning thermal conductivity, thermal expansion, and the modulus of elasticity, showing the extent to which these properties are influenced by exposure to low temperature.

Caution must be used in selecting the proper metal for a particular service at low temperature, in order to assure satisfactory performance; otherwise the equipment may fail because of inadequate toughness and ductility, and both time, money and life may be lost. In the selection of the metal, attention should be given to the specified composition as well as the manner in which the metal part or parts are to be fabricated into the finished article. For example, the influence of heat treatment may be so important that it determines whether the fabricated metal has or has not the properties necessary to insure successful application at low temperature. Usually a frank discussion between producer and consumer will clarify the problems to be encountered, and will provide a practicable plan for solving them.

Fields of Application. The use of metals at subatmospheric temperature has spread to virtually all the basic industries producing commodities for general consumption. During the past few years the tonnage of metals required to withstand the effects of exposure to low temperature has increased appreciably. The field of application for metals at low temperature is broad, involving conditions that vary widely in regard both to temperature and to the properties required in a metal article to meet the needs of its particular service. In the chemical industry, the temperatures most frequently encountered are as low as minus 150 F, and the equipment involved may be a large gas-fractionating column or a retort with extremely heavy wall. Refrigeration has provided important applications for metal construction in which liquid compounds are employed at temperatures as low as minus 75 F. This application will be increasingly important when such low temperatures are commonly used in homes to preserve fruits, vegetables, meats and other foods. The petroleum industry requires large quantities of metal equipment for the refining of oil and oil products, as in the dewaxing process. The equipment used in these three well-known fields may consist of relatively small articles produced from thin sheets, thin-wall tubes, small bars and such; on the other hand, the equipment may be large pressure vessels with heavy walls fabricated either by welding or by bolting. The aircraft, automotive and marine industries as well as the railroads are concerned with subatmospheric temperature from the standpoints of refrigeration and of direct exposure during the winter months. Military requirements for metals at low temperature are varied and widespread, including almost all the normal civilian low-temperature applications, and many others.

Probably one of the most important applications for metals at low temperature is in the production of the indispensable gas, oxygen. Virtually all the equipment employed in the production, transportation and use of this gas is built from a metal of some kind. At one time the transportation of liquid oxygen from one part of the country to another was a problem. It is common practice now to use a large metal container so satisfactory that the early accidents arising from the handling of liquid oxygen have been reduced to a negligible number. This problem has been solved solely by the selection of the proper metal—an example given merely to emphasize the importance of selecting the right metal, after applying the necessary tests to determine the adequacy of the metals in question.

General Behavior of Metals at Low Temperature. The ferrous metals, such as ordinary carbon and low-alloy constructional steels, exhibit a characteristic loss of toughness suddenly when a certain low temperature is reached. This "transition temperature" may occur near the freezing temperature of water or at a much lower temperature. Most of the nonferrous metals, such as copper, nickel and alloys of these metals, are relatively free from this behavior, particularly if the alloys represent a comparatively stable solid solution. On the contrary, the unstable precipitation-hardening alloys of these and other nonferrous metals should be suspected of brittle behavior at temperatures below normal. The austenitic type of stainless steel, categorically referred to as 18-8 steel, is virtually free from the embrittling effect at low temperature. Although this alloy is predominantly iron, it has no transition temperature in any of the ranges extending as low as minus 300 F. Some of the iron-nickel alloys do not have the transition

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point at low temperatures even though they contain more iron than nickel. These remarks apply particularly to the comparatively stable austenitic solid-solution type of alloys, because when these ferrous alloys are made subject to precipitation hardening, they too should be suspected of brittle behavior at low temperature.

As indicated above, under the conditions of stress imposed by a notch, at some temperature below normal, referred to as the "transition temperature", steel may be expected to change from a tough to a rather brittle behavior, generally accompanied by a coarse-grained fracture. The brittle behavior of a given steel can be evaluated best at present by the notched-bar impact test. Standard bend or tensile tests do not reveal such behavior, as data accompanying this article indicate.

For a discussion of notch sensitivity versus velocity sensitivity, the reader may refer to the article entitled "Notched-Bar Impact Tests" on page 112.

When constraint is increased by the sharpness of the notch, by the shape and size of the sample, by the reduction of temperature or by other factors of stress concentration, the notched-bar impact values approach zero.

Table I. Coefficients of Thermal Expansion of Metals at Low Temperature

Metal	Temperature or Temperature Range, deg Cent	Coefficient of Thermal Expansion, 10^{-6} in. per in. per °C	Reference
Aluminum	+ 27	23.2	37
	−173	11.9	37
Antimony	0	11	44
	−100	10	44
Bismuth	0	...	44
	−100	12.5	44
Copper	0 to − 20	16.27	43
	−160 to −183	12.34	43
Electrolytic Chromium, 99.3%	− 15 to + 20	5.8	39
	− 15 to − 50	5.5	39
	− 50 to −100	5.3	39
Hot Swaged Chromium, 98.3%	− 15 to + 20	0.1	40
	− 50 to −100	6.5	40
	−100 to −125	4.4	40
Cast Chromium, 96.3%	+ 20 to − 20	7.2	40
	− 15 to − 50	1.1	40
	− 50 to −100	2.6	40
Gold	+ 27	13.9	37
	−173	11.4	37
Indium	0 to − 80	27.9	41
	− 80 to −190	25.3	41
Iridium	0	6.41	44
	−100	5.63	44
Iron	0 to − 20	10.93_5	43
	−160 to −180	5.85	43
Lead	+ 27	29.3	38
	−173	25.5	38
Magnesium	0	25	44
	−100	21.7	44
Manganese	0	23.03	44
	−100	15.6	44
Molybdenum	+ 27	5.2	38
	−173	2.8	38
Nickel	+ 27	12.6	37
	− 73	11.3	37
	−173	6.6	37
Palladium	+ 27	11.7	38
	−173	8.2	38
Platinum	+ 27	9.0	38
	−173	7.0	38
Rhodium	0	8.19	44
	−100	6.8	44
Silicon	0	2.5	44
	−100	0.9	44
Silver	+ 27	18.7	38
	−173	14.8	38
Sodium	0	64	44
	−100	62	44
Tantalum	+ 27	6.6	38
	−173	5.12	38
Tin	0	20.9	44
	−100	16	44
Tin (gray)	0	...	..
	−100	5.3	..
Titanium, 97.2%	+ 20 to − 80	8.3	42
	− 80 to −190	5.5	42
Tungsten	+ 27	4.7_5	38
	−173	2.8	38
Zinc	0	29.5	..
	−100	26	..

Table II. Mean Coefficients of Thermal Expansion of Alloys at Low Temperature

Material and Composition	Temperature Range, deg Cent	Temperature Range, deg Fahr	Coefficient of Thermal Expansion, 10^{-6} in. per in. per °C	Reference
Pb — 46 Sb	−100 to 0	−148 to +32	14.40	45
Pb — 29 Sb	−100 to 0	−148 to +32	19.29	45
Pb — 11.6 Sb	−100 to 0	−148 to +32	24.83	45
Constantan. 60 Cu — 40 Ni	−191 to +16	−312 to +61	12.22	44
Stellite. 55 Co — 35 Cr — 10 W	− 94 to +19	−137 to +66	10.2	44
Gray Cast Iron. 3 to 4% C	−191 to +16	−312 to +61	8.5	44
Steel. Less than 1.4 % C	−200	−328	5.8 to 8.4	44
Invar. Fe — 36.1 Ni	−200 to −20	−328 to − 4	0.25	44
	−100	−148	1.06	44
99.4% Ni	0 to 40	+ 32 to + 104	12.09_5	46
	−182 to 0	−295.6 to +32	10.14_6	46
50 Ni — 50 Cu	0 to 40	+ 32 to + 104	13.71	46
	−182 to 0	−295.6 to +32	11.80_2	46
99 Cu — 1 Ni	0 to 40	+ 32 to + 104	15.86_5	46
	−182 to 0	−295.6 to +32	14.12	46
80 Pt — 20 Ir	−190 to +16	−310 to +61	7.502	44

Table III. Thermal Conductivity of Metals at Low Temperature

Metal	Temperature, deg Cent	Thermal Conductivity, cal/cm/sec/°C	Reference
Aluminum	−193	0.612	47
	0	0.531	47
Cadmium	−170 to +18	0.223	49
	−185	0.244	49
Copper	−125 to + 18	0.925	49
	−125 to −170	1.00	49
Gold	0	0.732	48
Iron	−183	0.224	47
	0	0.168_8	47
Ingot Iron	0	0.177	47
Lead	−173	0.0842	47
	+ 27	0.070	47
Magnesium	−193	0.447	47
	0	0.411	47
Molybdenum	0	0.333_5	48
	0	0.343	48
Nickel	−173	0.198	47
	+ 27	0.153	47
Commercial Nickel	−173	0.155	47
	+ 27	0.131	47
Tin	+ 18 to −100	0.157	49
	−100 to −170	0.173	49
Tungsten	0	0.393	48
	0	0.397	48
Zinc	0 to −170	0.270	49

Notches produced by thermal and corrosion cracks are serious when the temperature is reduced. Large masses of steel sometimes undergo brittle failures because of residual stresses augmented by decreasing temperature. Contraction stress, effect of plasticity, and thermal gradients are all emphasized by reduction of temperature.

Various investigators have obtained data indicating how exposure to low temperature affects certain physical properties of metals—thermal expansion, thermal conductivity and the modulus of elasticity. The data of the accompanying Tables I to VI inclusive indicate clearly that the coefficient of thermal expansion decreases with a decrease in temperature; that the thermal conductivity increases with a decrease in temperature; and that the modulus of elasticity increases with a decrease in temperature. There may be exceptions, but these broad generalizations apply to most metals exposed to subatmospheric temperatures.

The changes occurring in some of the physical and mechanical properties of metals are undoubtedly connected with metallurgical changes brought about by exposure at low temperature. It is known that steels of low carbon content retain their toughness to a lower transition temperature than do steels of relatively high carbon content. Presumably steels decrease in toughness when the ferritic solid solution becomes at least partially decomposed, forming a precipitate of carbide. The changes occurring in the microstructure of ferrite in low-carbon steels have not been well identified, but when the carbon content is high,

Table IV. Thermal Conductivity of Light Alloys at Low Temperature[a]

Alloy	Thermal Conductivity, cal/cm/sec/°C 0 C	−186 C	Alloy	Thermal Conductivity, cal/cm/sec/°C 0 C	−186 C
Al — 8 Cu	0.315	0.212	Mg — 8 Cd	0.338	0.311
Al — 15 Cu	0.354	0.216	Mg — 8 Zn	0.289	0.212
Al — 8 Mg[b]	0.239	0.174	Mg — 0.5 Mn	0.382	0.320
Al — 8 Mg[b]	0.250	0.183	Mg — 2 Mn	0.281	0.161
Al — 12 Mg	0.185	0.134	Mg — 3.54 Mn	0.244	0.135
Al — 14 Mg	0.165	.....	Mg — 0.7 Si	0.352	0.262
Mg — 12 Al	0.140	0.080	Mg — 1.5 Si	0.334	0.227
Mg — 8 Al	0.155	0.100	Mg — 8 Ce	0.299	0.253
Mg — 6 Al	0.091	0.144	Mg — 12 Ce	0.246	0.193
Al — Cu — Mg Duralumin	0.383	0.312	Mg — 20 Cu — 3 Si	0.258	0.213
Al — 4 Cu — 2 Ni — 1.5 Mg[b]	0.388	0.267	Mg — 2 Si — 6 Al	0.164	0.115
Al — 4 Cu — 2 Ni — 1.5 Mg[b]	0.365	0.330	Mg — 2 Si — 8 Al	0.145	0.090
Mg — 8 Cu	0.298	0.210	Mg — 2 Si — 12 Al	0.128	0.066
Mg — 15 Cu	0.369	0.360			

(a) Tables Annuelles de Constantes et Données Numériques, Vol XI (1931–1934) sections 8-9
(b) Heat treatment not specified

Table V. Temperature Coefficients of the Modulus of Elasticity[a]

Alloy	Treatment	Coefficient of Thermal Expansion × 10^5	Coefficient[b] of Modulus of Elasticity, $e_0 \times 10^5$	e_{25}/e_{-25}
Chromium-Vanadium Steel	T	1.17	−26.3	1.13
	A	1.17	−25.5	1.07
Nickel Steel, 5% Ni	A	1.05	−28.6	1.06
	T	1.05	−26	1.10
Nickel Steel, 3½% Ni	A	1.04	−27	1.08
	T	1.04	−27.1	1.09
Stainless Steel (KA_2) 0.14% C	HD	1.64	−43.2	1.13
	A	1.6	−39.7	1.16
Stainless Steel (KA_2) 0.05% C	HD	1.6	−37.9	1.19
Stainless Steel (Enduro A)	HD	0.99	−26.6	1.10
	A	0.99	−28.6	1.06
Stainless Steel (Enduro AA)	HD	0.99	−25.9	1.04
	A	0.99	−27.3	1.15
Stainless No. 12	HD	1.04	−25.6	1.12
	A	1.04	−27	1.13
Silicomanganese Steel	A	1.1	−24.5	1.12
	T	1.1	−25.1	1.16
High-Carbon Steel No. 10	A	1.1	−20.1	1.12
	T	1.1	−26.0	1.07
High-Carbon Steel	A	1.1	−19.3	1.12
	T	1.1	−26.2	1.11
Phosphor Bronze	HD	1.7	−38.0	1.02
	HD	1.7	−40.0	1.06
	HD	1.7	−36.0	1.05
Nickel Silver, 10% Ni	HD	1.8	−34.6	1.06
Nickel Silver, 14% Ni	HD	1.8	−34.7	1.03
Nickel Silver, 19% Ni	HD	1.8	−34.8	1.06
Nickel Silver, 10% Ni	HD	1.8	−37.9	1.06
Nickel Silver, 15% Ni	HD	1.8	−34.5	1.07
Nickel Silver, 18% Ni	HD	1.8	−35.2	1.05
Nickel Silver, 19% Ni	A	1.8	−33.0	1.05
Duralumin	Ag H	2.3	−58.3	1.12
Monel Metal	HD	1.3	−29.7	1.02
	A	1.3	−29.5	1.12
Brass, 73% Cu	HD	1.8	−38.9	1.17
Elinvar	HD	0.6	− 6.6	...
Modulvar	HD	0	+48.2	...
Tungsten	As R	0.4	− 9.5	...
Beryllium Bronze, 1.9% Be	Ag H	1.7	−35.0	1.06

(a) G. H. Keulegan and M. R. Houseman, J Research Nat Bur Standards, 10, 289 (1933)
(b) Coefficient $= e = \frac{1}{E} \cdot \frac{dE}{dT}$, where E = the modulus of elasticity. e_0 is the average value for the temperature range from −50 to +50 C.
T, Tempered; A, Annealed; HD, Hard Drawn; Ag H, Age Hardened; As R, As Received.

Table VI. Temperature Coefficients of the Elastic Modulus of Light Alloys[a]

Chemical Composition of Alloy	Heat Treatment	Temperature Range, deg Cent	Temperature Coefficient,[b] $e \times 10^5$
92 Al — 4 Cu — 1.2 Mg — 1.2 Mn	Q	−190 to −48	−46
	Q	− 50 to +70	−32
93 Al — 1.9 Cu — 0.8 Mg — 1.2 Ni — 1.4 Fe — 0.1 Ti — 0.6 Si	Ag H	−190 to −56	−53
	Ag H	− 56 to +68	−31
94 Al — 1.2 Ni — 0.9 Si — 0.7 Mg — 2.5 Cu — 1 Fe — 0.1 Ce	Ag H	−190 to −44	−57
	Ag H	+ 20 to −44	−28
97.5 Al — 0.1 Mn — 1.5 Si — 0.01 Mg — 0.8 Fe — 1.1 Cu	Q	−190 to −70	−62
	Q	+ 20 to −70	−34
89.85 Al — 9.5 Mg — 0.35 Mn — 0.20 Fe — 0.10 Si	A	−190 to −41	−37
	A	+ 20 to −41	−13
97.9 Al — 0.7 Si — 0.28 Fe — 1.10 Mg — 0.01 Mn	Q	−190 to −50	−48
	■	0 to 50	−29
95.5 Mg — 0.2 Mn — 4 Al	As R	−190 to −61	−41
	As R	+ 20 to −50	−20

Q, Quenched; A, Annealed; As R, As Received; Ag H, Age Hardened.
(a) Publi Sci Tech du Ministère de l'Air, No. 122, 1938, Paris.
(b) $e = \frac{1}{E} \cdot \frac{dE}{dT}$ for the range of temperature indicated.

Table VII. Toughness of Carbon Steels at Low Temperature

Steel, Composition and Grain Size	Condition	Hardness or Tensile Strength at Room Temperature, psi	Notched-Bar Charpy Impact Values (Keyhole Notch) ft-lb	Temp, °F	ft-lb	Temp, °F	ft-lb	Temp, °F	ft-lb	Temp, °F	Reference
SAE 1010, Bessemer Structural, 0.10 C..	AR	55,000	37	148	26	68	4	32	3	0	1
Open Hearth Structural, 0.10 C.....	AR	48,000	36	148	32	68	26	32	3.5	0	1
Ingot Iron, Open Hearth.....	AR	.....	[illegible]	68	46	32	25	0	5	— 40	1
Izett Steel, Aluminum-Killed.....	AR	.....	47	68	42	0	35	— 40	[illegible]	— 80	1
Bessemer Steel. 0.16 C, 0.50 Mn, 0.08 P, 0.22 Si, 0.03 Al.....	N	65,000	39	68	26	32	20	— 25	10	— 50	1
Open Hearth. 0.20 C, 0.90 Mn, 0.22 Si, 0.03 Al. FG	N	65,000	57	70	59	—50	36	—100	31	—150	2
Open Hearth. 0.31 C, 0.74 Mn, 0.22 Si, 0.03 Al. FG	WQ 1575 F, T 1000 F	82 R_B	40	70	37	0	20	—100	4	—200	2
Open Hearth. 0.39 C, 0.80 Mn, 0.19 Si, 0.02 Al. FG	N	85,000	[illegible]	70	25	0	20	— 50	12	—100	2

N, Normalized; AR, As Rolled; FG, Fine Grain; WQ, Water Quenched; T, Tempered; R_B, Rockwell B.

the changes in microstructure are associated with carbide precipitation. Copper, nickel, chromium and molybdenum are added to steels of relatively low carbon and alloy content to prevent the occurrence of harmful transformations. It is generally conceded that if the carbon content is much more than 0.30%, great difficulty is encountered in preventing loss of toughness, even though the metal has been thoroughly deoxidized by additions of aluminum.

The more highly alloyed ferrous metals that contain nickel and chromium in such proportions as to give a relatively stable austenitic structure, retain their toughness at the lowest temperatures because the metal is free from decomposition products that decrease toughness. The same is true when the face-centered cubic type of structure is relatively stable in copper-base or aluminum-base alloys but, even in these alloys, the toughness will be reduced if the solid solution is made unstable by the introduction of some element that induces precipitation.

Properties of Ferrous Materials at Low Temperature. *Ferritic Steels.* Data relating to the toughness and strength of carbon steels are given in Tables VII and VIII. These data, selected from the work of various investigators, make it clear that the impact toughness of ordinary carbon steel in the as-rolled condition, decreases to a low value at minus 40 F, unless the steel is properly deoxidized. When the as-rolled steel is properly deoxidized, the toughness remains high in the as-rolled condition down to minus 40 F, but is reduced to a low value at a temperature of minus 80 F. When low-carbon steel is deoxidized by means of aluminum and is then normalized, good toughness is retained as low as minus 100 F and somewhat lower. The strength and ductility of these carbon steels are not affected in the same manner. The data of Table VIII show that the strength of the carbon steels is increased greatly with little or no change in ductility, as measured by elongation and reduction of area, when temperatures as low as about minus 150 F are reached; whereas, under the same conditions, the impact toughness of the steel is at a low value. The tensile characteristics, therefore, are less indicative of what happens when low-carbon steel is subjected to low temperature than are the data obtained through the impact test. However, the tensile test data indicate that, as the carbon content of steel is increased, the exposure to the low temperature causes a decided decrease in ductility, even though the steel has been heat treated. These data illustrate the beneficial effect of deoxidation and heat treatment in obtaining fine-grained steels that are superior to the coarse-grained steels in toughness at low temperature.

The data of Tables IX and X, concerning the low-temperature characteristics of the alloy constructional steels, indicate that in general the fine-grained steels are superior to the coarse-grained steels in toughness at low temperature. These steels contain relatively small percentages of nickel, chromium, molybdenum or vanadium or combinations of these metals, in addition to the usual

Table VIII. Strength and Ductility of Carbon Steels at Low Temperature

Alloy and Composition	Condition	Temp, °F	Yield Strength, psi	Tensile Strength, psi	Percentage Elongation in 2 in.	Percentage Reduction of Area	Reference
Ingot Iron. 0.035 C.....	AR	70	.....	45,700	27.9	73.2	3
	AR	— 4	30,700	53,750	42	75	3
	AR	— 58	42,200	59,400	43	74	3
	AR	— 94	43,400	61,700	37.5	72	3
	AR	—148	57,200	66,800	26.5	70	3
	AR	—184	66,700	77,000	17	68	3
	AR	—292	.....	112,000	nil	nil	3
Carbon Steel. 0.13 C	AR	70	54,700	66,300	29.7	71.8	3
	AR	— 85	67,700	80,700	33.6	70.3	3
	AR	—292	.....	121,300	26.5	55	3
Carbon Steel. 0.14 C	A 1472 F	70	42,700	45,700	27.5	77.5	4
	A 1472 F	—296	.....	137,000	7.5	....	4
	A 1472 F	—423	155,000	155,000	0.3	2.5	4
Carbon Steel. 0.21 C	AR	70	39,800	62,600	35.5	53	5
	AR	—114	47,780	69,000	35.5	56.8	5
SAE 1035	N	25	50,000	85,000	29	52	6
	N	— 25	60,000	95,000	29	48	6
	N	— 60	76,000	102,000	30	48	6
	N	—190	143,000	144,000	5	5	6
Carbon Steel. 0.37 C, 0.20 Mn	A 1472 F	70	.....	76,000	20	63	4
	A 1472 F	—296	.....	148,000	17	39	4
	A 1472 F	—423	151,000	151,000	nil	nil	4
Carbon Steel. 0.40 C	A	70	45,800	79,400	30.8	49	7
	A	—300	114,100	139,400	7.3	7.1	7
	HT	70	76,900	104,400	25	61.3	7
	HT	—300	150,200	160,400	9.8	9.4	7
Carbon Steel. 0.78 C, 0.10 Mn	A 1472 F	70	95,000	99,000	12	35	4
	A 1472 F	—296	.....	154,700	nil	nil	4
	A 1472 F	—423	123,000	123,000	0.2	nil	4

A, Annealed; AR, As Rolled; HT, Heat Treated; N, Normalized.

Table IX. Toughness of Alloy Constructional Steels at Low Temperature

SAE Number, Composition and Grain Size	Condition	Brinell Hardness Number	Notched-Bar Impact Value								Reference and Type of Notch
			ft-lb	Temp, °F	ft-lb	Temp, °F	ft-lb	Temp, °F	ft-lb	Temp, °F	
2315. 0.16 C, 0.62 Mn, 3.52 Ni. FG	AR	197	43	75	25	−40	11	−100	4	−180	8, K
	N 1525 F	186	52	75	37	−80	26	−180	5	−310	8, K
	WQ 1525 F, T 1000 F	262	53	75	51	−80	47	−180	17	−310	9, K
2330. 0.31 C, 3.47 Ni. FG	N 1700 F	197	24	75	20	0	15	− 40	..	...	8, 10, K
	N 1675 F	192	49	75	32	0	17	− 40	9	−100	8, 10, K
	OQ 1450 F,T 1050 F	217	106	75	106	0	105	− 40	106	−100	10, 11, V
2340. 0.39 C, 0.73 Mn, 3.50 Ni. FG	OQ 1425 F, T 500 F	495	16	75	11	−80	8	−180	6	−310	10, 12, K
	OQ 1425 F, T 1200 F	235	45	75	37	−80	27	−180	16	−310	10, 12, K
3130. 0.32 C, 0.71 Mn, 1.16 Ni, 0.60 Cr. FG	N 1700 F	192	88	75	46	0	30	− 40	11	−100	8, 9, K
	OQ 1500 F, T 1175 F	207	120+	75	120+	0	120+	− 40	107	−100	9, 10, K
4023. 0.20 C, 0.76 Mn, 0.23 Mo. FG	N 1600 F, T 1000 F	156	62	75	34	−80	16	−180	4	−310	12, 13, K
4120. 0.24 C, 0.47 Mn, 0.78 Cr, 0.39 Mo. FG	A 1550 F	136	45	75	32	0	2	− 80	1	−310	9, K
4130. 0.32 C, 0.66 Mn, 0.71 Cr, 0.20 Mo. CG	N 1650 F	217	9	75	6	0	4	− 40	3	−100	9, V
	WQ 1575 F, T 1260 F	217	120+	75	120+	0	120+	− 40	120+	−100	9, V
0.30 C, 0.51 Mn, 0.91 Cr, 0.18 Mo. FG	OQ 1650 F, T 900 F	363	58	75	26	−80	18	−180	9	−310	8, 12, V
4140. FG	N 1650 F	255	18	75	9	0	6	− 40	5	−100	8, 11, V
	OQ 1575 F, T 1075 F	286	93	75	87	0	87	− 40	65	−100	8, 11, V
4340. 0.39 C, 0.71 Mn, 1.71 Ni, 0.75 Cr, 0.30 Mo. FG	N 1630 F	440	13	75	7	0	6	− 40	5	−100	8, 9, V
	OQ 1525 F, T 1100 F	302	82	75	82	0	82	− 40	77	−100	9, 10, V
4615. FG	N 1630 F	192	100	75	50	0	28	− 40	15	−100	8, 11, V
4640. 0.41 C, 0.65 Mn, 1.84 Ni, 0.26 Mo, 0.18 Cr. FG	WQ 1525 F, T 1100 F	235	120	75	120	−40	120	−100	8	−310	10, 11, V
	N 1700 F	235	26	75	14	0	10	− 40	6	−100	8, 11, V
4815. 0.19 C, 0.48 Mn, 3.38 Ni, 0.25 Mo, 0.13 Cr. FG	OQ 1525 F, T 1240 F	217	110	75	106	−40	78	−100	11	−310	10, 11, V
	N 1700 F	202	86	75	62	0	31	− 40	18	−100	11, 13, V
	OQ 1475 F, T 1100 F	228	120	75	120	−40	118	−180	25	−310	11, 13, V
5120. 0.15 C, 0.67 Mn, 0.83 Cr. FG	N 1600 F	149	103	75	77	0	59	− 40	9	− 80	8, 9, 13, V
6130. 0.29 C, 0.69 Mn, 0.86 Cr, 0.17 V. 60% CG, 40% FG	N 1700 F	269	9	75	7	0	5	− 40	6	−100	9, V
	OQ 1625 F, T 1175 F	277	104	75	83	0	26	− 40	16	−100	9, V
6145. 0.44 C, 0.70 Mn, 0.88 Cr, 0.19 V. FG	N 1650 F	286	19	75	14	0	9	− 40	6	−100	8, 11, V
8620. 0.23 C, 0.89 Mn, 0.53 Cr, 0.50 Ni, 0.27 Mo. FG	OQ 1525 F, T 1125 F	286	77	75	38	0	24	− 40	15	−100	9, 11, V
	N 1600 F, T 1000 F	217	57	75	35	−40	22	−100	7	−180	12, 13, K
	OQ 1600 F, T 900F	352	45	75	42	−40	26	−180	19	−310	12, 13, K
8750. 0.49 C, 0.81 Mn, 0.59 Cr, 0.56 Ni 0.21 Mo. FG	N 1550 F	277	21	75	19	−40	12	−100	7	−180	12, 13, K
	OQ 1550 F, T 1000 F	388	25	75	25	0	20	−100	14	−310	12, 13, K
9260. 0.55 C, 0.92 Mn, 1.82 Si, 0.32 Cr. FG	OQ 1550 F, T 850 F	444	17	75	8	−40	6	−100	5	−310	8, 12, K
9420. 0.23 C, 0.90 Mn, 0.50 Si, 0.33 Cr, 0.31 Ni, 0.11 Mo. FG	N 1600 F, T 1000 F	170	54	75	38	−80	27	−180	3	−310	12, 13, K
	WQ 1600 F, T 1000 F	262	51	75	40	−80	34	−180	12	−310	12, 13, K
9440. 0.45 C, 1.25 Mn, 0.33 Cr, 0.24 Ni, 0.13 Mo. FG	N 1525 F, T 1000 F	269	25	75	15	−100	14	−180	6	−310	12, 13, K
	OQ 1525 F, T 900 F	375	26	75	15	−100	14	−180	8	−310	12, 13, K
9540. 0.43 C, 1.38 Mn, 0.59 Si, 0.57 Cr, 0.52 Ni, 0.23 Mo. FG	N 1525 F, T 1000 F	321	22	75	18	−80	16	−180	6	−310	12, 13, K
	OQ 1525 F, T 900 F	388	19	75	16	−80	12	−180	9	−310	12, 13, K

A, Annealed; AR, As Rolled; CG, Coarse Grain; FG, Fine Grain; K, Charpy Keyhole Notch; N, Normalized; OQ, Oil Quenched; T, Tempered; V, Charpy V Notch; WQ, Water Quenched.

Table X. Strength and Ductility of Alloy Constructional Steels at Low Temperature

Type of Steel, Composition and Grain Size	Condition	Temp, °F	Yield Strength, psi	Tensile Strength, psi	Percentage Elongation in 2 in.	Percentage Reduction of Area	Reference
Cr-V. 0.29 C, 0.69 Mn, 0.96 Cr, 0.17 V. 60% CG, 40% FG	N 1700 F	75	97,000	134,000	13	59	9
	.....	−105	104,000	150,000	14	53	9
Cr-Mo. 0.31 C, 0.69 Cr, 0.65 Mn, 0.2 Si, 0.22 Mo	OQ 1625 F, T 1100 F	70	122,000	128,000	20	65	14
	.....	− 40	130,000	149,000	19	64	14
Cr-Mo. 0.22 C, 0.83 Cr, 0.60 Mn, 0.33 Si, 0.22 Mo	WQ 1560 F, T 1120 F	68	95,300	114,000	22	75	15
	.....	−297	165,000	172,000	22	57	15
Cr-Mo-V. 0.31 C, 2.36 Cr, 0.67 Mn, 0.29 Si, 0.24 Mo, 0.19 V	OQ 1560 F, T 1130 F	68	123,000	140,000	18	70	15
	.....	−297	191,000	206,000	19	45	15
Cu-Mn. 0.17 C, 2.87 Cu, 1.04 Mn, 0.15 Si	AC 2015 F, FC 1430 F	70	.....	76,200	20	..	16
	.....	−295	.....	150,000	2.5	..	16
	FC 1470 F	70	81,100	93,400	16	56	16
	.....	−423	.....	174,000	0.8	0	16
Ni. 0.26 C, 0.58 Ni, 0.33 Si, 0.18 Mn	AC 2015 F, FC 1430 F	70	.....	75,000	25	..	16
	.....	−295	.....	143,000	15	..	16
Ni-Cr-Mo. 0.47 C, 1.08 Ni, 1.04 Cr, 0.80 Mn, 0.29 Si, 0.22 Mo	FC 1450 F	70	72,000	96,500	23	67	9
	.....	−105	90,000	116,000	26	62	9
Ni-Cr. 0.35 C, 3.34 Ni, 0.71 Cr, 0.56 Mn, 0.18 Si	OQ 1560 F, T 1200 F	70	133,000	146,000	14	60	16
	.....	−423	.....	243,000	4.5	48	16
Ni. 0.13 C, 5.13 Ni, 0.41 Mn, 0.19 Cr, 0.15 Si	OQ 1560 F, T 1200 F	68	.....	103,000	25	74	17
	.....	−242	.....	153,000	25	57	17
	.....	−297	.....	160,000	19	47	17
	.....	−319	.....	175,000	21	50	17
Ni-Cr-Mo. 0.33 C, 0.67 Cr, 2.45 Ni, 0.64 Mo	OQ 1560 F, T 1185 F	70	137,700	152,000	14	65	3
	.....	− 6	141,000	154,500	15.6	64	3
	.....	− 90	145,000	163,000	15.6	62	3
	.....	−141	149,000	170,000	16.4	61	3
	.....	−292	183,500	201,500	17	63	3
Ni-Cr. 0.35 C, 0.71 Cr, 3.34 Ni	OQ, T 1200 F	70	133,000	146,000	13.5	59.5	4
	.....	−423	243,000	243,000	4.5	48.5	4

AC, Air Cooled; FC, Furnace Cooled; FG, Fine Grain; CG, Coarse Grain; N, Normalized; OQ, Oil Quenched; WQ, Water Quenched; T, Tempered

percentages of manganese and silicon. It is unnecessary to discuss in detail the properties of the various SAE and AISI steels except to state that their best low-temperature toughness is generally obtained as a result of cooling rapidly from temperatures in the vicinity of 1500 to 1600 F and then tempering in the range from 1000 to 1200 F. After this type of heat treatment many of the steels exhibit excellent toughness at temperatures approaching minus 200 F, particularly those steels that have a martensitic structure after rapid cooling. The strength increases without serious loss of ductility during exposure to low temperature, a fact leading to the question of whether this marked increase in strength can be utilized in low-temperature application of the steels that have adequate toughness, permitting the production of lighter structural parts in order to save weight.

Table XI. Toughness of Low-Alloy, High-Strength Structural Steels at Low Temperature

Steel and Composition	Condition	Tensile Strength at Room Temperature, psi	Notched-Bar Impact Values								Reference and Type of Notch
			ft-lb	Temp, °F	ft-lb	Temp, °F	ft-lb	Temp, °F	ft-lb	Temp, °F	
Hi-Steel. 0.10 C, 0.7 Mn, 0.10 Si, 1.08 Cu, 0.57 Ni, 0.15 Mo, 0.17 Al	AR	77,500	54	75	54.5	0	54.2	— 25	45.2	— 50	19, K
	SR 4 hr, 1050 F	82,200	55	75	41.5	0	38.5	— 25	37.5	— 50	19, K
Mayari R. 0.10 C, 0.7 Mn, 0.34 Si, 0.10 P, 0.57 Cu, 0.31 Ni, 0.55 Cr	AR	80,840	47.5	75	38	0	35	— 25	29	— 50	20, K
	N	78,130	64	75	51	0	50	— 25	43	— 50	20, K
Yoloy. 0.12 C, 0.60 Mn, 0.30 Si, 1 Cu, 1.75 Ni	N 1600 F	78,000	130	78	125	— 25	95	— 75	70	—100	21, V
NAX. 0.13 C, 0.67 Mn, 0.84 Si, 0.50 Cr, 0.11 Zr	AR	72,100	67.5	75	53	— 50	41.5	—100	17	—125	22, K
	N 1630 F	.....	78	75	48	— 50	52	— 75	47	—100	22, K
Otiscoloy. 0.12 C, 1 Mn, 0.10 Si, 0.10 P, 0.10 Cr, 0.50 Cu	AR	80,000	35	75	15	— 50	..	.....	..	.....	23, K
Dyn-el. 0.12 C, 0.60 Mn, 0.08 P, 0.40 Cu	....	72,000	44	75	38	0	27	— 40	..	.....	9, K
Cor-Ten. 0.10 C, 0.35 Mn, 0.41 Si, 0.080 P, 0.75 Cr, 0.42 Cu, 0.47 Ni	AR	73,560	44.3	70	32	— 25	..	.....	..	.....	86, K
Cor-Ten. 0.09 C, 0.26 Mn, 0.84 Si, 0.13 P, 0.92 Cr, 0.38 Cu	....	77,500	40	70	29	0	15.5	— 50	11	— 75	9, K
Man-Ten. 0.18 C, 1.32 Mn, 0.13 Si, 0.014 P, 0.023 S, 0.26 Cu	AR	75,380	48.3	70	20.3	— 25	..	.....	..	.....	86, K
Jal-Ten. 0.13 C, 1.29 Mn, 0.70 Si, 0.48 Cr, 0.12 Cu	AR	75,500	74	70	79.5	0	39.5	— 50	34.5	— 75	9, K
Aldecor. 0.08 C, 0.21 Mn, 0.09 P, 0.49 Si, 0.38 Cu, 0.2 Mo	AR	79,500	44	70	38	0	23	— 25	14	— 40	9, K
	A 6 hr 1115 F	.....	40	70	42	0	32	— 25	28	— 40	9, K
Cromansil. 0.09 C, 1.47 Mn, 0.55 Si, 0.48 Cr	....	75,000	48	75	11	— 60	10	—110	..	.....	25, Iz
Cr-Cu. 0.14 C, 0.22 Si, 0.76 Cr, 0.62 Cu, 0.07 Al	N	72,000	82.6	68	87.9	—112	86.9	—148	..	.....	6, Iz
Cr-Cu. 0.16 C, 0.17 Si, 0.78 Cr, 0.60 Cu, 0.12 V	N	85,000	56.8	68	38.5	—112	40.5	—148	..	.....	6, Iz
Cr-Cu. 0.13 C, 0.19 Si, 0.71 Cr, 0.60 Cu, 0.05 Zr	N	70,000	75.3	68	80.6	—112	48.8	—148	..	.....	6, Iz
Cr-Cu. 0.16 C, 0.25 Si, 0.73 Cr, 0.49 Cu, 0.16 Cb	N	70,000	75.1	68	67	—112	40.8	—148	..	.....	6, Iz
Cr-Cu. 0.17 C, 0.33 Si, 0.77 Cr, 0.6 Cu, 0.11 Ti.	N	78,000	73.1	68	9.9	—112	12	—148	..	.....	6, Iz

A, Annealed; AR, As Rolled; Iz, Izod V Notch; K, Charpy Keyhole Notch; N, Normalized; SR, Stress Relieved; V, Charpy V Notch.

Table XII. Toughness of Cast Steels at Low Temperature

Type of Steel, Composition and Grain Size	Condition	Bhn or Tensile Strength at Room Temperature, psi	Notched-Bar Impact Values								Reference and Type of Notch
			ft-lb	Temp, °F	ft-lb	Temp, °F	ft-lb	Temp, °F	ft-lb	Temp, °F	
Carbon. 0.20 C, 0.70 Mn	N	127 Bhn	80	70	7	— 50	..	.....	..	.....	8, V
Carbon. 0.14 C, 0.70 Mn, 0.38 Si	Al-Killed, N 1750 F, T 1200 F	64,200	22	70	20	0	20	— 25	9	— 50	34, K
Carbon. 0.23 C, 0.65 Mn, 0.28 Si	As Cast	.....	16	60	6	20	2	— 20	..	.....	35, K
Carbon. 0.28 C, 0.74 Mn, 0.28 Si	A	.....	25	75	8	0	5	— 50	..	.....	12, K
FG	WQ 1575 F, T 900 F	.....	25	75	22	0	20	— 50	15	—100	12, K
	WQ 1575 F, T 1200 F	.....	33	75	28	0	25	— 50	20	—100	12, K
Carbon. 0.42 C, 0.78 Mn, 0.30 Si	WQ 1500 F, T 900 F	.....	19	75	16	0	13	— 25	10	—100	12, K
	OQ 1500 F, T 1200 F	.....	32	75	30	0	26	— 50	22	—100	12, K
Nickel. 0.12 C, 0.65 Mn, 0.35 Si, 1 Ni	Al-Killed, DN-T 1200 F	59,500	39	75	16	—100	2	—150	..	.....	36, K
Nickel. 0.14 C, 0.65 Mn, 0.35 Si, 2 Ni	Al-Killed, DN-T 1200 F	69,000	37	75	19	—100	16	—150	7.5	—200	36, K
Nickel. 0.15 C, 0.58 Mn, 0.30 Si, 2.9 Ni	Al-Killed, DN-T 1200 F	76,800	30	75	21	— 75	17	—150	▮	—200	36, K
Nickel. 0.11 C, 0.64 Mn, 0.34 Si, 4.95 Ni	Al-Killed, DN-T 1200 F	90,200	30	75	20	—100	19	—150	10	—200	36, K
Nickel. 0.03 C, 0.70 Mn, 0.26 Si, 3.61 Ni	Al-Killed, DN-T 1200 F	62,800	58.5	75	58.5	— 50	53.2	—150	41.5	—175	34, K
Ni-Mo. 0.17 C, 0.6 Mn, 0.15 Si, 2.83 Ni, 0.31 Mo	DT 1525 F	83,500	47	75	35	— 50	31	—100	2.5	—200	9, K
Mn-Mo. 0.29 C, 1.66 Mn, 0.47 Si, 0.41 Mo	N 1850 F, WQ 1625 F, T 1200 F	.....	46	75	42	0	39	— 50	28	— 75	12, K
	WQ 1625 F, T 1200 F	.....	36	75	32	0	24	— 50	19	— 75	12, K
Mn-Mo. 0.34 C, 1.1 Mn, 0.18 Mo	N 1700 F	.....	9.1	65	4.2	— 40	..	.....	..	.....	35, K
	N 1700 F, T 1200 F	.....	33.5	65	7.2	— 40	3.3	— 94	..	.....	35, K
	N 1700 F, WQ 1600 F, T 1200 F	.....	68.7	65	34.8	— 40	24.7	— 94	..	.....	35, K
Ni-V. 0.24 C, 0.79 Mn, 1.52 Ni, 0.10 V	.....	89,000	35	75	24	— 50	..	.....	..	.....	8, K
	DN	.....	37	75	24.5	— 50	21.5	— 90	..	.....	35, K
Mn-V. 0.29 C, 1.67 Mn, 0.41 Si, 0.09 V	N 1650 F + 1500 F, T 750 F	.....	39.5	75	26	— 50	25.5	— 75	23.5	— 90	9, K
Mn-V. 0.27 C, 1.55 Mn, 0.45 Si, 0.10 V	N 1600 F + 1500 F	66,500	39.5	75	26	— 25	27.5	— 50	7	— 75	9, K
Cu-V. 0.19 C, 1.46 Mn, 0.12 Cu, 0.10 V	N 1700 F	82,000	48	75	31	— 25	32.5	— 50	27	— 75	9, K
Cr-Mo. 0.22 C, 0.56 Mn, 4.77 Cr, 0.47 Mo	N 1750 F + 1575 F, T 1250 F	104,500	41	75	25.5	— 45	31.5	— 60	22	— 90	9, K
Mn-Ni-V. 0.29 C, 1 Mn, 1.54 Ni, 0.10 V	N 1775 F + 1475 F	195 Bhn	37	75	24.5	— 50	22.5	— 75	21.5	— 90	9, K
C-Mo. 0.33 C, 1.23 Mn, 0.24 Mo	WQ 1600 F, T 1275 F	.....	57.7	65	34.2	— 40	14.4	— 94	..	.....	35, K

A, Annealed; DN, Double Normalized; DT, Double Tempered; FG, Fine Grain; K, Charpy Keyhole Notch; N, Normalized; OQ, Oil Quenched; T, Tempered; V, Charpy V Notch; WQ, Water Quenched.

Table XIII. Strength and Ductility of Cast Steels at Low Temperature

Type of Steel and Composition	Temp, °F	Yield Strength, psi	Tensile Strength, psi	Percentage Elongation in 2 in.	Percentage Reduction of Area	Reference
Carbon. 0.21 C, 0.70 Mn	75	37,195	71,840	35	55	24
	−114	39,540	77,585	33	53	24
Nickel. 0.10 C, 0.69 Mn, 2.48 Ni	75	50,925	68,300	37	66	24
	−114	52,370	73,590	38	65	24
Ni-V. 0.17 C, 1.05 Mn, 1.73 Ni, 0.10 V	75	64,405	91,906	28	61	24
	−114	69,295	95,805	29	58	24
Vanadium. 0.23 C, 0.93 Mn, 0.20 Cr, 0.19 V	75	54,665	84,775	33	58	24
	−114	57,965	90,015	33	58	24

Table XIV. Strength and Ductility of a 3.5% Ni Steel at Low Temperature

Composition	Condition	Temp, °F	Yield Strength, psi	Tensile Strength, psi	Percentage Elongation in 2 in.	Percentage Reduction of Area	Reference
0.30 C, 0.70 Mn, 3.5 Ni	A	70	57,000	79,400	31.5	57.2	7
	A	−300	111,000	116,600	6.8	6.7	7
	HT	70	76,400	98,800	27.3	65.9	7
	HT	−300	132,900	148,700	15.5	17.6	7

A, Annealed; HT, Heat Treated.

The low-alloy, high-strength structural steels are being widely utilized and their toughness at low temperatures has received a great deal of consideration. Data obtained from studies of low-temperature toughness of these steels are presented in Table XI, where it is seen that most low-alloy, high-strength structural steels are superior to the ordinary carbon steels in low-temperature toughness. This should be expected because these low-alloy, high-strength steels are relatively low in carbon content and are thoroughly deoxidized. Although data are not available, it is probable that, as in other steels, the strength of these steels is greatly increased at low temperature. Thus these materials also might be utilized to greater advantage at low temperature if the increase in strength is considered and if their toughness is adequate. It should be noted that normalizing improves toughness at low temperature.

A good deal of information has been obtained concerning cast steels that vary widely in composition. This information, presented in Tables XII and XIII, indicates that, in general, at low temperature, cast steels are less tough than wrought steels. However, good toughness can be obtained in cast steels of relatively low alloy content if they are properly heat treated and are not exposed to temperatures lower than about minus 100 F. The data of the tables reveal that a number of cast steels have adequate toughness, provided they are conditioned properly for service at low temperature.

A considerable amount of work has been done to develop special steels for service in which the temperature is reduced to minus 300 F. The steels in one series are low in carbon content and contain as much as 8½% Ni. The data indicate that when the carbon content is low, no great advantage is obtained by increasing the nickel content to much more than 3% if the service does not

Table XV. Toughness of Some Special Steels at Low Temperature

Type of Steel, Composition and Grain Size	Condition	Bhn or Tensile Strength at Room Temperature, psi	Notched-Bar Impact Values								Reference and Type of Notch
			ft-lb	Temp, °F	ft-lb	Temp, °F	ft-lb	Temp, °F	ft-lb	Temp, °F	
2% Nickel. 0.15 C, 0.50 Mn, 2 Ni	N	128 Bhn	61	75	54	— 40	32	—100	7	—180	18, K
3.5% Nickel. 0.10 C, 0.50 Mn, 3.5 Ni	N	133 Bhn	58	75	51	— 80	40	—180	3	—310	18, K
5% Nickel. 0.10 C, 0.50 Mn, 5 Ni	N	147 Bhn	55	75	51	— 80	42	—180	6	—310	18, K
8.5% Nickel. 0.10 C, 0.50 Mn, 8.5 Ni	N	224 Bhn	44	75	40	— 80	35	—180	20	—310	18, K
Cr-Cu. 0.15 C, 0.45 Cu, 0.20 Si, 0.73 Cr	N	76,000	78	70	50	—110	37.5	—150	..	.....	6, Iz
Cr-Cu. 0.14 C, 0.76 Cr, 0.62 Cu, 0.27 Si, 0.07 Al	N	72,000	82.5	70	88	—110	87	—150	..	.....	6, Iz
Cr-Cu. 0.12 C, 0.75 Cr, 0.50 Cu, Al Treated	AR	.....	66.5	70	66.5	— 60	65	—110	23	—185	6, Iz
	N	.....	70.5	70	75	— 60	61	—110	48.5	—185	6, Iz
	N and T	.....	68.5	70	55.5	— 60	30.5	—110	16.5	—185	6, Iz

AR, As Rolled; Iz, Izod V Notch; K, Charpy Keyhole Notch; N, Normalized; T, Tempered.

Table XVI. Toughness of Chromium-Nickel and Chromium-Manganese-Nickel Steels at Low Temperature

Type of Steel and Composition	Condition	Tensile Strength at Room Temperature, psi	Notched-Bar Impact Values								Reference and Type of Notch
			ft-lb	Temp, °F	ft-lb	Temp, °F	ft-lb	Temp, °F	ft-lb	Temp, °F	
302. 0.11 C, 16.2 Cr, 11.5 Ni	WQ 2010 F	85,000	118	70	118	— 85	118	—292	..	.....	3, Iz
302. 0.09 C, 18.51 Cr, 9.65 Ni	A 1900 F	87,200	119	75	119	— 58	113	—110	119	—300	26, Iz
304. 0.07 C, 18.51 Cr, 9.65 Ni	A	87,200	119	70	117	— 60	113	—110	119	—300	26, Iz
304. 0.07 C, 17.14 Cr, 8.24 Ni	A, CD	135,900	66	75	67	— 58	68	—110	65	—300	26, Iz
Cr-Mn-Ni. 0.10 C, 17.62 Cr, 5.63 Mn, 4.75 Ni	A 1900 F	106,800	76	75	70	— 58	61	—300	..	.....	26, Iz
	A, CD	135,650	45	75	36	—300	..	.....	..	.....	26, Iz
316. 0.07 C, 18.41 Cr, 7.88 Ni, 2.80 Mo	A, CD	133,000	105	70	90	— 40	84	—110	..	.....	32, V
321. 0.05 C, 19.04 Cr, 9.15 Ni, 0.29 Ti	WQ 1900 F	86,000	183	70	177	— 40	169	—110	..	.....	32, V
	CD	131,000	91	70	87	— 40	83	—110	..	.....	32, V
347. 0.07 C, 18.97 Cr, 10.29 Ni, 0.95 Cb	WQ 1900 F	92,000	124	70	121	— 40	123	—110	..	.....	32, V
	A, CD	145,000	36	70	37	— 40	38	—110	..	.....	32, V

A, Annealed; CD, Cold Drawn; Iz, Izod V Notch; V, Charpy V Notch; WQ, Water Quenched.

Table XVII. Strength and Ductility of Chromium-Nickel and Chromium-Manganese-Nickel Steels at Low Temperature

Type of Steel and Composition	Condition	Temp, °F	Yield Strength, psi	Tensile Strength, psi	Percentage Elongation in 2 in.	Percentage Reduction of Area	Reference
302. 0.11 C, 16.2 Cr, 11.5 Ni	WQ 2010 F	70	44,800	93,000	48	52	3
	WQ 2010 F	−292	118,000	220,000	55	75	3
302. 0.12 C, 18.8 Cr, 8.1 Ni	WQ 2100 F	70	58,000	118,000	56	54	16
	WQ 2100 F	−423	125,000	269,000	25	30	16
304. 0.06 C, 18.25 Cr, 9.7 Ni	A	70	32,000	87,200	69	81	26
	A	− 60	44,800	143,700	66	75	26
	A	−150	51,000	164,000	54	71	26
	A	−300	87,600	225,000	44	63	26
304. 0.07 C, 18.22 Cr, 8.63 Ni	A and CD	70	91,500	152,000	22	64	9
	A and CD	−105	103,000	196,000	29	67	9
316. 0.07 C, 18.41 Cr, 9.88 Ni, 2.80 Mo	A and CD	70	119,000	133,000	23	73	9
	A and CD	−105	135,000	186,000	31	60	9
321. 0.05 C, 19.04 Cr, 9.15 Ni	WQ 1900 F	70	36,000	86,000	45	79	9
	WQ 1900 F	−105	38,000	143,000	46	74	9
321. 0.05 C, 19.04 Cr, 9.15 Ni	A and CD	70	85,000	131,000	22	69	9
	A and CD	−105	89,000	174,000	32	67	9
347. 0.07 C, 18.97 Cr, 10.29 Ni, 0.95 Cb	WQ 2000 F	70	50,000	92,000	41	76	9
	WG 2000 F	−105	52,000	146,000	40	69	9
	A and CD	70	128,000	145,000	14	60	9
	A and CD	−105	135,000	165,000	[illegible]	63	9
Cr-Mn-Ni. 0.07 C, 17.62 Cr, 4.57 Ni, 5.61 Mn	A and CD	70	86,600	135,650	43	62	26
	A and CD	−290	96,500	195,650	17	15	26

A, Annealed; CD, Cold Drawn; WQ, Water Quenched.

involve temperatures below minus 180 F. But if the temperature in question approaches minus 300 F, it appears that as much as about 8½% Ni is required to give high toughness, which can be retained in the steel if it is normalized. The strength and ductility of a 3½% Ni steel at low temperature are given in Table XIV. At temperatures as low as minus 185 F, satisfactory low-temperature toughness is obtained also in the chromium-copper steels when they have been normalized and properly deoxidized, as shown in Table XV.

Austenitic Alloys. The austenitic chromium-nickel and chromium-manganese-nickel types of stainless steels are especially adapted for service at low temperatures because of their high degree of stability at minus 300 F and lower. The austenitic chromium-nickel steels are somewhat tougher than the chromium-manganese-nickel steels, and the addition of molybdenum, titanium and columbium to the well-known 18% Cr—8% Ni steel does not affect toughness greatly at low temperature. Moreover, only the simplest solution heat treatment is required in fabricating these alloys, regardless of the size of section. As shown in Tables XVI and XVII, the toughness of 18-8 steel is not reduced when the temperature is decreased to minus 300 F, and the yield strength and tensile strength of the metal are greatly increased without appreciable loss of ductility. This combination of properties is considered unique in the field of ferrous metallurgy because the 18-8 steel is the only steel that retains its toughness unimpaired at such a low temperature. Furthermore, welds of the 18-8 steels have high toughness at low temperature, and much welded equipment has been used successfully under such conditions.

It has been known for a long time that nickel and nickel alloys retain their toughness to a remarkable extent at low temperature. The toughness of iron-nickel alloys reaches a maximum when the nickel content is approximately 40%. At this point the iron-nickel alloy is as tough and ductile at minus 300 F as at room temperature. Evidently the structural stability is at a maximum when this percentage of nickel is present. Data are given in Tables XVIII and XIX concerning the toughness, strength and ductility of iron-nickel alloys at low temperature.

The use of manganese for imparting low-temperature

Table XVIII. Toughness of Annealed Iron-Nickel Alloys at Low Temperature

Percentage Nickel	Notched-Bar Impact Values						Reference and Type of Notch
	ft-lb	Temp, °F	ft-lb	Temp, °F	ft-lb	Temp, °F	
25.9	28	75	6.3	−112	3.3	−310	27, K
28.9	26	75	10	−112	4.3	−310	27, K
32	26	75	18	−112	6.6	−310	27, K
35.3	28	75	19	−112	11.3	−310	27, K
37.3	27	75	26	−112	12.3	−310	27, K
40	25.3	75	27.6	−112	27	−310	27, K
45.7	26.3	75	29.3	−112	27.6	−310	27, K
49.4	25.3	75	29.3	−112	29.3	−310	27, K
68.4	28.6	75	25.3	−112	27.6	−310	27, K
98.7	27.6	75	27	−112	29.3	−310	

K, Charpy Keyhole Notch.

Table XIX. Strength and Ductility of Iron-Nickel Alloys at Low Temperature

Alloy and Composition	Condition	Temp, °F	Yield Strength, psi	Tensile Strength, psi	Percentage Elongation in 2 in.	Percentage Reduction of Area	Reference
Fe-Ni. 0.16 C, 35.8 Ni, 0.86 Mn	WQ 1920 F	70	52,400	81,100	32	[illegible]	16
	WQ 1920 F	−423	127,000	144,000	20	60	16
Fe-Ni. 0.04 C, 35.98 Ni, 0.29 Mn	.....	70	60,500	75,000	28	72	9
	.....	−300	91,000	129,000	32	61	9
Fe-Ni. 0.12 C, 42.06 Ni, 0.94 Mn	.....	70	50,500	81,500	36	70	9
	.....	−300	73,000	132,000	41	62	9
Nickel. Commercially Pure	A	70	24,600	65,500	42	78	28
	A	−112	27,600	76,400	43	73	28
	A	−292	27,900	97,000	53	74	28

A, Annealed; WQ, Water Quenched.

Table XX. Toughness of High-Manganese Steels at Low Temperature

Composition	Condition	Tensile Strength at Room Temperature, psi	Notched-Bar Impact Values								Reference and Type of Notch
			ft-lb	Temp, °F	ft-lb	Temp, °F	ft-lb	Temp, °F	ft-lb	Temp, °F	
0.07 C, 9.64 Mn	AC 1850 F	96,000	1	70	1	— 58	1	—148	1	—300	26, Iz
0.06 C, 16 Mn	AC 1850 F	100,800	64	70	9	— 58	7	—148	5	—300	26, Iz
0.10 C, 19.32 Mn	AC 1850 F	119,500	88	70	52	— 58	41	—148	9	—300	26, Iz
0.11 C, 24.26 Mn	AC 1850 F	111,000	90	70	43	— 58	39	—148	24	—300	26, Iz
0.11 C, 29.82 Mn	AC 1850 F	80,000	90	70	97	— 58	75	—148	36	—300	26, Iz
0.10 C, 50.1 Mn	AC 1850 F	78,500	82	70	57	— 58	31	—148	9	—300	26, Iz
0.11 C, 15.85 Mn, 5.52 Cr	AC 1850 F	145,000	85	70	84	— 58	69	—148	28	—300	26, Iz
0.11 C, 19.78 Mn, 5.57 Cr	AC 1850 F	116,000	80	70	72	— 58	78	—148	36	—300	26, Iz
0.11 C, 24.5 Mn, 5.61 Cr	AC 1850 F	99,000	90	70	91	— 58	79	—148	78	—300	26, Iz
0.09 C, 19.30 Mn, 12.96 Cr	AC 1850 F	105,000	96	70	97	— 58	112	—148	106	—300	26, Iz
0.06 C, 16 Mn, 5 Ni	AC 1850 F	.....	97	70	36	—300	..	.....	..	.....	26, Iz
0.10 C, 16.82 Mn, 2.01 Ni, 0.98 Cu, 3.14 Cr	AC 1850 F	103,500	102	70	41	—300	..	.....	..	.....	26, Iz
0.15 C, 16 Mn, 2 Ni, 1.5 Cu, 3 Cr	AC 1850 F	109,150	99	70	94	—300	..	.....	..	.....	26, Iz
0.14 C, 16.17 Mn, 13.2 Cr, 2.07 Ni	AC 1850 F	110,000	100	70	95	—300	..	.....	..	.....	26, Iz
1.18 C, 13 Mn, 0.50 Si	C, WQ 1850 F	.....	105	75	58	—100	..	.....	..	.....	29, V
1.03 C, 12.9 Mn, 0.52 Si	C, WQ 1850 F	.....	94	75	50	—100	..	.....	..	.....	29, V
1.17 C, 12.7 Mn, 0.53 Si, 3.56 Ni	C, WQ 1850 F	.....	103	75	88	—100	..	.....	..	.....	29, V
	AF	.....	198	75	140	—103	12	—300	..	.....	29, V

AC, Air Cooled; AF, As Forged; C, Cast; Iz, Izod V Notch; V, Charpy V Notch; WQ, Water Quenched.

toughness to iron has been thoroughly considered and, as indicated in Tables XX and XXI, the addition of as much as 50% Mn to iron fails to produce a material as tough at minus 300 F as at room temperature. However, the addition, for example, of 5% Cr to iron containing about 25% Mn produces a material that is fully austenitic in character, and that does retain full toughness when exposed to temperature as low as minus 300 F. The manganese content of iron can be reduced further to about 16% with low carbon content when small amounts of nickel, chromium and copper are added, without sacrificing toughness at about minus 300 F. The reason for this is apparently that the manganese austenite is fully stabilized in the presence of low carbon content, by the small percentages of nickel, chromium and copper. When the carbon content is increased to about 1% in steels that contain about 12 to 14% Mn, the resulting metal has excellent toughness at minus 100 F, but does suffer a loss in toughness when the temperature is decreased further to minus 300 F. These latter steels represent the well-known Hadfield's manganese steels that have been used successfully at moderately low temperatures down to about minus 100 F.

Properties of Nonferrous Alloys at Low Temperature. The available data concerning aluminum and aluminum alloys show that the wrought commercial aluminum designated as 2 S-O retains its toughness in the annealed condition down to temperatures in the vicinity of minus 300 F. The Al-Cu-Ni-Mg alloy designated as 18 S-T has relatively low toughness and does not change noticeably when it is exposed to similar low temperature. The 24 S-T aluminum alloy, containing copper and magnesium, also retains its toughness when exposed to temperatures as low as minus 105 F. The same is true of the 52 S alloy and the cast aluminum alloy designated as 195T. In Tables XXII and XXIII, concerning the toughness and tensile strength of the different aluminum alloys, the data indicate that neither the strength nor the ductility of the various aluminum alloys changes greatly when subjected

Table XXI. Strength and Ductility of High-Manganese Steels at Low Temperature

Composition	Condition	Temp, °F	Yield Strength, psi	Tensile Strength, psi	Percentage Elongation in 2 in.	Percentage Reduction of Area	Reference
0.06 C, 16 Mn, 2 Ni, 1.5 Cu, 3 Cr	AC 1850 F	70	41,300	103,000	44	47	26
	AC 1850 F	—300	.....	179,300	43	35	26
0.15 C, 16 Mn, 2 Ni, 1.5 Cu, 3 Cr	AC 1850 F	70	48,350	109,150	34	29	26
	AC 1850 F	—300	.....	157,750	17	15	26
0.09 C, 16.4 Mn, 12.9 Cr	AC 1880 F	70	28,000	120,500	58	55	26
	AC 1880 F	—300	.....	139,600	16	13	[illegible]
0.14 C, 16.17 Mn, 13.2 Cr, 2 Ni	AC 1880 F	70	36,000	110,000	63	63	26
	AC 1880 F	—300	.....	166,450	30	25	26
0.07 C, 16.5 Mn, 12.6 Cr, 2 Ni, 1 Cu	AC 1880 F	70	60,000	98,500	49	73	26
	AC 1880 F	—300	.....	187,750	53	62	26
1.27 C, 12.69 Mn, 0.12 Si	WQ 1830 F	70	77,300	148,000	44	49	16
	WQ 1830 F	—423	.....	146,000	[illegible]	0	16

AC, Air Cooled; WQ, Water Quenched.

Table XXII. Toughness of Aluminum Alloys at Low Temperature

Alloy Number and Composition	Condition	Tensile Strength at Room Temperature, psi	Notched-Bar Impact Values								Reference and Type of Notch
			ft-lb	Temp, °F	ft-lb	Temp, °F	ft-lb	Temp, °F	ft-lb	Temp, °F	
2 S-O. 0.07 Fe, 0.054 Si	A	13,200	19	75	20	—112	21	—184	27	—292	28, Iz
3 S. 1.04 Mn, 0.14 Si, 0.12 Cu	AR	19,500	36	75	36	—110	..	.....	..	.....	32, V
17 S-T. 0.6 Mn, 0.6 Mg, 3.72 Cu	WQ 940 F	59,500	15	75	18	—110	..	.....	..	.....	32, V
	WQ 940 F, CR 5.5% red	64,500	12	75	14	—110	..	.....	..	.....	32, V
18 S-T. 3.5 Cu, 1.86 Ni, 0.76 Mg	WQ 970 F, Ag 1 hr 212 F	48,000	7	75	7.5	—112	8	—184	8	—292	28, Iz
24 S-T. 4.32 Cu, 1.44 Mg, 0.48 Mn	WQ 920 F	65,500	13	75	16	—110	..	.....	..	.....	32, V
25 S-T. 3.99 Cu, 0.81 Si, 0.79 Mn	WQ 965 F, Ag 320 F	56,000	13	75	16	—110	..	.....	..	.....	32, V
52 S. 2.35 Mg, 0.12 Si, 0.14 Fe	AR	31,500	58	75	58	—110	..	.....	..	.....	32, V
195 T. 4.35 Cu, 0.84 Si, 0.53 Fe	C, 16 hr 960 F, WQ 210 F	33,500	4	75	5	—110	..	.....	..	.....	32, V

A, Annealed; Ag, Aged; AR, As Rolled; C, Cast; CR, Cold Rolled; Iz, Izod V Notch; V, Charpy V Notch; WQ, Water Quenched.

to temperatures as low as minus 112 F. In fact the indications are that the ductility of the aluminum is increased slightly as a result of exposure to low temperature. It is apparent that cold rolling the aluminum alloys does not affect the ductility at low temperature, which means that aluminum and aluminum alloys have a high degree of structural stability when exposed under such conditions.

As shown in Tables XXIV and XXV, copper and most copper alloys possess remarkable toughness when exposed to extremely low temperature. The only exceptions are the copper-beryllium and the cast Cu-Zn-Pb-Sn alloys. The copper-beryllium alloys have good low-temperature toughness in the annealed condition but, when these alloys are aged to obtain high strength, their toughness reaches a low point and remains low when exposed to low temperature. The same is true of the Cu-Zn-Pb-Sn alloys, particularly in the cast condition, in which their toughness is low and remains so at low temperature. Copper and copper alloys increase greatly in tensile strength when they are exposed to low temperature, and the increase in tensile strength is not generally accompanied by a decrease in ductility. The wrought silicon bronzes containing 1½ to 4% Si have been used to a wide extent, as well as the copper-nickel alloys for low-temperature service involved in the handling of liquid oxygen. Experience has indicated that welds made in silicon bronze have excellent toughness at low temperature. Copper and copper alloys

Table XXIII. Strength and Ductility of Aluminum Alloys at Low Temperature

Alloy Number and Composition	Condition	Temp, °F	Yield Strength, psi	Tensile Strength, psi	Percentage Elongation in 2 in.	Reference
2 S-O. Commercially Pure Aluminum	A	75	4,150	13,200	41.5	30
	A	−112	4,150	15,200	47.5	30
2 S. Commercially Pure Aluminum	HR	75	19,700	23,500	16	30
	HR	−112	21,350	24,700	18	30
3 S. 1.2 Mn	¼ HR	75	18,300	19,900	24	30
	¼ HR	−18	18,800	21,200	24	30
	¼ HR	−112	19,700	23,300	28	30
	HR	75	25,300	28,700	10	30
	HR	−112	28,200	31,900	12.5	30
17 S-O. 4 Cu, 0.5 Mn, 0.5 Mg	A	75	9,800	27,500	22	30
	A	−112	10,500	29,300	26	30
17 S-T. 4 Cu, 0.5 Mn, 0.5 Mg	ST	75	45,500	68,000	15	30
	ST	−112	46,500	70,000	16	30
18 S-T. 4 Cu, 0.5 Mg, 2 Ni	ST—PT	75	54,800	66,500	12.3	30
	ST—PT	−112	56,000	68,900	14	30
24 S-T. 4.5 Cu, 0.6 Mn, 1.5 M■	ST	75	43,700	70,100	23.3	30
	ST	−112	46,400	74,100	25.3	30
25 S-O. 4.5 Cu, 0.8 Si, 0.8 Mn	A	75	19,000	28,100	15	30
	A	−112	.....	29,500	18	30
25 S-T. 4.5 Cu, 0.8 Si, 0.8 Mn	ST—PT	75	36,500	61,600	20	30
	ST—PT	−112	37,000	63,700	20.6	30
52 S. 2.5 Zn, 0.25 Cr	¼ HR	75	29,300	35,000	19.5	30
	¼ HR	−112	29,300	36,700	23	30
61 S-T. 0.25 Cu, 0.6 Si, 1 Mg, 0.25 Cr	HR	75	38,600	43,500	14	30
	HR	−112	39,200	45,600	18.5	30
	ST—PT	75	39,200	46,000	21	30
	ST—PT	−112	41,700	50,400	22.5	30
75 S-T. 1.6 Cu, 0.2 Mn, 2.5 M■, 5.6 Zn, 0.3 Cr	ST—PT	75	70,300	81,300	15	30
	ST—PT	−112	73,300	85,400	15.3	30
43. 5 Si	As Cast	75	8,500	20,000	4.5	30
	As Cast	−112	8,000	20,200	5	30
112. 7 Cu, 1.7 Zn	As Cast	75	20,900	26,100	0.75	30
	As Cast	−112	22,500	28,200	1	30
122. 10 Cu, 0.2 Mg	As Cast	75	27,000	30,100	0.25	30
	As Cast	−112	27,500	28,900	0	30
142T-61. 4 Cu, 1.5 Mg, ■ Ni	C, ST—PT	75	.....	37,000	0	30
	C, ST—PT	−112	.....	42,500	0	30
195T-4. 4.5 Cu, 0.8 Si	ST	75	23,200	35,100	4.5	30
	ST	−112	25,200	36,800	4	30

A, Annealed; C, Cast; HR, Hard Rolled; PT, Precipitation Treatment; ST, Solution Treatment.

Table XXIV. Toughness of Copper Alloys at Low Temperature

Alloy and Composition	Condition	Tensile Strength at Room Temperature, psi	Notched-Bar Impact Values: ft-lb	Temp, °F	ft-lb	Temp, °F	ft-lb	Temp, °F	ft-lb	Temp, °F	Reference and Type of Notch
Pure C. 99.98 Cu	A	31,400	43	75	44	−112	44	−184	50	−290	28, Iz
Cu-Al-Zr. 7.31 Al, 1.02 Zn, 0.44 Mn	A	77,300	24	75	24	−112	21	−184	20	−290	28, Iz
Cu-Be. 2.56 Be	WQ 1470 F	76,200	41	75	40	−112	40	−292	..	.....	28, Iz
	WQ 1470 F, Ag 2 hr 570 F	187,000	2	75	3	−112	3	−292	..	.....	28, Iz
Cu-Ni-Al. 5.86 Ni, 1.73 Al	WQ 1650 F	51,500	58	75	67	−292	..	.....	..	.....	28, Iz
Cu-Ni. 20.58 Ni	A	51,500	77	75	79	−112	85	−292	..	.....	28, Iz
Cu-Ni. 45.78 Ni	A	60,000	80	75	81	−112	86	−292	..	.....	28, Iz
Cu-Ni-Zn. 19.49 Ni, 5.43 Zn	A	54,700	68	75	56	−110	53	−175	..	.....	31, K
Cu-Si. 3.05 Si, 0.98 Mn	A	62,400	66	75	69	−110	64	−175	..	.....	31, K
Cu-Sn-P. 3.99 Sn, 0.40 P	HD	87,000	46	75	44	− 42	..	.....	..	.....	9, Iz
Admiralty Metal. 28.44 Zn, 0.95 Sn	A	46,500	61	75	62	−110	59	−175	..	.....	31, K
Cu-Zn. 3.05 Zn, 0.10 Fe	A	51,100	66	75	69	−112	78	−290	..	.....	28, Iz
Naval Brass. 36.96 Zn, 0.31 Sn, 0.08 Pb	HD	72,000	38	75	37	− 42	..	.....	..	.....	9, Iz
Cu-Zn-Pb-Sn, 38.85 Zn, 1.43 Mn, 1.25 Pb, 0.9 Sn	A	72,400	20	75	22	−112	20	−292	..	.....	28, Iz
Cu-Zn-Pb-Sn. 5 Zn, 5 Pb, 5 Cu	C	.....	5.5	75	6	− 60	6	− 75	..	.....	9, K

A, Annealed; Ag, Aged; C, Cast; HD, Hard Drawn; Iz, Izod V Notch; K, Charpy Keyhole Notch; WQ, Water Quenched.

in general have a high degree of structural stability and can be depended on to remain relatively free from notch sensitivity accompanied by brittleness at subatmospheric temperature.

Magnesium alloys have comparatively little toughness at room temperature and, as shown in Tables XXVI and XXVII, the toughness does not change with decrease in temperature. However, there is a marked increase in

Table XXV. Strength and Ductility of Copper Alloys at Low Temperature

Alloy and Composition	Condition	Temp, °F	Yield Strength, psi	Tensile Strength, psi	Percentage Elongation in 2 in.	Percentage Reduction of Area	Reference
Pure Copper. 99.98 Cu	A	75	8,600	31,400	48	76	28
	A	−112	10,100	38,500	47	74	28
	A	−184	10,800	41,200	45	70	28
	A	−292	11,500	50,800	58	77	28
Cu-Al-Zn. 7.31 Al, 1.02 Zn, 0.44 Mn	A	75	26,700	77,300	29	29	28
	A	−112	27,100	82,700	31	30	28
	A	−292	29,200	96,100	28	30	28
Cu-Be. 2.56 Be	WQ 1470 F	75	24,900	76,200	36	50	28
	WQ 1470 F	−112	29,100	86,700	38	54	28
	WQ 1470 F	−292	50,000	112,000	41	57	28
	WQ 1470 F, Ag 1 hr 570F	75	125,000	187,000	2.6	5	28
	WQ 1470 F, Ag 1 hr 570 F	−112	147,000	202,000	4	5	28
	WQ 1470 F, Ag 1 hr 570 F	−292	155,000	214,000	3	6	28
Cu-Ni-Al. 5.86 Ni, 1.73 Al	WQ 1650 F	75	11,400	51,500	42	80	28
	WQ 1650 F	−112	16,400	57,300	42	79	28
	WQ 1650 F	−292	22,800	67,200	49	82	28
Cu-Ni. 20.58 Ni	A	75	27,700	51,500	[illegible]	78	28
	A	−292	32,500	73,700	36	72	28
Cu-Ni. 45.78 Ni	A	75	19,600	60,000	40	77	28
	A	−112	22,100	72,200	48	75	28
	A	−292	26,000	89,600	57	76	28
Cu-Si. 2.75 Si, 0.97 Mn	CD	75	.....	74,200	40	75	31
	CD	−112	.....	82,900	32	72	31
	CD	−310	.....	100,000	[illegible]	72	31
Cu-Sn-P. 3.99 Sn, 0.40 P	HD	75	82,500	87,000	20	70	9
	HD	− 42	85,000	93,000	20	60	9
Cu-Zn. 30.5 Zn, 0.10 Fe	A	75	28,200	51,100	49	77	28
	A	−112	27,300	57,100	60	79	28
	A	−292	29,600	73,500	75	73	28
Naval Brass. 36.96 Zn, 0.31 Sn, 0.08 Pb	HD	75	54,000	72,000	24	65	9
	HD	− 42	58,000	74,500	26	65	9
Cu-Zn-Pb-Sn. 38.85 Zn, 1.43 Mn, 1.25 Pb, 0.9 Sn	A	75	24,000	72,400	28	44	28
	A	−112	27,000	75,500	31	43	28
	A	−292	28,800	94,800	37	41	28

A, Annealed; WQ, Water Quenched; Ag, Aged; CD, Cold Drawn; HD, Hard Drawn

Table XXVI. Toughness of Magnesium Alloys at Low Temperature

ASTM Designation and Composition	Condition	Tensile Strength at Room Temperature, psi	Notched-Bar Impact Values				
			ft-lb	Temp, °F	ft-lb	Temp, °F	Reference and Type of Notch
M1. 1 Mn	Ex	39,000	3.9	77	2.6	−110	32, V
AZ61. 6 Al, 1 Zn	Ex	46,800	6.9	77	2.9	−110	32, V
A10. 10 Al	C	22,300	0.9	77	0.7	−110	32, V
	C, HT	34,700	3.2	77	2.6	−110	32, V
	C, HT, Ag	38,500	0.8	77	0.8	−110	32, V
AZ63. 6 Al, 3 Zn	C	27,100	1.8	77	1.6	−110	32, V
	C, HT	34,500	4.1	77	3.4	−110	32, V
	C, HT, Ag	38,900	1.6	77	1.5	−110	32, V

Ag, Aged; C, Cast; Ex, Extruded; HT, Heat Treated; K, Charpy Keyhole Notch.

Table XXVII. Strength and Ductility of Magnesium Alloys at Low Temperature

ASTM Designation and Composition	Condition	Temp, °F	Yield Strength, psi	Tensile Strength, psi	Percentage Elongation in 2 in.	Percentage Reduction of Area	Reference
M1. 1 Mn	Ex	77	28,000	39,000	6	7.0	32
	Ex	−110	30,900	52,000	3	4.5	32
AZ61. 6 Al, 1 Zn	Ex	77	33,900	46,800	12.7	17.0	32
	Ex	−110	41,000	50,000	12.2	16.5	32
A10. 10 Al	C	77	15,800	22,300	1.7	2.1	32
	C	−110	17,900	22,000	1	1.6	32
	C HT	77	15,500	34,700	8.5	9.8	32
	C HT	−110	18,400	38,400	7.2	8.5	32
	C HT Ag	77	24,600	38,500	3	2.9	32
	C HT Ag	−110	25,900	38,900	2	2.6	32
AZ63. 6 Al, 3 Zn	C	77	13,800	27,100	4.5	5.6	32
	C	−110	15,400	24,900	2.7	4.3	32
	C HT	77	14,200	34,500	8.7	10.9	32
	C HT	−110	17,100	37,200	8.2	9.7	32
	C HT Ag	77	21,500	38,900	4.5	5.8	32
	C HT Ag	−110	24,400	35,400	2.5	3.4	[illegible]

Ag, Aged; C, Cast; Ex, Extruded; HT, Heat Treated.

Table XXVIII. Toughness of Nickel Alloys at Low Temperature

Trade Name and Composition	Condition	Bhn and Tensile Strength at Room Temperature, psi	Notched-Bar Impact Values						Reference and Type of Notch
			ft-lb	Temp, °F	ft-lb	Temp, °F	ft-lb	Temp, °F	
Monel. 28.86 Cu, 0.28 Mn	A	70,800	90	75	90	—112	97	—292	28, Iz
	C	135 Bhn	74	75	90	—310	..	.....	33, V
"H" Monel. 29.5 Cu, 3 Si	C	210 Bhn	44	75	47	—310	..	.....	33, V
"K" Monel. 29.9 Cu, 3.1 Al, 0.27 Si	CD and T	157,000	27	75	28	— 40	28	—110	32, V
Inconel. 13.4 Cr, 7.4 Fe, 0.53 Mn, 0.06 C	Q 1750 F	94,000	130	75	136	— 40	134	—110	32, V
	CD, T 525 F	152,000	54	75	61	— 40	59	—110	32, V

A, Annealed; C, Cast; CD, Cold Drawn; Iz, Izod V Notch; Q, Quenched; T, Tempered; K, Charpy Keyhole Notch; V, Charpy V Notch.

Table XXIX. Strength and Ductility of Nickel Alloys at Low Temperature

Trade Name and Composition	Condition	Temp, °F	Yield Strength, psi	Tensile Strength, psi	Percentage Elongation in 2 in.	Percentage Reduction of Area	Reference
Monel Metal. 28.86 Cu, 0.28 Mn	A	75	20,900	70,800	41	75	28
	A	—112	27,100	85,300	40	74	28
	A	—292	29,600	113,000	51	72	28
K Monel. 29.9 Cu, 3.1 Al, 0.27 Si	CD and T	75	126,000	157,000	15	37	32
	CD and T	—110	134,000	172,000	17	41	32
Inconel. 13.4 Cr, 7.4 Fe, 0.53 Mn, 0.06 C	Q 1750 F	75	36,000	94,000	37	64	32
	Q 1750 F	—110	42,500	106,000	40	64	32
	CD and T 525 F	75	147,000	152,000	7	49	32
	CD and T 525 F	—110	155,000	164,000	10	51	32

A, Annealed; CD, Cold Drawn; Q, Quenched; T, Tempered.

tensile strength when wrought magnesium alloys are cooled to subnormal temperatures. The cast magnesium alloys designated as A10 and AZ63 undergo neither a decrease nor an increase in tensile strength during exposure at low temperature, which indicates that in the cast condition the magnesium alloys are considerably more stable structurally than they are in the wrought condition. In this respect the magnesium alloys are similar to the aluminum-base alloys; however magnesium alloys are not so tough at room temperature as aluminum alloys.

The nickel-base alloys known as Monel and Inconel have excellent toughness at low temperature. Even in "K" Monel, which has less toughness at room temperature than standard Monel, no change occurs at low temperature. Also these nickel alloys increase greatly in tensile strength at low temperature without a serious sacrifice of ductility. The information in Tables XXVIII and XXIX indicates that the nickel alloys are structurally stable at low temperature, and it can be assumed that welds of the alloys will be tough at subatmospheric temperature as low as minus 300 F and even lower.

Factors Involved in Fabrication of Metals for Low-Temperature Service. Welding has become so important a process for fabrication of equipment operating at low temperature that it deserves special mention. The two methods of welding generally practiced are gas welding and electric welding. Ordinarily an electrical method is employed for welding the ferrous metals. The only exception is that atomic hydrogen welding is sometimes used for joining ferrous alloys such as 18-8 steels. The nonferrous metals are commonly welded by a gas process, usually oxyacetylene.

When fabrication includes welding, it is necessary first to select the parent metal that has ample toughness for the service under consideration, and then to join the sections of parent metal with a weld metal of similar composition that has been proved by testing to be substantially as tough as the parent metal. Welded joints are generally considered to include three zones, which merge into one another. These zones are the base or parent metal, the weld metal and the heat-affected zone between the weld metal and the base metal. Great emphasis should be placed on the quality of weld metal, since usually the adjacent zone and the parent metal will have sufficient toughness if the proper metal is selected. If the weld metal is of poor quality or if harmful notches exist between the weld and the parent metal, difficulty may result from low toughness in the weld or from a notch effect in the metal immediately adjacent to the weld.

Residual stresses exist in welded structures and, in instances where it is possible to do so, the equipment should be stress relieved before installation, in order to avoid difficulties that might result from concentration of stresses. One of the important locations in which stress concentration can occur is in the heat-affected zone, which may be stronger and less ductile than either the base metal or the welded metal. In air-hardenable steels, for example, a stress-relieving treatment will serve a useful purpose in avoiding stress concentration. Welds are essentially cast metal, and the use of heat treatment should be considered as with steel castings.

The thickness of section is important in building equipment for service at low temperature. Where heavy sections are involved, it is necessary to deposit several beads successively during the welding operation. In this process, the metal adjacent to the weld is heated and cooled several times, during which structural changes occur in the metal. These changes are controlled to a large extent by the type of heat treatment to which the parent metal has been subjected previously, and thorough investigation should be made concerning the properties of the metal next to the weld. Samples should be tested to determine the final heat treating procedure that should be applied to the finished equipment. If these precautions are observed and if the material for the particular service has been selected judiciously, the weldment should have adequate toughness at low temperature.

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Wear of Metals

BY THE SUBCOMMITTEE ON WEAR OF METALS*

WEAR is one of the most destructive influences to which metals are subjected. Nearly everything that moves causes and is exposed to wear, simultaneously bringing about and undergoing progressive destruction. The problem of wear is thus of vital concern to metallurgists and engineers. The purpose of this article is to discuss the variables connected with the wear of metals and to suggest means for minimizing the undesirable effects of wear.

Wear resistance is not an inherent property of a metal, which may be considered by itself. It is complicated by many factors and cannot be determined apart from the specific conditions of service. Wear is the resultant of the material itself, of the mating material, and of the operating conditions of service. In combination, these varying factors serve to cause different types of wear. Since there is no universal type of wear, there is no universal method or machine for testing wear.

Definition. For the purpose of this article wear may be considered essentially a surface phenomenon, and consists of the gradual mechanical deterioration of contacting surfaces, as by tearing off particles through friction. Wear may be modified by the simultaneous effect of corrosion or other chemical attack.

Theory and Mechanism of Wear. *Types and Classifica-*

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tions. Wear occurs by the displacement and detachment of metallic particles from a metallic surface. This process may be caused by contact with another metal (metallic wear), by contact with either a metallic or a nonmetallic abrasive (abrasion), or by contact with flowing liquids or gases (erosion). This last type is frequently combined with some form of corrosion, whereas metallic wear and abrasion may or may not be.

A logical method of classifying wear depends on the nature of the contacting surfaces, as follows:

I Metal against metal
  A Sliding friction
    1 Lubricated (engine crosshead, shaft in bearing)
    2 Nonlubricated (brake shoe against wheel)
  B Rolling friction
    1 Lubricated (roller bearings, gears)
    2 Nonlubricated (wheel on track)
II Metal against nonmetal or abrasive
  A Sliding friction
    1 Wet (conveyer screws for wet sand)
    2 Dry (plowshares)
  B Rolling friction
    1 Wet (ball and rod mills)
    2 Dry (jaw crushers, crushing rolls)
  C Impact of loose abrasive
    1 Wet (impellers)
    2 Dry (sand blast)
III Metal against liquids or vapors
  A Wet steam (turbines)
  B Combustion gases (gas turbines)

Frequently these conditions of service are combined so that an application which was originally metal against metal may evolve into metal against nonmetal or abrasive by the introduction of nonmetallic abrasive particles or of the abraded particles of the original surfaces; rolling and sliding friction are frequently combined, and too often lubrication fails.

The usual conception of metal-to-metal wear involves the mechanical interference of tiny projections or asperities. These produce friction when they interfere with the relative motion of contacting surfaces. When two rather smooth surfaces are in contact, the first step in producing wear—penetration or displacement of small particles—is more difficult than when the contacting surfaces are rough. When two surfaces are moving in contact, some of the projections of the one will find the depressions in the other and will increase the resistance to further movement. If the driving force is sufficient to maintain movement, the interlocked projections are deformed and, if made of sufficiently brittle material, may break or be torn off.

A consideration of this idea leads to the belief that hardness, toughness and surface smoothness are necessary for wear resistance—hardness to resist initial indentation, toughness to resist the dislodgment of metallic particles, and surface smoothness to eliminate the projections.

In abrasive wear it is probable that the abrading particles first penetrate the metal and then cause the tearing off of the metallic particles. Since the ease with which the abrading particles may dig in depends on the hardness of the metal, and since the ease with which the deformed metal may be torn off depends on the toughness, it is apparent that the properties necessary for resistance to abrasive wear are the same as those necessary for resistance to metallic wear. However, of the two factors, hardness and toughness, hardness is probably more important, a fact that accounts for the frequent use of surface-hardened metals primarily to minimize wear.

When two surfaces move one across the other, as in Fig. 1a, it is apparent that the peaks of the irregularities must either shift position or break. If the local stresses, which may be quite complex, are sufficiently great, failure occurs as in Fig. 1b. Such failure may also be caused by fatigue resulting from the local stresses. Wear of this type may occur regardless of whether the contact is by sliding, rolling or impact; it is particularly severe in the case of abrasive wear (Fig. 1c).

Wear of metal against metal may be minimized by increased smoothness of the rubbing faces and by lubrication that separates the surfaces. If the film of lubricant is sufficiently thick, metallic contact may be completely eliminated; friction then depends on viscosity of the oil film, and metallic wear is reduced to a negligible amount. This condition, known as "thick or fluid film" or "complete lubrication", can be controlled chiefly by means of design.

Complete lubrication is not always attainable. More frequently partial failure of the oil film occurs and "boundary lubrication" results. Friction and removal of metal occur as described above; the amount depends on speed, pressure, nature of the surfaces, and efficiency of the residual oil film. The extreme example is dry wear with no lubricant.

Dry wear permits friction to generate considerable heat. As temperatures rise, the strength and hardness of metallic materials decrease, rendering them more susceptible to wear. Oxidation or other chemical attack is facilitated on the faces subjected to friction and this may cause further loss of metal. The temperatures involved are much higher than might be suspected. Intrinsic hardness or hardness resulting from massive or very stable structural compounds, may be useful in combatting dry wear. The hardness of heat treated structures is often less valuable, perhaps because it is readily reduced by the heat of friction.

Abrasive wear is most frequently caused by nonmetallic materials, usually as a result of scratching. In general, a substance is seriously scratched only by materials harder than itself. Most protection against abrasion is based on this principle. However, the principle is not always true, perhaps because even nominally pure substances may contain harder foreign particles, or because there are additional factors that are unknown or insufficiently understood. Rubber provides an interesting exception where toughness or elasticity appears much more important than hardness in many applications.

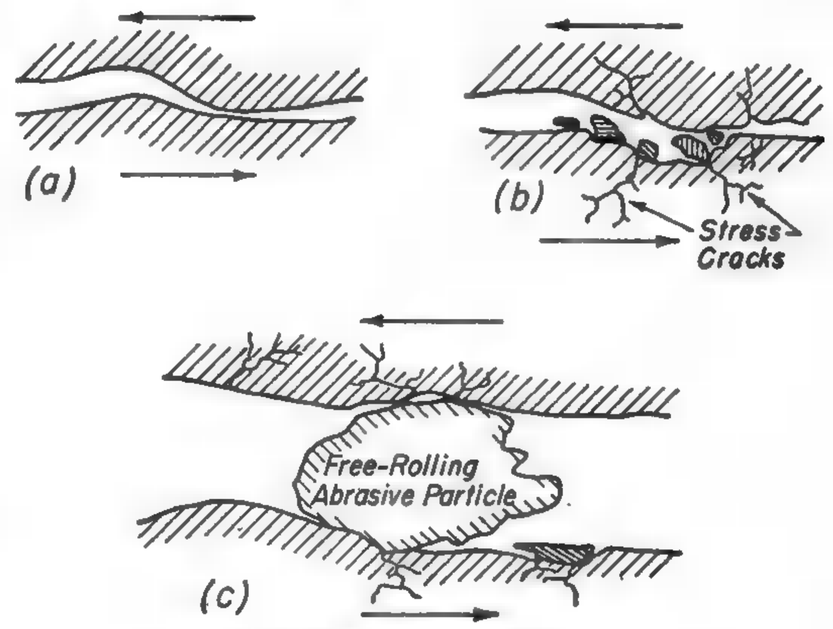

Fig. 1 Schematic illustration of wear

Cold work and plastic flow may accompany the wear of metals. During cold work the dimensions of the wearing objects change slightly to accommodate plastic compression of the metal. Such work hardening is especially important in wear resulting from impact, since appreciable hardening of the surface increases the strength and endurance limit. The operation of this factor is important in the wear resistance of the bronzes and austenitic manganese steels.

Some forms of abrasion involve little or no impact, but in other forms the kinetic energy of a blow is an important factor. Although wear, in the ordinary sense, does not result from stresses sufficient to cause fracture, in actual applications a brittle material may have its useful life terminated by a sudden blow. Impact may cause failure on a smaller scale also. The shear stresses under a point or an edge that has been applied with a blow are quite large. These stresses can easily exceed the elastic strength of the material struck; if the material is brittle, it then shatters readily. Extreme brittleness, as of glass that contains high residual stresses, or a perfect cleavage coupled with high hardness, is favorable to this type of failure, which may simulate erosion rather than fracture if it occurs on a microscopic scale. Shot or sand blasting may be accompanied by this type of wear as well as by the scratching of abrasive particles. Yielding of the surface by either elastic deformation or plastic flow tends to relieve these stresses and prevent fracture. A fine-grained structure

may also minimize failure and consequent wear by localizing cleavage cracks in microscopic crystals, rather than by permitting them to be propagated across a large grain. The greater resistance to impact abrasive wear of flint in comparison with quartz, or of molded versus massive crystalline boron carbide, may tentatively be attributed to such a mechanism.

Metallic substances and intermetallic compounds, even when they are brittle by engineering standards, probably owe their superior wear resistance to some ductility which, in combination with great strength, provides toughness considerably greater than that of most minerals and ceramic substances. The qualitative difference between such materials can be demonstrated easily by an attempt to measure the penetration hardness of a brittle mineral, such as quartz, by means of the Brale diamond cone (the Rockwell hardness test). The mineral will fracture while a piece of the most brittle cast iron (if reasonably large in size) will yield, permitting the hardness determination. This hypothesis explains partially why hardness alone is not a reliable index to wear resistance.

Resistance to wear that involves heat checking, as in brake shoes, is also influenced by brittleness. Here the stresses are the result of temperature gradients rather than of the kinetic energy of impact, but the capacity to absorb the stresses is similarly aided by plasticity. A metal with a low modulus of elasticity, such as gray cast iron, is generally considered more resistant to thermal cracking than a hard white iron, though it may be less able to withstand frictional wear. The low modulus is associated with lower stresses for a given amount of thermal expansion. The greater plasticity of gray irons, along with their lower moduli, may explain their popularity in brake service, particularly as brake drums.

Seizing and galling, wear phenomena quite different from those above, are attributed to the forces of atomic attraction. Atoms of the same or very similar metals cling to one another powerfully. The forces of cohesion decrease as the sixth power of the distance and when the separation is greater than a millionth of an inch they are probably negligible.

If two clean surfaces of the same metal actually touch each other they will weld together, giving evidence of this atomic attraction. Even with apparently smooth surfaces, however, the actual contact points are few under ordinary circumstances, and the effect is obvious. The thinnest films of oil, dirt or absorbed moisture may cause separation beyond the critical distance. When conditions include carefully smoothed faces, removal of films and dirt by friction, pressure sufficient to break through any residual separating material and to facilitate intimate contact by elastic or plastic deformation, and favorable combinations of adjacent metals, the power of atomic attraction becomes apparent and seizing or welding takes place. High temperatures are not necessary, but they facilitate this welding since they soften materials and make plastic flow easier.

If small areas "seize" but operation of the machine is not arrested, pieces of the opposite face may be pulled out. The resultant projection will then cause scoring or excessive local wear, and serious damage may result. This tearing and scoring, as well as complete stoppage by seizure, are the most serious occurrences that may follow the failure of lubrication.

Seizure is combatted by lubrication, by provision of contacting metals that have little tendency to weld together (such as steel and silver), and by design or surface finish that favors the retention of some lubricant even if the main supply fails. Thus, a slightly rough surface may require a thicker, more viscous oil film for complete lubrication, but will retain traces of oil under pressure, and will consequently discourage seizure more effectively than a very smooth surface—superfinished, for example.

An important practical consideration conforming with this hypothesis is the selection of a contacting metal that will provide a film-forming material (such as lead oxide from leaded bronze and babbitt, or graphite from gray cast iron) to supplement failing lubrication.

Corrosion may be considered a type of wear, since it causes material loss that may be expressed in the same units as mechanical attrition. Here, however, corrosion should be considered a complicating or contributing factor. It may cause direct metal loss, pitting, or the formation of films. The pitting may invite fatigue failure or may supply minute oil reservoirs. The films may be brittle, easily removed, abrasive or otherwise undesirable; but if tough and tenacious, they may be invaluable, as experience with the corrosion products of extreme-pressure lubricants has demonstrated.

Thus, the product of a single mechanism is very difficult to predict without careful analysis and study of the contributing factors. This is perhaps the major problem in wear; the several chief sources of deterioration may combine in such a way that they obscure or greatly complicate what might otherwise be a reasonably clear problem. To identify and weigh these factors for practical purposes requires engineering skill, experience, and good judgment.

The hypotheses presented here are based on many observations, and will be found useful in the analysis of wear problems. They are not all firmly grounded on many rigorous experiments, however, and observations at variance with them should not be rejected as unreliable without further scrutiny, but should be carefully examined for clarification of the complex phenomenon of wear.

Factors Influencing Wear. The chief factors that influence wear may be listed as follows:

I Variables connected with metallurgy
- *A* Hardness
- *B* Toughness
- *C* Constitution and structure
- *D* Chemical composition

II Variables connected with service
- *A* Contacting materials
- *B* Pressure
- *C* Speed
- *D* Temperature
- *E* Surface finish

III Other contributing factors
- *A* Lubrication
- *B* Corrosion

The complexity of the problem of the wear of metals is emphasized by a consideration of the many factors involved. Even a general appraisal of each of these factors is difficult, for a more or less rigid but still unclarified interrelationship exists among many of them. Thus, to say that a certain composition is the most wear resistant is obviously impossible without considering many of the other factors associated with the metal, as well as the conditions of service. Two materials, one of which is definitely superior to the other in a particular service, may suffer a reversal in wear resistance by a slight change in the conditions of service.

No one property can always be associated with high resistance to wear. The mechanical properties known to be of importance are strength, indentation hardness, and ductility or toughness. In general, resistance to wear does not increase directly with the tensile strength or with the hardness, important as they may be. High hardness tends to decrease wear by making the metal resistant to penetration, scratching and deformation. Toughness tends to decrease wear by making it difficult to tear off small particles of deformed metal. When the normal pressure is high, the hardness and toughness of the deformed material are important, since the actual wear occurs on material which has been work hardened by the pressure. The relative importance of hardness and ductility may be expected to vary with the conditions under which the wear occurs.

Methods of Testing. There can never be a "universal" wear test, because there are many different types of wear and a material that is advantageous in one application may be disadvantageous in another. Equipment for wear testing must be designed to simulate actual service conditions. Results from any type of wear test cannot be accepted until it has been proved that those results actually check service data. The rating of materials obtained by any one test ordinarily cannot be applied to a different type of wear.

Many wear-testing machines have been placed on the market from time to time. Others have been designed and built in individual laboratories, for specific applications.

In the descriptions which follow, the symbols indicate the types of wear (*see* the first outline above) for which the machines are normally used. Often it is possible to modify the equipment, adapting it to other types of wear.

Class 1. Metal Against Metal. One of the oldest and most widely used commercial machines is that manufactured by Alfred J. Amsler & Company, Schaffhouse, Switzerland.[8] The essential features of this machine are (1) a gear train so constructed as to subject the test specimens to either sliding or rolling friction or to a combination of both, (2) a calibrated spring for adjusting the contact pressures between the test specimens, (3) a cam device that may be used to produce a lateral sliding motion between the test specimens, and also to produce a pounding action between them if desired, and (4) a friction dynamometer and torque indicator and recorder for determining the frictional work done on the test specimens and the frictional torque developed during the test. For rolling friction, the specimens used are 2 in. in diam by 0.4 in. thick; for sliding friction, the upper specimen is usually modified so that the test is of the brake shoe type. This machine is designed primarily for metal-to-metal wear under relatively heavy pressure. While it has been used most generally for dry metal-to-metal tests, it has also been adapted for use with lubricants. Further adaptations have been made for testing at elevated temperatures.[8] (Types IA1, IA2, IB1, IB2.)

The Skoda-Savin machine,[9] manufactured by the Limited Company (formerly the Skodaworks), Praha, Czechoslovakia, consists essentially of a thin tungsten carbide disk which is rotated under load against a preferably flat specimen. The machine is equipped with a pump for supplying a coolant to the specimen (Type IA1, IA2). The Spindel machine[10] uses a somewhat similar principle; a flat test specimen is pressed against the edge of a disk 1 mm thick, rotating at a peripheral speed of 25 mm per min under a pressure of 5 kg for soft materials and 10 kg for hard materials. The disk acts as a blunt circular saw and the surface of the segment ground away is used as a measure of wear. For some purposes, the amount of wear of the steel disk is also measured (Type IA2).

For testing lubricants and wear, the Timken Roller Bearing Company, Canton, Ohio, manufactures a machine in which a steel ring is rotated against a stationary test piece. Two lever systems are provided, one for loading and one for measuring friction of the stationary test block. If lubricants are used, provision is made for heating the oil. Wear is measured by a loss in weight of the test specimen or by the width of the scar on the test block or stationary test piece. (Type IA1, IA2). A somewhat similar test, in which a flat specimen is held against a steel cylinder rotating at constant speed, was developed by Jannin[11] (Type IA1, IA2).

The Saniter test[12] consists of a revolving horizontal cylindrical specimen that drives, by friction, the inner race of a loaded ball bearing, the inner diameter of which is considerably larger than the diameter of the specimen. The Saniter wear number is based on the reduction in diameter of the specimen measured in ten-thousandths of an inch and compared with the loss from a standard bar under similar conditions (Types IA1, IA2).

A machine for the rapid determination of frictional wear is described by Coberly and Arnold.[13] The machine reciprocates test samples, prepared by lapping them optically flat, under load in an oil bath. The small amount of wear which occurs in a few hours is measured by the refraction pattern produced between the worn surface and an optical test plane. An electrical gage and the profilograph are used as supplementary methods of measuring wear. In this machine various materials are tested in pairs and the best combinations of mating materials under the specific test conditions imposed may thus be determined (Type IA1).

The evaluation of material by the use of a machine designed specifically to simulate a certain type of wear is the most practical method of approach, although usually not the easiest. This principle of design was used by Frencn and Herschman,[14,15] in their machine for testing the wear of plug gages. In this machine a cylindrical test specimen (the gage) was moved vertically in a split ring (the material being gaged) by means of a connecting rod working from a crank. The split ring was rotated to simulate the wringing action of gaging. Pressure between ring and gage was adjusted by means of springs. Means were also provided for flooding the specimens with coolants or lubricants, in which abrasives could be incorporated. Test data secured by using this machine were found to check service results, (Types IA1, IA2, IIA1, IIA2).

Another example of an apparatus designed for a specific type of wear is the machine for testing brake shoes, built by the American Brake Shoe Company, Mahwah, N.J. This machine duplicates in the laboratory, on full size wheels, the actual operating conditions of braking a train with any predetermined wheel load and from any desired speed (Type IA2).

Class 2. Metal Against Nonmetal or Abrasive. The Brinell machine,[20] manufactured by Aktiebolaget Alpha, Stockholm, Sweden, is an apparatus for testing the resistance of metal to abrasion by dry sand, which abrading medium must be carefully standardized. The circumference of a slowly rotating soft iron disk, 100 mm in diam and 4 mm thick, is held against the flat surface of a specimen under load while a stream of sand is fed in between from a hopper (Type IIA2).

Blake[21] describes a machine developed for testing materials under conditions of wet grinding. In principle, this device is an accurately controlled grinding machine in which all conditions concerning abrasive, pressure, speed, time, and moisture or other liquid content are under the control of the operator. Test specimens are rotated circumferentially on an annular copper ring, placed in a trough containing the abrasive medium (Type IIA1).

A sandblasting machine for making impact abrasive tests under controlled conditions has been manufactured by Carl Zeiss, Switzerland[24] (Type IIC2). A simple apparatus using the sandblast principle, and easily built in the laboratory, is described by Rosenberg[20] (Type IIC2).

The Taber Abraser, manufactured by the Taber Instrument Company, North Tonawanda, N.Y., consists of a pair of small abrasive wheels which wear a circular path on a rotating test specimen. It is designed for measuring the abrasion resistance of metal finishes (Type IIA2).

In the literature may be found references to various types of tests—metals against abrasive papers, against grinding wheels, against sand or other abrasive on a lap; metal in loose sand, either dry or wet; metal balls or cylinders tumbled in sand in a ball mill; sand blast on metal; rotating thin steel disk or tungsten carbide disk gouging into a flat specimen; brake shoe type of test (rotating metal member against stationary metal member); moving endless steel belt rubbing against steel; reciprocating, metal-to-metal, either flat or curved plates; cylinder or rod between three rolls; rotating disks; rotating the flat end of a rod against metal; rotating the hollow end of a cylinder against a flat block; scratching tests and others. Conditions of these various types of tests can be and have been varied almost without limit—pressure, temperature, speed, surface finish, lubrication, different abrasives, and such. Schematic descriptions of various types of apparatus for testing wear are given by Tichvinsky.[7]

Such a variety of tests and test conditions is bewildering. The selection of a wear test is logically based on the type of service and conditions involved; the test should simulate these as closely as possible.

Precautions in Interpreting Results of Wear Tests. Data from wear tests must be interpreted with caution. Neglecting even one factor may lead to erroneous conclusions.

Obviously the first precaution to take is the adoption of a test which simulates service conditions. The use of an arbitrary test will rarely yield data of value. When the proper type of test has been selected, test conditions must be adjusted so as to correspond to service conditions. This is not always easy. The temptation to exaggerate service conditions in order to shorten the period of testing will frequently cause an unbalance in other conditions—for example, higher operating temperatures because of increased friction; excessive work hardening or deformation of contacting surfaces because of increased pressure.

In metal-to-metal wear, the condition of the contacting surfaces is important. Rates of wear after the mating surfaces are "worn in" are usually different from the previous rates. Data based on the wearing-in portion of an

individual test should not be used. A better understanding of the rate of wear will be gained by plotting the cumulative wear, as determined by a series of consecutive tests, against some factor such as time or total travel. During the wearing-in period the slope of the resultant curve is frequently different from the later slope and will depend somewhat on the type of surface finish.

Many investigators have expressed wear resistance as the ratio of the loss in weight of test materials as compared with that of an arbitrarily selected "standard" material tested under similar conditions. Such procedure permits some variation of test conditions, but the standard must be uniform and reproducibility must be established, or the results obtained can easily complicate the interpretation of the data. This method is valuable when test conditions cannot be strictly controlled and the "standard" specimen can be tested simultaneously with the test specimen, thus assuring that both are subjected to whatever variations may occur during the course of the test. Where test conditions can be kept under strict control, and uniformity is thus established, the method described in the preceding paragraph is more direct than comparison with a selected "standard".

In evaluating the wear resistance of metals for a specific application, the test method used *must* rank different materials in the same order of merit as that established by service experience. Only then can that test procedure be trustworthy for evaluation of new or untried materials.

Strict control of test conditions is absolutely essential. The literature is replete with cases where slight changes in test conditions have reversed the order of merit of test materials. Ellis[22] for instance, testing materials in a ball mill, found that a change from one type of abrasive to another reversed the wear resistance of many of his test materials, as did a change in the pH value of the grinding mixture, or a change of atmosphere within the ball mill.

The influence of oxides that frequently form on the wearing surfaces during test should not be overlooked. It has been shown that the formation of certain oxide films frequently acts as a protection against wear.[16]

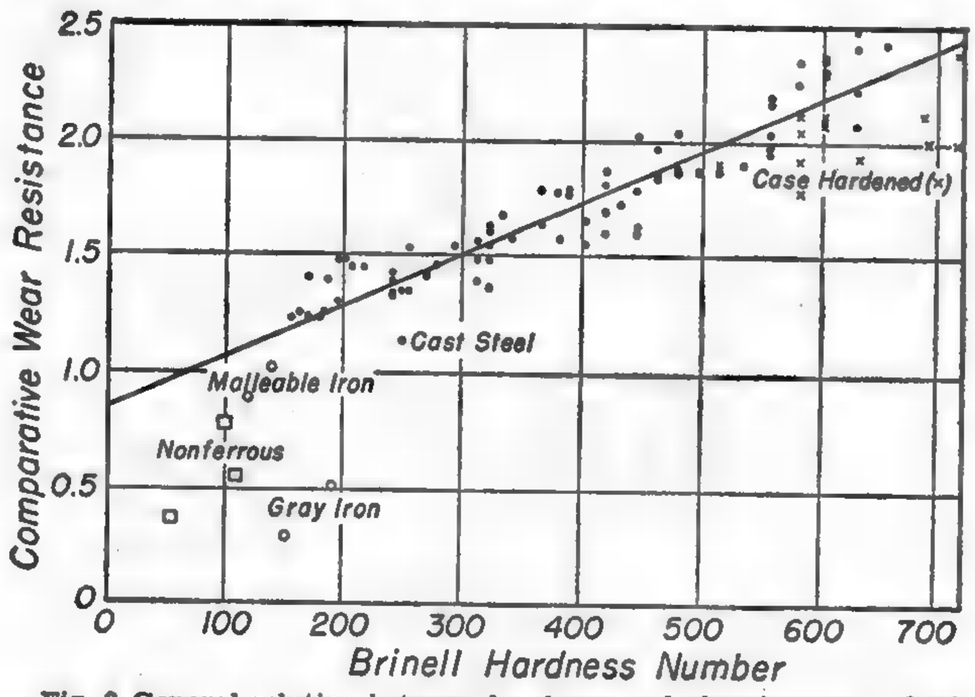

Fig. 2 General relation between hardness and abrasive wear of miscellaneous materials. Wet 80-mesh Crystolon abrasive on cast-iron lap. (Wear type IIA1.) Comparative wear resistance is the ratio of weight loss of specimen to weight loss of SAE 1010 steel (treatment not given). Unit pressures also not given. (From data by Weiss[23])

Test Results and Correlation with Service Data. It is not possible in an article of this type to review the enormous amount of work that has been done in this field. Attention will be directed, however, to selected data, both published and unpublished. A concise, yet extensive, review of the literature up to 1937 was written by Gillett.[1]

In steels, a fair correlation between hardness and wear resistance has been noted by many investigators, even though numerous exceptions to this statement may be found. In the absence of any other data, the selection of a steel hardened to as high a degree as is practicable for the application at hand is usually acceptable engineering. Thus, using a lapping type of wear test employing silicon carbide abrasive and a cast iron lap on both carbon and alloy structural steels subjected to a variety of heat treatments, Weiss[23] gives results that, when plotted, show a fairly linear relation between hardness and wear resistance in this particular type of test (Fig. 2). (Wear type IIA1). The application involved was the selection of materials and heat treatments for power transmission chains, and a private communication from the author indicates that the rating of steels as determined in this test has been found to check service results.

Unpublished data from the American Brake Shoe Company (Table I) show the relative abrasion resistance of various structures (Wear type IIA1). The apparatus used was quite similar to that described by Blake.[21] Conditions of test were as follows:

Abrasive, 40 lb of quartz sand, grain fineness No. 50, mixed with 30 liters of water

Specimen travel, 119 fpm for 1.35 miles (7130 ft)

Bearing surface pressure, 38.5 psi

A 2½ to 1 life ratio has been reported for Ni-Hard as compared with ordinary chilled white cast-iron balls.[25] This ratio agrees well with the ratio implied in Table I.

Table I

Typical Wet Sand Abrasion Factors (Wear type IIA1)[a]

Material	Bhn	Abrasion Factor
Ferrite (ingot iron)	90	1.40
Gray cast irons	200±	1.00 to 1.50
SAE 1020, annealed	107	1.00 (Standard)
White cast irons	400±	0.90 to 1.00
Pearlite	220 to 350	0.75 to 0.85
Austenite (12% Mn)	200	0.75 to 0.85
Bainite	512	0.75±
Martensite	715	0.60±
Martensitic cast irons (Ni-Hard)	550 to 750	0.25 to 0.60

(a) The abrasion factor is the ratio of weight lost by specimen during test to the weight lost by a "standard" specimen. This arbitrarily selected standard was annealed SAE 1020 steel, Bhn = 105 to 110.

Results obtained by this test showed excellent correlation with field results from milling siliceous ore (Table II). It is significant that a substitution of calcite, fluorite, feldspar, or other minerals for quartz, may alter considerably the behavior in tests of this type.

Table II. Correlation of Laboratory and Field Tests

Material	Abrasion Factor — Laboratory Test[a]	Abrasion Factor — Field Test[b]
Air-hardening steel liners	0.69	0.70
Air-hardening steel liners	0.65	0.68
Air-hardening steel liners	0.73	0.69
Air-hardening steel liners	0.68	0.69
Air-hardening steel liners	0.65	0.64
Air-hardening steel liners	0.70	0.68
Air-hardening steel liners	0.69	0.70
Water-quenched steel balls—outside	0.54	...
center	0.65	...
volumetric average	0.56	0.56
White cast-iron balls	0.92	0.93
SAE 1020 steel, annealed	1.00	1.08

(a) American Brake Shoe Company
(b) Climax Molybdenum Company (9-ft diam ball mills)

Rosenberg[20,17] used the Brinell sand abrasion and the Amsler wear-testing machines in studying the wear of carbon steels. He found that in these two particular types of test the harder steels were more resistant to wear or abrasion (Fig. 3 to 7) (Wear types IIA2 and IA2 plus IB2). This same trend for alloy steels has been observed with the Timken machine (unpublished data from Timken Roller Bearing Company). Thus, a graphitic steel (0.50% C; 0.45% Mn; 0.75% Si; 0.25% Mo) tested in the presence of an extreme pressure oil under a unit load of approximately 20,000 psi, gave the following results:

Hardness, Rockwell C	Loss in Weight of Test Piece (Wear type IA1) after 2-hr run, grams
40	0.0770
45	0.0117
59	0.0093
58	0.0067

A study of various test results indicates that resistance to wear generally increases with carbon content. Exceptions to this may usually be explained by microstructural

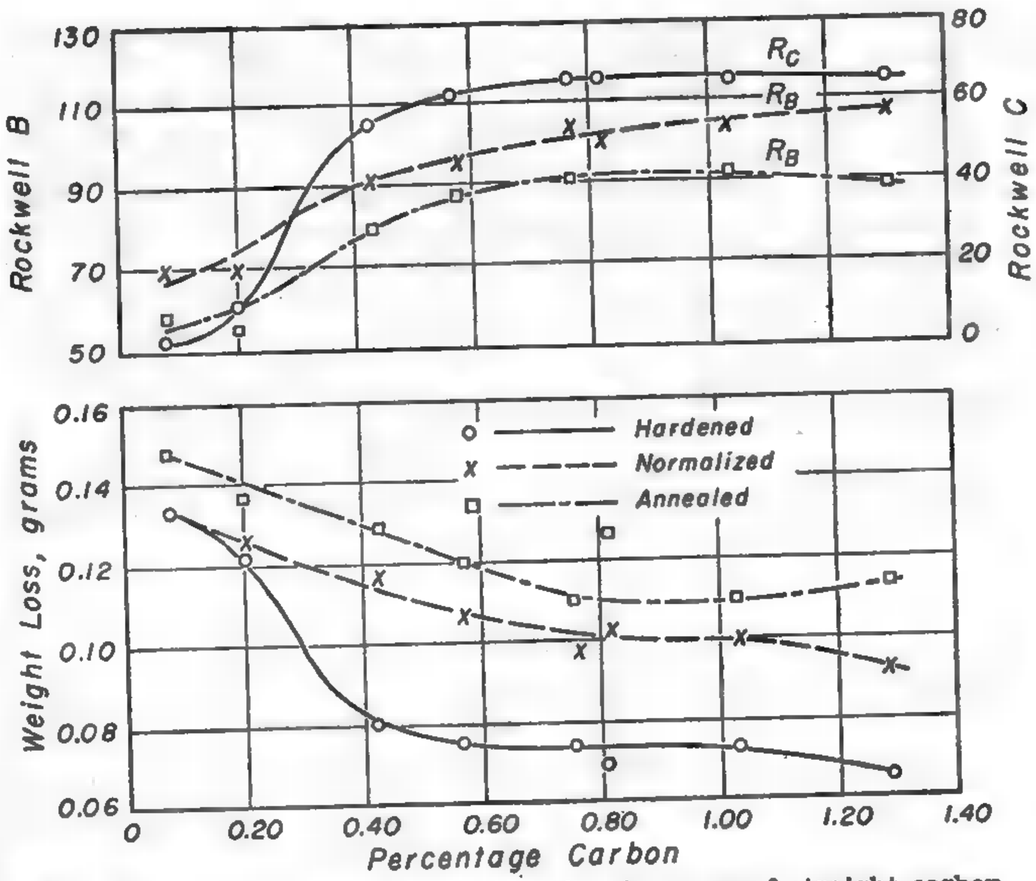

Fig. 3 Effect of carbon content on abrasive wear of straight carbon steels. Brinell sand abrasion (Wear type IIA2). Illinois glass sand passed through sieve of 0.297-mm opening. Pressure of rotating disk, 10 kg. Length of test, 60 meters travel of disk (Rosenberg[20])

features. In normalized steels the presence of free ferrite is deleterious to the wear resistance; increasing the carbon content until a pearlitic structure is obtained is usually beneficial. Hypereutectoid carbon steels may show a slightly improved resistance to wear if the carbides are small and well distributed. Although the presence of a network of excess cementite in hypereutectoid steels is undesirable for many applications, such a structure is more resistant to abrasion than one where the excess cementite is globular.

The wear resistance of carbon steels is markedly improved by heat treatment. Unfortunately, however, the brittleness of such structures renders them unsuitable for many purposes; in such metals some resistance to wear must be sacrificed by tempering to improve toughness.

The technical literature is not always in agreement concerning the effect of alloying elements on wear. In unhardened steels alloying elements appear to affect wear resistance only insofar as they cause the formation of more pearlite and of finer pearlite. The effect of alloying elements in hardened steels is generally less noticeable, except as they cause the formation of hard excess carbides, or serve to decrease the rate of softening under the influence of frictional heat.

Fig. 4 Effect of tempering temperature on abrasive wear of 0.81% C steel. Brinell sand abrasion (Wear type IIA2). Illinois glass sand passed through sieve of 0.297-mm opening. Pressure of rotating disk, 10 kg. Length of test, 60 meters travel of disk (Rosenberg[20])

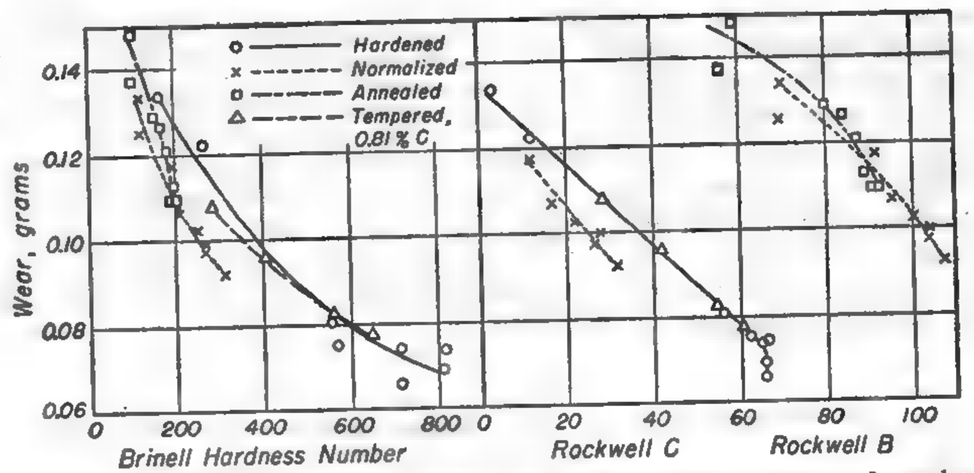

Fig. 5 Relation between hardness and abrasive wear of carbon steels. Brinell sand abrasion (Wear type IIA2). Illinois glass sand passed through sieve of 0.297-mm opening. Pressure of rotating disk, 10 kg. Length of test, 60 meters travel of disk (Rosenberg[20])

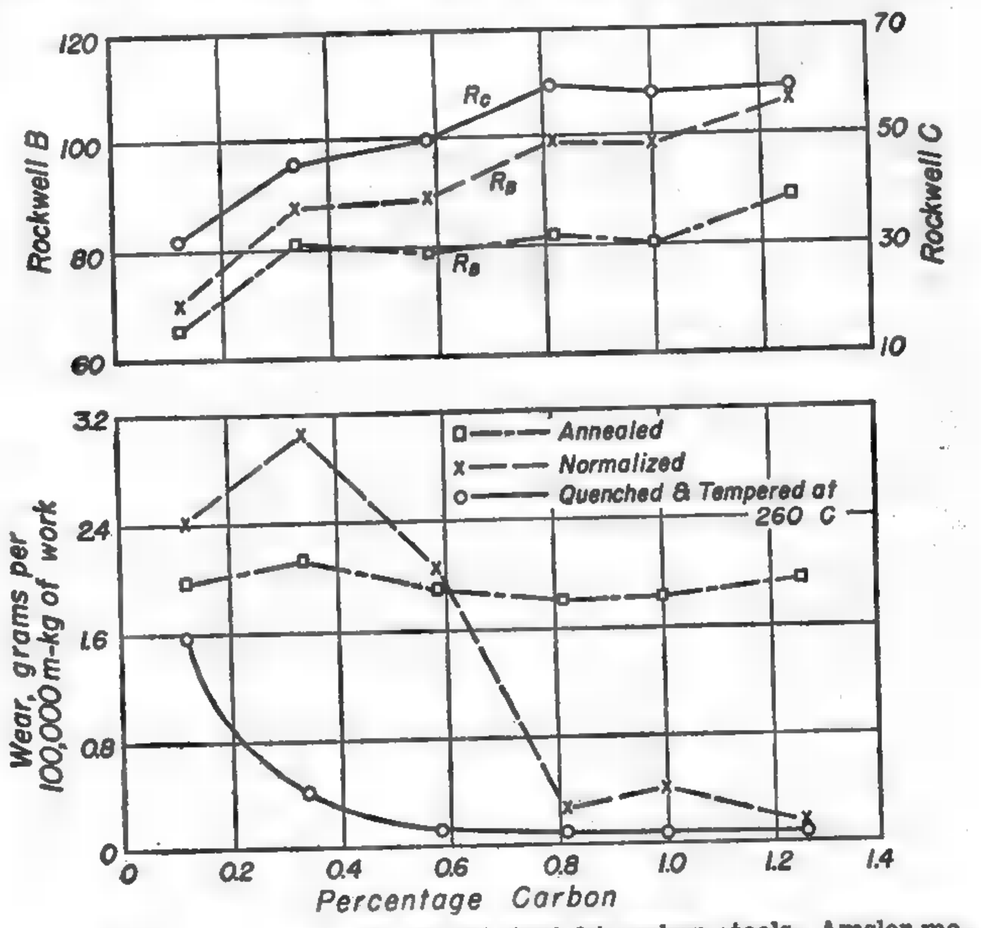

Fig. 6 Effect of carbon on wear of straight carbon steels. Amsler machine (Wear type IA2 plus IB2). Pressure, 60,000 to 70,000 psi. Length of test, 10,000 revolutions of contacting (standard) specimen. Speed, 220 rpm. Slip between specimens, 10%. Contacting specimen, 0.81% C steel, quenched and then tempered at 260 C (Rosenberg[17])

Fig. 7 Effect of tempering temperature on wear of 0.81% C steel. Amsler machine (Wear type IA2 plus IB2). Pressure 60,000 to 70,000 psi. Length of test, 10,000 revolutions of contacting (standard) specimen. Speed, 220 rpm. Slip between specimens, 10%. Contacting specimen, 0.81% C steel, quenched and then tempered at 260 C (Rosenberg[17])

graphite flakes is superior to one having small coarse flakes. Figure 8 shows the effect of combined carbon on the wear of cast iron, as determined by Boegehold in the brake shoe type of test[18] (Wear type IA2). Hardening cast iron to produce a martensitic structure causes a marked improvement in wear resistance, and the resistance of chilled iron to certain types of wear is well known. Gray cast iron is remarkably free from any tendency to gall and seize and is very effective for use with materials as hard or harder than the iron itself.

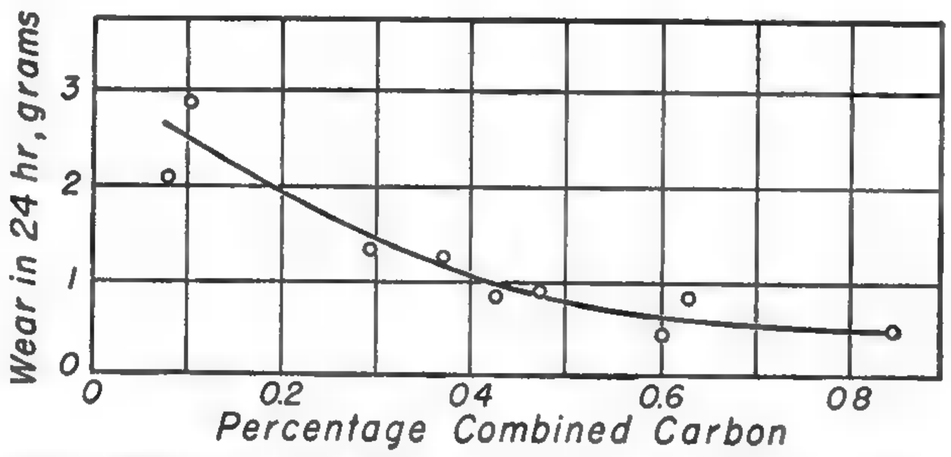

Fig. 8 Effect of combined carbon on wear of cast iron. Brake shoe type test. (Wear type IA2). Standard material (the drum) was cast iron of 180 Bhn and 0.46% combined carbon. Sliding speed, 1600 ft per min. Pressure, 12 psi (Boegehold[18].)

As with steels, disagreement exists concerning the specific effects of other elements on the wear resistance of cast iron. These differences are probably more apparent than real, since they are very likely the result of the specific test conditions used. Boegehold[6] writes: "Certain conclusions to the contrary, the general picture obtained from all this work is that increased hardness, or the addition of elements which form hard constituents in the iron, either by going into solution or by combining chemically, results in decreased wear."

Solid solution alloys, either ferrous or nonferrous, generally lack wear-resisting qualities, perhaps because of their relative softness as well as their homogeneous structures, and such alloys should not be used when wear is an important consideration. Such materials also tend to gall and seize. Austenitic manganese steel is a notable exception, but its best performance depends on service conditions that cause work hardening. The wear resistance of most of these materials, such as the austenitic and ferritic stainless steels, can be improved markedly by nitriding.

Herschman and Basil[19] have shown that in their investigations the wear resistance of tin-base bearing alloys was greater than that of lead-base alloys. (Wear type IA1 plus IB1). Service tests corroborated their laboratory results.

Protection Against Wear. Adequate lubrication, smoothness and soundness of the metal surfaces, and the prevention of corrosive conditions are the most effective methods of eliminating wear. If lubrication is impossible, low specific pressures should be employed and recourse may be made to the most efficient materials.

Surface hardness, usually beneficial in protecting against wear, may be secured in ferrous alloys by heat treatment. Induction hardening, flame hardening, case hardening, cyaniding, nitriding, Ihrigizing (siliconizing), chromium plating, and hard surfacing have all been found useful. Surfaces that are too hard and brittle may spall if the application involves impact as well as wear. For such applications, hard surfacing with the cobalt-chromium-tungsten alloys, with air-hardening steels, or with austenitic manganese steel is probably best. Sintered carbides have a high degree of wear resistance.

Platings of soft metals (such as tin on piston rings) have been used, but their primary function is to assist in the wearing-in operation. Applications of "Granosealing" (a phosphate treatment)[26] and the "Sulfide process" (a caustic-sulfur treatment)[27] have been reported as reducing wear and scuffing, particularly between piston rings and cylinders. Porous chromium platings on piston rings have proved very efficient in preventing wear.[28]

Wear of lead bearings has been reduced by plating with indium. The indium also protects against corrosion.

Galling and seizure may be minimized by the use of dissimilar metals and by avoiding the use of solid solution alloys. The use of at least one metal that forms some sort of lubricating film, or of a thin, tightly adherent oxide coating, or of a sulfide, chloride or phosphide coating, is frequently helpful. Plastic deformation may permit almost perfect contact of mating surfaces under pressure, thus facilitating seizure. This may be prevented by using materials with higher elastic limits. For parts that operate under such extreme pressures that elastic deformation permits intimate contact, as in certain gears, the best preventive measure is a lubricant that combines with the metal surface to form a tenacious "corrosion" product of sufficient strength to keep the parts separated.

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The Resistance of Metals to Oxidation at Elevated Temperature

By Benjamin Lustman*

THE NATURE and extent of the attack on metals and alloys, when heated in oxidizing environments, are determined largely by the properties of the scale that is formed—its structure, chemical composition, melting point and boiling point. The metal base and gas environment are usually important only as they affect the scale. From numerous investigations, it has been found that at high temperatures the oxidation of many metals proceeds according to a parabolic relation:

$$x^2 = kt \qquad (1)$$

where x is weight or thickness of metal consumed or formed into scale, t is time and k the rate constant. Theoretically such an equation is to be expected if oxidation proceeds by the diffusion of metal or oxygen through the scale.

The essential condition for the validity of equation (1) was shown by Pilling and Bedworth[1] to be the formation of a dense and adherent scale, a condition that obtains when the specific volume of the oxide is equal to or greater than the specific volume of the metal; that is, when

$$\frac{M \cdot d}{m \cdot D} \geqq 1 \qquad (2)$$

where M and D are the molecular weight and density of the oxide, and m and d those of the metal. Values of this ratio for the oxides formed on various metals are shown in Fig. 1. The metals that are underlined in this diagram have been found by experiment to form adherent protective scales, increasing in weight or thickness with time according to equation (1). The almost general validity of the Pilling and Bedworth rule may be appreciated by examining this diagram.

Li 0.57	Be 1.59								
Na 0.57	Mg 0.79	Al 1.28	Si 2.27						
K 0.45	Ca 0.65		Ti 1.95	V 3.18	Cr 1.99	Mn 1.79	Fe 1.77	Co 1.99	Ni 1.52
Cu 1.68	Zn 1.62		Ge 1.64	As 2.15					
Rb 0.45	Sr 0.65		Zr 1.51	Cb 2.61	Mo 3.4				Pd 1.60
Ag 1.59	Cd 1.21	In 1.23	Sn 1.32	Sb 2.35					
Cs 0.46	Ba 0.74	La 1.11	Ce 1.16		W 3.4				
			Hf 1.48	Ta 2.33					
	Hg 1.31	Tl 1.38	Pb 1.40	Bi 2.27					
			Th 1.32		U 3.05				

Fig. 1. Ratios of specific volumes of oxides and metals, arranged in the periodic sequence. The underlined metals have been found by experiment to form adherent protective seals in hot oxidizing environments.

As in other diffusional processes, the variation of the rate of oxidation with temperature, or the rate constant k of equation (1), may be expressed by an Arrhenius equation:

$$k = Ae^{-\frac{Q}{RT}} \qquad (3)$$

where A and Q are constants, R is the gas constant, T is absolute temperature, and e is the base of natural logarithms. Thus, when the logarithm of oxidation rate is plotted against the reciprocal of absolute temperature, the graph will be a straight line.

The weight of scale formed on those metals having oxides of specific volume smaller than that of the metal, increases linearly with time. The resultant scale is porous and crumbly, and the rate of attack is controlled only by the specific reactivity of the metal, and the composition of the gas atmosphere. Exceptions to the Pilling and Bedworth rule have thus far been noted only for tungsten and molybdenum, which, in spite of a much higher specific volume of oxide than of metal, as shown in Fig. 1, form nonprotective oxides that increase in weight proportionally to reaction time.[2] The oxidation of molybdenum is complicated further by the high vapor pressure and relatively low melting point of the predominant oxide, MoO_3.

A third class of metals, the noble metals, have oxides with higher dissociation pressures than the partial pressure of oxygen in air at the oxidation temperature; therefore the noble metals form no superficial oxide. Thus, at low temperatures, silver forms a superficial oxide that decomposes on heating to 375 F (190 C), at which temperature the decomposition pressure of Ag_2O equals the partial pressure of oxygen in air. Palladium and rhodium behave similarly; their oxides decompose at about 800 C and 1100 C, respectively. Cladding of base metals with such noble metals has been proposed as a means of protection, but such cladding is useful only at moderate temperatures. Because of the appreciable solubility and high rate of diffusion of oxygen in such metals at elevated temperatures, oxygen penetrates to the base metal and forms a layer of oxide at the interface.

The theory of the scaling of metals that form protective oxides has been advanced greatly in recent years by the researches of Wagner.[3] On the basis of various experimental facts, Pfeil[4] concluded that, during the oxidation of iron, iron ions diffuse from the metal through the oxide to the oxide-gas interface and there react with oxygen. Wagner showed that in addition to negatively charged oxygen ions, both electrons and positively charged metal ions migrate through the oxide layer. The scale may be considered an electrolytic cell with its metal-base cathode and gas-atmosphere anode short-circuited by an external resistance (analogous to electron conduction through the oxide). The electromotive force of such a cell is given by the free energy of formation of the oxide. From a knowledge of the conductivity of the oxide and the relative mobilities of positive and negative ions, it is possible to calculate values of the constant k in equation (1), and these calculated values are in good agreement with experimental determinations.

It follows from this work that the lower the electrical conductivity of the oxide, the lower the rate of scaling. Since, in general, the more refractory oxides have lower electrical conductivity, those metals forming oxides of high melting point are most useful as alloying additions to confer resistance to oxidation.

When the temperature and duration of oxidation yield oxide films thinner than 2000 A (0.0002 mm), the composition, the structure, and the rate equations governing the growth of the films (as well as the methods for measuring film weight and thickness), may be quite different from the corresponding relations of the thicker films or scales discussed here. Such thin films are of interest mainly in connection with studies of corrosion.

Structure of Scales. Scales generally consist of a layer-like structure, each layer comprising an oxide phase that is stable at the reaction temperature. Thus, when iron is heated in air or oxygen at atmospheric pressure and temperatures above 1000 F (550 C) an outside layer of Fe_2O_3, an intermediate layer of Fe_3O_4, and an inner layer of FeO appear in succession on the iron base. The surface of the iron itself is also saturated with the quantity of oxygen soluble at the oxidation temperature. The relative thickness of each layer is governed by the relative diffusivities of iron ions in each phase. Thus, since the FeO layer has the highest conductivity, it constitutes 85 to 90% of the total scale thickness; the Fe_3O_4 layer 10 to 15%; and the Fe_2O_3 layer 0.5 to 2%. When removed mechanically from the base metal, the scale separates into three sections. The

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outer section consists of the layers of the Fe_2O_3 and Fe_3O_4 phases; the middle section consists of the FeO phase bounded on one side by the Fe_3O_4 layer and on the other by a plane representing the original surface of the specimen; and the inner section consists of the FeO phase bounded by the original surface of the iron specimen and the surface of the still unoxidized metal.

In alloys, the added element may occur in the scale in several forms, depending on its relative oxidizability with respect to the base metal. Thus, when small amounts of the additions (alloying elements) form refractory oxides—for example, aluminum, silicon and chromium when added to iron—the added element may occur in the inner (FeO) scale layer adjacent to the steel base, either as its own oxide or as a double oxide with FeO. The concentration of such elements in the inner layer of scale may be as high as four times the concentration of the element in the alloy. In the two outer layers of scale, the added element may decrease to 10% of its concentration in the base metal.

In richer alloys, when such elements are increased in content, the concentration in the inner scale layer rises continuously until the layer consists almost entirely of the refractory oxide with a correspondingly low rate of diffusion. Marked decrease in the rate of oxidation is to be expected only when the scale adjacent to the metal consists entirely of such ■ refractory oxide. Thus, by using a slightly oxidizing atmosphere for preheating copper that contained an amount of aluminum insufficient to retard oxidation appreciably during heating in air, Price and Thomas[5] were able to form on the copper a layer of refractory aluminum oxide that effectively stopped further scaling when the metal was reheated in air.

When metals are added that are less reactive with oxygen than the base metal, the added metal is also enriched in the layer of scale adjacent to the metal surface; however, in this instance the added metal occurs as fine metallic particles embedded in the scale. Thus, on an iron-nickel alloy containing 5% Ni, metallic particles containing 30% Ni or more are found in the scale.[6] Similar precipitates occur when cobalt and copper have been added to iron. The structure of the scale is otherwise altered only slightly. Since refractory oxides do not result from such additions, little improvement can be expected in the resistance of the alloy to oxidation.

The action of hot air on metals causes not only the formation of external scales, but oxygen also diffuses into the metal base, resulting in "internal oxidation", metallographically visible as a layer that contains particles of oxide of the alloying element embedded in the essentially pure solvent metal. Steels that contain chromium, aluminum or silicon form internal oxides of these elements (or their double oxides with FeO) embedded in the surface of the metal, often at grain boundaries. One important result is that subsequent pickling for the complete removal of scale is difficult.[7] In steels that contain copper, the diffusion of oxygen into the surface, and the formation of oxides with iron, leads to the precipitation of metallic copper at the grain boundaries; in the presence of excessive amounts of sulfur in the steel, such liberation of copper may cause surface defects during hot working.[8]

It has been shown quantitatively[8,9] that the depth of the subscale and the distribution of oxides or of precipitated noble elements in the internally oxidized zone, may be calculated from a knowledge of the rate of diffusion of oxygen and of the alloying element in the base metal, and the solubility of any reaction product formed.

Determination of Resistance to Oxidation. A number of methods are available for measuring the resistance of metals to attack by oxidizing atmospheres; the choice of method will depend on the particular application of the metal and on its physical form. Methods that have been used are:

1 Determination of the Increase in Weight of Specimens After ■ Given Duration of Exposure. Such a method is particularly applicable for the continuous measurement of the course of oxidation, and enables the experimenter to compare materials that are to be subjected to attack at a constant temperature. Spalling of the oxide at temperature or during cooling, and vaporization of the oxide at elevated temperature lead to inaccuracies in this method. However, difficulties caused by spalling during cooling, may be overcome by collecting the spalled-off oxide in ■ boat surrounding the specimen.

2 Determination of the Decrease in Weight After Removing the External Scale. This method is particularly useful in evaluating the effect of various furnace atmospheres on the rate of loss of metal, or damage to surface finish, and on the ease of pickling. This method suffers the disadvantage that complete removal of the oxide without affecting the base metal is often difficult and practically impossible when the oxide penetrates the metal and no sharp division exists between oxide and metal phases.

3 Measurement of the Amount of Gas Consumed in the Oxidation Reaction. This, like method 1, is particularly applicable to the continuous determination of the rate of attack. Such a method would be limited to closed systems and to simple atmospheres.

4 Determination of the Time Necessary for the Destruction of a Given Size of Material. This method has been used extensively in the testing of wire to be used in electric heating devices. Bash and Harsch[10] devised a method of testing that, with slight modification, has been adopted in ASTM Standard Method B 76-39 as a life test for electrical heating alloys. A 12-in. length of No. 20 or No. 22 gage wire is suspended between a fixed upper clamp and a mercury cup. Current through the wire is adjusted so as to yield a temperature of 2050 to 2150 F (depending on the alloy), as measured by an optical pyrometer. The time required to burn out the wire with the current alternately on 2 min and off 2 min, is accepted as the life of the material. The life of wire is comparatively unaffected by variation in size for diameters larger than No. 24 American wire gage. However, the actual and relative durations of heating and cooling have considerable effect. A time cycle of 2 min on, ▮ min off, was found to be most injurious. This method is standard for evaluating the life of electrical resistance alloys but is applicable only to alloys that can be fabricated to wire.

5 Metallographic Examination of the Oxidized Material. Such examination will reveal not only the depth but also the distribution of oxidizing attack, as well as certain changes in composition or structure within the metal, such as decarburization and internal oxidation. Metallographic examination of the oxidized specimens should be an essential step in determining resistance to oxidation.

Each of the above methods reveals different oxidation characteristics, and the relative as well as absolute oxidation behavior of alloys will vary with the method of test.

Rate of Oxidation of Alloys. The principal criterion for an oxidation-resistant alloy is the ability of the alloy to form an oxide scale of low electrical conductivity, which indicates a low rate of diffusion of metal ions, as outlined above. Equally important for resistance at high temperature is the melting point of the oxide. In general, the higher the melting point of an oxide, the lower its conductivity. Presence of alloying elements that form low-melting eutectics or compounds with other constituents of the scale must be avoided, since molten scales give no protection. Thus the presence of 0.04% B in a 30% Cr steel completely destroys resistance to scaling at 2200 F (1200 C).[11] Likewise, steels that contain more than 5% Si are useless above 2200 F because of the $FeO\text{-}SiO_2$ eutectic, which melts at 2250 F (1240 C). In the following paragraphs it may therefore be noted that those alloys which form refractory oxides are most resistant to oxidation.

Iron-Chromium Alloys. The most important component of heat-resistant alloys is chromium, both because it forms a highly refractory oxide and because its alloys with nickel and iron, or both, are workable even when the percentage content of chromium is high. The effect of increasing chromium content in a 0.15% C, 0.7 to 0.9% Si steel, heated in air for 120 hr at various temperatures, is shown in Fig. 2. It may be noted that, at each temperature, with increasing chromium content the amount of scale decreases continuously to a low value. After this low value has been reached, further additions of chromium cause little improvement. The chromium content at which a low rate of scaling is obtained denotes the composition at which the scale consists entirely of refractory Cr_2O_3; it may be noted that the proportion of chromium required increases with increasing temperature.

Curves of the type shown in Fig. 2 are general for all alloy additions that confer resistance to oxidation. For temperatures higher than 1800 F (1000 C), alloys that contain 26% Cr or more, may be necessary. Oxidation characteristics of iron-chromium alloys may be improved still further by additions of aluminum or silicon in amounts greater than 2%.[13]

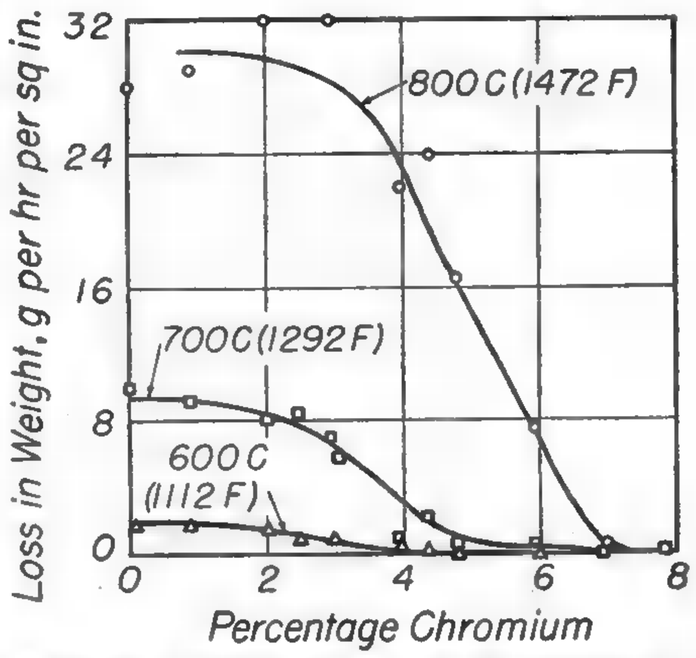

Fig. 2 Effect of chromium content on the scaling of a steel containing 0.15% C and 0.7 to 0.9% Si (Houdremont[12])

Nickel-Chromium Alloys. It may be noted from Fig. 3, in which the logarithm of oxidation rate is plotted against chromium content, that improvement in the resistance of nickel to oxidation, is concurrent with chromium additions up to its solubility limit. Since the widely used chromium-nickel alloys nearly always contain manganese and silicon, which decrease the solubility of chromium in nickel, such alloys are limited to a maximum of 25% Cr. It has been shown by Horn[14] that the oxidation of nickel-chromium alloys of relatively high chromium content cannot be described by a simple equation of the form of equation (1); for long durations of exposure to oxidation, such alloys oxidize much more slowly than would be expected from a parabolic relation between increase in weight and time, so that the decrease in oxidation attack of nickel by chromium additions (Fig. 3) would be much more pronounced had the changes in weight been observed over a longer period of time. In tests similar to the Bash and Harsch test, it has been found that 20% Cr alloys withstand 1200 intermittent heatings to 1050 C as compared with 150 for a 6% alloy.[15] A chromium content of 20% appears to be optimum in the absence of iron.

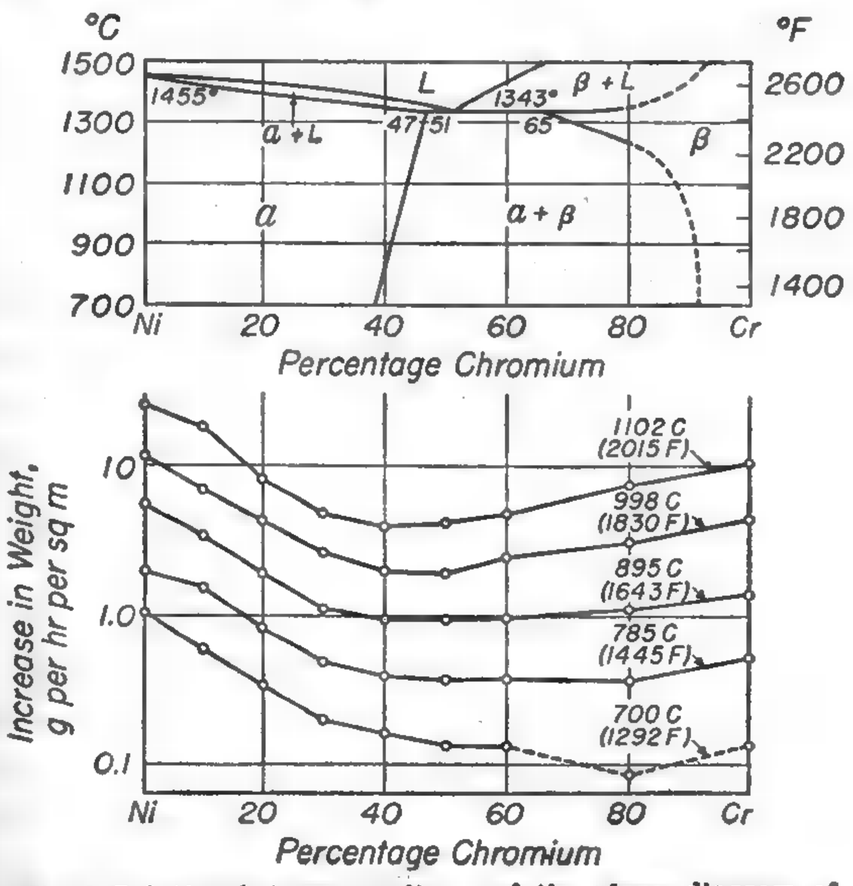

Fig. 3 Relation between scaling and the phase diagram of chromium-nickel alloys (Matsunaga[18])

It has been noted that small additions of chromium (2 to 3%) decrease the resistance of nickel to oxidation. An addition of about 0.25% Cr induces free spalling of the oxide, a fact not disclosed by Fig. 3 because no opportunity was afforded for spalling by cooling. This behavior is explicable to some extent by the type of scale formed on these alloys. On the nickel-chromium axis of Fig. 4 are plotted the structures of the oxides formed on binary nickel-chromium alloys at 1000 C (1830 F). Up to about 10% Cr the oxide formed is NiO. With higher chromium contents the resulting oxide has the crystal structure of Cr_2O_3, which is more refractory than NiO and affords greater protection. The good resistance to oxidation of nickel-chromium alloys has been attributed to the presence of the spinel $NiO \cdot Cr_2O_3$, which has been reported in alloys containing 15 to 20% Cr.

Carbon, by combining with chromium to form insoluble carbides, decreases the resistance of nickel-chromium alloys to scaling; the life of an 80% Ni, 20% Cr alloy is reduced one-half by the presence of 0.30% C.[15] Manganese also causes a slight increase in the rate of scaling, while silicon and aluminum, even in amounts insufficient to reduce the workability appreciably, improve resistance to oxidation. Tungsten and molybdenum, which may be added to improve the strength at high temperatures, have little effect on the resistance to scaling.[16]

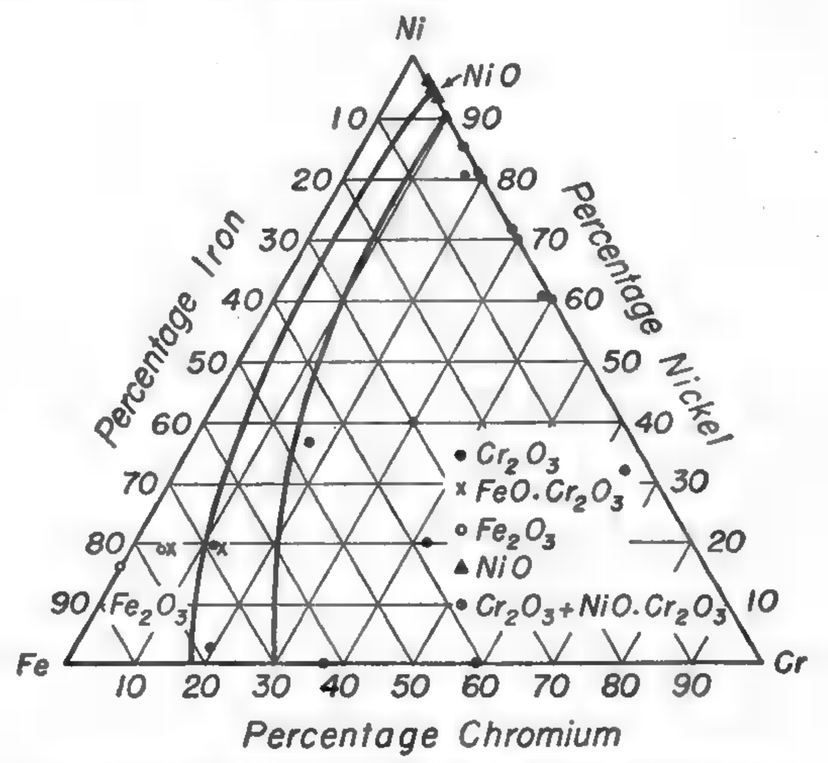

Fig. 4 Constituents of scale layers on Fe-Ni-Cr alloys[7,14,16]

*Iron-Nickel-Chromium Alloys.** Still more important than the iron-chromium alloys as heat-resistant materials are the iron-chromium-nickel alloys. Nickel is added to such alloys principally to render the alloy austenitic at room temperature; nickel also improves the mechanical properties of the alloys. The improvement in oxidation resistance conferred by additions of nickel, is minor in comparison with the effect of chromium. This is shown in Fig. 4, in which are plotted the principal constituents of the scale formed on various alloys at 1830 F (1000 C). The lines divide the composition range into three regions; the one at the right (high chromium contents) denotes alloys that, when oxidized, have an increase in weight of less than 0.001 g per sq cm in 7.5 hr at 1000 C; the increase in weight at low chromium contents is more than 0.01 g per sq cm; and the increase in weight in the intermediate region is less than 0.01 g per sq cm. In the region of low increase in weight the scales that form are predominantly Cr_2O_3, and the scales containing NiO or Fe_2O_3 form in the region of high increase in weight. It is evident from this diagram that chromium is mainly responsible for decreasing the scaling attack. Similar results were obtained by Brasunas, Gow, and Harder[17] in 100-hr continuous tests in air. It was found that the beneficial influence of increased additions of nickel was most prominent at low chromium contents. As the chromium content of the alloys increases, the influence of nickel becomes less pronounced. This is shown in Table I, in which are listed

* *See also* STAINLESS STEELS AND HEAT RESISTING ALLOYS.

the minimum nickel contents required with various chromium contents to render Fe-Ni-Cr alloys resistant to oxidation. A loss in weight of 0.04 g per sq in. per day (0.1 in. penetration per year) was considered satisfactory resistance. Carbon was found to have little effect on the resistance to oxidation; additions of silicon improved the oxidation behavior appreciably.

Table I. Minimum Nickel Contents Required With Various Chromium Contents to Render Iron-Nickel-Chromium Alloys Resistant to Oxidation in Air[17]

(A loss in weight of 0.04 g per sq in. per day was considered satisfactory resistance.)

Percentage Chromium	Minimum Nickel Content, %			
	1600 F	1800 F	2000 F	2200 F
11	26	34	48	56
16	0	16	30	41
21	0	0	4	9
26	0	0	3	■
31	0	0	0	8

Iron-Aluminum Alloys. Aluminum is the most effective addition for suppressing the scaling of iron. Ziegler[19] showed that during a two-hour testing period an 8% Al alloy has the same oxidation resistance as an 80% Ni, 20% Cr alloy. If the scaling rate of iron-aluminum alloys is plotted against aluminum content, curves will be obtained similar to those shown in Fig. 2 for chromium steels;* similarly also, larger concentrations of aluminum are required as the reaction temperature increases. Low rates of oxidation are obtained only when a white Al_2O_3 scale forms over the surface of the alloy. Internal oxidation is severe in such alloys, causing an impoverishment of the alloy in aluminum. Thus after long periods of oxidation, severe local attack may occur at damaged places in the oxide coating; by internal oxidation of the aluminum, the material will have lost the ability to repair the protective coating. These alloys are difficult to fabricate.

Iron-Aluminum-Chromium Alloys. These alloys are resistant to oxidation even at very high temperatures, but in sensitivity to damage of the oxide film and difficulty in fabrication, suffer the disadvantages of the iron-aluminum alloys, although to a lesser extent. Even in such alloys, aluminum is the most effective agent for restraining oxidation; minimum attack is noted when the principal scale constituent is Al_2O_3.[6] The optimum composition of such alloys appears to be from 20 to 30% Cr and 3 to 8% Al.

Iron-Silicon and Iron-Silicon-Chromium Alloys. Silicon behaves like aluminum in decreasing the scaling of iron, although silicon is somewhat less effective than aluminum. Because of the low melting point of the FeO-SiO_2 eutectic, these alloys are not considered heat-resistant. Alloys containing 12 to 30% Cr and 5 to 10% Si are quite resistant to scaling but, like the Fe-Al-Cr alloys, are hard to work.

Table II. Minimum Nickel Contents for Satisfactory Resistance to Corrosion of Iron-Nickel-Chromium Alloys at 1800 F in Air and in Oxidizing and Reducing Atmospheres; 0.1-In. Penetration per Year[27]

% Cr	% Ni necessary for oxidation resistance in				
	Air	Oxidizing Flue Gas		Reducing Flue Gas	
		5 grains sulfur per 100 cu ft gas	100 grains sulfur	5 grains sulfur	100 grains sulfur
11	34	38	40	33	More than 60
13	27	30	32	27	55
15	20	23	22	22	42
17	13	14	13	18	26
19	5	5	5	13	17
21	0	0	0	8	10
23	0	0	0	■	0
25	■	0	0	■	0
27	■	0	0	0	0
29	0	0	0	0	0

Copper Alloys. Oxidation-resistant copper alloys are obtainable only when the low-melting, highly conductive copper oxide scale is replaced by a refractory oxide scale. Thus, Dunn[20] showed that copper-zinc alloys are appreciably more resistant than copper only with zinc contents greater than 25%, when a ZnO scale forms. Frohlich[21] found that additions of aluminum, beryllium, magnesium and silicon afford real protection to copper; zinc and tin provide somewhat less; while iron, nickel, manganese, calcium, chromium and other elements give no protection. The addition of several per cent of beryllium, silicon (or both) to constantan (55% Cu, 45% Ni) increases the maximum temperature for use of the alloy from 1100 to 1475 F (600 to 800 C).[22]

Effect of Minor Additions on Oxidation Resistance. Smithells, Williams and Grimwood[23] found that the purity of the initial materials had an appreciable effect on the life of nickel-chromium alloys. Alloys made of electrolytic chromium failed much more quickly than did those made of chromium reduced by the thermit reaction ($Cr_2O_3 + 2\ Al = 2\ Cr + Al_2O_3$). This effect was further investigated by Hessenbruch[24] who found that, by suitable additions, the life of various heat-resistant alloys could be prolonged as much as 10 times. Additions of calcium, thorium and, notably, cerium in amounts less than 0.5% improved the resistance to scaling to a degree out of all proportion to the amounts of added element. Such improvement was found to be general with additions of the alkaline earths and rare earth elements. The service life of nickel-chromium alloys in American practice is greatly extended by the addition of 0.01 to 0.2% Cu, 0.01 to 0.5% Zr, and 0.01 to 1.0% Al.[25]

Hessenbruch offered a tentative explanation of these results, based on the observation that those elements which, when present in small amounts, prolong the life of nickel-base alloys, have atomic volumes greater than that of nickel oxide, whereas those elements which have smaller atomic volumes have no effect. Presumably such minor impurities are to be considered as obstacles to the passage of nickel ions through the scale.

Influence of Gas Atmosphere. In any discussion of the oxidation resistance of metals, the effect of gas atmosphere must be considered, since the composition, pressure, and

Table III. Maximum Temperature for Stability of Various Alloys in Air[20]

(Temperature for stability chosen as that below which losses caused by scaling are less than 0.0002 to 0.0004 ■ per sq cm per hr.)

Material	Composition (Remainder Fe)	Maximum Temperature for Stability, deg Cent
Copper	.....	450
Iron	.....	500
Brass	70% Cu, 30% Zn	700
Nickel	.....	800
Chromium	.....	900
Iron-Chromium Alloys	4 to 6% Cr, 0.1 to 0.2% C, 0.5% Mn, 0.5% Si	650
	8 to 10% Cr, 0.15% C max, 0.5% Mn, 0.5% Si	750
	12 to 14% Cr, 0.10% C max, 0.5% Mn, 0.5% Si	750 to 800
	16 to 18% Cr, 0.10% C, 0.5% Mn, 0.5% Si	850 to 900
	25 to 30% Cr, 0.10% C, 0.5% Mn, 0.5% Si	1050 to 1100
Fe-Cr-Ni Alloys	17 to 19% Cr, 8 to 10% Ni, 0.5% Mn, 0.5% Si, 0.1% C	850 to 900
	17 to 19% Cr, 25 to 26% Ni, 0.5% Mn, 3.0% Si max, 0.2% C max	1050 to 1100
	22 to 28% Cr, 12 to 16% Ni, 0.5% Mn, 0.5% Si, 0.15% C max	1000
	24 to 26% Cr, 19 to 21% Ni, 0.75% Mn, 1.0% Si, 0.15% C max	1050 to 1100
	15 to 20% Cr, 30 to 35% Ni, 0.5 to 1.0% Mn, 1 to 2% Si, 0.15% C max	1050 to 1100
	14 to 18% Cr, 60 to 65% Ni, 1 to 2% Mn, 1.5 to 2% Si, 0.1 to 0.5% C	1000 to 1100
	12 to 20% Cr, 70 to 80% Ni, 2% Mn, 2% Si, 0.15% C	1100 to 1150
Chromium-Nickel Alloy	19 to 20% Cr, 77 to 79% Ni, 2.5% Mn, 0.5% Si, 0.25% C max	1150
Fe-Cr-Al Alloys	5 to 6.5% Cr, 0.6 to 0.8% Al, 0.45% Mn, 0.5% Si, 0.10% C	800
	6.5 to 8.5% Cr, 1.2 to 2.0% Al, 0.45% Mn, 1.0% Si, 0.10% C	900
	12 to 15% Cr, 2.5 to 3.5% Al, 0.5% Mn, 0.5 to 1.0% Si, 0.12% C	900 to 1000
	18 to 20% Cr, 3 to 4% Al, 0.5% Mn, 0.5 to 1.0% Si, 0.12% C	1200
	20 to 22% Cr, 3 to 5% Al, 0.5 to 1.5% Mn, 0.5% Si, 0.10% C	1250 to 1300
	20% Cr, 5% Al, 1.5 to 3.0% Co	1150 to 1300
	30% Cr, 5% Al, 0.5% Mn, 0.5% Si, 0.1% C	about 1330

* See Fig. 1 in the article on iron-aluminum alloys, page 606.

rate of flow of the atmosphere may affect the structure, composition and adherence of the oxide scale. Thus, steel is oxidized at an increasing rate by atmospheres of carbon dioxide, dry air, oxygen and steam, respectively. To be stable in steam at 925 F (500 C) a steel must be resistant in air at 1200 F (650 C), and to withstand steam at 1750 F (950 C) a steel must withstand air at 2200 F (1200 C).

The oxidation of mild steel in air was shown by Hatfield[26] to be trebled by the addition of 5% SO_2 and 5% H_2O. Likewise the rate of oxidation of 18-8 Cr-Ni steel in air is increased ten times by the addition of 5% CO_2 + 5% H_2O, eight times in the presence of 5% SO_2 + 5% H_2O, and seven times by 5% H_2O. Nickel and alloys that contain nickel are seriously attacked by reducing atmospheres that contain sulfur. This effect is shown in Table II.

Griffiths[28] found that the adherence of scale to steel is markedly affected by gas composition and rates of heating and cooling. The factors that control the adherence of scales to metal surfaces have been investigated only sparingly. The oxidation stability of alloys is affected not only by oxidizing constituents in the atmosphere but also by carburizing and nitriding constituents that decrease the resistance to oxidation through reacting with alloying elements in the steel, such as chromium and aluminum.

Oxidation Stability of Alloys. Because of the marked effect of small amounts of impurities in the gas atmosphere and in the base metal, and because of the sensitivity of scaling rate to factors such as heating cycles and rate of heating, it is impossible to state with certainty the range of stability of metals in oxidizing atmospheres. Any listing of alloys in their order of merit with respect to scaling, must therefore be considered as comparative only for given atmospheres, heating and cooling cycles and other test conditions. The temperature of stability in Table III is chosen as that temperature below which losses caused by scaling are less than 0.0002 to 0.0004 g per sq cm per hr (0.03 to 0.06 g per sq in. per day).

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The Stress Corrosion of Metals

BY THE SUBCOMMITTEE ON STRESS CORROSION*

THE STUDY of stress corrosion concerns the behavior of metal under the combined action of corrosive environment and enduring high tensile stresses. Corrosion fatigue, which results from frequently repeated stresses of lower magnitude combined with a corrosive environment, is not considered as coming within the above definition; neither is failure that is produced by penetration of a liquid metal into a solid metal.

"Stress corrosion" is a general term that may be considered to include acceleration of corrosion by stress as well as the limiting situation, stress-corrosion cracking.[1] Both terms may be defined more easily after the diagrams of Fig. 1 and 2 have been considered. Three identical test specimens may be assumed as examples. Specimen *A* is the unexposed, unstressed blank; its breaking load is

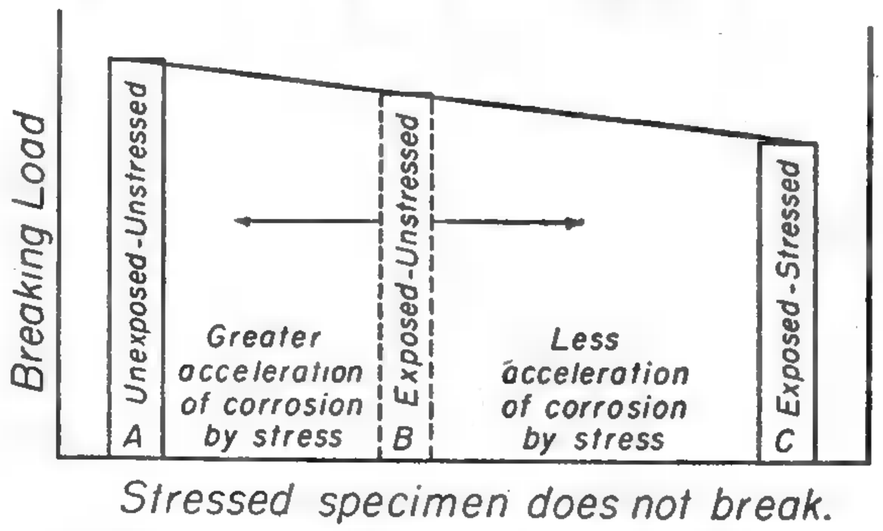

Fig. 1 Influence of stress and exposure on the rate of corrosion. (Dix and Brown)

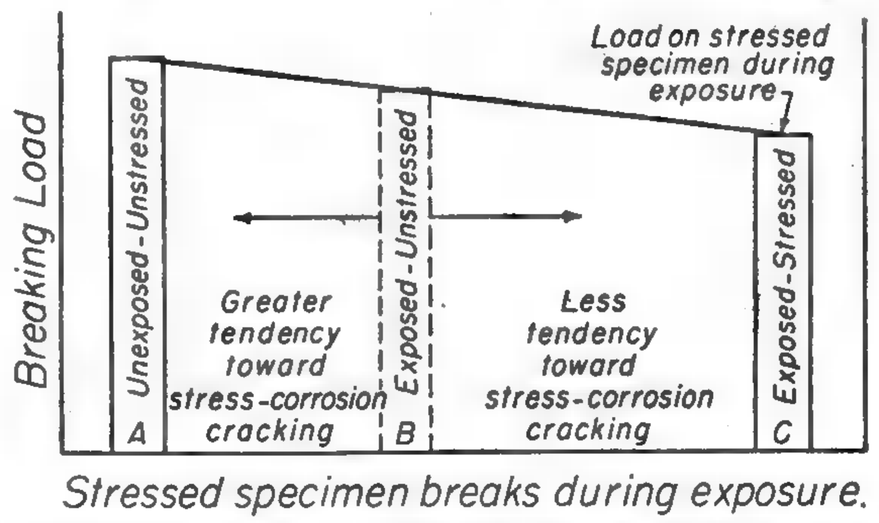

Fig. 2 Influence of stress and exposure on the tendency toward stress-corrosion cracking. (Dix and Brown)

* The members of this subcommittee are M. A. Hunter, *Chairman;* R. H. Brown, E. H. Dix, Jr., A. L. Jamieson and H. H. Uhlig.

represented in the diagrams by block *A*. Specimen *B* is exposed to a corrosive environment in the unstressed condition. Specimen *C*, exposed to the same corrosive environment, is stressed by a constant load equal, for instance, to three-quarters of the breaking load of specimen *A*.

During the period of exposure, specimen *C* may or may not break. Figure 1 represents the situation when *C* does not break. Specimens *B* and *C* are both tested. The breaking load of specimen *B*, as related to the breaking load of specimens *A* and *C*, shows the extent of the acceleration of the rate of corrosion of specimen *C* by the stress. The closer the breaking load of *B* to that of *C*, the less has been the acceleration of corrosion by stress; and the closer the breaking load of *B* is to that of *A*, the greater the acceleration by stress.

Figure 2 shows the situation when specimen *C* breaks under the combined action of stress and corrosion. The closer the breaking load for specimen *B* to the load on specimen *C* during exposure, the less the tendency toward stress-corrosion cracking. For example, if the breaking load for *B* is sufficiently close to the load on specimen *C* to be within experimental error, then although specimen *C* broke, the failure should not be attributed to stress-corrosion cracking, but rather to the probability that corrosion had reduced the cross section to such an extent that the specimen could no longer support the load. On the other hand, the closer *B* is to *A*, the greater the tendency toward stress-corrosion cracking to be ascribed to specimen *C*. It is common knowledge that stress-corrosion cracking often occurs, with very little general corrosion, in some of the metals that are considered resistant to corrosion.

Mechanism of Stress-Corrosion Cracking. Susceptibility to stress-corrosion cracking results when, within the structure of the metal or alloy, more or less continuous zones exist that are more susceptible to corrosion than the rest of the metal. Usually the corrosive attack in these zones occurs because they are anodic to the rest of the structure.[2,3] Fissures in the metal are initiated as a result of the electrochemical action between the anodic zones and the cathodic areas of the structure. If high tensile stresses are present at the surface, these small fissures increase the magnitude of local stress, tending to pull them apart. As the action proceeds, new metal at the base of the fissures is exposed and consumed by electrolytic corrosion. Thus, further concentration of the stress occurs and the depth of the fissures is increased. If the part breaks because of these mutually accelerated processes of increasing stress and corrosion, the failure is said to be from stress-corrosion cracking.

The rate of corrosion of many metals not susceptible to stress-corrosion cracking may be accelerated by high enduring tensile stresses at the surface. However, in those metals in which corrosion occurs selectively along more or less continuous zones, for the reasons stated above, the acceleration of the rate of corrosion by stress is much more marked.

The Stress Corrosion of Aluminum Alloys

By E. H. Dix, Jr.* and R. H. Brown*

GENERALLY, the magnitude of stress required to produce stress-corrosion cracking is high, perhaps half to three-quarters of the yield strength, and the stress must endure over a considerable period of time. Thus stresses induced by service loads are seldom the cause of stress-corrosion cracking. High residual stresses from quenching, forming, welding or misalignment in assembly are more likely to be the cause.

The Stress Factor. It is generally agreed that the stresses causing stress-corrosion failures are tensile or have tensile components at the surface of the metal, which is in contact with a corrosive environment. Such stresses are more likely to cause stress-corrosion cracking when they occur transversely to the elongated wrought grain structure. For example,[4,5] in aluminum alloy tubing sunk after heat treatment, the transverse stress was half the magnitude of the longitudinal stress, and yet longitudinal stress-corrosion cracks were caused by the lower transverse stress, in effect, pulling the grain fibers apart. No transverse cracks occurred, presumably because of the greater difficulty of following a more tortuous path.

In many metals high residual stresses may be reduced by stress-relieving treatments at temperatures lower than the recrystallization temperature. Unfortunately, with heat treated aluminum alloys, the temperatures[6] required to produce satisfactory stress relief have a markedly adverse effect on the mechanical properties and resistance to corrosion of the product. Therefore, in aluminum alloys susceptible to stress-corrosion cracking, manufacturing practices that will not produce high residual stresses should be employed; for instance, the alloy should be in the annealed temper when subjected to severe forming operations, and the part should be heat treated subsequently. Often too, the forming may be done shortly after quenching, at which time the yield strength is relatively low.

In the heat treatment of parts that are large in cross section, rapid quenching in cold water—a practice required by some alloys in order to produce maximum resistance to corrosion—may produce high residual stresses. For a certain alloy in large volume production, it was found that

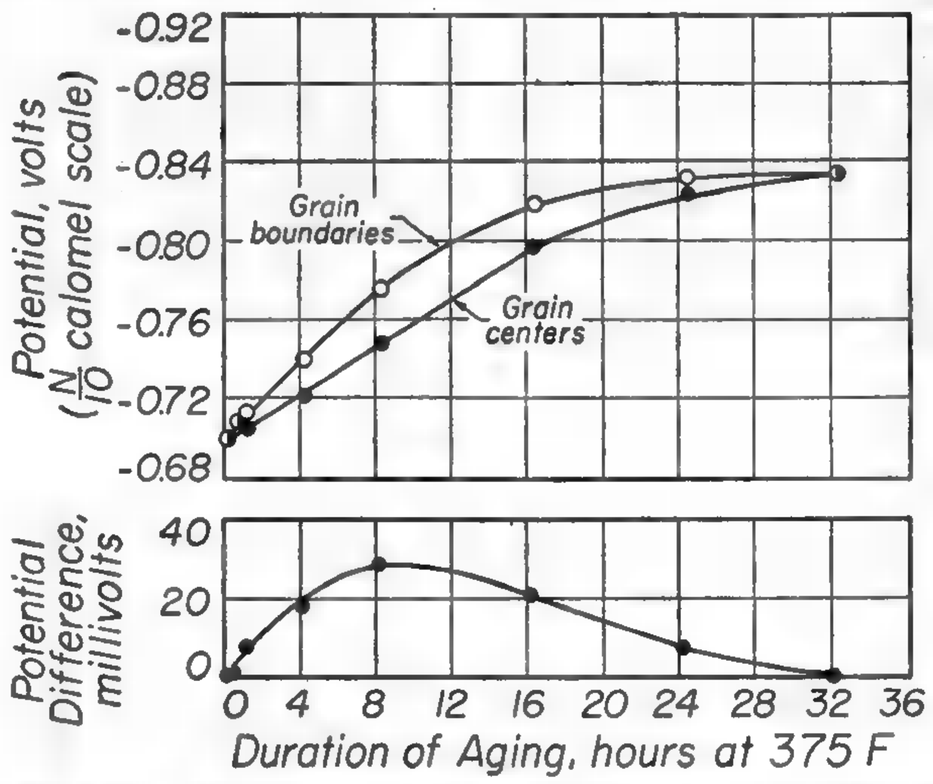

Fig. 3 Effect of duration of aging at 375 F on the electrode potentials of grains and grain boundaries of a high-purity aluminum-copper alloy containing 4.10% Cu (R. H. Brown)

quenching in boiling water, thus producing a much lower order of residual stress, avoided stress-corrosion cracking in service even though the slower quenching produced lower resistance to corrosion.

The Electrochemical Factor. The importance of electrochemical relationships within the structure of the metal or alloy, may be illustrated by considering the effect of thermal treatments on the susceptibility to stress-corrosion cracking of an aluminum-copper alloy. For an alloy of aluminum containing about 4% Cu, a solution treatment that puts most of this copper in solid solution, changes the electrode potential of the alloy from about minus 0.84 v to minus 0.69 v. Artificial aging at temperatures in the vicinity of 375 F produces precipitation from the aluminum-copper solid solution and a subsequent increase in the electrode potential of the alloy.

By a technique previously described,[7] it is possible to measure the potential at the grain boundaries and at the grain centers. Figure 3[3] shows the change in potential at the grain boundaries and grain centers with the duration of aging at 375 F. It will be observed that precipitation occurs more rapidly at the grain boundaries than within the grains, the boundaries becoming anodic to the grain centers. The maximum difference in potential between the grain boundaries and grain centers, as shown by the lower curve, occurs after aging for about 8 or 9 hr at this temperature. Beyond this period, the precipitation

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within the grain centers begins to catch up with that at the grain boundaries, and after the alloy has been heated for approximately 32 hr, virtually complete precipitation has occurred both at the grain boundaries and within the grains. Thus, the difference in potentials between the two has been reduced to almost zero.

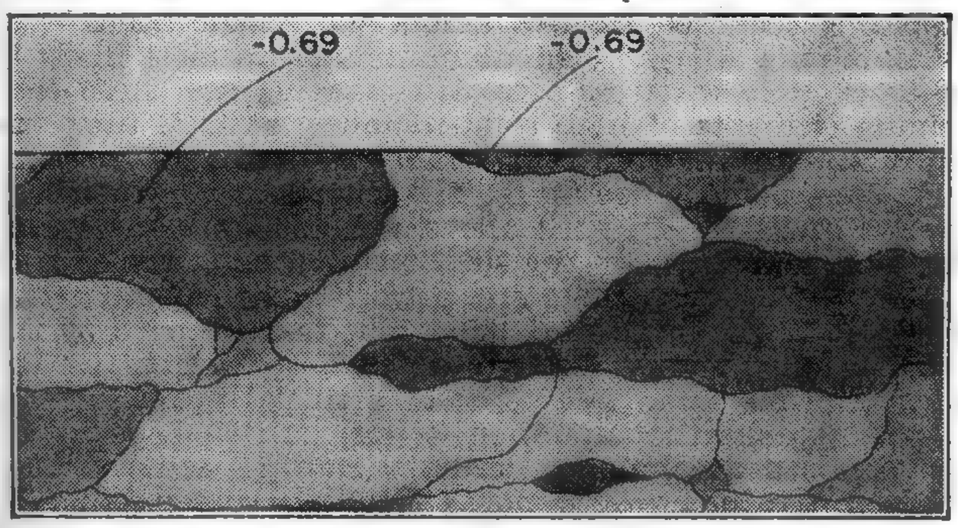

Fig. 4 Schematic illustration of the microstructure of a wrought aluminum-copper alloy containing 4% Cu. A uniform solid solution has been retained after rapid quenching from the temperature of solution heat treatment. The electrode potentials of grains and grain boundaries are equal.

The microstructural changes that bring about these differences in electrode potential are illustrated schematically in Fig. 4 to 7, inclusive. Figure 4 illustrates the uniform solid solution of copper in aluminum, produced by rapid quenching following a solution treatment. The electrode potential both within the grains and at the grain boundaries is minus 0.69 v. Figure 5 illustrates the beginning of precipitation caused along the grain boundaries by the first short periods of reheating at 375 F. The electrode potential of the grain masses has not changed measurably, but that of the depleted solid solution immediately surrounding the precipitated particles has become slightly more anodic. The precipitated particles of aluminum-copper constituent have an electrode potential of minus 0.53 v. Figure 6 illustrates the condition that exists at the time of maximum difference in electrode potential between the grains and boundaries. At this stage, the anodic material along the grain boundaries forms an almost continuous network that is anodic to the grain masses and to the particles of precipitate. In this condition the alloy is markedly susceptible to intergranular corrosion and, in the presence of high enduring tensile stresses at the surface, to stress-corrosion cracking. Figure 7 illustrates the structure after precipitation is nearly complete. There is no measurable difference in electrode potential between the grain boundaries and the grain masses, so this cause of selective corrosion has been eliminated. In a corrosive environment, electrolytic corrosion will occur between the particles of constituent and the base material, but the attack will be spread fairly uniformly, since the whole mass of metal, rather than just the grain boundaries, is anodic to the precipitate.

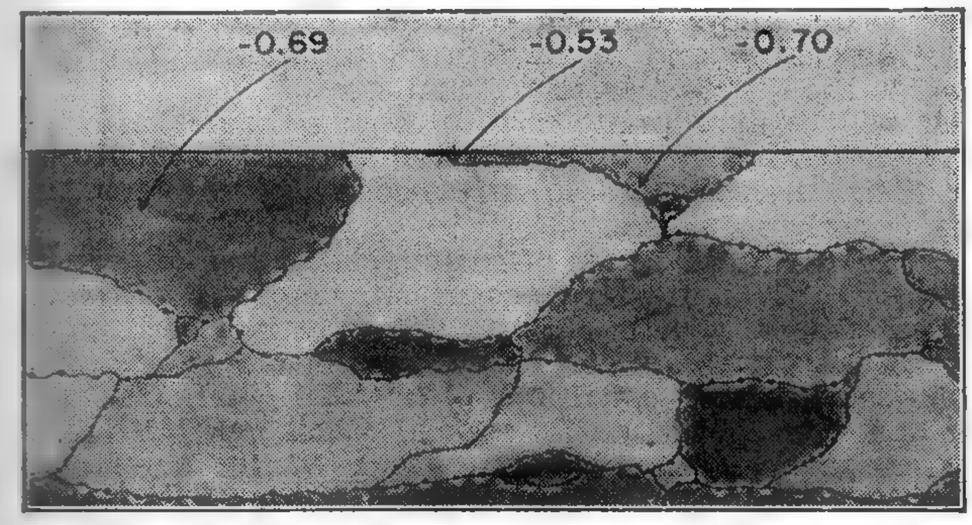

Fig. 5 The same alloy as Fig. 4 after a short period of reheating that caused the beginning of precipitation along grain boundaries. Surrounding each particle of the precipitate is a volume of solid solution that has been depleted in copper content and is anodic to the rest of the structure.

Fig. 6 The same alloy as Fig. 4 after a period of reheating that caused a maximum difference between the electrode potential of the grains and that of the grain boundaries. The volumes of solid solution immediately surrounding the precipitate form continuous zones along the grain boundaries.

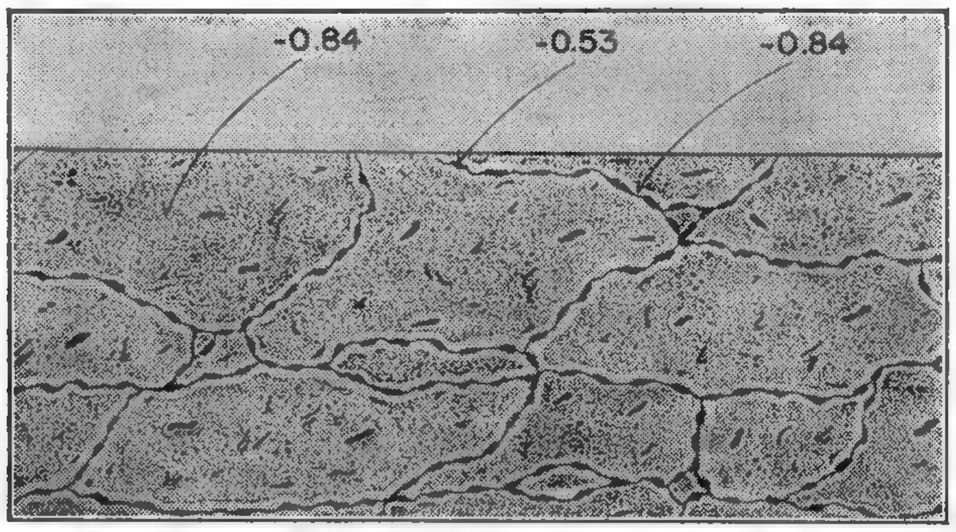

Fig. 7 The same alloy as Fig. 4 after a long period of reheating that caused nearly complete precipitation. The centers of grains and the volumes of solid solution at the grain boundaries have equal electrode potentials; both are anodic to the particles of precipitate.

Table I gives a number of values for electrode potential of interest in connection with various commercial aluminum alloys. It will be observed that the addition of manganese, or of magnesium and silicon in the ratio of the compound Mg_2Si, does not alter appreciably the electrode potential of the alloy, whereas copper in solid solution lowers the potential, and magnesium and zinc in solid solution raise the potential.

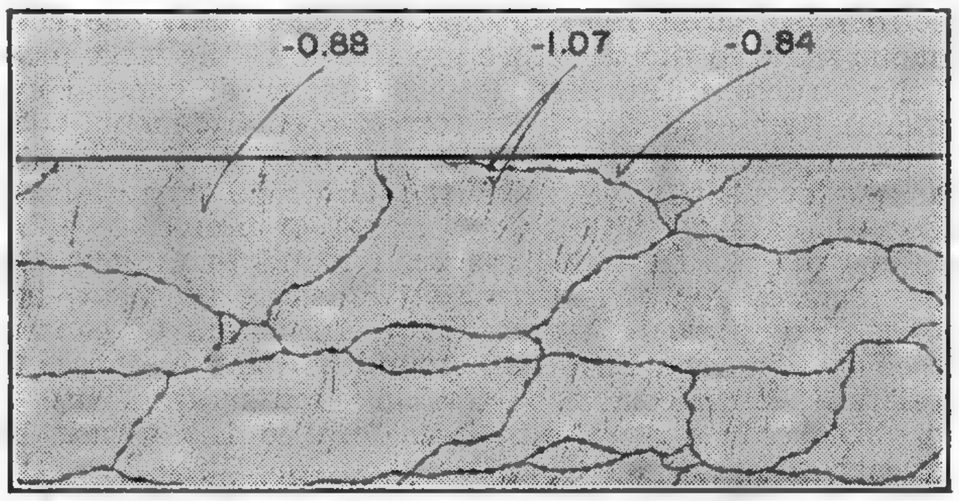

Fig. 8 Schematic illustration of the microstructure of a cold rolled aluminum-magnesium alloy containing 10% Mg. Continuous zones of anodic particles of precipitate occur on grain boundaries and slip planes.

In the aluminum-magnesium alloys containing magnesium in excess of the solubility limit, the aluminum-magnesium constituent is anodic to the aluminum-magnesium solid solution. Under certain conditions, precipitation may occur in a more or less continuous zone, either at the grain boundaries or along planes of slip caused by plastic deformation. In a corrosive environment, selective corrosion of these chains of precipitated particles will then occur and, in the presence of enduring high tensile stresses at the surface, the metal will fail by stress-

corrosion cracking. This microstructural condition is illustrated schematically by Fig. 8.

The importance of electrochemical relationships in the mechanism of stress corrosion is further emphasized by the fact that the application of a sufficiently large cathodic current will prevent failure of an alloy in a solution in which the alloy is normally susceptible to stress-corrosion cracking.[8]

Table I. Electrode Potentials of Aluminum Solid Solutions and Constituents[a]

Solid Solution or Constituent	Potential, volts 0.1 N Calomel Scale[b]
α(Al-Mg) (Mg_5Al_8)	−1.07
β(Zn-Mg) (Mg-Zn_2)	−1.04
Al-4% Zn solid solution	−1.02
Al-1% Zn solid solution	−0.96
Al-4% Mg solid solution	−0.87
α(Al-Mn) ($MnAl_6$)	−0.85
Aluminum	−0.84
Al + Mg + Si (1% Mg_2Si) solid solution	−0.83
Al-1% Si solid solution	−0.81
Al-4% Cu solid solution	−0.69
α(Al-Fe) ($FeAl_3$)	−0.56
Iron	−0.55
Al-Cu ($CuAl_2$)	−0.53
Silicon	−0.26
Copper	−0.20

(a) Data from Aluminum Research Laboratories
(b) Measured in an aqueous solution of 53 g NaCl + 3 g H_2O_2 per liter

The values of electrode potential quoted in the foregoing discussion are those obtained against a 1/10 normal calomel electrode in a sodium chloride solution to which hydrogen peroxide has been added.[8] Measurements obtained by this method have been found to indicate potential relationships that agree well with the behavior of the alloys in most service environments. However, in acid or strongly basic solutions, these relationships are no longer maintained. In fact, cold worked aluminum-magnesium alloy specimens (10% Mg) that cracked in a 6% NaCl solution, did not crack when 10 g per liter of sodium hydroxide was added in the solution.[2]

The Environment Factor. The preceding discussion has indicated that the corrosive environment most likely to produce stress-corrosion cracking is one in which the electrode potential relationships are such that the continuous zones in the structure are anodic to the large mass of the structure. Further, it is a matter of general experience that even very mild corrosive environments such as atmospheric moisture, will produce stress-corrosion cracking eventually, provided the electrode potential relationships are as indicated. Coatings of protective paint or films of oil and wax have been found to prolong the time required for stress-corrosion cracking to occur, but they do not prevent the cracking. Inhibitors of general attack by corrosion have been found in some instances to accelerate stress-corrosion cracking markedly. This is probably because such inhibitors localize the attack by corrosion under some conditions.

The above discussion suggests some of the reasons why evaluation of susceptibility to stress-corrosion cracking by accelerated laboratory tests entails so many difficulties.[9] Reliance should not be placed in results of accelerated laboratory tests unless the testing method has been correlated with actual service experience for the particular type of alloy under investigation. It is probable that almost any metal or alloy can be made to crack when highly stressed and exposed in specially selected solutions. However, such results may be entirely unrelated to conditions that would be encountered in normal service.

Other Factors. It has been explained that precipitation in aluminum-base alloys may produce localized zones anodic to the mass of the metal. Extensive testing and experience in service have indicated beyond a doubt that this condition may be one cause of susceptibility to stress-corrosion cracking. Experience with some other metals seems to indicate that precipitation is not the only cause, although more exhaustive fundamental research may indicate that, even in those instances, constituents are precipitated that are not now recognized. It has been suggested that the disorganized nature of the crystal structure at the grain boundaries or high localized stresses may also produce differences in electrode potentials. Other factors also increase susceptibility to stress-corrosion cracking. For example, volume changes resulting from precipitation from solid solution may induce microscopically localized stresses across the anodic zones.

Aluminum Alloys.* The aluminum alloys most likely to be susceptible to stress-corrosion cracking are those containing elements of high solid solubility at high temperatures, and in amounts considerably in excess of the solubility at room temperature, for instance, copper, magnesium and zinc. In such alloys, the microstructural condition is influenced by the solution treatment, the rate of cooling during quenching, and artificial and natural aging. The rate of cooling during quenching is influenced by the mass of the product being quenched, as well as by the quenching medium. The effect of artificial aging in some alloys, notably the aluminum-copper alloys, depends on the previous quenching procedure. Natural aging after a solution treatment does not affect the susceptibility to stress-corrosion cracking of alloys of the aluminum-copper group, but does have a marked effect on the susceptibility of wrought aluminum-magnesium alloys that contain more than about 4½% Mg.[11] In this group, a period of months or even years is required before precipitation is sufficient to make the alloy susceptible to stress-corrosion cracking. Often the aging process is proceeding simultaneously with exposure to a corrosive environment. Because of this characteristic, available information concerning aluminum-magnesium alloys is often confused. Plastic deformation may accelerate and localize precipitation and may also change the distribution of residual stress.

It will be appropriate now to discuss the various types of aluminum alloys, both cast and wrought, with respect to their susceptibility to stress-corrosion cracking and the underlying causes.

Aluminum. Aluminum of commercial or higher purity is not susceptible to stress-corrosion cracking. However, very high-purity aluminum, 99.95% min, has been shown to be susceptible to intergranular corrosion in hydrochloric acid under conditions of thermal treatment[12] that make the grain boundaries anodic in this acid.[8] No satisfactory explanation has been suggested for the anodic condition of the grain boundaries.

Aluminum-Manganese Alloys. The solid solubility of manganese in aluminum is low and the aluminum-manganese constituent has about the same electrode potential as aluminum; hence no susceptibility to stress-corrosion cracking would be anticipated and none has been found in accelerated tests or experience in service.

Aluminum-Silicon Alloys. The solid solubility of silicon in aluminum is relatively low and precipitation is sluggish. The electrode potential of the silicon constituent is strongly cathodic to aluminum, but aluminum and the aluminum-silicon solid solution have nearly the same potential. Aluminum-silicon alloys are used far more extensively in castings than in wrought products. No examples have been reported of susceptibility to stress-corrosion cracking in cast or wrought products of these alloys.

Aluminum-Magnesium Alloys. The solid solubility of magnesium in aluminum near the eutectic temperature is about 15% but is less than about 2% at room temperature. The aluminum-magnesium constituent is highly anodic to aluminum and the aluminum-magnesium solid solution. Binary alloys containing more than about 4½% Mg are susceptible to stress-corrosion cracking, particularly when they are cold worked.[11] By the addition of inhibitors such as manganese and chromium, satisfactory freedom from stress-corrosion cracking can be obtained in aluminum-magnesium wrought products containing as much as 5½% Mg.[13] Castings that contain about 10% Mg, although susceptible to stress-corrosion cracking, have been used successfully with no reported failure from this cause.

Aluminum-Magnesium-Silicon Alloys. When magnesium and silicon are present in commercially useful aluminum alloys in the ratio of the compound Mg_2Si, the electrode

* For further discussion see reference 10.

potential of the alloy is not affected by a variety of thermal treatments. Several commercial wrought alloys containing these elements in the compound ratio are highly important because of their good resistance to corrosion. They are not susceptible to stress-corrosion cracking. One of the older wrought alloys that contains silicon in excess of the Mg_2Si ratio, when in the artificially aged temper, is susceptible to intergranular corrosion and, under some conditions, to stress-corrosion cracking.

Aluminum-Silicon-Magnesium Alloys. An important group of casting alloys contains from 5 to 7% Si with less than about 0.5% Mg. These alloys have high resistance to corrosion and have not been found susceptible to stress-corrosion cracking. The addition of about 1½% Cu increases the tensile strength but lowers somewhat the resistance to corrosion, and produces susceptibility to stress-corrosion cracking. Still, no examples have been reported of stress-corrosion cracking in service from castings made of alloys of this type.

Aluminum-Copper Alloys. The aluminum-copper alloys have already been discussed. When rapidly quenched and naturally aged, these alloys are not susceptible to stress-corrosion cracking. After being reheated under some conditions or after being artificially aged to maximum strength and hardness, these alloys are susceptible to stress-corrosion cracking. For several decades large tonnages of aluminum-copper alloy castings, both in the "as-cast" and heat treated conditions, have been used under a variety of service environments without difficulty from stress-corrosion cracking, even though many were used in the artificially aged temper.[14]

Aluminum-Copper-Magnesium Alloys. In general, these alloys behave the same as aluminum-copper alloys except for the influence of magnesium on the aging characteristics. Thus, when rapidly quenched, they are not susceptible to stress-corrosion cracking although, under some conditions of reheating, they become susceptible. The rate of aging of one of these alloys (24 S) is influenced by cold working subsequent to the solution treatment, and this alloy, if artificially aged to just a little past maximum strength and hardness, is free from susceptibility to stress-corrosion cracking.[15] Examples of stress-corrosion cracking in service are rare.

Aluminum-Copper-Magnesium-Silicon Alloys. In these alloys, the silicon in excess of the Mg_2Si ratio, affects markedly the response to artificial aging. In the rapidly quenched condition, these alloys are not susceptible to stress-corrosion cracking. When slowly quenched and naturally aged or when rapidly quenched and artificially aged to maximum strength and hardness, these alloys are susceptible to stress-corrosion cracking. However, when the rate of cooling during quenching is relatively slow, either because of the quenching medium or because of the mass of the section, artificial aging is not harmful and may even be beneficial, especially if the quenching rate is properly controlled. Only isolated instances of stress-corrosion cracking have occurred in service.

Aluminum-Zinc Alloys. These alloys were among the first to be recognized as susceptible to stress-corrosion cracking. The solubility of zinc is high and the aluminum-zinc constituent is strongly anodic to aluminum. The high-zinc aluminum-base alloys have not achieved commercial importance.

Aluminum-Zinc-Magnesium Alloys. This series of alloys, with other additions, offers the greatest possibilities for high-strength aluminum alloys. The development of these alloys has been limited because of marked susceptibility to stress-corrosion cracking. Within recent years, by the proper selection and control of the zinc and magnesium contents, together with additions of copper and of inhibiting agents such as chromium, alloys have been developed that are satisfactory in resistance to stress-corrosion cracking, and they are giving satisfactory service.[15,16]

Practical Considerations. Very few aluminum alloy parts have failed in service because of stress-corrosion cracking. Aluminum is not susceptible to stress-corrosion cracking, nor are the aluminum alloys that are not heat treatable and that are in commercial use in this country. One group of such alloys used abroad, namely the wrought aluminum-magnesium alloys containing more than 5% Mg, have been used successfully in many applications, in spite of the fact that under some conditions of service they are susceptible to stress-corrosion cracking. The heat treatable alloys containing magnesium and silicon in the ratio of Mg_2Si, compose an important group of alloys used because of their high resistance to corrosion, their good forming characteristics, and weldability; these alloys also are not susceptible to stress-corrosion cracking.

In the higher-strength heat treatable aluminum alloys containing principally copper or magnesium and zinc, susceptibility to stress-corrosion cracking may be present under some conditions of thermal treatment. However, these conditions are well understood and the available knowledge has made it possible to avoid stress-corrosion cracking in service except in a few isolated instances.

It should be repeated that in order for stress-corrosion cracking to occur, high enduring tensile stresses must be present at the surface. In structural applications, stresses from working loads must be kept lower than the value required to produce stress-corrosion cracking, because of normal factors of safety, avoidance of fatigue failures, and other considerations. An exception to this statement should be made in such an application as gas cylinders, produced from high-strength aluminum alloys, in which the surface stresses may approach those required for stress-corrosion cracking, and these high stresses act for long periods of time. Failures of aluminum castings in service because of stress-corrosion cracking are virtually unknown. A contributing influence is the larger factor of safety employed for castings, and the generally thicker section that tends to reduce assembly stresses.

In wrought products, residual stresses may be kept to a minimum, in quenching, fabricating and assembly, by the use of information now available, so that stress-corrosion failures in service may be avoided, even in alloys that are susceptible to stress-corrosion cracking.

The Season Cracking of Copper Alloys

By A. L. Jamieson*

SEASON cracking is the apparently spontaneous cracking of stressed copper alloys, with little or no deformation of the adjacent metal. The mechanism of the formation of these cracks is obscure although the factors involved are well understood.

Two factors, stress and corrosion, are prerequisites; the other factors, composition and microstructure, affect only the rate of progress of the cracks. However, these factors can be controlled and the occurrence of season cracks can be substantially eliminated through the use of improved fabricating techniques and preventive measures after fabrication. Several methods have been developed for detecting the tendency of an article to season crack, and the success of an article in passing these tests is indicative of freedom from the tendency to season crack, although such an indication should not be mistaken for assurance of freedom from season cracking.

Stress. When related to season cracking, stresses are divided into two sources, that is, applied and residual, although there is no evidence that the origin of stresses has any effect on the mechanism of failure.

Applied stresses result from either an assembly operation or a service load. Assembly stresses result from the joining of two or more integral parts by welding, riveting, screwing or inserting. Service stresses, although usually quite obvious, are frequently overlooked when they are cyclic or fluctuating.

Residual stresses are of two types—strain hardening and cooling. Strain hardening stresses originate from a nonuniform cold working process, such as drawing, pressing, rolling, stretching, spinning or bending. Cooling stresses result from nonhomogeneous thermal contraction or change of volume that occurs during quenching (with differential cooling rates) and phase transformations.

The magnitude of the stresses, however, is vitally important, since the tendency to season crack is a function

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of the magnitude of the stress. In specimens exposed to ammoniacal corrosion, the rate of cracking is relatively low for values of stress considerably lower than the elastic limit, but with stresses near the elastic limit, corrosion may proceed very rapidly.

The relationship of cold work to elastic limit and hardness, has led to the erroneous belief that season cracking is a function of hardness. Although the maximum possible stress is equivalent to the elastic limit, numerous investigations have indicated that residual stresses are a function of the method of fabrication and that high degrees of cold work may be obtained with little or no residual stress. In drawing, the two most important factors involved in obtaining low stresses are the angle of the die[17] and the ratio of hollow sinking to ironing.[18] Dies of shallow angle (4 deg) do not stress tubes as much as dies of steeper angle (25 deg). Crampton[18] demonstrated that residual stresses in tubes are increased by increased wall thickness, by hollow sinking and by greater reduction of diameter, and are decreased by greater reduction of wall thickness. It is possible, therefore, to plan most drawing operations so that season cracking is negligible. Other operations usually involved (upsetting, spinning, stretching, bending) are more difficult to evaluate, and freedom from residual stresses is impossible to obtain by operational control.

Corrosion. Although season cracking occurs in what seems to be clean air, it is known that such cracking will not occur in the absence of a corrosive environment.[19] Therefore, the agents necessary for producing the specific corrosion must be present virtually always in the normal atmosphere. Of the numerous reagents known to cause stressed copper alloys to crack,[19–23] ammonia and its derivatives are the only ones usually found in the atmosphere. It has been proved recently[24] that ammonia in the absence of oxygen and water vapor will not cause cracking. It has been demonstrated that several other reagents,[24,25] such as CO_2, accelerate the cracking in ammoniacal atmospheres, but they are not essential to the instigation of cracking. The minute quantities of ammonia usually found in the air seem too small to produce cracking, but the concentration that develops in the adsorbed moisture film soon becomes appreciable.

Composition. Apparently all copper alloys, regardless of the alloying constituents, are susceptible to season cracking. In copper alloys, the tendency to season crack increases as the zinc content increases to a maximum of 40%. Practical experience indicates that brasses with less than 15% Zn are usually immune to season cracking although, under severe conditions, commercially pure copper has season cracked.[26] Experimentally[27] in an atmosphere of ammonia, copper is immune to season cracking, but the addition of as little as 3% Zn increases the susceptibility markedly. Brasses with 40% Zn, although highly susceptible, are only slightly more so than alloys that contain 20% Zn. The susceptibility of copper alloys to season cracking has been attributed to impurities. Recently[28] it has been shown that high-purity cartridge brass (70% Cu, 30% Zn) containing only spectroscopically detectable traces of impurities, has the same tendency as commercial cartridge brass to season crack. Additions of various elements have been investigated systematically in regard to their effect on the season-cracking tendency of cartridge brass, and no acceleration of season cracking was indicated. Several elements (P, As, Ba, Ce, Mg, Te, Sn, Be and Mn) decreased the susceptibility to season cracking under some conditions. Silicon additions of as much as 1.5% decreased the season-cracking tendency of brasses under all conditions.

Microstructure. The importance of microstructure in the season-cracking phenomenon is frequently dismissed as inconsequential because it is not an essential factor. However, since it has been established that rapidity of cracking correlates definitely with the grain size and structure of the metal, microstructure is of considerable practical importance.

When all other conditions are identical, the rapidity of season cracking increases proportionally with the grain size and inversely with the degree and direction of cold work. In single-phase alpha brasses where the cracking is intercrystalline, it is obvious that the shorter path is the reason. In the limiting condition, that is, in a single crystal, the tendency to crack is at a minimum but not eliminated.[27] A similar grain-size effect is more obscure in alpha-beta alloys, because the cracks run between the phases or through the beta phase.[18]

Since the structure of all metals depends on composition and on thermal and mechanical treatment, it is understandable that the effects of structure on season cracking are obscure and interlocked with both the composition and the stress factors. Because of this effect of interlocking, it is difficult to separate the influence of structure from the other influencing factors, and in some instances the effects of structure may appear to be contradictory. For example, although it is known[29] that traces of beta in brass that is assumed to be wholly alpha, increase the susceptibility to season cracking, a slowly cooled alpha-beta brass has a greater tendency to season crack than the same alloy that has been quenched to retain a greater percentage of beta.[30] This apparent anomaly is the result of varied cooling stresses (from volume change and quenching) functioning in the quenched alloys, and compositional differences in the slowly cooled alloys. The increased resistance achieved by quenching brasses that contain silicon, is an excellent example of the influence of structure. The improvement results from the introduction of a second phase, which persists through cold working but is destroyed by annealing at a low temperature.

Detection of Season Cracking. The tendency to season crack may be detected by several methods. The simplest method is the mercurous nitrate test, which reveals whether stresses that exist in the cold worked or stressed brass, are of a magnitude likely to cause the brass to season crack. Briefly,* this test consists of immersing the clean article to be tested in an acidified (1% HNO_3) aqueous solution of mercurous nitrate (usually 1 or 10% $HgNO_3$) for a predetermined period (15 min to 1 hr) and then examining for cracks. The presence of cracks indicates that the article is likely to season crack in service. Mercury, like liquid tin, lead and solder, is a reagent that causes copper alloys to fail in a brittle way at stresses considerably lower than the yield strength. These reagents will not cause cracking at stresses lower than a definite minimum, but that minimum stress may result in season cracking. It is because of this threshold stress (12,000 psi) that the mercury cracking test, although fairly reliable, is not a positive test for susceptibility to season cracking. However, experience has indicated that if an article can pass a 15-min immersion period successfully, its susceptibility to season cracking is fairly low.

A second method of testing consists in exposing the brass to a gaseous atmosphere of ammonia, water vapor and air for 4 to 24 hr before the examination for cracks.[32] It is common practice to deform the article slightly in order to exaggerate the cracks, which are frequently very fine. This test has not been used sufficiently to permit a correlation of test results with service failures and therefore has not been generally accepted; also this test is more difficult to maintain and requires equipment of a more specialized nature than the mercury test.

A third method of testing, a mechanical method for measuring stress, stems from the method used originally by Heyn,[31] in which stresses were measured by evaluating the dimensional changes that occur with the removal of small successive increments of metal. From this technique, modified by a number of investigators, the split ring, the tongued beam, and several methods involving drilling have been developed. Through the use of these various techniques, the stresses in complicated shapes may be evaluated, but the accuracy decreases with the complexity of the article that is being tested. This obviously difficult and time-consuming procedure does permit the evaluation of the magnitude of the average stress, but does not reveal concentrated or localized stress peaks.

A fourth method for detecting susceptibility to season cracking uses a complicated X-ray diffraction technique that is controversial when applied to copper alloys. This

* In ASTM Standard Method B 154-45

method, which measures distortion of reflected rings, has one advantage over all the test procedures mentioned previously; that is, it is a nondestructive test. Like the mechanical method, this procedure measures the stresses only in the area examined, whereas the ammonia and mercury tests have the advantage of testing the entire surface of the article. For this reason the mercury test, though not infallible, remains the standard industrial test for season cracking. Material used in either the mercury or ammonia test should be considered destroyed even if cracking does not occur during the test, since any subsequent use may result in premature failure if the material is subject to additional stress or strain.

Prevention. There are only two effective preventives for season cracking: one is the elimination of the stress factor; the other is the elimination of the corrosion factor. Obviously neither of these factors may be eliminated in service, but either or both may be reduced to a minimum where season cracking is an improbability.

Residual and assembly stresses may be eliminated by a recrystallizing anneal, after the final operations of forming or assembling. Such a softening anneal is often unsatisfactory, since the properties of the strain hardened metal may be required for satisfactory functioning of the material. When such a condition exists several methods are practicable for reducing the stresses to a safe magnitude without affecting the properties desired. The most common procedure, thermal stress relieving,* consists in heating the cold worked article for a short period at a low temperature. The exact time and temperature depend on the severity of the deformation, the composition of the metal and the degree of softening permissible. For most copper alloys the time varies from 30 min to 1 hr and the temperature varies from 300 F (150 C) to 575 F (300 C). The typical treatments for stress relieving, shown in Table II, may not be adequate for a given article but are indicative of the usual temperature and time.

Table II. Typical Thermal Stress-Relieving Treatments for Copper Alloys

Alloy	Composition, % Cu	Zn	Sn	Ni	Temp deg Fahr	deg Cent	Time, hr
Copper	100	..	..	..	300	150	½
Commercial Bronze	90	10	..	..	400	215	1
Low Brass	80	20	..	..	500	265	1
Cartridge Brass	70	30	..	..	500	265	1
Yellow Brass	63	37	..	..	475	250	1
Muntz Metal	60	40	..	..	375	200	½
Admiralty Metal	70	29	1	..	575	300	1
Cupro-Nickel, 15%	85	..	..	15	475	250	1
Cupro-Nickel, 30%	70	..	..	30	475	250	1
Nickel Silver	64	[illegible]	..	[illegible]	475	250	1
Phosphor Bronze	95	..	5	..	375	200	1
Phosphor Bronze	90	..	10	..	375	200	1

Several less common methods—stretching, flexing, bending, straightening between rollers, reeling and peening (shot blasting)—used to reduce the residual stress to a safe minimum, depend on plastic deformation to decrease dangerous tensile stresses or to convert them into the less objectionable compressive stresses.

In establishing any procedure for relief of stress, it is essential that treated pieces be tested in order to make sure that the stresses have been sufficiently relieved. Care should be taken also to ensure that no subsequent operation follows the stress relieving, since a further operation may introduce high stresses.

Because it would not be feasible to stipulate the corrosive atmosphere to which a fabricated article may be subjected in service, elimination of corrosion is difficult. It is possible, however, to minimize the corrosion by protecting the fabricated metal with a nonporous coating of lacquer or electroplated metal. To rely on either of these coatings alone is unwise, since they may be removed by corrosion, abrasion or chipping.

The most reliable procedure for eliminating season cracking is to combine the techniques for elimination of stresses and for protection against corrosive atmosphere. When such a combination is commercially impracticable or economically unsound, the procedure for stress relieving is the most desirable of the techniques for prevention of season cracking.

* For additional information on the thermal stress relieving of copper alloys the reader may refer to the COPPER SECTION.

The Stress-Corrosion Cracking of Iron and Some Ferrous Alloys

BY H. H. UHLIG*

MILD steel and other low-alloy steels, iron-nickel alloys, and austenitic stainless steels are the ferrous materials that have been studied most extensively in relation to stress-corrosion cracking.

Mild Steel and Other Low-Alloy Steels. Stress-corrosion cracking of mild steel in alkaline solutions is called "caustic embrittlement" or sometimes "boiler embrittlement". The failure is largely intergranular and usually occurs only with concentrated sodium hydroxide in the presence of one or more impurities that act as accelerators. Stress-corrosion cracking may occur when certain kinds of alkaline boiler waters concentrate at seams of riveted boiler drums or wherever slow leakage acts to concentrate the boiler water. Welded boilers are less susceptible to damage from this source.

Failure may be accelerated by the presence of silicates[32] in waters of high-pressure boilers, but damage can be retarded or completely inhibited by sodium nitrate[33] (added to the extent of 20 to 30% of the alkalinity expressed as sodium hydroxide), quebracho extract[33] or phosphates.[34] However, with boiling temperatures at atmospheric pressure in contrast with higher pressures, 0.13% $NaNO_3$ in 33% NaOH solution accelerated stress-corrosion cracking of steel.[35] Among other accelerants at atmospheric pressure are PbO, $KMnO_4$ and Na_2CrO_4.

Formerly sodium sulfate was added in concentrations prescribed by the alkalinity of boiler waters, but it has not prevented caustic embrittlement detectors from failing[33] and is no longer considered necessary.

Iron and steel are subject to rapid stress-corrosion cracking in nitrate solutions.[36] The fractures are largely intergranular. Mixtures of concentrated calcium and ammonium nitrates at the boiling temperature are especially effective in causing damage, as are 60 to 95% ammonium nitrate solutions.[37] Concentrated HNO_3 at 20 C can also cause cracking of stressed specimens,[37] as can dilute nitric acid containing a small amount of $MnCl_2$ as accelerator, held at 60 to 80 C. However, 46% $MgCl_2$ at 125 C is ineffective despite its ability to crack stressed stainless steels.[37]

A 0.7 to 0.8% C steel wire, used as bridge cable, failed in service by stress-corrosion cracking and afterward was found to crack within 3½ to 9½ months when highly stressed and immersed in 0.01*N* NH_4NO_3 or in 0.01*N* $NaNO_3$. No cracking occurred in distilled water, in 0.01*N* $(NH_4)_2SO_4$, NH_4NO_2 or NaOH.[38]

Stresses beyond the elastic limit (plastic flow) are especially conducive to stress-corrosion cracking of iron in caustic solutions; hence rivet holes of boilers are likely to show cracking first, if cracking occurs at all. Stresses lower than the elastic limit can cause rapid cracking of iron or steel in calcium-ammonium nitrate solutions at 100 C.[39]

Stresses lower than the elastic limit also cause cracking of mild steel or low-alloy steels in aqueous solutions of HCN. The fractures are *transgranular* in contrast with intergranular fractures in caustic or nitrate solutions mentioned above. A 0.4% C – 0.6% Cr – 0.3% Mo – 0.5% Ni steel (elastic limit, 125,000 psi) stressed to 57,000 psi and immersed in a solution of 2.6 g HCN per liter of water, failed within 14 days; in a solution of 3.5 [illegible] HCN per liter of water, the steel failed within 7 days. Stressed to 99,500 psi, this same steel failed within 7 days in the first solution.[40]

Failures resulting from the presence of HCN have occurred when illuminating gas was stored under pressure in steel tanks. The gas contained both moisture and traces of HCN as impurities.[40] It has been suggested that failures

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caused by HCN could be avoided to some extent by drying the illuminating gas; by removing HCN; or by employing zinc-coated or aluminum-coated steel.

Steels containing interstitial nitrogen appear to be more susceptible than low-nitrogen steels to stress-corrosion cracking in alkalies and nitrates, but it has not been established conclusively that nitrogen is the only factor, nor the only important one. Increased carbon content reduces the tendency of a steel to fail by intergranular corrosion cracking.[37] Stressed aluminum-killed steels show less tendency to crack in caustic soda at 200 to 250 C[38] or in concentrated nitrates at 100 C[37] than those free from aluminum. Apparently, low concentrations of phosphorus and nitrogen in steel, made possible by reaction of these components with aluminum, accompany optimum resistance to corrosion cracking.[41,42] The factors that decrease aging of iron appear to decrease susceptibility to intergranular corrosion cracking.[37,41,42]

Preliminary heat treatment for 2 to 4 hr at high temperatures (1080 to 1230 C) in CO_2, H_2O and especially nitrogen, is detrimental to the life of stressed steel in nitrate solutions. Heating in air at 1050 to 1200 C followed by slow cooling, is likewise detrimental.[37]

Iron-Nickel Alloys. Alloys of iron and nickel may stress-corrosion crack in dilute hydrochloric or sulfuric acid unless the nickel content is greater than 35%.[43] Stressed alloys containing 18% and 28% Ni were found to crack in 0.4% HCl or 16.4% H_2SO_4 in 2-month tests at room temperatures. The alloy containing 28% Ni, 16 to 18% Mo and 2.5% Cu is not subject to cracking in the same mediums under identical test conditions.

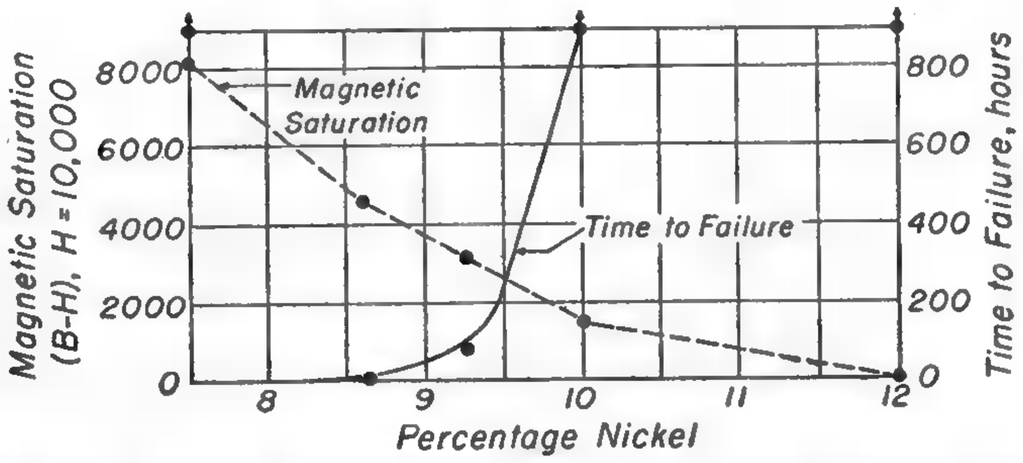

Fig. 9 Influence of nickel content on stress-corrosion cracking of 18% Cr-Ni steels (stressed 28,450 psi) in $CaCl_2 + HgCl_2$ at 80 to 100 C. Values of magnetic saturation are for alloys extended 30%.

Stress-corrosion cracking of the 25% Ni-Fe alloy in the form of steam turbine blades has been reported. The cracks were transgranular.[44]

Stainless Steels. Stainless steels are subject to stress-corrosion cracking in specific mediums, particularly acid chlorides or dilute hydrochloric acid. The failures of annealed and quenched alloys are usually transgranular, distinguishing stress-corrosion cracking of these alloys from intergranular corrosion not requiring stress. Intergranular corrosion occurs particularly with austenitic alloys when they have been heat treated so that carbides precipitate at grain boundaries. Stress-corrosion cracking of stainless alloys does not depend on precipitated carbides. It rarely occurs in service, but a few instances have been observed; for example, in deep-drawn coffee urns and in equipment to condition wool or handle dye solutions.[45]

Boiling 42% $MgCl_2$ is extremely active in producing transgranular cracking of stressed 18-8 alloys, including alloys stabilized with columbium or titanium. Types 302, 304, 316, 317, 321 and 347 have cracked in short-time tests in this medium. $BaCl_2$ is not effective in the same sense as $MgCl_2$ but accelerated cracking has been accomplished by the use of boiling solutions of $CaCl_2$, $CoCl_2$, $ZnCl_2$, LiCl, or NH_4Cl.[46,47] Ethyl chloride containing water has caused stress-corrosion cracking of 18-8,[48] presumably because of liberated hydrochloric acid. A solution of 100 g NaCl and 9.3 g H_2O_2 per liter at room temperature will cause stress-corrosion cracking of stainless steels within periods of weeks.[49]

Free-machining stainless steel is very susceptible to corrosion cracking in some of the caustic and nitrate solutions used by Schroeder, Berk and O'Brien to test mild steel.[35]

The stress necessary to cause transgranular cracking of stainless steels in specific mediums can be residual or applied. Stencil-stamped specimens and deep-drawn 18-8 sheet crack in some of the hot chloride solutions listed above. Stresses resulting from cold straightening, quenching, grinding or differential thermal expansion are sufficient to cause stress-corrosion cracking.[50] A type 316 steel (18-8 containing molybdenum), water-quenched from 1070 C (1950 F), cracked when exposed later to a boiling calcium-magnesium chloride brine, but resisted cracking in a 17-day test after being stress-relieved at 730 C (1350 F) for 1 hr and then cooled in the furnace.[51] The applied threshold stress necessary for cracking 18-8 in boiling 42% $MgCl_2$ is less than 20,000 psi.[50]

Ferritic stainless steels are less susceptible to stress-corrosion cracking than are the austenitic alloys. Austenitic chromium-nickel steels immersed in boiling 42% $MgCl_2$ and stressed to 40,000 psi, cracked in 7 to 72 hr, whereas 18.6% Cr steel (type 430) and 12% Cr – 0.2% Al steel (type 405) when stressed the same amount, did not crack in tests continued for 504 to 624 hr.[50]

In the 18% Cr-Ni alloys, stressed 28,450 psi and immersed in 40 to 60 parts $CaCl_2$, 60 to 40 parts water plus 0.1 to 1% $HgCl_2$ at 80 to 100 C, resistance to cracking increases with the nickel content (Fig. 9). From the behavior of the magnetic saturation for specimens extended 30%, the resistance to cracking in the $CaCl_2$ medium appears to be a function of austenite stability, since the 12% Ni alloy exhibits both maximum resistance to stress corrosion and least tendency to transform to ferrite during cold working.[52]

The sensitivity of 18-8 to cracking, increases with carbon content up to 0.045% C and then decreases. For similar alloys containing higher percentages of nickel, the corresponding carbon content for greatest sensitivity is higher.

The Stress Corrosion of Magnesium Alloys

By M. A. Hunter*

FORMERLY the behavior of magnesium alloys under stress corrosion was not a matter of recognized importance. However, the extended use of these alloys as structural materials in airplane manufacture, during the recent war, has sharply focused the attention of designers on the possibilities of structural failure arising from the stress-corrosion cracking of magnesium alloys used in construction.

Recent research projects have determined many of the conditions that lead to stress-corrosion sensitivity and have indicated means by which such sensitivity can be minimized or perhaps even eliminated. The recently published symposium on Stress-Corrosion Cracking of Metals[53] contains several papers that summarize the results of some of these investigations.

General Susceptibility of Magnesium Alloys. Investigators agree that failures of magnesium alloy castings in service because of stress-corrosion cracking are virtually unknown. This statement seems to hold for all cast alloys, regardless of composition. However, cast test bars of several magnesium alloys, stressed to approximately one-half the yield strength, have failed by stress-corrosion cracking during outdoor atmospheric exposures.

Some wrought alloys appear to be particularly sensitive under certain conditions, while others appear to be immune under all conditions encountered in service. The three most important alloys used in sheet form are:

ASTM Designation	Nominal Composition
M1	Mg — 1.5% Mn
AZ31X	Mg — 3 Al — 1 Zn — 0.3 Mn
AZ61X	Mg — 6.5 Al — 1 Zn — 0.2 Mn

No stress-corrosion cracking has been reported in the M1 alloy, either in laboratory experiments or during extensive field tests in various atmospheres. However, AZ61X

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can be very sensitive to stress-corrosion cracking; the susceptibility depends on the physical condition of the alloy. Alloy AZ31X, with a lower aluminum content, is less sensitive than AZ61X, but is still not immune to cracking, under all conditions.

Mechanism of Cracking in Magnesium Alloys. Stress-corrosion cracking in aluminum alloys has been the subject of intensive investigation.[54] In aluminum-base alloys stress-corrosion cracks are intercrystalline; in magnesium alloys cracks may be transcrystalline or intercrystalline, depending on the conditions of the experiment.

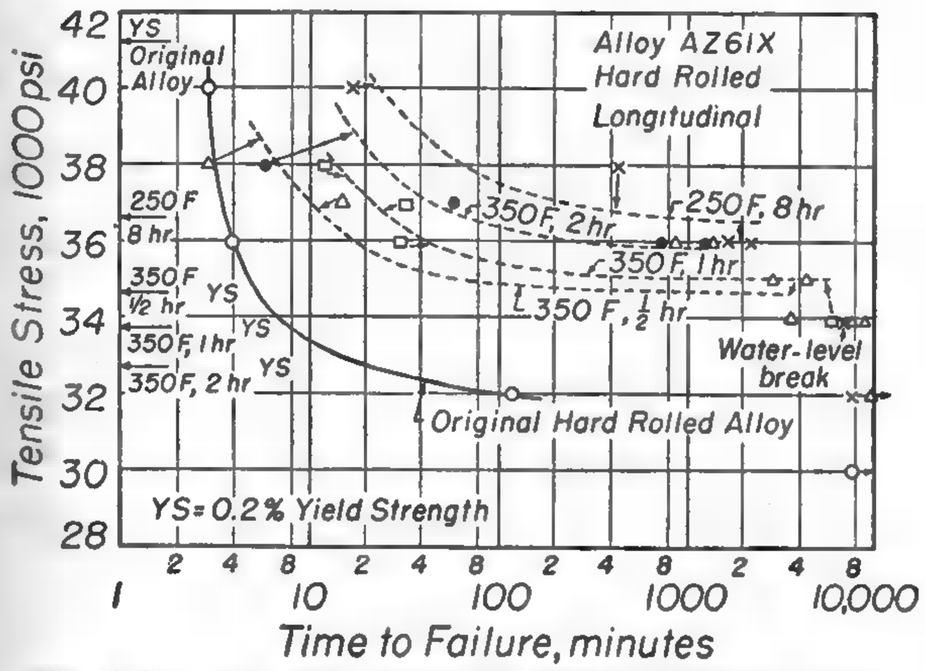

Fig. 10 Stress-corrosion cracking of AZ61X magnesium alloy, longitudinal specimens

L. Graf[55] investigated the processes leading to the formation of cracks and attempted to determine the possible cause. Samples of AZM alloy (AZ61X) under a tensional stress were observed directly under the microscope, with distilled water as the corroding agent. In polycrystalline specimens, cracks appeared perpendicular to the direction of tension, diagonally through grains, and occasionally along grain boundaries or slip bands or twin lamellae. Graf concluded that the fine lines that appear in plastically deformed material are not the primary cause of the cracks in stress corrosion; neither are the twin lamellae the chief cause of these cracks.

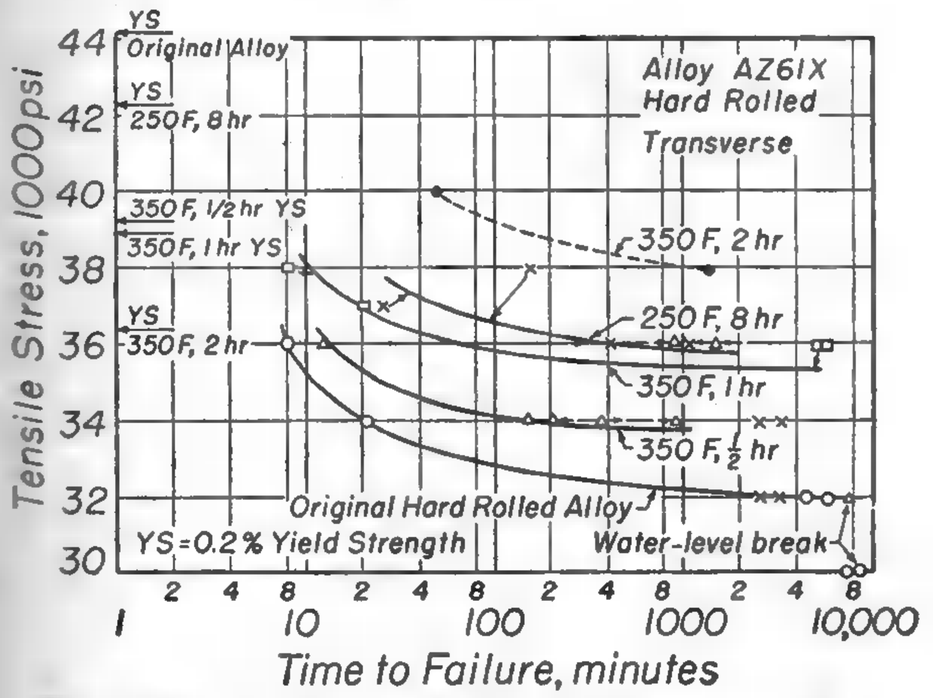

Fig. 11 Stress-corrosion cracking of AZ61X magnesium alloy, transverse specimens

In single crystals of AZM sheet, 0.5 mm thick (oriented so that the hexagonal base is nearly perpendicular to the plane of the sheet and nearly parallel to the longitudinal axis or direction of tension), Graf found cracks developing as fine lines, exactly straight and exactly perpendicular to the direction of tension, with no preference for any crystallographic direction in the sample. Small inclusions of differently oriented crystals did not disturb the exact alignment of cracks perpendicular to the pull.

In this connection, Mears, Brown and Dix report[56] that in an accelerating solution containing 35 g NaCl and 20 g $K_2Cr_2O_7$ (pH = 5.0), specimens from AZ61X failed when exposed in a stressed condition along a path that followed grain boundaries or slip planes. When the same alloy was exposed to a similar solution (pH = 8.1), the failure was transgranular and had little relation to boundaries or slip planes. From an electrochemical viewpoint, it would appear that in acid solutions the grain boundaries and slip planes are anodic to the rest of the metal, whereas these zones are cathodic when the solution is basic.

The greater the number of localized paths of corrosion, the longer the period required for complete failure. If there is considerable general corrosion, stress-corrosion cracking may not occur. If the corroding paths are regarded as notches in the surface of the specimen, the stress concentration at the base of each notch will be less than if only one notch were present.[56] According to this line of reasoning, any form of transgranular stress-corrosion cracking of magnesium alloys can be attributed to the combination of stress and electrochemical action.

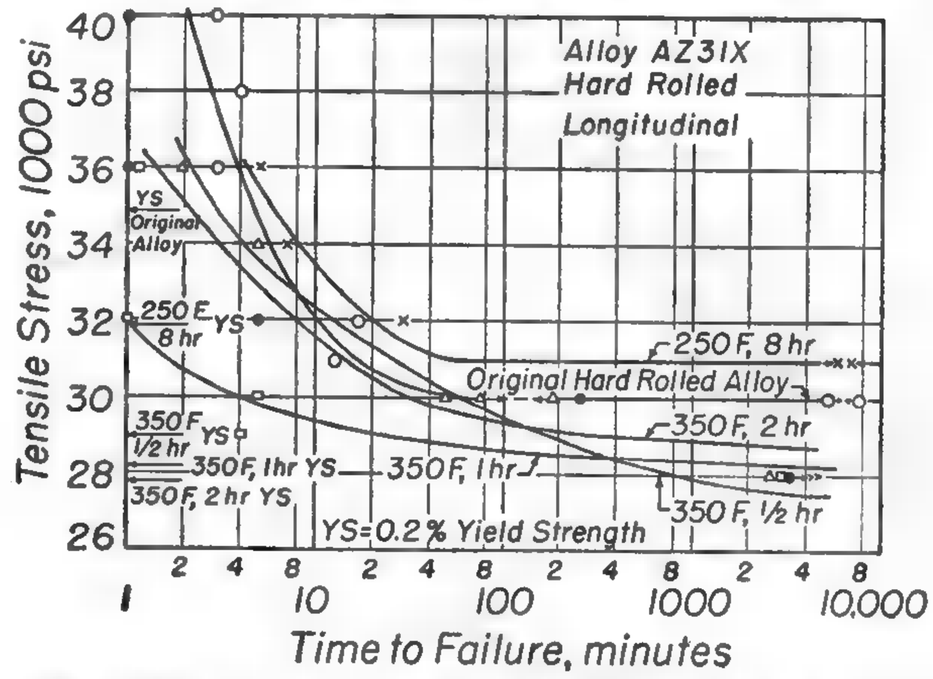

Fig. 12 Stress-corrosion cracking of AZ31X magnesium alloy, longitudinal specimens

Effect of Plastic Deformation. Graf[55] found that the "stress-corrosion limit"* below which no breaks occurred was 8 kg per sq mm (11,400 psi) for samples of AZM (AZ61X) corroding in distilled water. This value is lower than the 0.2% offset value for yield strength of 20 kg per sq mm (28,400 psi) and even lower than the 0.02% offset value for elastic limit of 12 kg per sq mm (17,000 psi). On the stress-strain curve for the material, the stress-corrosion limit coincides closely with beginnings of plastic deformation.

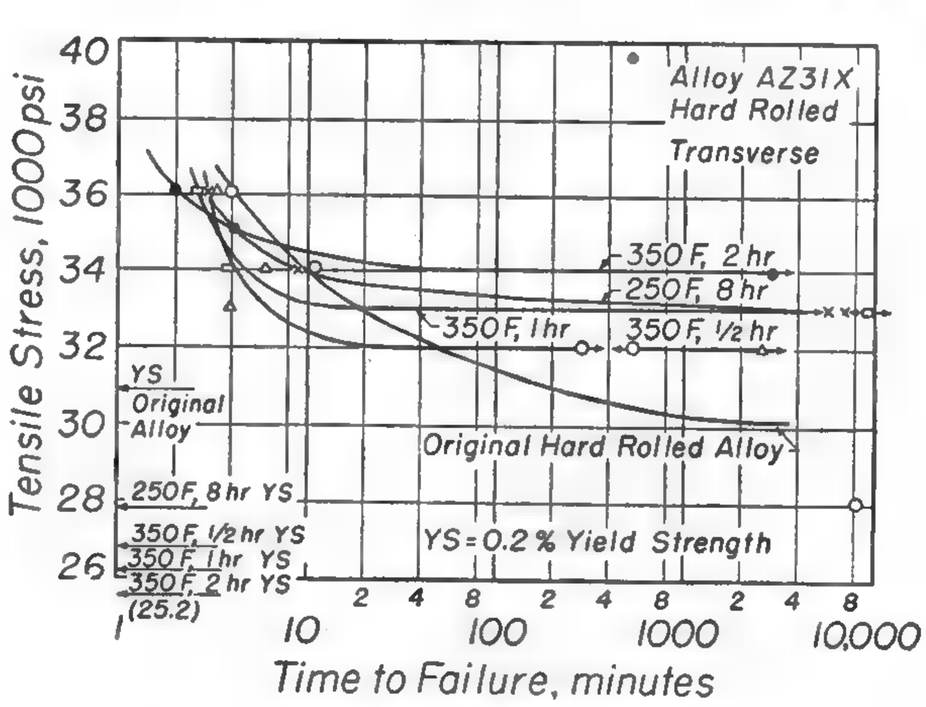

Fig. 13 Stress-corrosion cracking of AZ31X magnesium alloy, transverse specimens

* The "stress-corrosion limit" is the maximum stress, resulting from external load, that the sample can carry in the particular corroding environment without cracking during an indefinitely extended period of time.

A number of samples were deformed about 8% in a tension-testing machine. Samples of deformed and undeformed material were subjected to corrosion alone with no application of external stress. When samples were tested in tension and torsion at definite intervals, no perceptible difference was observed in the two classes of material. In the absence of an external load, both were equally resistant to corrosion.

Specimens were then predeformed to the extent of 0.2%, 2% and 8%, as well as 8% by rolling, and were subjected to corrosion while under stress. With increasing plastic deformation the stress-corrosion limit moves to lower and lower values of stress and, at great deformation, could become vanishingly small. This establishes the fact that with high residual stresses from previous plastic deformation, the stress-corrosion limit can be very low indeed. Such material is highly sensitive to stress-corrosion cracking.

Heat Treatment and Sensitivity to Stress Corrosion. Heat treatment affects the behavior of magnesium alloys to a marked degree in stress corrosion. Figures 10 and 11 give typical examples of the variations in sensitivity to cracking that can be produced in longitudinal and transverse specimens of AZ61X by variations in heat treatment. Figures 12 and 13 give similar variations for AZ31X.[57] These observations were made by a cantilever testing method,[58] using a salt-chromate bath to accelerate corrosion.

It is evident from these figures that the original cold rolled material of AZ61X has a much lower stress-corrosion limit in both longitudinal and transverse directions than similar material subsequently heat treated for various periods at 250 or 350 F. The same is true, though less pronounced, for the AZ31X alloy.

The effect of these various heat treatments on the yield strength and on the stress-corrosion limit is given in Fig. 10 to 13. If both yield strength and stress corrosion must be considered, a heat treatment of 8 hr at 250 F appears to give the best results. Where the time element is important, 2 hr at 350 F is a satisfactory period.

Before heat treatment the cold rolled specimen gives no evidence of precipitation, but after heat treatment, precipitation appears to be complete. It is safe to conclude that this precipitation, along with a reduction in residual stress, has had an effect in raising the limit of stress-corrosion cracking or reducing the sensitivity to cracking.

Service Tests for Determining Susceptibility. Many of the tests that have been devised for determining susceptibility do not represent actual conditions of service. This is particularly true of those experiments that are carried out under laboratory conditions in solutions that accelerate cracking but find no counterpart in actual service. Although such methods are useful in evaluating the effect of variations in composition in new alloys and the effects of mechanical procedures and heat treatments in fabrication, still these methods cannot be used as infallible guides in determining the life of magnesium alloys as structural materials or in industrial service.

Service tests using outdoor exposures have been devised by B. C. Madden, Jr.,[60] by Sager, Brown and Mears,[61] and by Loose and Barbian.[62] Reports by these investigators may be consulted for further information.

The results of Loose and Barbian[63] concerning service data can be summarized as follows:

1 M1 alloy is not sensitive to stress-corrosion cracking under any conditions of testing devised so far (1946).
2 When AZ31X (annealed at 275 F) is subjected to constant axial stress, the stress-corrosion limit is about 20,000 psi.
3 With bending stress under constant load, the minimum stress to produce fracture was 25,000 psi. Four sheets stressed at the tensile yield strength of 34,000 psi had not cracked in 220 days.
4 Under constant deformation stress, no failures occurred at 95% of the tensile yield strength after 17 months of exposure.
5 The stress-corrosion limit under axial loading of AZ61X sheet (annealed at either 350 or 600 F) appears to be of the order of 12,000 to 15,000 psi. Under a constant load in bending, the limit is 15,000 to 20,000 psi.

Loose and Barbian conclude that because of superior resistance to stress corrosion, equal or better physical properties and superior toughness, AZ31X sheet is preferable in all structures except in those that require welding.

Summary of Service Information. J. D. Hanawalt[64] reviews the salient facts about stress corrosion in service and concludes that stress corrosion will not limit the use of magnesium alloys in applications for which they are otherwise adapted. The susceptibility to cracking that results from high residual stresses can be removed by an anneal at a temperature that does not decrease the mechanical properties greatly. Shot peening also is suggested as a means for reducing the sensitivity.

If a constant service stress exists, approaching the tensile yield point, the regular AZ31X or AZ61X should be clad with the magnesium-manganese alloy that is not susceptible to stress-corrosion cracking. A sheet clad with this material has developed no cracks in a seacoast exposure of more than six months, when loaded at 90% of the tensile yield strength in a direct tension test.

In situations where lower service stresses are encountered, AZ31X (annealed at 275 F) is considered a satisfactory material. Under a constant stress in tension, numerically equal to 70% of the compressive yield strength, no cracks occurred in samples exposed for one year at Kure Beach (a seacoast exposure).

In the absence of stress, AZ31X and AZ61X resist corrosion so well that cladding is not needed—that is, not to combat corrosion alone. In four years of seacoast exposure in the unstressed condition, test bars lost about 4% of their tensile strength.

With the knowledge that is now available concerning stress corrosion in wrought magnesium alloys and methods for its control, stress corrosion is not a determining factor in limiting the structural applications of wrought magnesium alloys.

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Relief of Residual Stress

BY THE SUBCOMMITTEE ON RELIEF OF RESIDUAL STRESS*

RESIDUAL stress, frequently called "locked-up" stress or "internal" stress, refers to the stress existing in a component part or assembly free from external loads.

Residual stresses can be produced in metal in various ways. When molten metal cools, certain portions—usually the outer layers—solidify first. As the metal proceeds to thermal equilibrium, further contraction is opposed by the material that has already become set, introducing residual stresses. Residual stresses may also be produced in a piece of material by thermal gradients, by cold working, shaping and forming, machining, and other processes that cause local plastic flow, and by changes in volume and coefficient of expansion that accompany metallurgical phase transformations.

Residual stresses caused by differential plastic flow, resulting from rapid and uneven cooling of hot metal, or from mechanical loading or working, are usually distributed through appreciable volumes and are referred to as "macrostresses". Residual stresses accompanying phase transformation are usually distributed through microscopic volumes only, and are called "microstresses".

The assembling of component parts into ■ structure may relieve some residual stresses but, in general, especially if fabrication includes welding, many additional residual stresses are introduced. Such stresses may or may not be harmful. Suitable residual stress or prestressing is helpful in increasing strength and life; for example, it is common practice to introduce residual compressive stresses into those parts of structures that must withstand tensile stresses in service. Compressive stresses are introduced by shrink-fits, as in built-up gun barrels, enabling parts that are so treated to withstand higher tensile loading without yielding. Surface compressive stresses, which may be introduced by shot peening, cold rolling, cold forming, nitriding, and carburizing, increase resistance to fatigue by changing the range of the tensile stresses at or near the surface, where fatigue cracks start. Thus, residual stresses are helpful if they are of such a nature as to oppose the working stresses at the point where failure would otherwise occur, but they are harmful if they add to the working stresses.

If tensile residual stresses and tensile service stresses act in two or three perpendicular directions, the resulting condition is particularly harmful because analysis indicates that the shearing stresses that cause plastic flow are inhibited and the ductility preceding fracture is decreased. Triaxial tensile stresses of nearly equal magnitude can so inhibit shear that yielding does not occur under stresses lower than the ultimate strength. The brittle fractures that result take place with deformations so small as to be considered elastic, permitting no readjustment or ironing out under proof or service loading.

Unfortunately, most macrostresses cannot be controlled, since they are usually of unknown magnitude and random orientation; however, by the simple law of equilibrium, and in the absence of external loading, opposing internal forces and moments must balance. Hence, the introduction of residual compressive stresses into one critical part of a structure must establish residual tensile stresses in another part, and the result may be a weaker structure. For example, excessive peening, cold working, nitriding, or carburizing at the surface, will produce high tensile stresses below the surface, which may cause failure.

Determination of Residual Stresses. It is difficult to determine the magnitude and direction of residual stresses. Several methods have been devised for sectioning or boring specimens carefully for detailed analysis of residual stresses throughout the interior of metal objects. In one of the first methods attempted, a hole was drilled in the metal and strain gages were used in an effort to determine the change in strain as a result of the stress relief at the free surface.[1] This method lacks accuracy in the field because of the complicated technique involved, especially if the directions of the principal stresses are unknown. Another method is to trepan a plug and measure the change in strain on three or more axes on both surfaces of the plug.[2] This method also lacks accuracy unless the residual stresses are essentially of the same magnitude and the same sign over the entire plug. If the hole is later

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filled with weld metal or the plug is welded back into position, a worse stress condition may result. A third method, which is nondestructive, employs X-ray diffraction, using a back-reflection camera.[3] This method detects surface stresses only. No satisfactory method has yet been devised for measuring the distribution of residual stresses nondestructively throughout a metal object.

Since residual stresses may affect safety or utility, and since no practicable method exists for determining the magnitude and distribution of stresses in a given location, the only safe recourse is to decrease their magnitude by stress relieving or, where possible, to introduce additional stresses deliberately that are opposite in sign to the working stresses.

Definition. The term "stress relief" is applied to any means for reducing residual stresses substantially. Such methods may be thermal, mechanical, or combinations of both; these methods will be discussed later in this article.

Unfortunately, there is considerable confusion regarding the term "thermal stress relief" and certain anomalies occur in the manner in which it is used. For purposes of this article, the term will be applied only to thermal treatments that are performed specifically for the purpose of reducing residual stress. Treatments such as normalizing, annealing, and quenching and tempering, will not be considered stress-relief treatments.

Reasons for Stress Relieving. Probably the most important reason for stress relieving is to effect sufficient reduction in residual stresses that might produce a harmful system of multiaxial tensile stress when combined with service stresses. Harmful tridimensional stress systems are not present in the majority of relatively light structures, as evidenced by satisfactory performance without stress relief. Some opinion justifies the omission of stress relieving when an adequate proof test precedes service. However, a stress level just short of failure may be present during this initial short-time loading, and the influences of time and repeated applications of load may produce later failure at this lower level.

Another reason for stress relieving is to improve the dimensional stability of structures, especially where close tolerances must be maintained. Residual stresses may be introduced by some types of machining, particularly rough machining and grinding operations. If not otherwise relieved, residual stresses will be reduced during light machining operations, since the removal of metal disturbs the equilibrium, with attendant readjustment and warping. Therefore, stress relieving is often performed between rough and finish machining. Stress relieving may also cause microstructural changes that decrease the variation in hardness somewhat, so that machining to close tolerances is more easily accomplished.

Stress relieving is important for structures subjected to cyclic loading, because stress reversals involving stress ranges approaching the yield strength, result in lower fatigue strength than the same number of reversals in stress ranges well below the yield strength. The hazard of stress corrosion and corrosion fatigue is also reduced or eliminated by stress relief or by the introduction of compressive stresses at the surface.

Stress relief is generally considered important for structures subjected to appreciable dynamic loading, since shock fractures usually originate at stress raisers, particularly on equipment that operates at subzero temperatures. Complete heat treatment is frequently specified in such instances, for homogenization and removal of the heat-affected zones of welds.

Mechanism of Stress Relief. For adequate stress relief, it is necessary that a structure be relatively free to adjust itself under the action of the residual stresses, since residual stress or strain can be reduced in magnitude only by plastic flow. This reduction can be accomplished mechanically by superposing additional strain through external or internal loading, or thermally, by reducing the yield strength of the material.

Both the modulus of elasticity and the yield strength of most metallic materials decrease with increasing temperature, and the reduction of the yield strength is usually relatively greater than that of the modulus at high temperatures. Only when the yield strength decreases by a greater percentage than the modulus, is stress relief achieved by temperature changes alone. However, when the influence of time is combined with that of temperature, plastic flow occurs at stresses well below the yield strength of the material because of creep or relaxation. The rate of flow is a function of both the stress level and time. Thus thermal stress relief combines the twofold action of reducing residual stress by the relatively greater reduction of the yield strength as compared with the modulus, and by relaxation in proportion to the soaking time.

Moderate heating sometimes produces a greater amount of stress relief than can be explained on the basis of increased relaxation or decreased yield strength. For example, residual stresses in steel are somewhat decreased as a result of heating to about 400 F. At this temperature, which is in the "blue brittle" range, the yield strength actually increases instead of decreasing, while the relaxation of steel is negligible. The exact reason for this phenomenon is not known.

Ideally, stress relief should reduce residual stresses without any change in dimension, since the permanent set induced should equal exactly the removed elastic strain, provided the stress distribution is uniform and the areas of opposing stresses are equal. In practice, particularly where complex distribution of stresses is involved, the uniformity necessary to maintain an equilibrium of stress and force distribution is not attained. The influences that disturb the equilibrium result in changes of the internal forces or moments that manifest themselves as dimensional changes if forces are affected, or as a curvature or distortion if moments are affected.

Stress Relieving by Thermal Means. Thermal stress relieving may be defined as reduction of the residual stress level by increasing the temperature of a metal object to a suitable value, and holding at that temperature for a suitable time. Since most high residual stresses are produced by thermal gradients caused by too rapid or uneven cooling, with attendant plastic flow, it is apparent that such stresses can be lowered or removed if the structure is properly reheated and then cooled slowly and evenly. Similarly, residual stresses can be decreased initially by reducing the thermal gradient, as in preheating before welding, thus minimizing the necessity for stress relief. Thermal methods are the most important and widely used of all procedures for stress relief, and when properly applied, they ordinarily achieve a greater reduction in the level of residual stress than any other method.

Metallurgical Limitations. Thermal stress relief cannot be applied freely to all materials, since the thermal cycles sometimes produce undesirable changes, either microstructural or of other kinds. For example, heat treatable aluminum alloys are aged at about 300 F after solution heat treatment, to produce a definite microstructure and definite mechanical properties. Temperatures of the order of 450 to 500 F are required for producing substantial relief of residual stresses in these alloys in a reasonable length of time, but these temperatures destroy the effects of the previous aging treatment. However, a compromise of slightly lower temperatures, or shorter times at these temperatures, is used for obtaining an optimum combination of the required mechanical properties and stress relief. It has also been found that the residual stress level in these alloys can be reduced to a very low value through a decrease in the temperature gradient during quenching, by the use of a boiling water quench rather than a cold water quench after solution treatment. This procedure does not usually reduce the tensile properties greatly, and yet it provides material comparatively free from stress.

At times it is impossible to avoid introducing residual stresses into a metal by treatments designed to enhance certain properties. Steels are often quenched from the hardening temperature in order to produce a fine-grained structure, which improves fatigue resistance, and to increase hardness, which improves wear resistance. The residual stresses induced by the rapid cooling may never be removed completely if low tempering temperatures are used to retain hardness. For some materials, such as copper and chromium-nickel stainless steels, maximum softness is obtained by rapid cooling. Many parts are

surface hardened by highly localized heating or by peening, carburizing, nitriding, or similar treatments that introduce residual stresses at the surface. In all such instances, the use of thermal stress relief must be limited or sacrificed, in deference to the other desired properties.

Residual stresses are lowered in many materials by the combined effects of temperature and time at temperature. Some materials, such as the austenitic heat-resistant steels, undergo very slight reduction in yield strength at the usual stress-relief temperatures; therefore the soaking time is prolonged, or the temperature is raised, or both measures are employed to increase relaxation. However, a greater degree of stress relief is apparently attained in these materials than would be expected from their decreased yield strength and increased creep at the higher temperature. This is indicated by the fact that work hardening disappears rapidly even at moderate temperatures, and it may also be connected with the time-elongation characteristics of some of these steels, which are stepped rather than continuous, and involve repeated cycles of strain hardening and softening.

Method of Heating. The input of heat required for thermal stress relief can be secured by combustion convective or radiant heat transfer, or both, or by electrical or electronic heating. The temperatures required for stress relief are lower than those commonly used in heat treatment, and furnaces of the convection type are employed more often, since better control of temperature is possible. Further improvement is usually obtained through recirculation of the furnace gases, in either stationary or portable furnaces. Electric resistance furnaces of the stationary type have been utilized occasionally; portable furnaces that heat by electrical resistance are used frequently. For some applications, particularly for high temperatures, resistance heaters of the radiant type, such as globar units, have been used. Induction heating is commonly applied for relieving local stress in both magnetic and nonmagnetic materials. Regardless of the method used, the source of heat should be such that the thermal input is distributed evenly over the receiving surfaces, and is controlled, preferably by instrumentation, to assure the desired rates of change in temperature. Instrumentation is particularly important where high rates of heating are possible, as in induction heating.

Proper control of change in temperature involves accurate measurement of the furnace gas temperature, and more particularly of the metal temperature. The generous use of thermocouples is advised, preferably in connection with a recording pyrometer; the location of the points for measuring the temperature of the metal is an important factor. The most critical locations are those that increase in temperature either more slowly or more rapidly than the average; for example, the temperature increases more slowly in heavy sections and more rapidly in extended sections, such as nozzles on pressure vessels. For reasonable accuracy, the thermocouples should be made of metals that resist oxidation at the furnace temperature, and the couples should be peened or inserted directly into slots in the structure rather than installed in blocks attached to the structure, in order to avoid heat input or loss resulting from the couple attachment. With high input of radiant heat, it may be necessary to surround the couple with a metallic shield.

In selecting a method of heating, consideration should be given to the ratio of heat-input surface to volume or weight of metal to be heated; where several parts are loaded into a single furnace, all surfaces should be exposed freely to the heating medium. Parts should be supported adequately in the furnace because of the decreased mechanical properties of the material at the stress-relieving temperature. Adequate support not only minimizes the bending moments involved, but also distributes the reactions at the points of support, so that undesirable localized bending is avoided.

Thermal Stresses. Thermal expansion with rise in temperature does not induce stress unless the object being heated is restrained; such restraint is possible not only from mechanical effects, such as friction at the points of support, but also from thermal effects where contiguous elements are not at the same temperature. Thermal stresses may exist through the thickness, when high rates of heat input are involved, or along the length, when the heat input varies; additional dynamic stresses are possible where extremely rapid change in temperature or thermal shock occurs. Thermal stresses of sufficient magnitude, alone or in combination with other stresses, will cause yielding with attendant distortion, and are particularly undesirable at stress raisers or where tridimensional stresses may exist.

Rates of Heating and Cooling. No clear-cut analysis has been made for establishing permissible rates of heating and cooling during thermal stress relief. Except in extreme degree, rates of temperature change are not significant in themselves; instead, the important factors are the resulting differences in temperature that provide the restraint necessary for producing temperature stress. Interruptions in flow of heat that result from inclusions, cracks and the like, are focal points for highly localized temperature stresses and, in sufficient degree, may propagate such defects. The maximum temperature stress permissible during heating, depends on the magnitude of the residual stresses already present, since if distortion is to be avoided, the combination of the two stresses must not exceed the yield strength at the temperature of stress relief. The maximum temperature stress permissible during cooling should be less than the yield strength at the stress-relief temperature in order to avoid the introduction of stress during cooling.

A moderate rate of cooling is generally favored—about one-half the rate of heating. When possible distortion and tridimensional stress failure are considered, however, the rate of heating assumes importance equal to that of the rate of cooling, if not greater.

Duration of Stress Relieving. As already pointed out, the soaking period is intended to promote stress relief through relaxation, and theoretically should depend on the creep strength of the material and be independent of the thickness. However, since tridimensional stresses are encountered more frequently in thick materials than in thin, longer periods are required for the adequate stress relief of heavy sections. In addition, large sections require long periods for reaching the furnace temperature. Accepted practice associates soaking time with thickness.

Unfortunately, no correlation has been established between rates of first-stage relaxation and the amount of stress relief produced by various soaking times. Some arbitrary standards have been set up on the basis of subjecting test specimens to various thermal cycles and measuring the amount of reduction in stress by unloading, or by boring or machining operations. The results from these methods indicate that a small increase in temperature is more effective in the relief of residual stress than a much greater soaking time at a lower temperature.[9,10] For example, SAE 4130 steel originally stressed to 62,500 psi, retains a residual stress of only 1900 psi after 1 hr at 1200 F. However, it retains a residual stress of 3150 psi after 8 hr at 1100 F and 15,300 psi after 8 hr at 900 F.[9]

Temperature Ranges for Stress Relieving. The three different temperature ranges listed below are generally used in thermal stress-relieving operations; the soaking time is increased as the temperature is reduced.

1 Elevated temperatures (just below the transformation range for steel) are used where the yield strength is reduced markedly, relative to the modulus.
2 Mildly elevated temperatures are used where the yield strength is reduced only slightly, relative to the modulus.
3 Low temperatures, slightly above room temperature, are used where the yield strength is not reduced or may even be increased.

For steel, thermal stress relief is generally performed at temperatures just below the transformation range. The temperature should be as high as practicable, but not high enough to impair the structure produced by any previous heat treatment. Where additional softening is required, and some structural transformation is not harmful, temperatures at the lower end of the transformation range are used. Subassemblies are often stress relieved before final assembly. One or more intermediate operations may be necessary for relieving stresses in heavy welds or complicated structures.

The usual temperatures for stress relief of steel range from 1100 to 1300 F. Stress relief at mildly elevated temperatures (approximately 900 F) is also used when, for any reason, higher temperatures are not possible.

Low-temperature stress relieving, sometimes called "aging", refers to those stress-relief treatments in which the part is held at room temperature, or at some slightly elevated temperature, generally below 300 F, for a considerable length of time in order to permit residual stresses to "creep" out. The time of holding may vary from about 8 to 75 hr, depending on the type of part and the relaxation rate of the material from which it is made. Aging has been used for parts such as cast-iron cylinder blocks for automobile engines, machine bases, aluminum and magnesium parts, and cold drawn austenitic steel wire.

Tables I and II show typical stress-relief treatments commonly used in industry. Readers of the Handbook are cautioned, however, that these represent only average practice for average work. Faster heating and cooling rates could be used for simpler structures, whereas slower rates are required for more complex structures. For example, a simple cylinder, without closures, openings or such, can withstand extreme rates of change in temperature without excessive stress. On the other hand, a complete pressure vessel, with many manholes, nozzles and the like, can withstand only slight nonuniformity in temperature without yielding and distortion.

Stress Relieving as a Unit. "Stress relieving as a unit" refers to those treatments in which the stresses in an entire part or structure are relieved at one time, generally in a furnace. Large vessels are sometimes heated by the circulation of hot gases from flue-gas generators, with or without recirculation, or from burners within the vessel.

In several borderline variations of stress relieving as a unit, large parts are heated in sections; or are heated progressively by passage through a furnace or by proximity to a portable furnace that is moved along the part. When parts are heated in sections, sufficient overlapping of successive steps is essential; with progressive methods, the rate of movement must not be excessive. Care is required to protect the portion adjacent to the heated zone from serious temperature gradients.

Local Stress Relief. Local stress relief is commonly applied to structures that have dimensions exceeding available furnace capacity, to heavy or complicated parts where the treatment serves as an intermediate step for the limiting of stress accumulations, or to field girth welds of critical piping. The degree of stress relief attained depends on the details of application and control, which, as in stress relieving as a unit, determine the magnitude of the thermal stresses introduced. However, in addition to the thermal gradients possible because of unevenness and excessive rates of heating, local stress relief involves thermal gradients around the boundary of the heated area, which introduce stresses into both the boundary and the heated zones.

Table II. Typical Stress-Relief Treatments for Certain Nonferrous Alloys[a]

Material	Temperature, deg Fahr	Time at Temperature, hr
Copper Alloys		
Copper	300	½
90 Cu – 10 Zn	400	1
80 Cu – 20 Zn, 70 Cu – 30 Zn	500	1
63 Cu – 37 Zn	475	1
60 Cu – 40 Zn	375	½
70 Cu – 29 Zn – 1 Sn	575	1
85 Cu – 15 Ni, 70 Cu – 30 Ni	475	1
64 Cu – 18 Zn – 18 Ni	475	1
95 Cu – 5 Sn, 90 Cu – 10 Sn	375	1
Magnesium Alloys		
M-1, Hard rolled sheet, 1.5 Mn	400	1
M-1 Extrusions, 1.5 Mn	500	¼
AZ31X Hard rolled sheet, 3 Al, 1 Zn, 0.3 Mn	300	1
AZ31X Extrusions, 3 Al, 1 Zn, 0.3 Mn	500	¼
AZ51X Hard rolled sheet, 5 Al, 1 Zn, 0.25 Mn	375	1
AZ61X Extrusions, 6 Al, 1 Zn, 0.25 Mn	500	¼
AZ80X Extrusions, 8.5 Al, 0.5 Zn, 0.15 Mn	400	1
AZ80X HTA Extrusions, 8.5 Al, 0.5 Zn, 0.15 Mn	600	¼
Nickel Alloys		
Nickel and Monel	525 to 600	3 to 1
"K" Monel and "KR" Monel	525 to 600	3 to 1
80 Ni – 20 Cr, Inconel, 60 Ni – 25 Fe – 15 Cr	700 to 900	3 to 1

(a) Optimum heating and cooling rates depend primarily on the size and shape of the part being treated.

Uniform change in temperature, without restraint, does not involve stress; this is equally true of a temperature gradient that permits every element of a structure to assume dimensions in proportion to its temperature. A cylinder that has a linear axial temperature gradient freely assumes conical shape; similarly a flat plate that has a linear temperature gradient across the width or thickness freely assumes curvature with the hot edge at the maximum radius.

On the other hand, if only a portion of the length of a cylinder or of the width of a flat plate is heated, the temperature gradient is interrupted, and expansion is almost completely prevented, even with moderate gradients at the boundaries. This causes temperature stress and plastic flow equal to the full amount of the strain produced by the temperature difference. Heating a small

Table I. Typical Stress-Relief Treatments for Certain Ferrous Alloys[a]

Type of Material, Composition, or Size of Section	Temperature, deg Fahr	Soaking Time,[b] hr per in. of thickness
Gray cast iron	800 to 1100	5 to ½
Carbon Steel		
Less than 0.35% C, less than ¾ in.	Stress relief usually not required[c]	
Less than 0.35% C, ¾ in. or greater	1100 to 1250	1
More than 0.35% C, less than ½ in.	Stress relief usually not required[c]	
More than 0.35% C, ½ in. or greater	1100 to 1250	1
Specially killed for service at low temperature	1100 to 1250	1
Carbon-Molybdenum Steel (all thicknesses)		
Less than 0.20% C	1100 to 1250	2
0.20 to 0.35% C	1250 to 1400	3 to 2
Chromium-Molybdenum Steel (all thicknesses)		
2% Cr, 0.5% Mo	1325 to 1375	2
2.25% Cr, 1% Mo and 5% Cr, 0.5% Mo	1350 to 1400	3
9% Cr, 1% Mo	1375 to 1425	3
Chromium Stainless Steel (all thicknesses)		
Types 410 and 430	1425 to 1475	2
Type 405	Stress relief usually not required for thicknesses less than ¾ in.[c]	
Chromium-Nickel Stainless Steel		
Types 304, 321 and 347	Stress relief usually not required for thicknesses less than ¾ in.[c]	
Type 316, more than ¾ in.	1500	2
Types 309 and 310, more than ¾ in.	1600	2
Welding Dissimilar Materials		
Cr-Mo steel to carbon steel or to C-Mo steel	1350 to 1400	3
Types 410 and 430 to any other steel	1350 to 1400	3
Cr-Ni stainless steel to any other steel	As required for the steel to which Cr-Ni stainless steel is joined	

(a) For chromium-nickel stainless steels and for weldments of dissimilar materials, the rate of heating should be less than 200 °F per hr. For the other materials a heating rate of less than 400 °F per hr is recommended. All materials should be cooled from the stress-relieving temperature at a rate not higher than 200 °F per hr.

(b) The interval during which the entire piece is at temperature (c) Unless necessary in order to obtain dimensional stability

local area of a flat plate or shell may cause elastic or plastic buckling. Since elastic buckling permits additional deformation, a higher temperature gradient can be sustained by the object without causing yielding. In plastic buckling, reintroduction of stress occurs in the boundaries and contiguous areas, and the most that can be accomplished is the relocation of the residual stresses.

When heat is applied to a complete circumferential band on a cylinder, the heated area expands, the boundary zone assumes conical shape, and restraint is limited to influences that provide continuity at the intersections of the heated boundary and cold zones. In this instance, the temperature stresses can be controlled by control of the gradient in the boundary zone, which establishes the angle of intersection between the cone and the cylinder.

The ASME Boiler Construction Code at one time contained provisions for stress relief of nozzles by heating a localized area around the nozzle. Some years ago the rules were revised to require all local stress relief to be applied around a complete circumferential band of the vessel with the nozzle in the center. Thermal stress relief of longitudinal elements in shells and of elements in flat plates is ineffective, as attested by many examples of failure or distortion. On the other hand, thermal stress relief that is achieved by heating a band on a surface of revolution, such as a girth weld on a pipe, is recognized as sound practice.

In the stress relieving of girth seams, the width of the heated band and the thermal gradients in the boundary zone determine the thermal bending stress in the heated area. The ASME and API-ASME Codes establish the total width of the heated band as 12 times the plate thickness, whereas the API-ASME Code limits the boundary gradient to 200 °F per ft along the shell. The width of the heated band should be sufficient to include the area of significant residual stress developed in the plate as a result of welding, and to prevent overstress that might develop at the center of the weld area as a result of overlapping of the bending effects induced from both sides by the thermal gradients in the boundary zone.

Stress Relieving by Mechanical Means. "Mechanical stress relieving" may be defined as the reduction of residual stresses by mechanical methods at moderate temperatures. This reduction is accomplished by introducing mechanically stresses that cause plastic flow. These stresses may be produced by direct loading, hydraulic pressure, cyclic loading, peening or similar means.

Mechanical methods of stress relief are applied to machines or structures either too large to be placed in a furnace, or of such a shape that thermal stress relief would cause excessive distortion. In contrast with stress relief by thermal means, mechanical methods usually involve less expensive equipment; however, they are seldom as effective.

Mechanical methods for relief of residual stresses can be classified as follows:

Hand Peening. This mechanical method of stress relief by hammer blows or similar means is used mostly for the relief of stress in welded structures, in order to cause plastic flow of the weld metal and thus to reduce the load that is placed on the structure as a result of weld shrinkage. The peened weld metal is cold worked and contains residual stress, which is removed to some extent by the penetration and heat of succeeding weld passes. For this reason, the depth of the weld pass should be proportioned to the effective depth obtainable from peening.

Hand peening is ordinarily performed with rounded tools used in pneumatic hammers; for soft alloys, wooden mallets are sometimes used. Many well-distributed, quick, light blows are preferable to heavy blows more widely spaced. Peening is omitted on initial passes until sufficient strength is developed to avoid cracking, and is also omitted after the last pass, which is often removed in the final dressing of the weld.

Although hand peening is frequently used, it is a somewhat uncertain method of stress relief because it is difficult to control; besides, there is some doubt as to its effectiveness. However, the process is considered useful where it is impracticable to stress relieve by more efficient methods. Good peening requires considerable experience and personal judgment. Frequently it is difficult to determine whether the weld has been peened sufficiently or whether it is overdone. Peening of austenitic materials is generally ineffective because of the tendency of these materials to work harden rapidly.

In order to obtain better control, punch marks are sometimes made in the base metal on opposite sides of a weld. Peening is then performed in such a manner as to maintain the separation of the marks, within about $\frac{1}{32}$ in., after the first two layers of weld metal have been deposited. When the weld has acquired a depth of 1¼ in. the subsequent movement of the gage marks is small, and peening is continued to the degree required initially. However, this method may result in overpeening of the weld.

Shot Peening. Shot peening is a process of projecting shot from an air nozzle, or from the rim of a rapidly rotating wheel, against the part to be treated. This method introduces compressive stresses at the surface of the metal, or reduces the maximum residual tensile stress at the surface if residual tensile stresses are present. In addition, the resistance to fatigue is increased—but only partly by the relief of the residual stresses. The increase can be attributed also to the work hardening of the material at the surface and to the resulting residual compressive stress. Shot peening can be applied to finished parts, such as springs, axles and gears, or to specific areas of large structural or machine parts. Careful control must be maintained for satisfactory results; the principal variables are the size and velocity of the shot and the time of exposure.

Stressing Beyond the Yield Point. Residual stresses may be reduced by mechanical means, such as direct loading or hydrostatic pressure, for stressing beyond the yield strength. The resultant plastic flow tends to obliterate the initial residual stress, with resulting cold work in proportion to the deformation produced. With drawn parts, such as bars, rods or tubes, this procedure is frequently combined with straightening.

One method of stress relief that falls into the classification of straining beyond the yield point is known as "overspeeding". It is applied to rotating parts, such as turbine wheels and centrifugal compressors, which operate normally at fairly high speeds.

In this process, the semifinished wheel is rotated in an evacuated test stand for ▮ to 10 min at a speed 10 to 15% greater than the highest speed at which it will be required to operate in service. Since the stresses in such rotating parts increase in proportion to the square of the speed, the stresses during overspeeding exceed the yield strength of the disk material. The resultant plastic flow helps to redistribute and reduce the residual stresses. In addition, because of the plastic yielding, the disk retains a certain amount of compressive stress at the center after the overspeeding has been completed. This residual compressive stress then increases the safe operating stress in the disk, since the operating stresses are all tensile, and are highest near the center.

Cyclic Loading. Structures are sometimes subjected to cyclic loading with low stress at their resonant frequency, by means of vibration generators.[7] This procedure is intended to reduce residual stresses by the stress that results from dynamic loading. Repeated slow loading at high stresses is sometimes used in order to produce a similar static effect. Care must be taken with this method to avoid stresses that are too high, or too many repetitions of stress, since either excess might lead to fatigue failure.

The data and information available, concerning the effectiveness of these methods, are insufficient to warrant the conclusion that vibration is a suitable method for stress relieving. Some evidence that superposed vibratory stresses produce relief of residual stress is found in the relieved stress condition of structures that have been in service. Formed plates, forced into position with considerable difficulty in the assembly of a ship, can be removed after the ship has been in service for a few months, and then replaced with ease. The plates may still contain high residual stresses, since extensive data, taken by using strain gages on board ships in service, indicate no appreciable decrease in residual stress resulting from normal operation.[8] However, the peak stresses have certainly been relieved, since the plates retain their original shape without forcing. It is probable that appreciable stress relief under cyclic loading is obtained only in those regions where the

increments of stress are sufficient to cause plastic flow.

Stress Relieving by Combined Mechanical and Thermal Means. Methods of mechanical and thermal stress relief are sometimes combined; that is, the mechanical loading required for producing plastic flow, is done while the structure is at a temperature above room temperature. The amount of thermal stress relief depends on temperature and time, thus reducing the mechanical stress relief required.

Peening at elevated temperature has the advantage that hot metal is less susceptible to failure from shock and lighter blows may be used; at the same time cold work is reduced in proportion to the temperature. The circularity of large pressure vessels may be improved or maintained if they are stress relieved by circulation of hot gases under pressure. Turbine and compressor disks are sometimes oversped while hot; if desired, only certain portions of a disk may be heated to produce local plastic flow. For example, a turbine disk with buckets welded to the out-

Table III. Code Requirements for Stress Relief

Reference	Materials Covered	Where Stress Relief is Required	Heating Rate, deg Fahr per hr	Stress Relief Temperature, deg Fahr	Soaking Time, hr per in. thick	Cooling Rate, deg Fahr per hr	Permissible Methods of Stress Relief*
ASME Power Boiler Code (Section I) Revised 6-4-46 Par. P-108	Killed and rimmed carbon steels, low-alloy and intermediate alloy steels, austenitic steels	All fusion-welded pressure parts of power boilers except welded carbon steel and C-Mo (0.20% max C) piping ⅜ in. thick and less	Slow and uniform	1100 to 1200 (Different temperature may be used where required by the characteristics of the material)	1 (min)	Slow, in still atmosphere to a temperature not exceeding 600 F	1, 2, 3, 4, and 5
ASME Unfired Pressure Vessel Code (Section VIII) Revised 6-4-46 Par. U-76	Same as ASME Power Boiler Code (Some special materials are covered by special rulings)	1 All Vessels built to Par. U-68 2 Vessels built to Par. U-69 where thickness is more than 1¼ in. or when diam is less than $d = 120t - 50$ and thickness exceeds 0.58 in.	Slow and uniform	1100 to 1200	1 (min)	Slow, in still atmosphere to a temperature not exceeding 600 F	1, 2, 3, 4, 5, and 6
U. S. Coast Guard Marine Engineering Regulations and Material Specifications (Aug 1943 Ed)	Carbon, carbon-silicon and carbon-molybdenum steels	1 All Class I Vessels 2 Class II Vessels of plate more than 1¼ in. thick	Slow and uniform	1100 to 1200	1 (min)	Slow, in still atmosphere	1, 2, 3, 4, and 7
API-ASME Code for Unfired Pressure Vessels for Petroleum, Liquids and Gases (1943 Ed) Paragraphs W-318-1, W-462, Appendix 6	Same as ASME Unfired Pressure Vessel Code	When $t > 1$ in. or $t > \frac{d + 50}{120}$ (t = thickness of welded main seams, *not* thickness of attachments) 3 Carbon-molybdenum steel when nominal wall thickness is ½ in. or greater	400/t max or 400 NOTE Gradient during heating shall not exceed 250 °F within any 1-ft interval. Gradient during soaking shall not exceed 150 °F in portion being heated	1100 or 1050 1000 950 900	1 (min) 2 3 5 10	Cool in furnace to 600 F at less than 500 F per hr and not more than 500/t max. Air cooling is permissible below 600 F	8, 9, 10, and 11
ASA Code for Pressure Piping ASA B31.1-1942 Par. 628	Cast iron, malleable iron, carbon steel, low-alloy and high-alloy steels	1 Welded joints in carbon steel when nominal wall thickness is 0.75 in. or greater 2 Carbon steel having carbon content 0.35% or greater 3 Carbon-molybdenum steel when nominal wall thickness is ½ in. or greater	Slow and uniform	1100 to 1250	1 hr for carbon steel ½ hr for carbon-molybdenum steel. In no instance less than ½ hr	Uniform	12, 13, and 14
Lloyd's Register of Shipping Rules & Regulations (1938 Ed) under Rules for Welded Pressure Vessels. Sections 2, 3 and 4 (clause 3) and Section 5 (clause 2a)	Carbon steel and low-alloy steels	All Class I Vessels Class II when $\frac{ID}{t^3} < 100$ Class III, depending on design and service for which vessel is intended	Slow and uniform	600 C to 650 C (1080 to 1170 F)	Not specified	Slow in still air	.....

*1 Heating complete drum as unit

2 Heating section of drum (head or shell-ring course) with attached parts before attachment to other sections of drum

3 When drum is stress relieved in sections, stress relieve final girth joints by heating uniformly a circumferential band having a minimum width six times the plate thickness on each side of welded joint, so that the entire band is brought up to the temperature and holding time specified in the above table. Maximum permissible gradient not specified.

4 Nozzles or other welded attachments may be stress relieved locally by heating a circumferential band around entire vessel (connection at middle of band). Band width to be at least 12 times the shell thickness wider than the attachment. Temperature and holding time to be as specified above. (Maximum permissible gradient not specified.) (Thickness refers to welded main seams, not to attachments.)

5 For welded joints in piping and tubing, the width of circumferential band should be at least three times the width of widest part of welding groove but in no instance less than twice the width of the weld reinforcement. (Maximum permissible gradient not specified.)

6 All connections and heavy attachments shall be stress relieved, where vessel is to be stress relieved.

7 All vessels for lethal or noxious gases shall be stress relieved.

8 Heating vessel as unit in an enclosed furnace (preferred whenever practicable)

9 Heating vessel in sections in an enclosed furnace, provided overlap of heated sections of vessel is at least 5 ft. Shell portion outside furnace should be protected so that temperature gradient will not exceed 200 °F per ft along shell.

10 Heating shell sections or portions of vessels or both before joining together. The final circumferential joints may be stress relieved after completion of the vessel, by heating uniformly a circumferential band having a minimum width six times the plate thickness on each side of welded joint. Shell portion outside furnace should be protected so that temperature gradient will not exceed 200 °F per ft along shell.

11 Mechanical peening is permitted by keeping punch marks on opposite sides of weld within ⅛ in. of original spacing for first two weld layers, and peening in same degree for remainder of weld.

12 Heating the complete structure as a unit

13 Heating a complete section containing the weld or welds to be stress relieved before attachment to other sections of work

14 Heating a part of the work by heating slowly a circumferential band containing the weld at the center. The width of the band that is heated to between 1100 F and 1250 F, should be equal to at least twice the width of the widest part of the welding groove, and the temperature should be allowed to diminish gradually outward from the ends of this band.

side periphery might be oversped while only the outside periphery near the weld is being heated; thus, the higher residual stresses could be reduced in this area.

The use of localized heating to provide mechanical loading and thus produce plastic flow in areas of residual stress, is properly a form of mechanical stress relief, but the practice is discussed in this section because of being commonly associated with stress relief by combined mechanical and thermal means. In its simplest application, localized heating is used to remove buckles or twists from plates or structural members. Recently a continuous or progressive method of thermal mechanical loading has been employed in the stress relief of welds in ship hulls, and has been described in a recent report.[12] In this reference, it is stated that the reaction stresses resulting from the shrinkage of the weld, against the restraint of the surrounding structure, are of secondary importance and that they may be minimized by proper welding procedure and sequence. On the other hand, residual stresses in the weld joints, or immediately adjacent to them, caused by the longitudinal shrinkage of the weld, are found almost invariably to approach the yield strength of the weld. The reference article describes the removal of these stresses by the heating of parallel bands progressively on each side of the weld, followed by cooling, in order to produce tensile stresses of sufficient magnitude to cause plastic flow in the weld and adjacent plate areas. Although a temperature differential of 225 F should be sufficient to produce stresses of yield point magnitude in mild steel, it was found that temperatures between 300 and 400 F were actually required because of the inevitable rise in temperature of the adjacent metal. The results of tests on unrestrained sample plates are given; residual stresses were evaluated by the removal of specimens to which electrical-resistance strain gages had been attached. As pointed out above, the measurement of residual stress by removal of a specimen may lack accuracy.

Removal of longitudinal weld stress by this method should be of considerable value in large structures for which no other satisfactory procedure for stress relief is available at present; however, adequate control and continuous inspection would be essential in order to obtain uniform results. All forms of mechanical loading involve the hazard of failure if tridimensional residual stresses of sufficient magnitude are present, and the additional loading involved would be expected to propagate flaws more readily than if such loads were not applied. Without such failure, reduction in the longitudinal residual stress in the weld lessens the possibility of failure from tridimensional residual stresses; and even with failure, the stress relief has located areas that might have fractured in service. So-called "reaction stresses" may be controlled successfully in ship welding, but such control is not possible in many other types of structures, such as pressure vessels.

Requirements of Various Codes and Standards. For convenience, the stress-relief requirements of existing Codes and Standards have been condensed in Table III. In general, these requirements have been formulated from a consideration of carbon steel exclusively. Details have not been systematized yet for low-alloy and high-alloy steels and nonferrous materials. It should be remembered that Code rules establish minimum requirements only, and are based on average conditions of design and fabrication. Judgement must be used in applying such rules to complex structures.

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Basic Causes of Service Failures in Metals

BY THE SUBCOMMITTEE ON SERVICE FAILURES*

THE CAUSES that might contribute to the failure of metal parts in service are too numerous to list. If it is assumed that a proper selection of metal has been made—and this is a reasonable premise, in view of the immense amount of data given elsewhere in this Handbook, concerning chemical composition and mechanical properties—then the causes for failures of metal in service may be grouped into three categories: design factors, processing, and service environment.

*The members of this subcommittee are H. L. Maxwell, *Chairman* (E. I. du Pont de Nemours & Company), J. O. Almen (Research Laboratories Division, General Motors Corporation), A. L. Boegehold (Research Laboratories Division, General Motors Corporation), O. J. Horger (The Timken Roller Bearing Company), J. B. Johnson (Air Materiel Command), H. W. McQuaid (Consultant), C. W. Obert (Union Carbide and Carbon Corporation), R. E. Peterson (Westinghouse Electric Corporation) and J. H. Romann (U. S. Engineering & Mfg. Co.).

The Influence of Design Factors

It is recognized that design is often a more questionable factor than the material used, when service failures must be eliminated. The proper distribution of stresses—a matter of paramount importance if mechanical failures are to be eliminated—is obtainable largely through the physical shape and position of the parts to be loaded.

Most design calculations are made on the basis of three elementary formulas:

For direct stress, $S = P/A$ where P is load, A is area.

For bending, $S = M/(I/c)$ where M is the bending moment and I/c is the section modulus in bending.

For torsion, $S = T/(J/c)$ where T is the torque and J/c is the section modulus in torsion.

These formulas apply only where there is no change of section for a considerable distance axially (of the order of the diameter or depth dimension), as shown in Fig. 1*a*.

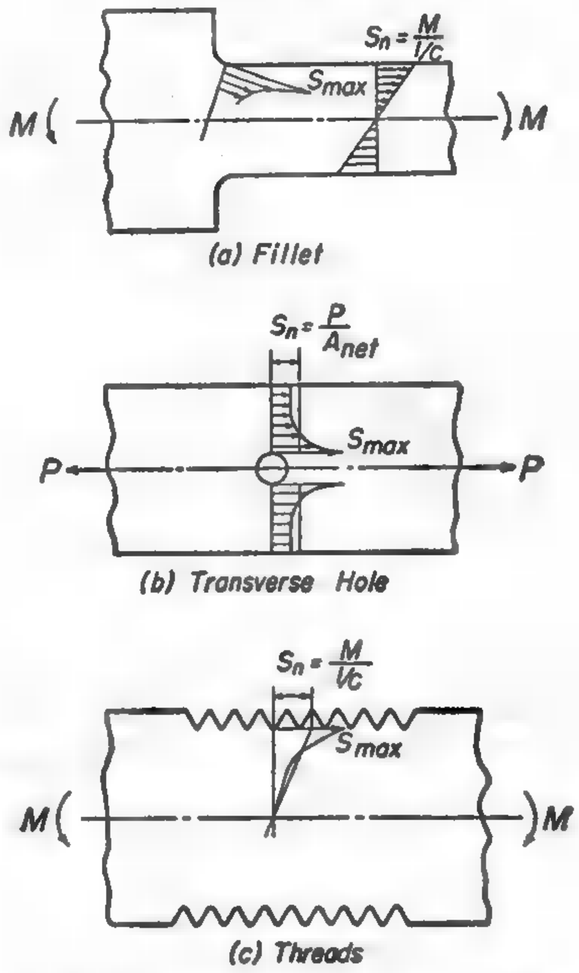

Fig. 1 Examples of stress concentration

In nearly all machine parts, however, the minimum section occurs at a region of changing section which, as shown in Fig. 1, introduces a redistribution of stress such that an increase of stress, or "stress concentration", occurs near the surface. The *stress concentration factor* is defined as $K = \frac{S_{max}}{S_n}$ where S_n = nominal stress (Fig. 1).

The nominal stress is computed by means of an elementary formula (usually on the basis of net area). This purely arbitrary procedure is convenient for designers; the simple basic definition should be kept in mind in proceeding to more complicated problems.

Factors of stress concentration are determined in numerous ways:[1] by mathematical analysis, photoelasticity (*see* Fig. 2), strain gages, brittle materials and coatings, soap film analogy and so on.

Values of the stress concentration factor for various examples are given in Fig. 3, 4 and 5. Such curves are of basic interest in design work, an example of which will be given later. When a metal part fails, the curves are useful in a relative way in judging the approximate benefit to be obtained by certain modifications. For example, if a shaft has a step-up of diameters from ⅝ in. to 1 in., a change of fillet radius from $\frac{1}{64}$ in. to $\frac{1}{16}$ in. (r/d of 0.025 to 0.1, corresponding to K_t' of 2.52 and 1.63 respectively, Fig. 3) results in a stress reduction of 0.89/2.52 = 35%; a change from ⅛ in. to ¼ in. radius results in 12% reduction.

When is stress concentration important? Generally in

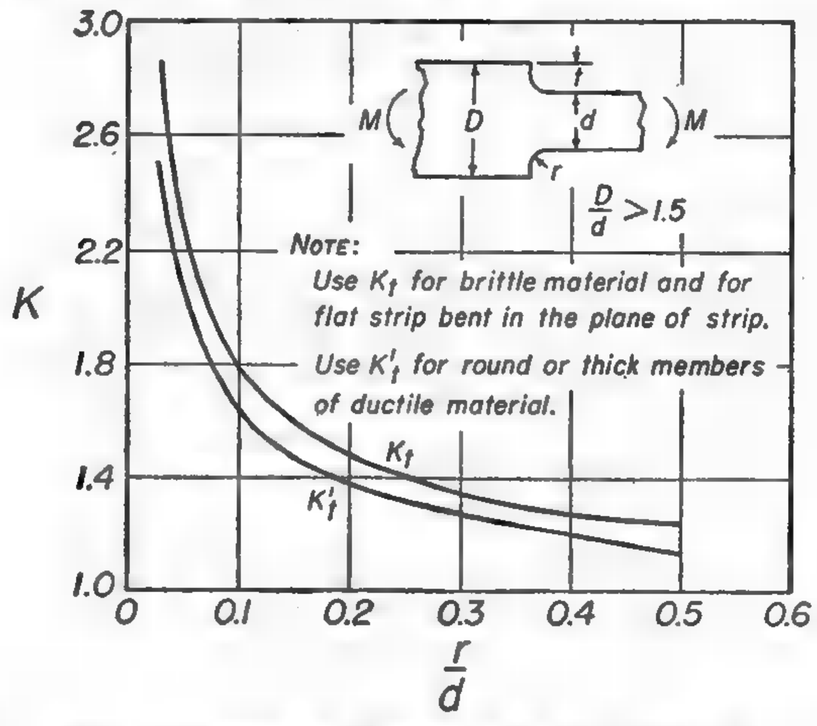

Fig. 3 K factors for fillets in bending. $D/d > 1.5$

brittle material or with repeated (fatigue) stressing. In such instances the material cannot flow and redistribute the stress more uniformly, as happens when a ductile material is loaded statically. For combined static and variable stresses, it is customary in design practice to apply the stress concentration factor to the variable portion only.

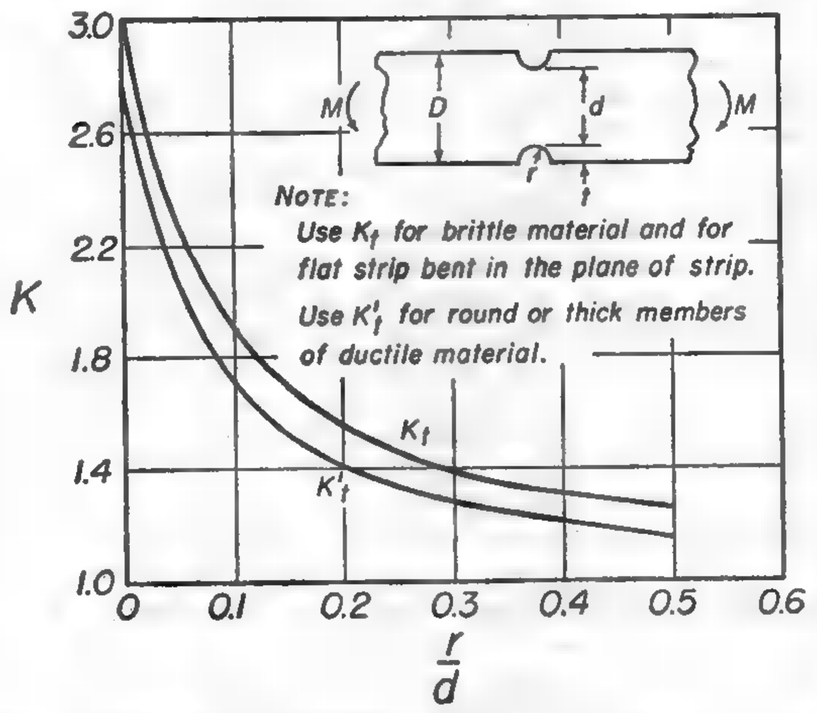

Fig. 4 K factors for semicircular notches and grooves in bending

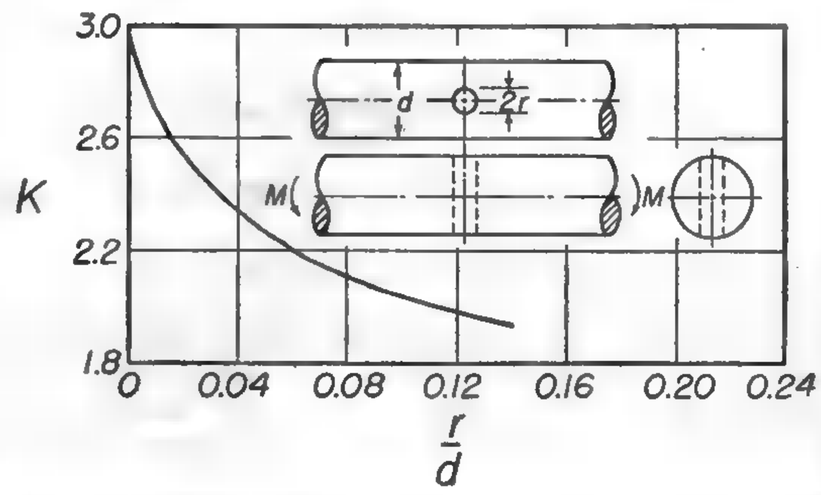

Fig. 5 K factors for shafts with a transverse hole (bending)

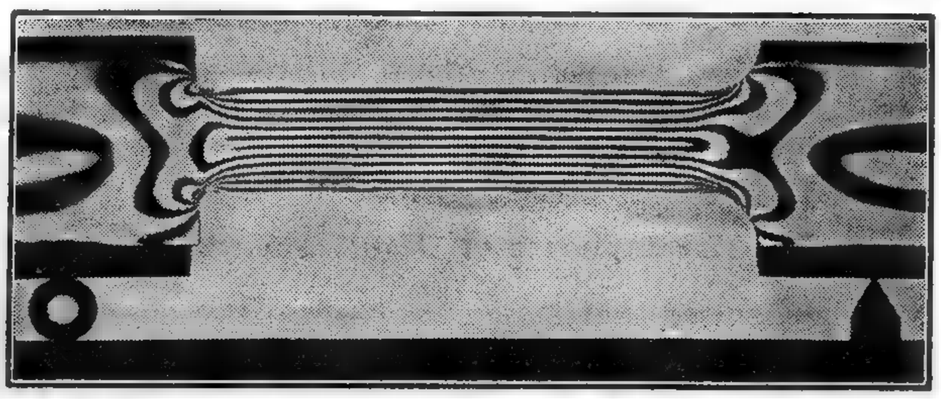

Fig. 2 Photoelastic fringe photograph of fillet section of a bar in bending. (Fringes are lines of constant shear stress. Uniformly spaced lines away from fillet correspond to linear stress distribution of bent bar. The crowding of fringes at fillets indicates stress concentration.)

This subject would not be complete without mention of "notch sensitivity". Experience has shown that in quenched and tempered steels, ordinarily the reduction in fatigue strength is approximately in accordance with the

stress concentration factor; but in hot rolled ("as received"), normalized or annealed steels the full reduction is not generally obtained and the amount of reduction depends on the geometry, chiefly the "notch radius".

The "notch sensitivity index" is defined as $q = \frac{K_f - 1}{K_t - 1}$

where $K_f = \frac{\text{fatigue limit of unnotched specimen}}{\text{fatigue limit of notched specimen}} = \frac{S_e}{S_n}$

The above definition of q provides a scale from zero, or no notch effect (that is, $K_f = 1$) to unity, or full theoretical notch effect (that is, $K_f = K_t$).

In Fig. 6, average q curves are given for a situation where the depth of notch or shoulder is not greater than three times the notch radius.

In a fatigue specimen or machine part that has a circumferential groove of semicircular contour or a transverse drilled hole, as the groove or hole becomes very small, the effect of strength reduction becomes less and

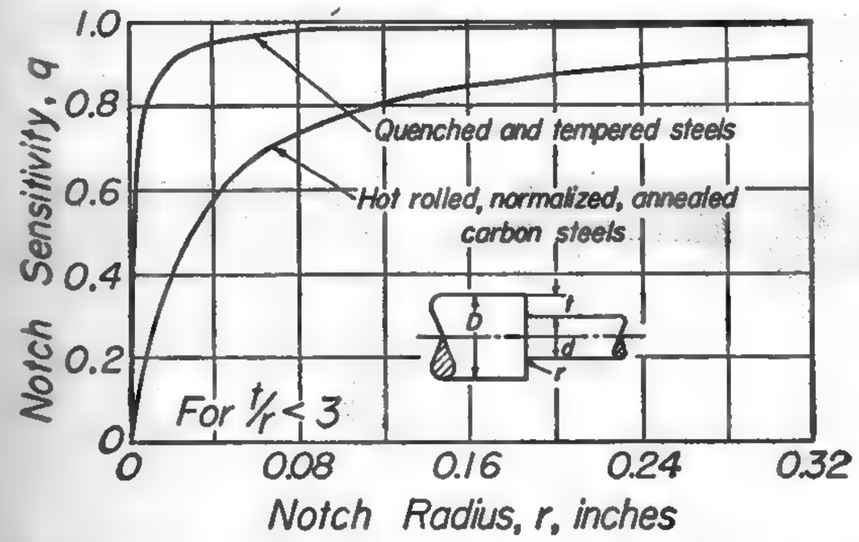

Fig. 6 Average notch sensitivity curves (grooves, fillets and transverse holes) for $t/r < 3$

approaches zero. This means that a tool mark might reduce the fatigue strength 10 to 20%, for example, instead of the full theoretical amount of about 60 to 70%; the exact amount depends on the material and shape of the groove.

An example involving the foregoing terms is illustrated by Fig. 7. The material is normalized SAE 1035 steel having an endurance limit of 34,000 psi. Figure 3 shows, for $r/d = \frac{1}{32}$, that $K'_t = 2.35$, and Fig. 6 shows that $q = 0.7$. The limiting stress in bending is

$$S_n = \frac{S_e}{1 + q\,(K'_t - 1)} = \frac{34{,}000}{1 + 0{,}7(2.35 - 1)} = 17{,}500 \text{ psi.}$$

Machine parts are not designed to this limiting value; the working stress used in design is the limiting stress divided by the "factor of safety".

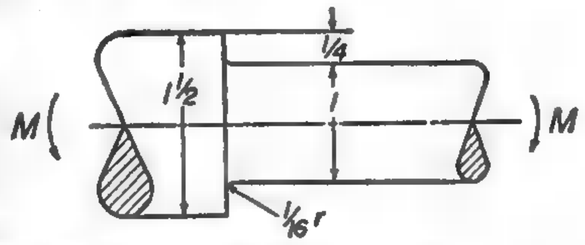

Fig. 7 Dimensions for design example

One of the implications of the foregoing discussion is that under certain circumstances, the gain in fatigue strength that can be obtained by changing, for instance, from a normalized axle steel to a quenched and tempered steel is not in proportion to the increase in tensile strength; in fact, in extreme situations there is no gain in fatigue strength. In general, the amount gained depends principally on the geometry (that is, notch radius and K_t). This fact is illustrated by Fig. 8 and 9, which represent average values for notch radii $\frac{1}{64}$ in. and ⅛ in. respectively.[2] It is evident that for small radii and large K_t values there is little or no gain in fatigue strength by changing to material high in tensile strength; whereas for large radii or low K_t values, or a combination of these, a large gain is obtained.

An obvious consequence of the foregoing is that if maximum benefit is to be obtained from heat treated parts, they should be designed carefully to reduce stress concentration to a minimum. Occasionally, however, the designer is left with factors of considerable magnitude; press fits and keyways, for example, ordinarily result in factors of two or greater. The general relationships illustrated by Fig. 8 and 9 will be helpful in judging individual problems.

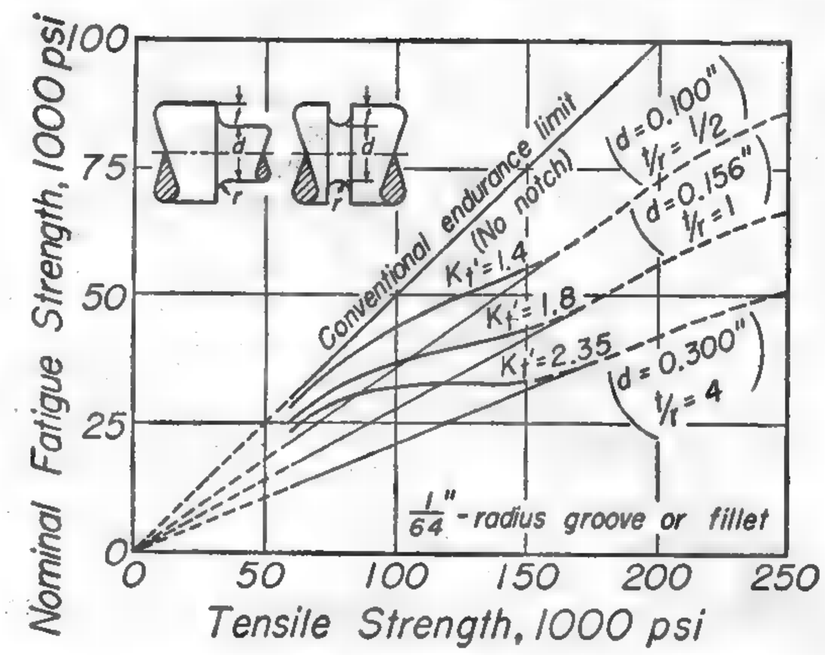

Fig. 8 Approximate fatigue strength in bending of steel shafts that have $\frac{1}{64}$-in. radius in the groove or fillet

In the foregoing discussion, a given condition of loading has been assumed for each example. Often the distribution or manner of loading is influenced by the deformations of the parts. The example of the overhung pinion is shown

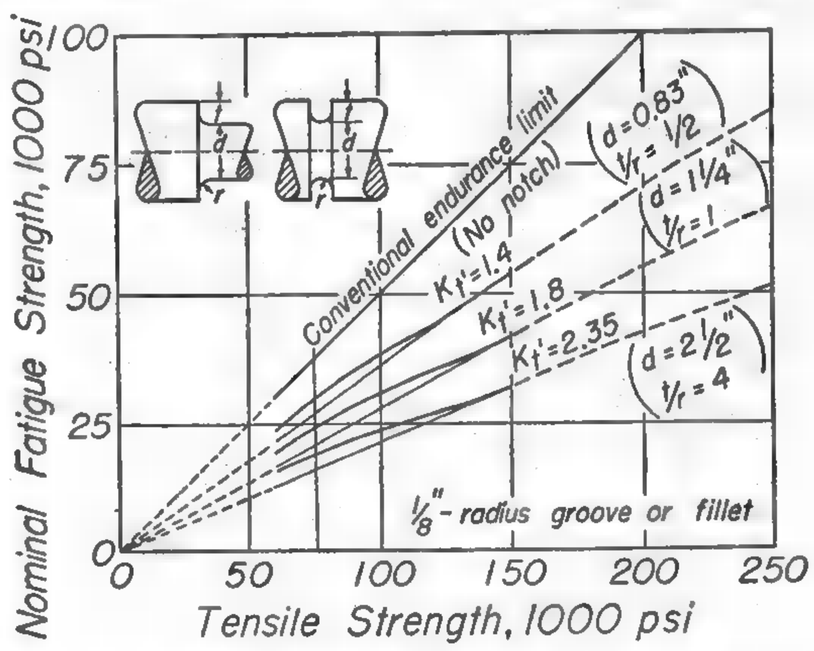

Fig. 9 Approximate fatigue strength in bending of steel shafts that have ⅛-in. radius in the groove or fillet

in Fig. 10. Instead of the uniform distribution usually expected, as in (*a*), the load distribution is more likely to be similar to (*b*) because of deflection of the shaft. In problems of this kind, deflections should be calculated or measured and account should be taken of the altered distribution of load in making the design. It is sometimes

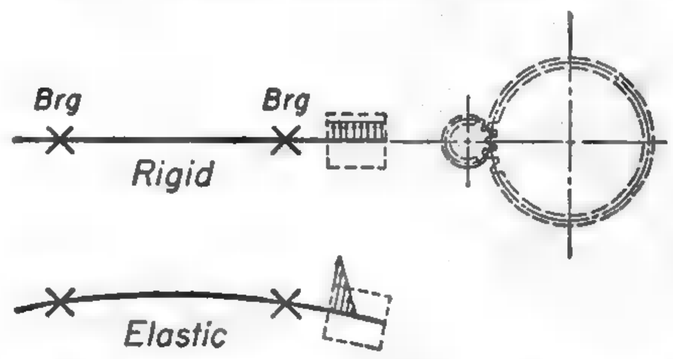

Fig. 10 Load distribution on overhung pinion

not recognized that a way to strengthen or reduce stress in a flat spring working between fixed stops (constant deflection) is to make the spring thinner. When combinations of materials are being used, the moduli of elasticity should be considered.

Influence of Metal Processing on Service Failures

Failures caused by poor design should be eliminated during the service testing of equipment before the production articles are approved. The majority of service failures that result in breakage or malfunctioning of equipment are caused by improper operation and maintenance; however, numerous failures are caused by lack of proper control in the inspection and fabrication operations during the manufacture of component parts. The responsibility for reducing failures in service is shared also by the mechanics who install the equipment; for example, "the man with the wrench" may nullify all the best efforts of design, metallurgical and process engineers, by overtightening bolts.

The large number of processes undergone by a piece of metal while it is being made into a finished machine part, requires that this discussion be restricted to the few processes that seem the most likely sources of service failures in metals. Metallurgical processing, such as heat treatment, is considered here, with emphasis on stresses induced during thermal changes; also, decarburized surfaces are discussed, with brief notes on induction hardening. Mechanical processing is included, with a brief discussion of shot peening, screw threading, surface rolling and straightening, and how these several processes may be related to service failures of metal parts.

Residual stress introduced in metal during heat treatment or fabrication may have an important influence on the service life of a part. For a discussion of this subject, see the article "Relief of Residual Stress", page 237.

Failures Related to Thermal Treatments Used in Processing. The responsibility for obtaining the correct thermal processing is shared by the mechanical engineer, the metallurgist and the supervisor of heat treating. The proper thermal treatment for obtaining the correct structure and distribution of residual stress in a thermally processed member, is only one treatment in contrast with a large number of possible wrong treatments. To consider all the possible wrong treatments and resulting structures would require many volumes.

The metallurgist may specify a satisfactory thermal processing to obtain adequate mechanical properties that have been specified by the engineer, but the heat treating department may fail to execute these specifications properly. The departure from the specified heat treating procedure may involve any one of a multitude of errors. The structure and mechanical properties associated with a failed member that has been improperly processed, may be characterized by an excessively overheated structure, lack of properly refined structure, lack of sufficiently hard structure, or the like. Examples of some of these inadequacies are given in accompanying illustrations.

Another class of defective material encountered outside the metallurgical specification includes defects that originate during the manufacturing of the metal. These defects, too, are caused either by the lack of adequate specifications and inspection for determining metal quality, or they result from failure to detect defects during inspection of the metal. This lack of thoroughness accounts for internal defects such as pipes, flakes, excessive banding, scale that has been rolled or forged in, and excessive nonmetallic inclusions—all defects that are frequently responsible for the failure of parts in service. Fig. 11 shows an example.

Failures in a second class originate from the engineer's neglect to specify suitable mechanical properties for withstanding the loads applied in service. The mechanical properties are specified by the engineer; then the metallurgist prescribes the material and heat treatment to obtain those properties. Although the material and heat treating processes may be faithfully executed, the part may still fail in service because the properties considered suitable by the engineer were actually inadequate. A deficiency in mechanical characteristics may be responsible for failure, in a variety of ways. The strength may be too low to resist the load in service; the hardness may be too low to prevent indentation as the result of concentrated loading; the hardness may be too high, with an accompanying lack of ductility or with accompanying residual tensile stresses that decrease the useful strength of the member; the hardness may be according to specification, but the heat treatment used for obtaining the hardness may be such as to produce an unsatisfactory structure.

Strength Too Low. Failure from too low strength may be illustrated by a bolt, heat treated to a hardness of Rockwell C 25 (equivalent to a tensile strength of 120,000 psi) and used in a highly stressed application, such as a cylinder-head bolt or a connecting-rod bolt, where the stresses involved require the use of material having a hardness of Rockwell C 32 to 36 with an accompanying tensile strength of 160,000 psi.

Hardness Too Low. Failure because of insufficient hardness may be illustrated by several different types of examples, one of which is in surfaces that are intended to be highly resistant to wear and are to have a hardness of Rockwell C 60 or higher. Frequently such surfaces are produced with the specified hardness by satisfactory thermal treatment and are then subjected to a grinding operation, which causes softening to a depth of 0.001 to 0.002 in., with the result that subsequent Rockwell tests fail to detect the soft layer at the surface—a layer that could be detected only by means of a file test. When placed in service, a member that has a soft surface fails very soon by scoring or galling.

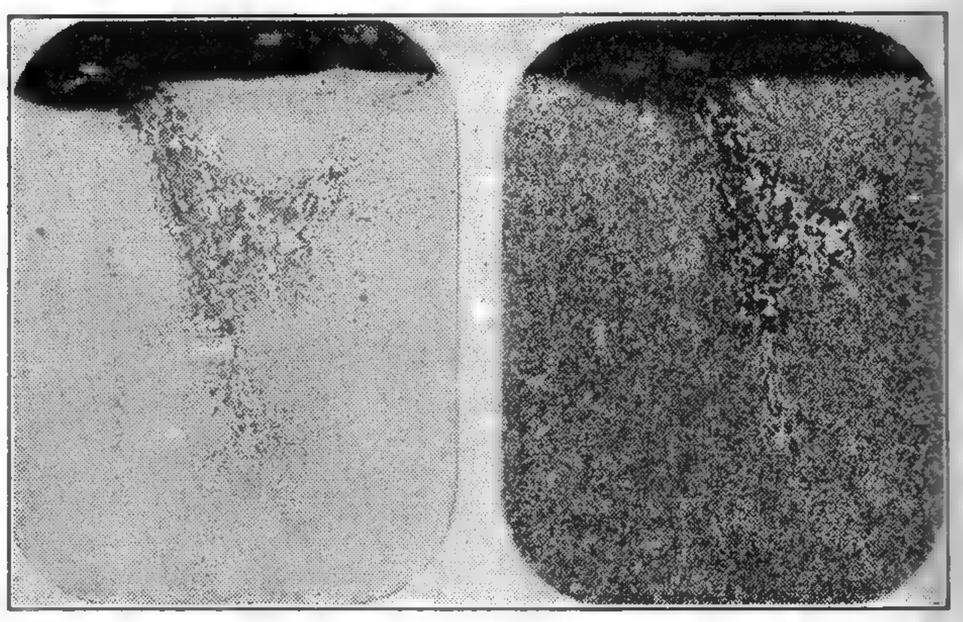

Fig. 11 Micrographs showing the nature of a forging lap in an aircraft engine part that gave a magnetic particle indication on the surface after a period of operation. The indication was caused by the forging lap shown, consisting of an enveloped area of forging scale. (× 100)

Another example is that of highly loaded gears that are made too low in hardness, in order to facilitate machining. The unit loading to which gear teeth are subjected determines the minimum hardness that must be obtained in order to prevent failure from wear in service. Some gears are quite satisfactory at a hardness of Rockwell C 25. On the other hand, highly loaded gears, such as automobile rear-axle ring-gears and pinions, must be file hard and not softer than Rockwell C 58; otherwise failure occurs from wear.

Hardness Too High. An example of failure resulting from too high hardness is the use of ball-bearing races or balls that have the full "as-quenched" hardness of approximately Rockwell C 65 to 68, without the application of any tempering treatment to relieve the quenching stresses.

Hardness Satisfactory but Structure Unsatisfactory. Associated with the type of failure that results when the hardness is satisfactory but the accompanying structure is not, the type of structure can be cited that is obtained in a carburized gear when the gear is allowed to cool in the box after carburizing, and is then reheated for hardening, to a temperature too low to redissolve the proeutectoid cementite. The case hardness, which, for example, may have been specified Rockwell C 58 minimum, may be satisfactory; but because of the presence of the cementite network in the case, failure may easily result from chipping caused by the weak cleavage surfaces along the cementite.

Failures from unsuitable metallurgical structure, as the result of an error made by either the engineer, the metallurgist, or the heat treater, can be traced to a wide variety of causes and deficiencies.

Case Too Thick. The majority of the failures that have occurred in carburized parts in aeronautical equipment have resulted from excessive case thickness in conjunction

with failure to mask off the thinner sections, such as webs and projections; consequently these thinner sections have been carburized all the way through and have failed under shock or impact loads in service.

Case Too Thin. Lack of case depth, encountered less often, is generally caused by a reduction in thickness of case as a result of grinding and machining operations. This lack is easily detected through the nonuniformity of case thickness in adjoining sections. Attempts to recarburize decarburized parts are not always successful. Under the carburized layer, there may be a band of soft decarburized material that is not strong enough to support the external load.

Since nitrided layers are thinner than carburized layers, the reduction in thickness as a result of grinding, may be more serious and must be watched, especially on cylindrical surfaces. Soft spots in a nitrided case have been traced to foreign materials that have adhered to the surface during the nitriding operation.

*Unfavorable Residual Stresses.** Another group of causes for failure results from the presence of unfavorable residual stresses produced either by thermal or by mechanical processing. The opportunity for setting up residual stresses of considerable magnitude exists in every type of heat treatment that is used for producing various types of metallurgical structure. The very process of heating or cooling a piece of steel is associated with temperature gradients and consequent accompanying volume-change gradients. These thermal gradients are complicated by temperature reversals and accompanying reversals in specific volume, which result in the generation of high residual stresses. The volume changes that occur at different times and at different locations in a piece of steel that is being heated or cooled, are first the result of the continuous expansion during heating and contraction during cooling, plus the retardation in expansion during heating through the transformation range and the retardation of contraction during cooling through that range.

The location of the transformation temperature range depends on the rapidity of heating or cooling. The rapidly cooling steel in the process of being quenched is damaged the most by these incidental stresses, because the gradients in temperature are high between surface and center and between light and heavy sections, and the volume change accompanying transformation at the temperature where austenite changes to martensite, occurs at a temperature where the steel is hard and lacking in plasticity. In steel that has been carburized, the volume changes that cause these stresses are further complicated by the fact that the high-carbon case changes much more in volume while passing through the transformation range than does the low-carbon steel in the core, and the temperature at which the change in volume occurs varies greatly with the content of carbon and alloying elements. It is impossible to measure residual stresses except by very tedious methods, and therefore it is necessary to perform empirical tests to determine the best combination of case depth and method of hardening, in order to leave the steel part in a condition of residual stress that will be most favorable to the requirements of the part in service.

The magnitude of the residual stress is affected by the relationship between the depth of the case and the thickness of the core, by the hardenability of the core and by the temperature used for hardening the piece. The exact method of cooling the piece during hardening at temperatures below 400 F, has a profound influence on the magnitude of the residual stresses.

When tests are performed on hardened carburized articles to determine the best heat treatment for producing the optimum properties, the results from the tests sometimes reflect the magnitude of residual stresses more than the strength of the heat treated structure. Ordinarily the residual stresses in the carburized and hardened surface layer are favorable in that they are usually opposite in direction to the applied stresses. Because the volume increase that occurs when the case hardens is greater than the volume increase that occurs in the core, the carburized case is in a state of compressive stress. This condition makes it possible for the part to sustain a higher external load—which normally tends to create tensile stresses—than if compressive stresses were not present.

The compressive stresses generated in the case are opposed by equivalent tensile stresses in the core. If the cross section of the core is insufficient to support the compressive stresses in the case, then failure occurs in the core—in some instances by transverse cracking through the core; in others, by cracking between the case and the core, causing a separation at the bottom of the case. Figure 12 illustrates the latter of these types of failure in the core of a carburized roller-bearing race. It can be realized readily that with slightly different conditions from those that were responsible for the cracks shown in this figure, the stresses resulting from hardening might have been not quite high enough to cause failure. However, the residual stresses would have been very high without actually showing evidence of their presence, such as the cracks shown in Fig. 12. When an article in this condition is placed in service, it is ready to fail at the first external load that is applied. Situations of this kind are probably more responsible for early failure than are unsatisfactory metallurgical structures. An acid treatment will sometimes reveal the presence of such high residual tensile stresses.

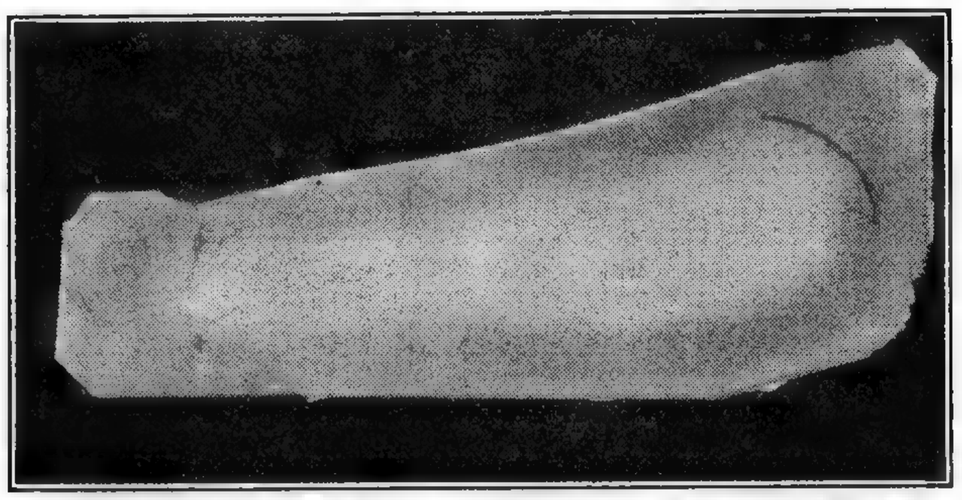

Fig. 12 Cross-sectional view of a roller-bearing race, showing separation of the case and core, resulting from excessive compressive stresses in the case and tensile stresses in the core. (× 5)

Carburizing steel of too high carbon content frequently results in tensile stresses in the case, instead of the customary compressive stresses. Whether the transformation of austenite takes place first in the case or in the core determines whether tensile or compressive stresses will be set up in the case. A high-carbon core will transform later than the case, because the core cools more slowly than the case. If the carbon content of the core is low enough, its martensite temperature will be high enough so that the core will transform before the case, in spite of the fact that the core cools more slowly. Figure 13 illustrates cracks in carburized gear teeth as a result of excessive core hardness.

Figure 14 shows an example of failure caused by residual stresses that resulted from the incorrect heat treatment of a carburized pinion.

Decarburized Surfaces. Various investigators have presented data showing the detrimental influence of a decarburized surface on resistance to fatigue. The decrease in carbon content of the surface layers is not always entirely responsible for the large losses of fatigue strength, since this decarburized surface is often accompanied by other deleterious surface conditions of a mechanical nature.

Hankins and Ford[10] and Burns[11] have made important contributions, and seem to be the only investigators who have shown the injurious influence of a decarburized skin both alone and in the absence of other damaging surface conditions. These investigators machined and polished steel specimens before heat treatment, and determined values for the endurance limit of a decarburized skin without surface irregularities. Another set of specimens was similarly machined and polished after heat treatment, in order to remove the low-carbon skin. The results indicated that depletion of surface carbon in itself, without surface irregularities, is a serious factor in giving considerably reduced values of resistance to fatigue for silicon-manganese and chromium-vanadium spring steels. Comparable data for other steels are not available.

* See also the article "Relief of Residual Stress", page 237.

Many other investigators who have contributed to this subject introduce in their findings the effects of both a decarburized skin and surface irregularities that constitute mechanical notches. The notch conditions are sometimes minimized, depending on the operations used in processing. In many instances, the combination of these surface conditions is the situation encountered in service.

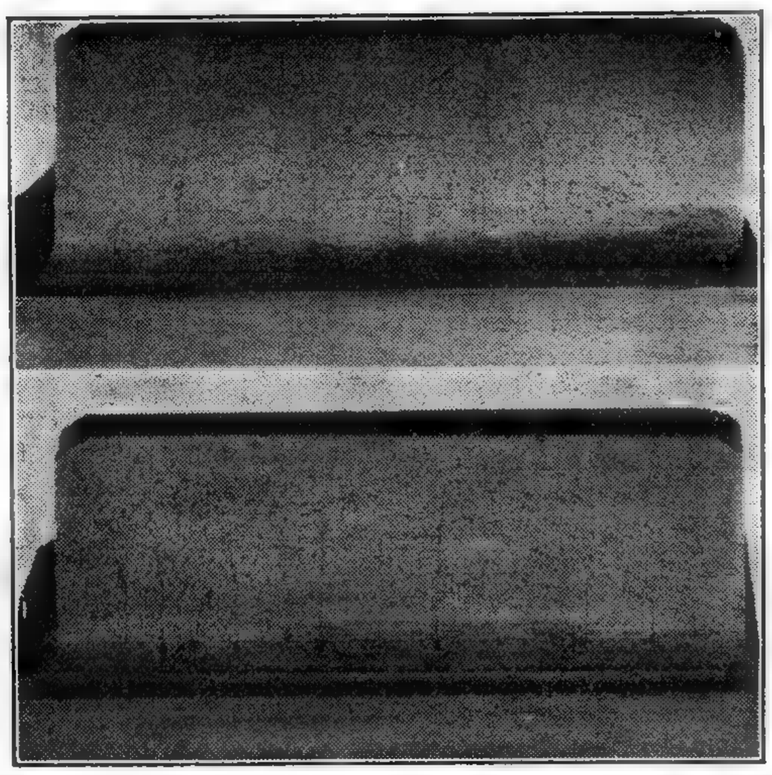

Fig. 13 Gear teeth showing cracks that result from high residual tensile stresses in the carburized gear teeth. Gears made of 2520 steel had excessive core hardness of Rockwell C 44 to 46, and case hardness of Rockwell C 58 to 62. The high hardness of the core indicates that the volume of the core has increased sufficiently to cause tensile stresses instead of the compressive stresses usual in a carburized case. (× 2)

Early systematic tests by Gill and Goodacre[12] gave a good basis for the manner in which a decarburized layer obscures the effect of carbon content on the fatigue resistance of patented drawn wire, 0.080 in. in diam. Their results indicated that the fatigue strength in reversed bending was virtually independent of the carbon content when a decarburized surface layer was present; the fatigue resistance of the wire was apparently determined by the fatigue strength of the material of lower carbon content in the ferrite skin. The example of the nondecarburized wire is in accordance with the usual relationship between carbon content and fatigue resistance.

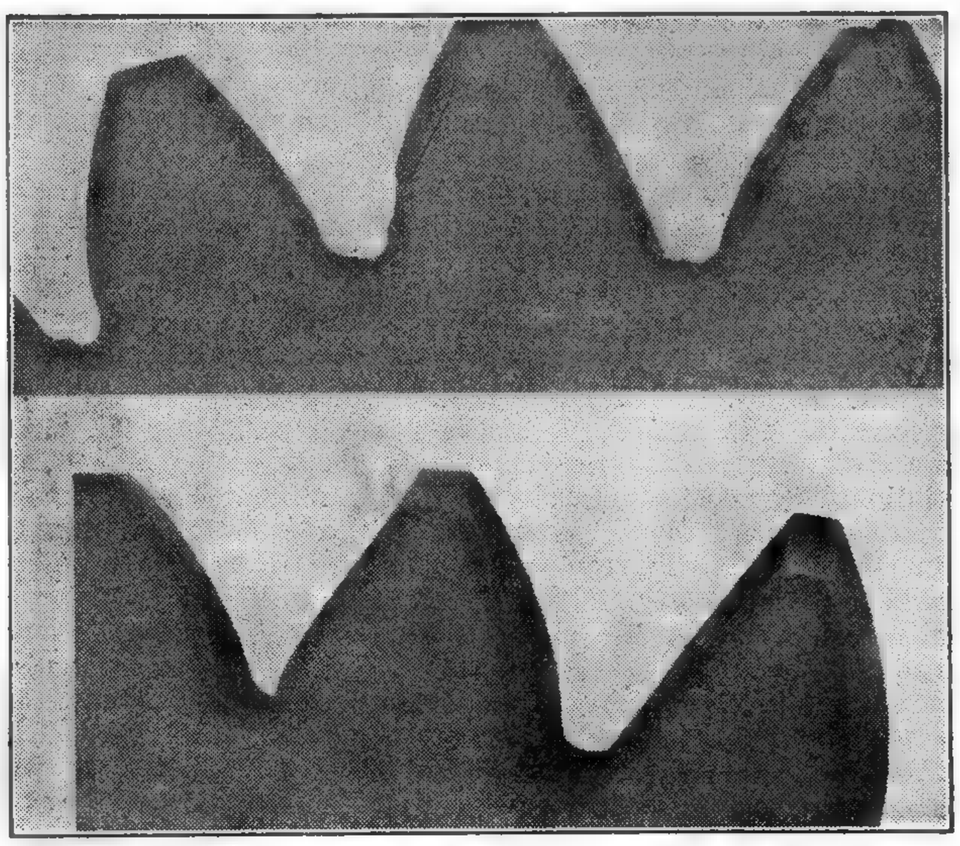

Fig. 14 Macrograph showing the cross section of two rear-axle drive pinions—the lower, in excellent condition after 30,000 miles of severe service; the upper, spalled after 3000 miles. The residual stresses in the short-life gear are the result of a double quench, using a low temperature for the second quench; thus a sharp decrease in hardness was produced between case and core, compared with a gradual decrease of hardness in the good gear, which was box quenched only. (× 2)

Hankins, Becker and Mills[13] made numerous investigations into the fatigue strength of steels for leaf springs, mild plate and forgings made from alloy steel of high tensile strength. Their findings indicate that it is highly inadvisable for forgings made of steel that has very high tensile strength, to be subjected to fatigue stresses in service when the surfaces are in the forged and heat treated condition. Spring steels with as-rolled surface subjected to plane bending (minimum stress, zero) had only about 60% of the maximum allowable stress obtained in the machined and polished state; for mild steel this ratio was about 77%. These reductions in resistance to fatigue are caused by a combination of (1) carbon depletion of the surface layers, which arises both in the manufacture and in the subsequent heat treatment of these parts, and (2) surface irregularities of shape, which occur as small pits and marks in rolling, drawing or forging operations, and as surface scale and oxide penetrations and inclusions.

Manteuffel[14] also obtained interesting torsional fatigue data for various surface conditions while investigating quenched and tempered chromium-vanadium steel spring wire, 0.492 in. in diam. In order to obtain the good results shown by recarburizing, the normally annealed spring material, having scale on the surface, was heated in a durferrite salt bath for 2 hr, then cooled, heated in the same bath to hardening temperature, quenched, and finally tempered in an air furnace. The increases in fatigue values given in this instance by recarburizing, are large compared with the relatively small increases found in similar steel and also in silicon-manganese spring steel treated in a carburizing bath of molten cyanide.[13]

McDowell[15] made rotating bending tests on killed, capped and rimmed steels. Capped steel specimens not heat treated gave an endurance limit value 18% lower than was obtained for the killed steel, with no depletion of carbon on the surface; but the rimmed steel was 25% lower.

Austin[16] made fatigue tests in rotating bending on an unalloyed steel containing 0.38% C and 1.51% Mn. Specimens that had a decarburized surface about 0.010 in. deep, gave an endurance limit of 38,000 psi compared with 47,000 psi for a nondecarburized surface, an increase of 42%.

Bollenrath and Bungardt[18] investigated aircraft wires; Eaton[19] and others[20,21,22] examined spring steels. They concluded that surface decarburization is an important factor in lowering allowable working stresses.

Figure 15 illustrates the fatigue failure of a leaf spring as a result of surface decarburization.

*Induction Hardening.** Surfaces hardened by induction offer high resistance to wear and fatigue but there are few published data concerning this resistance to fatigue. Such parts as piston rods in steam hammers often develop fatigue fracture in the tapered portion that fits into the ram; consequently this section has been induction hardened,[23] and a substantial increase in service life of piston rods has been reported by forge shops. A surface hardness of Rockwell C 50 to 55 is obtained with a core hardness of C 30 to 35.

Crankshaft journals are induction hardened in order to resist wear. Residual compressive stresses are present in the surface of the hardened portion and opposing tensile stresses are produced at the ends of the hardened portion. If hardening stops in the base of the fillet, then such initial tensile stresses have a deleterious influence on the fatigue strength of the journal radius. To overcome this damaging effect, the fillet is surface rolled.

Highly stressed gear teeth have been induction hardened along the tooth profile and root radius. Such gears have been reported[24] to run 3000 hr without failure in an accelerated fatigue test, whereas oil-quenched and tempered gears were pitted after 100 hr.

Comparative fatigue results have been reported from test specimens of three different steels treated in the furnace and by induction.[25] Also the influence of case depth on the amount of residual stress was determined for four different steels.[26] The residual stresses were shown to be compressive, ranging upward to ■ maximum of 100,000 psi before tempering. After being tempered at 390 F, a 0.45% C plain carbon steel had the residual stress decreased by 50%

* For information concerning the process of induction hardening, the reader may refer to the article on page 280.

but stress in an alloy steel (0.12% C, 1.3% Cr, 4.45% Ni, 0.85% W) was reduced only 25%. These initial compressive stresses have been associated with increased fatigue resistance;[27] the same investigators have stated that the complete elimination of ferrite in the hardened layer is probably desirable for applications involving fatigue, since cracks will form in this weak constituent at a much lower stress than in the surrounding martensite. It has also been concluded that tempering, after hardening by induction, is not advisable for parts in which maximum resistance to wear or fatigue is desired. It has been asserted that for applications where fatigue properties are important, it may be necessary to limit the higher heating temperature in order to obtain optimum residual compressive stresses in the case layer. Martin and Wiley[27] do not suggest that the fatigue strength would not increase after reaching an optimum magnitude and distribution of residual stress; however, this may occur. Apparently very high residual stresses result from induction hardening, and it seems questionable, until factual information is available, that tempering at a low temperature would have any beneficial influence on the resistance to fatigue.

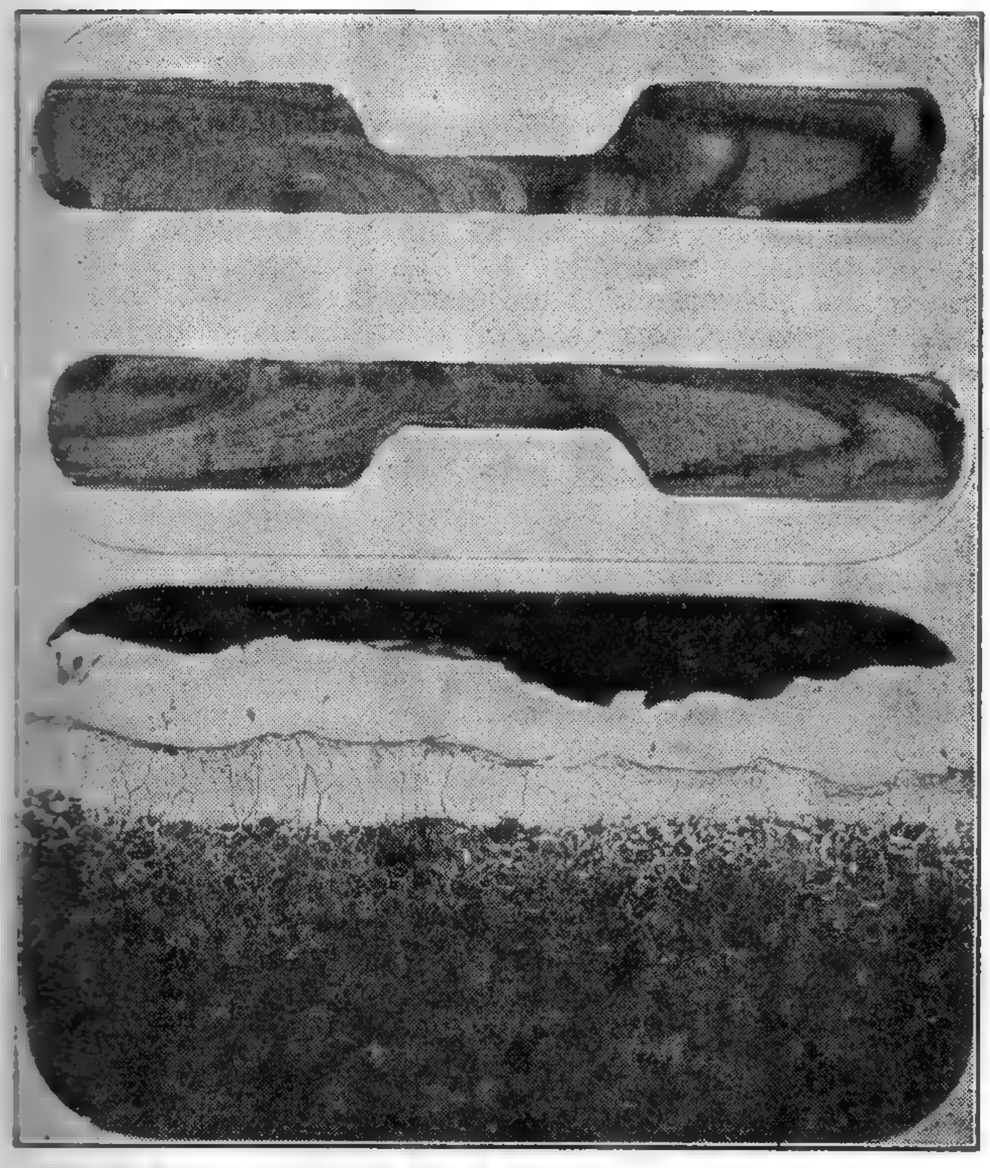

Fig. 15 Fatigue failure of a leaf spring, shown in the above macrograph, is attributed to complete decarburization at the surface, as shown in the above micrograph. (*Upper*, × 1½; *lower*, × 100)

For a further discussion of induction hardening and the resultant distribution of stresses, the reader is referred to J. O. Almen's article, Induction Hardening Problems, in Metal Progress, Dec 1944.

Welding. Welding involves the rapid application of heat near or above the melting point of the metals to be joined. This heating causes localized expansion and subsequent contraction of the metal during cooling, and also causes changes in metallographic structure and mechanical properties as a result of thermal effects. Service failures in welds are caused primarily by the presence of cracks and by lack of fusion. Other flaws in welded joints, such as blowholes, fisheyes and foreign impurities, may occasionally contribute to failure. Cracks caused by expansion and shrinkage can generally be eliminated by proper jigging, preheating, speed of welding and sequence of welding operations. Cracks look very much alike and it is often difficult to determine the cause positively. If the surfaces of a crack are decarburized, it can be assumed that the cracking took place while the parts were at high temperature. Laboratory investigation has established the fact that chemical composition and microstructure affect the tendency to crack. The cause of weld failures is often difficult to determine without a complete history of the materials and processes used in fabricating the weld.

Mechanical Processing. *Shot Peening.* Most equipment is subjected to dynamic loading or repeated stressing of the design members, and for such service the process of shot peening has contributed much toward improving resistance to fatigue. In fact, merely adding the operation of shot peening to the production of machinery and ordnance parts has often effected the difference between failure and successful performance in service.

Fatigue failure generally starts at the surface, where the stress is often greatest and boundary conditions are unfavorable. Therefore, it is only natural that consideration should be given to means of preparing and improving this surface layer. Increasing recognition is being given to shot peening or other methods of cold working, as a surface treatment that not only increases resistance to fatigue but also, in some instances, simultaneously eliminates the necessity for polishing and even machining the surface after heat treatment, and yet serves as a means of cleaning or descaling.

A shot peening operation is applied on production parts either by mechanical means or by compressed air so as to obtain considerable velocity of the shot against the work piece. The technique is discussed in detail elsewhere;[36] properties of different types of cast-iron shot have been investigated by Harder and Gow.[37] A bibliography concerning shot peening has been published that includes material released in 1945.[38]

The American spring industry was the first to make practical use of shot peening. Zimmerli,[39] apparently the first to publish technical papers on shot-peened valve springs, stated that in 1929 the company with which he was associated sent out the first production springs, in this country, that had been shot blasted to increase fatigue strength.

Steele[40] also used shot blasting on production springs. Gagnon[41] has stated that since 1935 such important automobile parts as axle shafts, connecting rods, steering arms, center arms and support arms have been shot blasted, with the result that fatigue failures in these parts are almost a thing of the past. Clutch-spring disks for Chevrolet[42] would not work until they were shot blasted. During World War II, Almen devoted much effort to the development and application of shot peening for machine elements.[43]

The engineer often finds it more desirable to prevent fatigue fractures by increasing the dimensions than by employing seemingly new methods of compressing the vulnerable surface layers. In springs, however, increasing the dimensions would certainly be an unsatisfactory method; the spring would become more rigid, thereby impairing its characteristics as a spring. This limitation of design encouraged the development of shot peening as a surface treatment and hastened its wide acceptance by the spring industry. An engineering expression of the value of shot peening coil springs of pretempered wire is shown by the modified Goodman diagram in Fig. 16. Here the permissible range of stress from minimum to maximum is given for peened and nonpeened springs, made of plain carbon or chromium-vanadium steel of valve-spring quality and having a wire diameter not exceeding 0.207 in. The designer would interpret Fig. 16, for example, to mean that the allowable maximum stress on a peened coil spring could be increased beyond that for a nonpeened spring, by the amounts shown in Table I.

Results by Lüpfert[44] in Fig. 17 indicate that the torsional fatigue resistance of spring wire may be increased by shot peening, even though surface defects are present on the wire. In condition (*a*) of Fig. 17, the fatigue resistance of wire that has no defects is increased 40% by peening. The wire in (*b*) had certain surface defects such as decarburization, flat or shallow scars, and ridges, yet peening gave an increase in fatigue strength of about 130%. In (*c*), wire with surface laps was improved 66% by peening, although the shot could not even penetrate to the bottom of the surface laps.

Micrographs contained in reference 45 illustrate the structure of the unmachined surface layer on both peened and nonpeened AISI 8650 forged steel automotive rear axles, 1⅜ in. in diam, which were quenched and tempered to a core hardness of Rockwell C 41 to 46. Structural changes approximately 0.001 in. deep were evident after peening, and micrographs indicate grain distortion, flattening, and sealing of the grain boundaries on the immediate surface that contains the ferrite layer. In this instance, the rotating bending endurance limit of the unpeened axles was approximately tripled by the shot peening of the forged and heat treated but unmachined surface.[45]

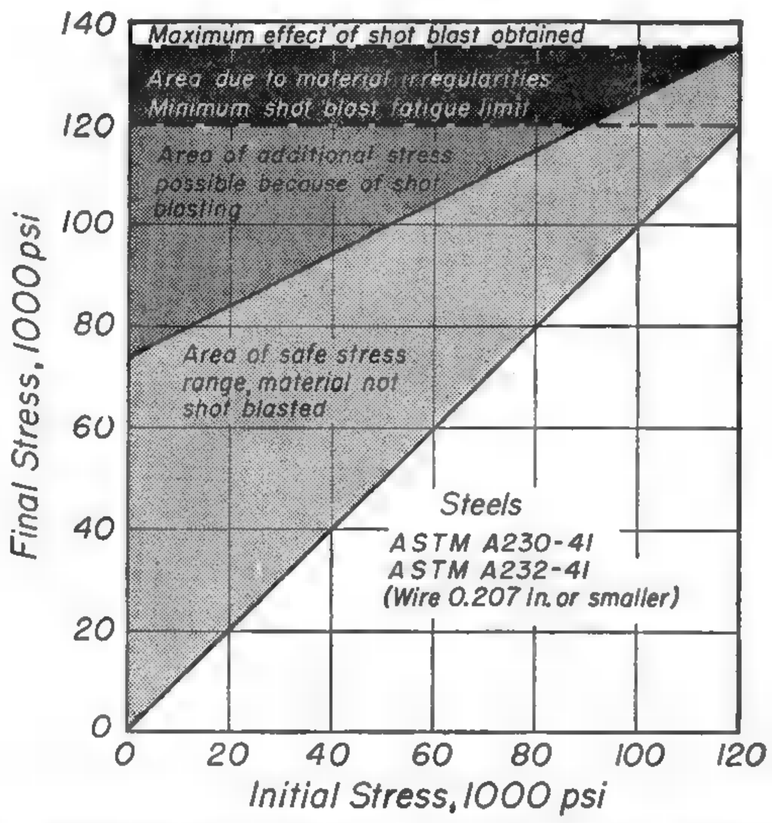

Fig. 16 Modified Goodman diagram showing that greater stresses are allowable on shot-peened springs of pretempered wire (Gibson Co.)

Shot peening greatly improves the fatigue resistance of steels that have been case carburized or quenched and tempered to high values of surface hardness. This increased resistance is important in intricately shaped parts that would be difficult to machine or grind after heat treating. Valentine[46] improved the resistance to impact fatigue in gun hammers. Improvement in other ordnance parts was reported by Frye[47] and by Lüpfert[44] on high-strength wires.

Additional literature[48] may be found on this subject, published since the bibliography[38] was compiled.

Table I. Increase of Allowable Maximum Stress on Nonpeened and Peened Coil Springs

Minimum Stress on Peened or Nonpeened Spring, psi	Maximum Stress Allowable, if Not Peened, psi	Lower Range of Maximum Stress Allowable, if Peened, psi	Minimum Increase in Stress Permitted by Peening, per cent
0	74,000	120,000	62
25,000	90,000	120,000	33
50,000	100,000	120,000	20
70,000	110,000	120,000	9
90,000	120,000	120,000	0

Prestressing. Prestressing, in its broad meaning, implies the stressing of a part beyond its yield strength.[56] For parts loaded in one direction, prestressing is a means of increasing the resistance to fatigue or reducing the danger that the part will take a permanent set later in service. The preload is applied in the same direction as that which occurs in service, so as to produce favorable residual compressive stresses and to increase the yield strength on the surface of the part. Prestressing could include surface rolling and pressing, shot peening and residual stresses obtained through heat treatment, but these phases are discussed under separate headings in this article. Special applications of prestressing will be discussed here.

The most common example of prestressing is the presetting or scragging of springs.[57,58] Although this treatment has been used for generations, the value of it has not been understood until recently.

Prestressing has been accomplished in guns[60] by shrinking several tubular members over one another; by wrapping wire under tension on a central tube; or, after World War I, by autofrettage. In autofrettage, a single cylinder is subjected to high hydraulic pressure so as to enlarge the bore permanently about 6% and to enlarge the outside diameter about 1% for the average wall ratio used. In this way, the elastic strength of a cylinder can be nearly doubled through the combined effect of the increased elastic limit and the residual compressive stress near the bore.

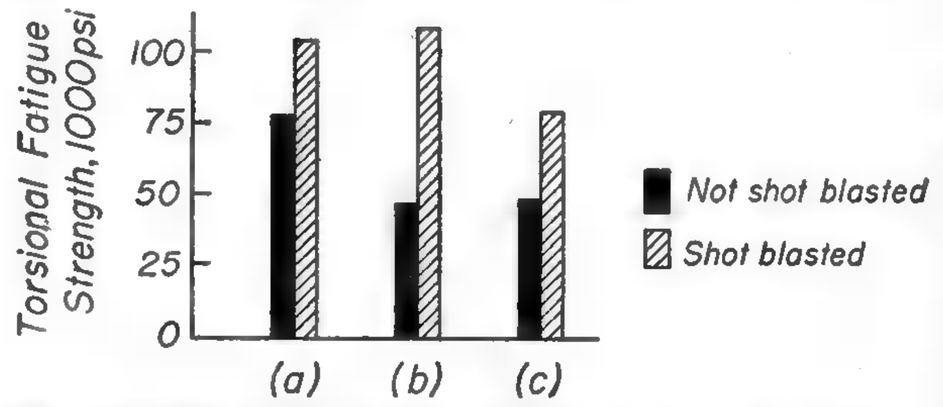

Fig. 17 Increase in fatigue strength of helical springs by shot blasting oil-quenched and tempered steel wire, 0.118 in. in diam with tensile strength 205,000 to 235,000 psi (*a*) without surface defects, (*b*) with small surface defects and (*c*) with surface laps (Lüpfert)

Fatigue failures often develop from holes or eyelets, as a result of sheared edges and poor surface conditions on the side walls of the hole. Stamping the edge of the hole and enlarging it with a conical pin,[61] as shown in Fig. 18, improved fatigue resistance 44%, as indicated in Table II. Almen and co-workers[62] have demonstrated that improvement in resistance to fatigue, in the presence of holes, may result from other types of cold working.

Table II. Results of Reversed Bending Fatigue Tests on Plates with Holes[a]

Condition	Endurance Limit Values, 2 × 10⁶ cycles: Conical Stamp psi	Conical Stamp %	Conical Pin psi	Conical Pin %
No stamping	34,100	100	34,100	100
Stamped, P = 1100 lb....	42,700	120	....	...
Stamped, P = 2200 lb....	45,500	133	49,100	144
Stamped, P = 3300 lb....	45,500	133	....	...

Cr-Mn-V steel annealed; 0.26% C, 1.1% Mn, 0.85% Cr, 0.13% V; yield strength 88,200 psi; tensile strength 106,700 psi; elongation 12%.

(a) See Fig. 20 (Burnheim[61])

A conventional tool for expanding boiler tubes was used to prestress the bores of connecting links,[63] as shown in Fig. 19. Resistance to fatigue around the bore hole was increased 25% max, by enlarging the bore 2.5% (Fig. 20). Other methods have been employed to cold work the bore ends of connecting rods[62] for internal-combustion engines.

Centers of cast steel driving wheels for steam locomotives are prestressed in the axle bore before pressing the wheel on the axle. This operation consists of pressing an oversize tapered plug through the bore[64] so as to deform the surface layers plastically. In this manner, the holding ability of press-fitted members is increased and they may be pressed on and off a number of times without losing their fit. Compressor and turbine rotors are also improved by overspeeding them as a means of obtaining centrifugal stresses higher than the yield point.[65]

Screw Threads. The screw-thread connection is one of the most important and most used machine elements, but often too little consideration is given to the way in which available methods of design and application can be utilized for obtaining great improvement in resistance to fatigue.[66] Ordinarily, threaded parts that fail do so in the first few supporting threads in the nut. This is explained as resulting from the fact that the first few threads transmit most of the force through the nut and the remaining threads carry a decreasing percentage of the load. The flow of force from the bolt through the nut must make a 180-deg turn (Fig. 21) resulting in a concentration of force on the first few threads. It is this concentration of force, combined with the notch effect of the thread shape itself, that results in low resistance to fatigue.

Many fatigue tests have been made on bolt threads alone, without a threaded connection. Such investigations[67] have shown how improved resistance to fatigue could be obtained by employing large root radii and certain thread forms. Values obtained in this manner are too high for purposes of design (Fig. 21). It is necessary to test the entire threaded assembly so that the flow of force through the threaded parts is comparable with the force to be expected in service. Tests have been made by Staedel[68] and others[69] concerning the influence of root radius, length of free thread under the nut, and general recommendations for the design of bolts.

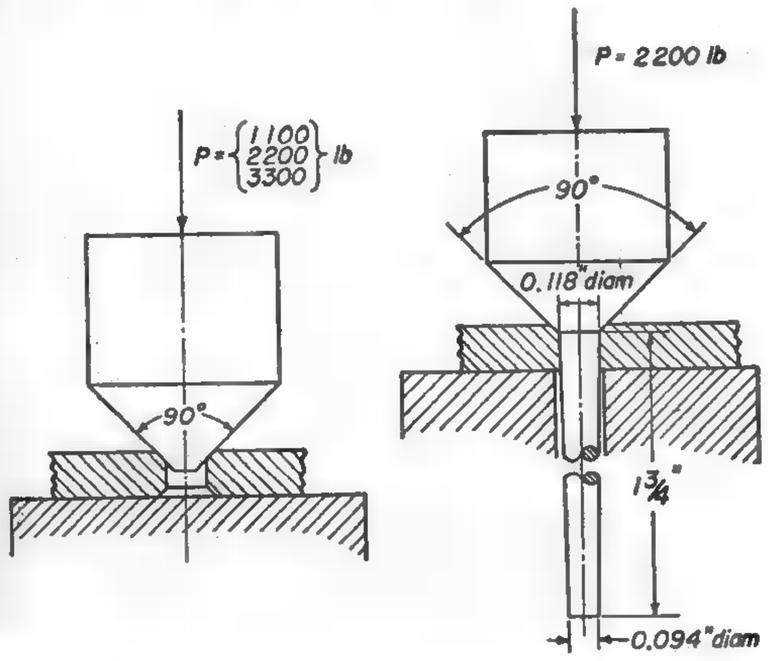

Fig. 18 Method of prestressing holes to improve fatigue resistance. *Left,* conical stamp; *right,* conical pin (Burnheim[61])

Other major factors influencing the fatigue resistance of threaded connections are (1) the material in the bolt, (2) the material and design of the nut,[69] (3) the flexibility of the bolt, (4) the tightening force or preload[71,72] and (5) the method of manufacture.[73] The effects of these and other elements have been referred to by Arnold[66] and considerable data useful in designing have been published by Martinaglia.[74] Manufacturing processes[75] have a decided bearing on fatigue strength, as shown by the superiority of the rolled thread in Fig. 21; the aircraft industry makes extensive use of rolled threads that can be produced so as to have thread tolerances in class 3 or better. Where the bolts are too large to form the threads by rolling, the threads may be cut and the root radii rolled.[69,76,77] Threaded connections of light metals are discussed by Lippert[78] and others.[79]

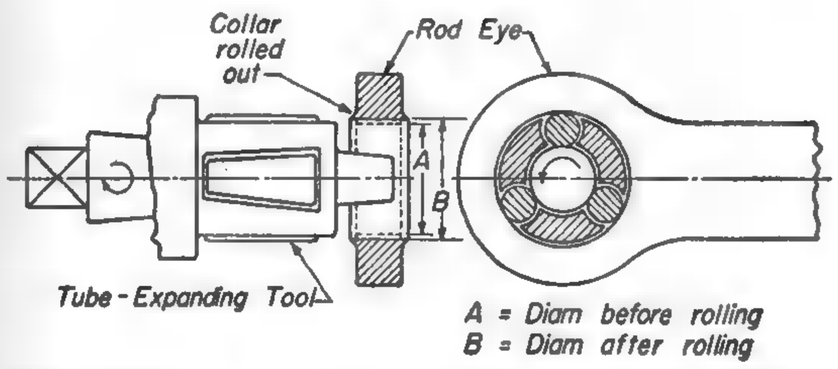

Fig. 19 Method of rolling rod-eye bore to improve fatigue resistance (Thum and Bruder[63])

Surface Rolling or Pressing. Surface rolling is very similar to the conventional burnishing operation used in shops for many years, in order to obtain a smooth surface as a means of decreasing bearing wear and friction. In surface rolling, however, the size and shape of the roller as well as the feed and pressure are controlled to obtain a definite plastic deformation of the surface layers for an appreciable depth. Such a cold worked layer has proved invaluable in decreasing the danger of failure of machine parts.[80] This general idea of cold working the surface layers by rolling, pressing or shot peening was developed by Föppl,[81] and reasons for the improved fatigue strength have been compiled from various sources.[80]

The method of rolling the fillet of a 5¼-in. shaft is shown in Fig. 22. By this means, the endurance limit in rotating bending was increased 30%. A hardness penetration of about ½ in. was obtained. Other investigators[82] have reported that fatigue resistance is increased by as much as 68%. Some automobile companies fillet roll the journals on crankshafts as standard practice.

A three-roller device has been used for rolling large shafts in the region where a press-fitted gear, pulley or wheel is applied. The endurance limit of shafts against breaking off in the fitted part is at least doubled by surface rolling. A hardness penetration of about ⅞ in. can be obtained with only 0.001 to 0.003-in. reduction in diameter of parts 9½ in. in diam; the depth of penetration depends on the surface roughness before rolling. Some railroads have adopted rolling as standard practice for fitted assemblies.

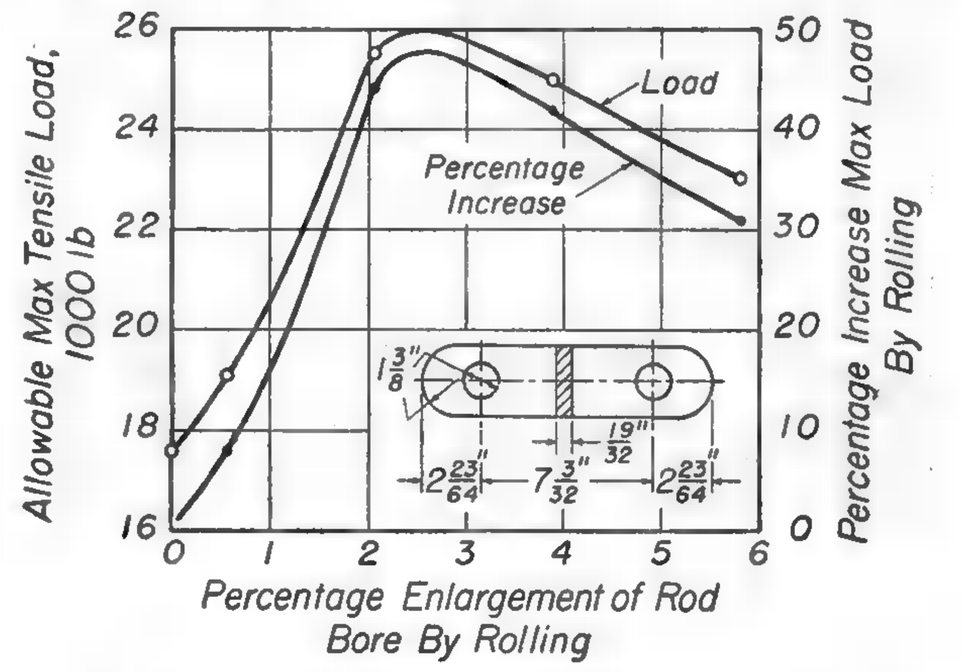

Fig. 20 Increasing load capacity of link rod by rolling bore

Shafts often fail through oil holes and Fig. 23 exhibits a method used for stamping notches on each side of the oil hole to improve resistance to fatigue. The use of 100,000-lb stamp pressure resulted in about one-third greater fatigue strength for 7¼-in. shafts than was obtained without the notches. This method of improvement was previously investigated by Thum and Bautz[83] on ¾-in. shafts that had $\frac{3}{16}$-in. oil holes, and an increase of as much as 88% was obtained. Design of stamp, pressure and kind of shaft material are important factors in obtaining maximum resistance to fatigue.

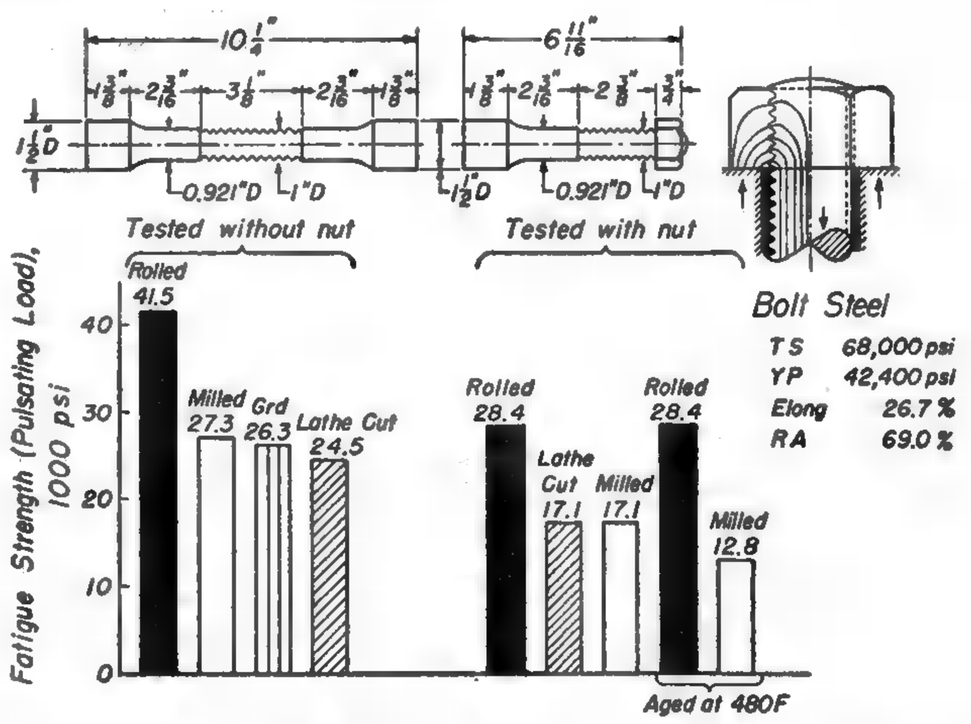

Fig. 21 Fatigue strength of 1-in. bolts having threads cut, ground, milled and rolled (Dinner and Felix)

The bore surface of railroad tires and the root radius of cut screw threads have been rolled. Other applications, discussed by Almen[84] and co-workers, present some novel designs of rolling equipment.

Straightening. Straightening operations are regular shop practice in producing certain manufactured parts. It has been found that the fatigue resistance of a part is often

influenced unfavorably by straightening. Schmidt[85] found that crankshafts for airplane engines developed distortion during processing and required a small amount of straightening when they were machine finished. When cold straightened, these crankshafts showed an endurance limit 20% lower in reversed bending than the limit for crankshafts that had not been straightened. The effect was even greater above the endurance limit, where the allowable stress was decreased by 33% for a life of 50,000 cycles and by 27% for 150,000 cycles.

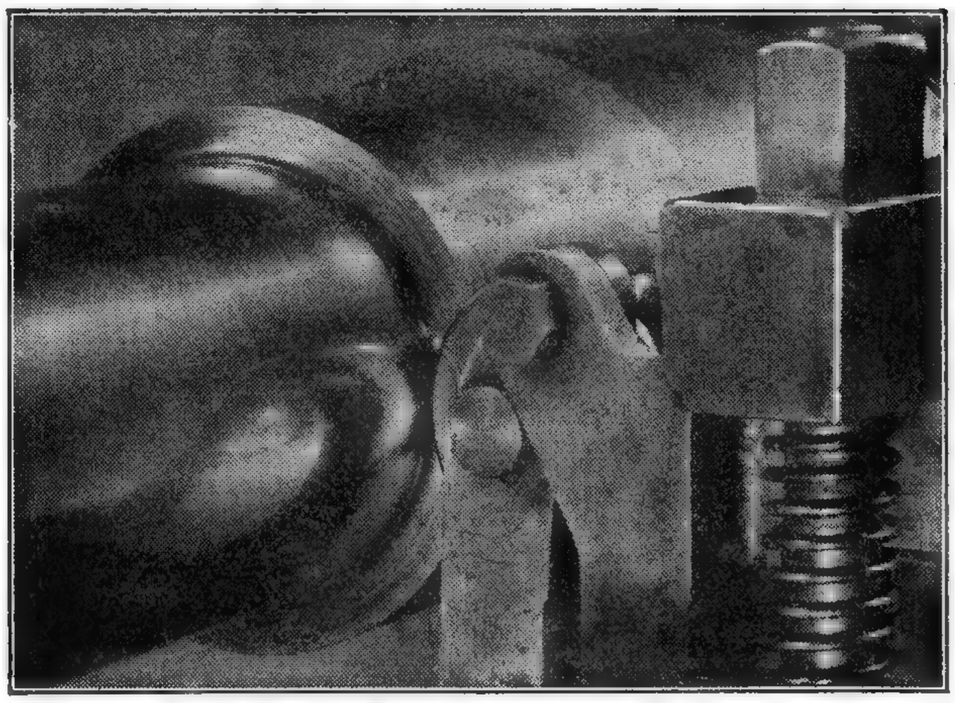

Fig. 22 Method of rolling axle fillet

Also, Horger and Lipson[86] found that the endurance limit in rotating bending of full-size automobile rear axles was 13,000 to 16,000 psi when the shafts were straightened in production. Similar unstraightened axles had an endurance limit of 20,000 psi, or at least 25% greater resistance to fatigue than the straightened shafts. The detrimental effect of straightening was overcome by shot peening after straightening.

In the above examples, the reduced resistance to fatigue found after cold straightening, was attributed to unfavorable residual tensile stresses established on one side of the crankshafts or axles.

Grinding. Residual surface stresses from grinding may be the cause of service failures (*See* Fig. 24 and 25).

Influence of Service Environment

A third general cause contributing to failure of metal parts is exposure to processes and environment, such as (1) corrosion, (2) galvanic corrosion, (3) corrosion fatigue, (4) fretting corrosion and (5) stress corrosion. Mechanical defects arising from the service environment may also cause failure. Limited space restricts the present discussion of a subject about which many volumes have been written.

Corrosion. The types of corrosive attack most commonly encountered may be limited to three: uniform thinning, pitting attack, and grain boundary attack. These are discussed in the various articles on corrosion.

Galvanic Corrosion. When two dissimilar metals are brought into electrical contact in an electrolyte, corrosion of the less noble metal (anode) occurs in excess of its normal rate in that electrolyte, while the more noble metal (cathode) is protected. This accelerated corrosion is known as galvanic corrosion. The amount of additional corrosion of the anode is proportional to the current flowing in the electrolytic cell, and the amount of current flowing is determined in turn by the emf of the cell, by the relative areas of the anode and cathode surfaces, by the conductivity of the solution, and by the rate of polarization of the electrodes. Galvanic corrosion is usually characterized by severe local corrosion at the point of contact of the dissimilar metals, if that contact takes place in the electrolyte. Galvanic corrosion is also frequently found at points, other than the contact point, where proximity of the dissimilar metal parts, relative anode and cathode areas, cell emf, and solution conductivity are properly adjusted.

Such solutions as rain water, sea water, battery acid, and some organic liquids may cause galvanic corrosion. In some instances, large quantities of salts such as hydroxides and sulfates are formed, which weaken the part through detrition and the building up of stresses, especially in faying surfaces. Corrosion of this type can be detected by visual examination.

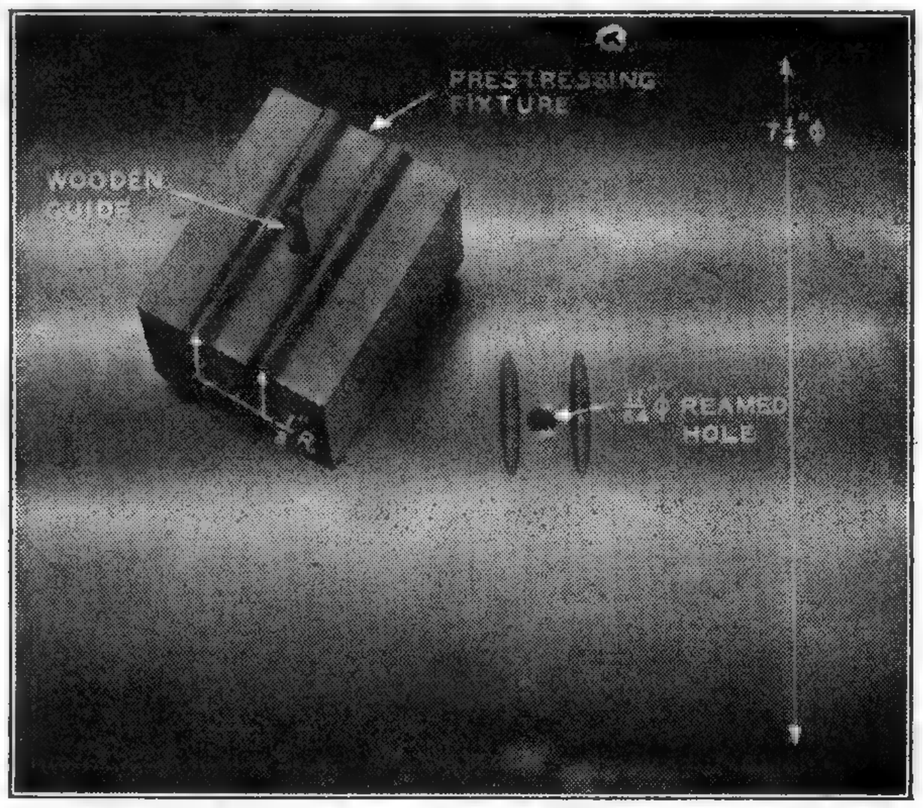

Fig. 23 Method of prestressing notches around transverse oil hole. Crankpin having transverse oil holes in bearing seat with 7.280-in. diam. Stamp used in prestressing oil holes and impression produced. Wooden plug protruding from stamp is used to locate stamp over hole. Pin No. A7-3; Type 5 oil-hole design

Corrosion Fatigue. Corrosion-fatigue failure in metals results from a wide variety of service conditions, ranging from those that are predominantly corrosive in character with minor effect from stresses, through the graduated conditions, to those in which corrosion is only a minor contributing factor and the destruction of the metal results almost entirely from mechanical stresses. Fretting

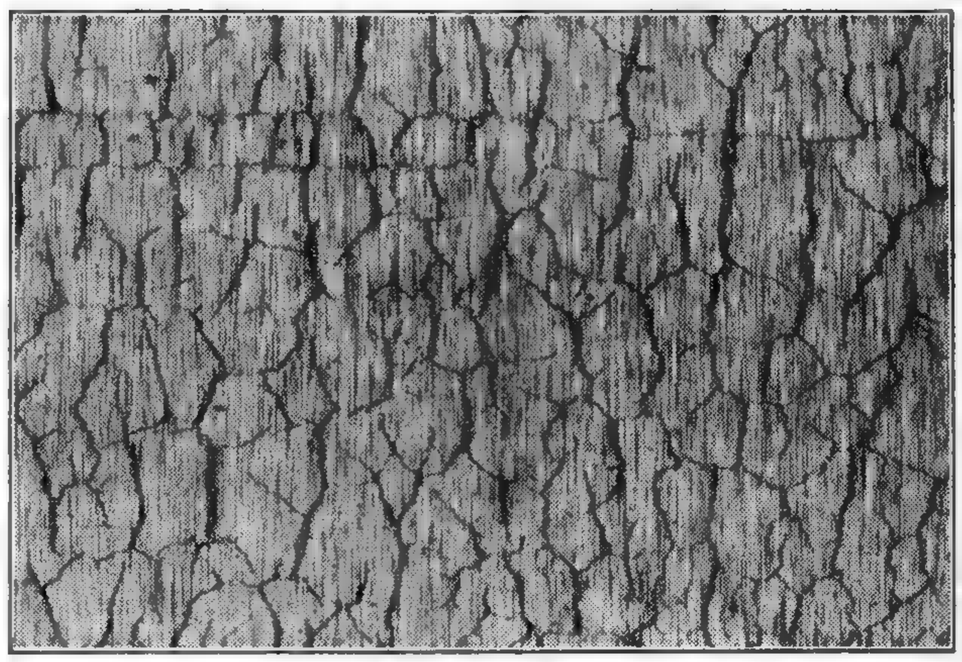

Fig. 24 Surface cracking caused by faulty grinding on a carburized and hardened 1020 steel guidepin. This type of surface on a part subjected to high stress will lead to early failure. (× 11)

corrosion, discussed below, is considered by many to be a special type of corrosion fatigue. The characteristic that identifies corrosion fatigue is the accelerating effect of a corrosive condition in promoting early failure of a member subjected to alternating stresses. Characteristically, the fractures are transcrystalline, the same as fatigue fractures in the absence of a corroding medium.

Fretting Corrosion. When two parts are clamped, press fitted or shrunk together and subjected to vibratory stresses, fretting corrosion may occur. In steel, this corrosion consists of the formation of red oxide[95] between the fitted surfaces, and particularly near the ends of the fit. Fretting corrosion is also known as "friction oxidation" or

"rubbing corrosion". Fretting is one of the most severe forms of weakening action on fatigue strength. A typical fatigue fracture resulting from this condition, is illustrated in Fig. 26. The endurance limit of a shaft to prevent breaking off in the fitted member is only about one-third to one-half of that for the shaft without a press fit.[96,97] Even though the shaft does not break off, because it is subjected to stresses lower than the endurance limit, fatigue cracks are often found when the assembly is pressed apart.[97]

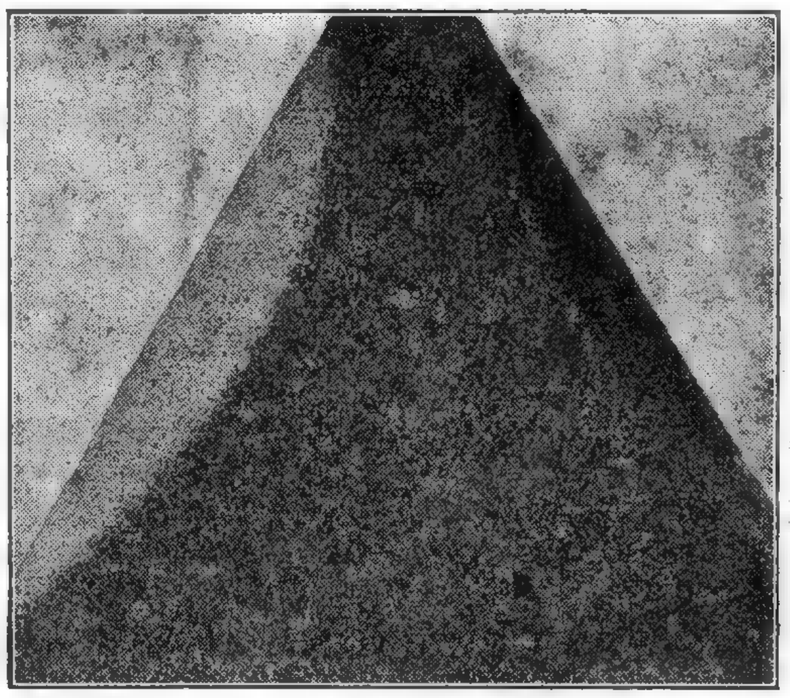

Fig. 25 Grinding of threads on bolts and screws is sometimes the cause of failure from residual stresses. The micrograph above shows hardening caused on the side of a thread by overheating in grinding. This hardening by heating in grinding leaves the thread in a highly stressed condition, which, coupled with service stresses, may cause failure. (× 100)

Fretting corrosion may occur when antifriction bearings are subjected to vibratory oscillating loads of small amplitude. Failures may be found in unused parts after shipment, and in used parts subject to the above conditions of loading. The failure is indicated by a "false brinelling" of the part and is generally accompanied by visible deposits of red oxide of iron.

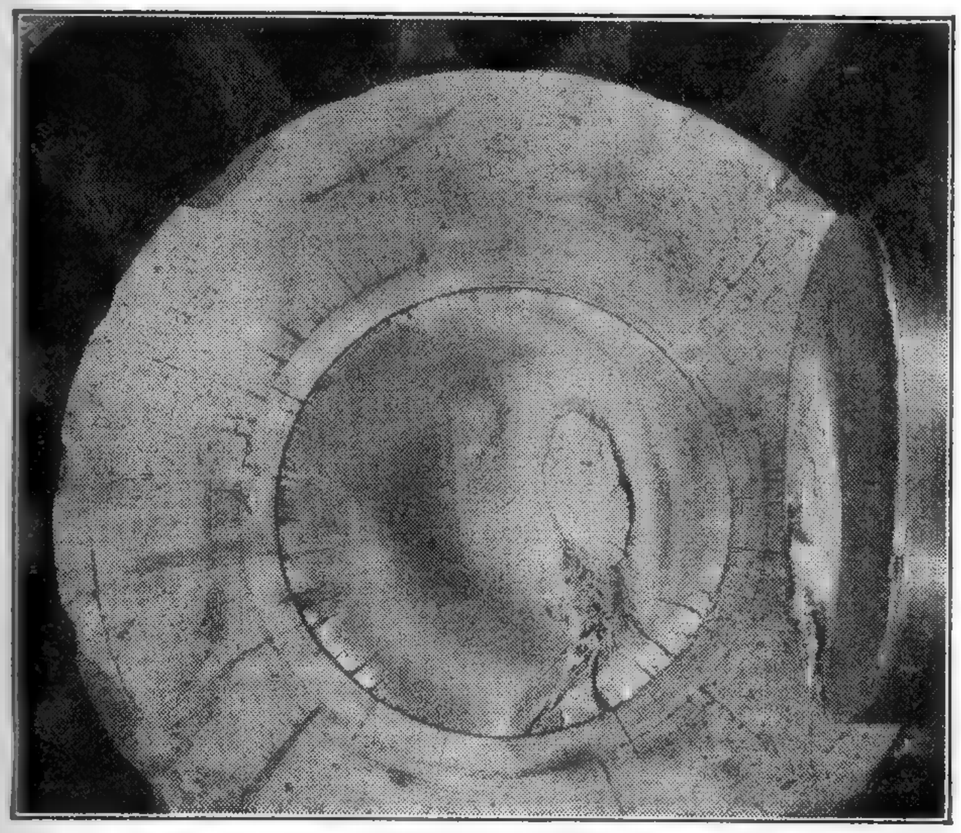

Fig. 26 Typical fatigue fracture of shaft, occurring at one end of a fitted part

Usually fatigue resistance in the presence of fretting corrosion can be greatly improved by the following methods: the shaping of the parts as shown in Fig. 27; residual compressive stresses obtained in the surface of the shaft by surface rolling;[96,97] the proper type of quench and temper;[98] induction or flame hardening;[98,99] nitriding or case carburizing; or a sprayed-metal layer of proper material.[99]

Stress-Corrosion Cracking. This type of failure in metals differs essentially from corrosion fatigue. The principles of stress corrosion are discussed in the article on page 227, and data are given there concerning the stress-corrosion cracking of common ferrous and nonferrous alloys. For information on stress relief, see the article on page 237.

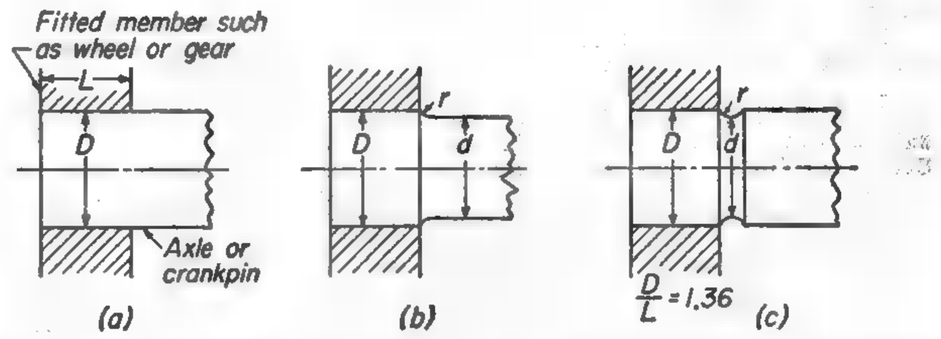

Fig. 27 Correct shaping of fitted parts. (*a*) Conventional method; bending fatigue resistance, 100%. (*b*) and (*c*) Improved methods; bending fatigue resistance, about 130%. Fillet and groove *r* to be surface rolled except when *r* in (*b*) can be large (about 0.4 *D*). If the portion of the shaft in (*a*), (*b*) and (*c*) over which outer part is fitted is surface rolled, then fatigue resistance is more than 200%. (The above data are based on breaking-off strength of full-size fatigue tests in rotating bending of shafts 7 to 9½ in. in diam and made of 0.50% C steel normalized and tempered.)

Mechanical Factors in Service Environment. Service environment may establish such conditions that the properties of the material are affected or the stresses in the material exceed the allowable design values. The loosening of a threaded connection, the hardening of gaskets and shock-absorbing devices because of aging and other factors that may affect clearances, change the rates at which loads are applied, which may mean that parts will be subjected to impact or repetition of loads that they were not designed to withstand. When the examination of a fracture indicates an impact failure or a progressive failure at a few alternations of stress, it is advisable to investigate the possibility that other parts of the machine may have become loose or distorted, thus throwing an excessively high or unusual load on the part that failed.

Temperature changes that result from unusual operating conditions, may cause failure on account of reducing the strength by an annealing action or by the melting and spheroidizing of the constituents that have low melting points. Measuring the hardness may indicate the damage, but a microscopic examination is often necessary, especially for aluminum-base and magnesium-base alloys. Low atmospheric temperatures are generally above the temperatures at which the properties of most metals are affected. However, high stresses may be induced by the unequal contraction of unlike metals with different coefficients of expansion.

Mechanical defects, such as scratches, cuts and bruises on the surface, are stress raisers and will lower the resistance to failure from alternating stresses. This subject has been ably discussed in a book entitled, "Prevention of Failure of Metals Under Repeated Stress",[70] prepared by the staff of Battelle Memorial Institute.

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FUNDAMENTALS OF HEAT TREATMENT

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Heat Treatment of Metals

BY R. S. ARCHER*

THE PURPOSE of this article is to present certain fundamental principles applicable to the heat treatment of all metals, ferrous or nonferrous. Another article (page 613) deals more fully with the heat treatment of iron and steel. Both of these articles, general in nature, are intended as a foundation for specific articles that describe the heat treatment of certain parts, such as gears and dies, and of particular ferrous and nonferrous alloys.

"Heat treatment" is defined as an operation or combination of operations that involves the heating and cooling of a solid metal or alloy, for the purpose of obtaining certain desirable conditions or properties. It is usually desired to preserve, as nearly as possible, the form, dimensions and surface of the piece being treated.

General Principles. The desirable changes in conditions or properties may be considered results of changes in structure. Frequently metal is heat treated in order to change residual stresses. Usually it is desired to decrease or relieve such stresses, although occasionally it is necessary to set up stresses of a definite kind.

More frequently, the changes effected by heat treatment involve changes in the nature, form, size or distribution of the structural constituents. Changes in the nature of the constituents result from the effect of temperature on phase equilibriums or from changes in the composition of material, as in carburizing or nitriding. The form of constituents is affected by the conditions under which they separate from solid solutions, and by the tendency to assume equiaxed shape at temperatures that permit diffusion and atomic rearrangement (spheroidizing). In a solid metal, changes in the arrangement or distribution of constituents can be brought about by solution and reprecipitation, as when the granular cementite of an annealed tool steel is converted to the lamellar cementite of pearlite by normalizing.

Factors in Heat Treatment. Heat treatment consists of subjecting a metal to a definite time-temperature cycle. The chemical effect of the medium surrounding the metal may be of importance, as in carburizing and in nitriding. The time-temperature cycle may be divided conveniently into three parts: (1) heating, (2) holding and (3) cooling.

Heating. The *rate* of heating determines the changes within the metal during heating. The heating medium is important since it affects this rate, and causes or prevents chemical changes, such as oxidation, that proceed from the surface of the metal. It is necessary to consider not merely the average rate of heating, but the rate of heating desirable or permissible at each stage of rise in temperature. The rate of heating is seldom constant and usually decreases as the final or holding temperature is approached, so that this temperature can be attained more accurately and uniformly.

The heat actually consumed, in the practical heating of a metal to a given temperature, is equal to the heat content of the metal at that temperature, minus the heat content of the metal at the beginning of the heat treatment operation, and plus the heat losses from radiation during the heating process. Other factors being equal, these heat losses increase with the duration of heating.

From the standpoint of the effect on the metal, the rate of heating may be important, since it influences stresses, distortion, grain growth or chemical changes such as oxidation.

If a piece of metal originally free from stresses is heated uniformly, no residual stresses will be set up. If the heating is not uniform, so that different parts of the piece acquire different temperatures at a given time, stresses will be set up that will cause distortion and, in brittle metals, may cause rupture. Uniform heating is favored by uniform application of heat, slow application of heat, and high heat conductivity of the metal itself. Particular care is required in heating brittle metals that have poor heat conductivity; for example, hardened high speed steel.

The extent of normal grain growth is determined chiefly by maximum temperature and the time at or near the maximum temperature. However, abnormal grain growth or germination may be affected by the rate of heating. Germination is likely to occur in metals that have been work hardened slightly rather than severely, or in metals in which the degree of work hardening varies considerably from one point to another. When such conditions exist, it is frequently possible to prevent or to minimize abnormal grain growth by heating the metal very rapidly to above the germinative temperature, which usually means heating rapidly to a temperature well above the temperature of recrystallization.

If other factors are equal, surface changes that result from contact with the heating medium are naturally slighter during the heating cycle, the shorter the duration of this cycle. On the other hand, rapid heating obtained by the use of a strongly oxidizing and active flame might result in more oxidation than slower heating with a more neutral flame.

Holding at Temperature. Usually a certain time period, more or less definite, is required at the maximum temperature of the heat treatment. First, the time must be sufficient to permit the entire article to come to a uniform temperature, except in comparatively rare instances where a nonuniform distribution of temperature is desired, as in the localized hardening of steel. The length of time required for attaining uniform temperature, increases with the thickness of the heaviest section of the piece and is greater the lower the thermal conductivity of the material. The rate of heating employed must also be considered, since with slow heating, a fair degree of uniformity may exist shortly after the metal has come to temperature.

The next requirement is that the time at temperature be sufficient to allow the desired changes to take place

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within the metal. Most of these changes involve diffusion, and in wrought metals, grain growth. The solution of constituents such as carbides in steel depends on diffusion away from the particles of such constituents. The conversion of combined carbon to graphitic carbon in the annealing of malleable iron castings involves the diffusion of carbon from the carbide particles to the graphite nuclei. Case carburizing is accompanied by the diffusion of carbon from the surface toward the center.

Grain growth does not occur to any appreciable extent during the reheating of cast metals that have not been subjected to plastic deformation after casting, except in iron and ferrous alloys that recrystallize during heating through the transformation range. Metals that have been deformed plastically, either hot or cold, exhibit grain growth at temperatures above what is known as the temperature of recrystallization. This grain growth is responsible for the softening of work hardened metals during annealing. Grain growth is therefore not only desirable but necessary in the annealing of cold worked metals for the purpose of softening. Occasionally a very large grain size is desired, as in the treatment of certain metals for strength at high temperatures. In general, however, the development of large grains should be limited, because excessively large grain size leads to various undesirable properties. Since both diffusion and grain growth require atomic mobility, these processes usually occur within approximately the same range of temperature. In the heat treatment of steel, it is commonly desired to bring about certain structural changes that depend on diffusion, and to avoid, as far as possible, the grain growth likely to occur in the same range of temperature.

It is thus evident that the laws of grain growth and diffusion have an important part in the determination of temperature and time at temperature.

Temperatures for the recrystallization of certain metals after severe cold plastic deformation are given in Table I.

Table I. Recrystallization Temperatures*

Approximate Lowest Recrystallization Temperature, deg Fahr			
Iron	840	Magnesium	300
Nickel	1110	Tantalum	1830
Gold	390	Tungsten	2190
Silver	390 (a)	Molybdenum	1650
Copper	390	Zinc	Room temperature
Aluminum	300	Lead	Below room temperature
Platinum	840	Tin	Below room temperature
		Cadmium	About room temperature

(a) Indications are that under certain conditions silver will recrystallize at lower temperatures.

These temperatures are higher, the less the amount of cold working. Time is also a factor; recrystallization can be brought about at lower temperatures if a longer time is allowed at temperature. Impurities and alloying additions raise the temperature of recrystallization; for example, brass requires a higher temperature than copper.

Grain size normally increases with both temperature and time of exposure. At ■ given temperature, eventually an apparent equilibrium grain size is reached that does not change greatly even if the time is increased further. The time required for attaining this condition may be a few seconds at temperatures just below the melting point, or a matter of days just above the recrystallization temperature. In heat treating, the temperature is usually high enough to permit fairly rapid approach to equilibrium of grain size, so temperature rather than time is the more important factor governing grain size. In general, however, time is sufficiently important that the duration of a heat treatment is not prolonged unnecessarily beyond the period required for producing whatever other changes in structure are desired.

The rate of diffusion increases rapidly with temperature, and also depends greatly on the nature of the dissolved substance. In most instances it seems that the dissolved substance diffuses in atomic form, and rapid diffusion is perhaps opposed by large atomic volume. Carbon diffuses rapidly in iron at temperatures above A_3, while phosphorus and certain other elements diffuse very slowly, even at much higher temperatures.

The time required for bringing about a certain change that involves diffusion, depends not only on the rate of diffusion, but also on the distances through which diffusion must take place. The time required is therefore longer, the coarser the initial structure of the material.

Metals and alloys that are elastic at ordinary temperatures are left in a state of stress by all commercial cold working processes. High residual stresses can also be produced by uneven temperature changes. Rapid cooling, uneven sections, and mass, contribute to such stresses. Severe stresses are set up in steel during the hardening operation, both by uneven changes of temperature in themselves and by the changes in volume incident to hardening and aging.

The reduction of residual stress by heat treatment depends on a slight plastic flow that is allowed to take place by the lowering of the elastic limit at the temperature at which it occurs. The extent to which stresses are removed is greater, the higher the temperature and the longer the time of heating. Even after stresses have been largely removed by heating at a relatively high temperature, new stresses may be introduced during cooling.

Sometimes the objective of heat treatment is best attained at temperatures just below the melting point of the most fusible portions of the material. This is likely to occur where the effect desired depends on bringing into solution one or more constituents of which the solubility increases progressively with temperature up to the point of incipient fusion, as in the hardening of high speed steel and duralumin. Occasionally materials of this class can be heated to such a temperature that some fusion takes place and then, either with or without subsequent treatment, they may have desirable properties. As a general rule, however, it is not safe to heat treat at temperatures that cause any fusion within the alloy.

When the purpose or one of the purposes of heat treatment is to bring about certain phase changes in an alloy, there are rather definite temperature limits within which the desired change can take place. The permissible range of temperature is defined by the phase diagram of the alloy. The selection of the most desirable temperature within the permissible range is influenced by the considerations mentioned above regarding grain growth, diffusion and residual stresses, as well as by other practical considerations of distortion, scaling and economy of operation.

Above the recrystallization temperature, metals deform plastically under low stresses. Therefore, pieces undergoing heat treatment may deform under their own weight or from any means of handling that imposes even fairly low stresses on the material. Low temperature and short heating time minimize the distortion of pieces under their own weight. Special means are often employed to hold articles in shape during heat treatment. Castings may have special sections cast into them solely for this purpose; such sections are cut out after heat treatment. Fixtures may be employed in the heat treating furnace to prevent sagging at high temperature. Closed hollow articles may be supported by internal air pressure.

The cost of holding metals at a given constant temperature is determined by the heat losses of the furnace because of radiation and the like; by the burden on the heat treating equipment; and, in long heat treatments, by the cost of holding the material itself in process. Heat treatments of long duration involve interest charges on the material itself, and also certain losses or difficulties resulting from interference with precise scheduling of manufacturing operations. The energy consumed or given off as a result of changes that take place within alloys during heat treatment, is very slight in comparison with other factors that affect the cost of heat treatment.

Cooling. Pure metals or single-phase alloys formed into simple shapes, are usually heat treated primarily for the purpose of softening after cold working. In such instances the rate of cooling is likely to be quite unimportant and therefore determined largely by convenience. The rate of cooling after the annealing of copper and alpha brass, for example, has little effect on the properties of the material, although the specific manner of cooling may have consid-

* Jeffries and Archer, "The Science of Metals", McGraw-Hill Book Company, 1924, p 86

erable effect on the surface of the material. Some commercially pure metals contain enough of certain impurities to produce appreciable effects during cooling. It is now recognized, for example, that very small amounts of carbon, oxygen, nitrogen and perhaps phosphorus, may cause substantial changes in the properties of iron at temperatures below the transformation range.

When the constitution of the material being heat treated is different at the maximum temperature of heat treatment from the constitution that is stable at low temperatures, the rate of cooling is of great importance in determining the result of the heat treatment. Very slow cooling permits full development of the constitution that is stable at low temperatures. Rapid cooling may preserve in an unstable condition the structure that was produced at the high temperature, as in the quenching of austenitic steels and duralumin. Frequently, as in plain carbon steels, the most rapid cooling possible will not preserve the high-temperature structure.*

Iron-carbon alloys, when cooled from above the transformation range slowly enough to permit the full development of structural equilibrium at low temperatures, would consist either of ferrite and graphite or ferrite and spheroidized carbides. The intermediate structures obtained in the hardening, normalizing and annealing of steel, thus result from intermediate and controlled rates of cooling. Not only the average rate of cooling, but also the rate of each stage of the cooling operation is important.

Heat Application. Heat is imparted to metal objects by the usual processes of radiation and conduction. At high temperature, radiation is a very important factor in the transfer of heat. In furnaces operating below approximately 1000 F, positive circulation of the furnace atmosphere is desirable to promote rapid and uniform heating. Heat may also be developed within the metal by the passage of electric current, which is led into the metal by means of contacts, or generated by induction. Means employed in heat treating include furnaces heated by oil, gas, coke or coal; furnaces heated by electrical resistors of both metallic and nonmetallic types; liquid baths of lead, salt or oil, in which the objects to be heated are immersed; and containers into which steam is introduced.

Heating by Electrical Resistance. The heating of metals by the direct passage of electric current through the work material itself, is quite limited in practical operation for obvious reasons. If a uniform temperature is desired, the metal object must have a uniform cross section. In order to heat steel tubing for hardening, contacts may be applied at the end of each tube and current may be passed through the tube until the desired temperature is reached. The passing of the tube through the transformation range is indicated by the discontinuity in thermal expansion. Resistance heating has been used in heating bar stock for forging, in heating rivets, and in the sintering of tungsten briquettes. In certain instances where a nonuniform distribution of temperature is desired, an article of nonuniform cross section may be heated by resistance (for example, when heating ends of valve stems for hardening).

Temperature Gradients in Heating. In resistance heating, the inside of the metal is normally hotter than the outside surface. Consequently, the estimation of temperature by the color of the piece, by radiation or optical pyrometers, or by thermocouples placed outside the piece, is likely to give low results.

In other methods the heat is introduced into the metal through the surface, and as long as the temperature is rising, the surface is hotter than the interior. Allowance must be made for this difference, and in practice, it is recognized that a certain period of time, increasing with the size of the section, is required for the penetration of heat through the entire cross section of the piece. Heavy sections therefore lag in coming up to temperature.

Limitations on Rate of Heating. With resistance heating, the rate of heating is limited only by the current available. With heat externally applied, the rate of heating is limited by the thermal conductivity of the metal. If it is assumed that the surface of the object to be heated is maintained at the maximum permissible temperature (for example, by immersion of a small object in a large bath of lead), the time required for saturating the object is determined by the heat capacity at the desired temperature and by the thermal conductivity of the metal under the temperature gradients that exist.

Fuel-Heated Furnaces. Any temperature employed in the heat treatment of the common metals can be readily attained in fuel-heated furnaces of either the directly fired or the muffle type. Furnace parts, including muffles, made of heat-resisting alloys can be used at temperatures as high as 1800 to 2000 F, but may be attacked by fuels of high sulfur content. Refractories are satisfactory up to considerably higher temperatures for hearth, walls and muffles. Conveying mechanism and rails, which must be made of metals, are at present limited to furnaces operating below about 2000 F, unless these parts are artificially cooled or are placed and operated in such a way that they do not attain the full temperature.

Electric Furnaces. Electric furnaces heated by metallic resistors of the nickel-chromium or nickel-iron-chromium types, are limited in working temperature to about 1800 to 2200 F, depending on the type of work and the cost permissible for replacement of resistors. Platinum-wound furnaces may be used at temperatures as high as 2700 to 2900 F, and resistors of molybdenum or tungsten operated in hydrogen provide furnace temperatures at least as high as 3100 F, limited by the refractory rather than by the resistor. Carbon (or graphite), in solid or granular form, can be used as resistor material up to very high temperatures, but carbon is attacked by both oxygen and hydrogen. Industrial electric furnaces operating above the temperature range for resistors made of nickel-chromium alloys, at present are usually heated by synthetic resistor bars consisting largely of silicon carbide, or by alloy resistors of the iron-chromium-aluminum type.

*Furnace Atmospheres.** One of the problems in the heat treatment of steel and some other metals is concerned with oxidation or the formation of scale,[1,2] and much is said regarding so-called "neutral" atmospheres. The only genuinely neutral atmospheres are the rare gases. These have actually been employed in special instances, but are too expensive for ordinary work. Other furnace atmospheres are to be regarded as chemically active; the kind and extent of the action depend on the composition of the metal and of the atmosphere as well as on the temperature.

The most common atmospheres are those resulting from the partial or complete combustion of coal, oil or gas. The possible ingredients of such atmospheres include oxygen, nitrogen, carbon dioxide, water vapor, carbon monoxide, hydrogen, hydrocarbons, sulfur dioxide, and (rarely) hydrogen sulfide. Of these, oxygen, carbon dioxide, water vapor, and sulfur dioxide are oxidizing. Hydrogen is reducing. Carbon monoxide may be reducing or oxidizing, but for iron its effect is predominantly reducing. Nitrogen is generally neutral toward most of the common metals at heat treating temperatures, but it reacts with magnesium at temperatures higher than about 750 F to form a nitride. Sulfur dioxide and hydrogen sulfide may impart sulfur to steel.[3,4] Hydrocarbons and carbon monoxide may carburize steel, while the oxidizing gases, and also hydrogen, may decarburize it.[5]

The most common kind of action during heat treatment is oxidation. All the common metals are oxidized readily at heat treating temperatures. The heat-resisting alloys depend for their protection on the formation of a thin scale of a kind that prevents or retards further oxidation.[6] The elements commonly used for producing these protective films are aluminum, chromium and silicon. It is interesting to note that all three have in themselves a very strong affinity for oxygen.

$$2\,Fe + O_2 \rightarrow 2\,FeO \qquad (1)$$

$$Fe + CO_2 \rightleftarrows FeO + CO \qquad (2)$$

$$Fe + H_2O \rightleftarrows FeO + H_2 \qquad (3)$$

Reactions (2) and (3) are reversible. If relatively rich in CO_2, a mixture of CO and CO_2 will oxidize iron at ele-

* It has been demonstrated that, in certain steels at least, the amount of austenite retained is greater after moderately rapid cooling, as in oil, than after more rapid cooling, as in water. Presumably this is because the residual stresses set up by water quenching, help to initiate the change from gamma to alpha iron.

* For a more detailed discussion of this subject, the reader may consult the article on page 294 of this Handbook.

vated temperatures, but if relatively rich in CO, such a mixture will reduce iron oxide. Likewise, a mixture of hydrogen and water vapor is oxidizing if high in water vapor, but reducing if high in hydrogen.

The compositions of gas mixtures that are neutral with respect to oxidation and reduction vary with temperature.[7, 8] For example, a mixture containing 65% hydrogen and 35% water vapor will reduce iron oxide at 1600 F, but will scale iron at 1000 F. Thus a piece of iron could be heated in such an atmosphere indefinitely at 1600 F without scaling, but would form a thin scale while cooling to room temperature in the same atmosphere. This atmosphere will not prevent the formation of scale on high-chromium steels even at a high temperature, because slight traces of water vapor will oxidize chromium. However, the scale will no longer have the normal brown appearance (caused by iron oxide) but will have a dark green color characteristic of chromic oxide.[9]

The gases discussed above (resulting from combustion) also include most of those that are sometimes injected into furnaces or heat treating containers to produce a definite desired atmosphere. Ammonia is of special interest since, in decomposing, it becomes a fairly inexpensive source of a mixture of hydrogen and nitrogen.

Steam Tanks. Steam may be used conveniently for attaining temperatures as high as 300 F, and has been used especially in the precipitation heat treatment of aluminum alloys. Condensation of the steam on the cold parts of the charge automatically results in rapid and uniform heating, and temperature can be controlled closely by the regulation of pressure.

Liquid Baths. Liquid baths are available for heat treatment at temperatures as high as 2400 F. The baths commonly employed cover approximately the following ranges:

Water	Up to 212 F
Oil	Up to 500 F
Salt	300 to 2400 F
Lead	650 to 1700 F

The range of temperature given for salt baths covers several types of salt, since no one type is suitable for the entire range. Liquid baths exclude air and furnace atmospheres from the work and are therefore protective unless the bath material itself has some undesirable action on the metal. Liquid baths have the advantage also of providing rapid heating, and great uniformity of temperature can be attained when the bath itself is circulated sufficiently and the work material is left in the bath for a sufficient time. The rapidity of heating, especially in a lead bath, is useful, too, for localized heating when this effect is desired.

Measurement of Temperature. Accurate measurement of temperature is vital in heat treatment. Usually it is best to measure the temperature of the work material itself, and the importance of placing thermocouples properly for this purpose is discussed in the section about "Pyrometry", on page 174 in this Handbook. In the heat treatment of many articles of the same material, form and size, when the articles are in the furnace for the same length of time, or travel through the furnace at the same rate, the operation is regulated by measuring the temperature, not of the articles themselves, but of some point in the furnace where the temperature bears a reasonably fixed relation to that of the work metal. In continuous furnaces, especially, this may be the most convenient method of control. There are obvious uncertainties in this method, however, and whenever possible, it is preferable to determine the temperature of the work metal itself.

Quenching. Heat can be removed from a solid object only by dissipation from the surface. The rate of cooling of a given work piece from a given temperature depends therefore on the surface temperature of the piece during the cooling process. The shortest possible time of cooling is obtained when the surface is maintained at or very close to the temperature of the cooling medium; the time required for cooling then depends largely on the thermal conductivity of the material.

The decreased surface temperature necessary to promote rapid cooling may be obtained by removing the object from sources of radiant heat, so that the metal can radiate its own heat freely without receiving return radiation; and by bringing into contact with the surface of the object some cooler material, which may be gaseous, liquid or solid. A fine wire or thin sheet will cool rapidly by radiation alone, especially in the high temperature range; for example, the filament in a vacuum lamp cools very rapidly when the current is turned off. Dissipation of heat by radiation is slow at low temperatures, however, and even at high temperatures is too slow to result in rapid cooling of any but very thin sections.

"Quenching" is the application of a cooler material to the surface of an object to promote rapid cooling. This may be accomplished by use of a current of some gas, such as air, or a spray or jet of liquid, such as water; by immersion in a liquid, such as water; by application of a cold solid, as in cooling (quenching) between plates or in a press; or by combinations of these means.

The cooling medium can seldom be applied to a clean surface of the metal itself, because the surface is usually covered with some sort of scale or oxide film. These nonmetallic coatings have lower thermal conductivity than the metals, and so retard cooling. Heating in such a way that oxidation is prevented or minimized, is therefore conducive to more rapid cooling during quenching.

To produce the most rapid quenching, the cooling medium must be kept in contact with the surface of the metal, and that portion of the cooling medium immediately in contact with the surface must be kept cool. With gases, such as air, there is no difficulty in maintaining close contact. The heat capacity and thermal conductivity of air are quite low, however, so very rapid and uniform circulation and large volumes of air are required to keep the air cool immediately in contact with the surface of the metal. Therefore, gases are not generally suitable or economical for rapid quenching.

Liquids have much higher heat capacities than gases; the specific heat of water is higher than that of most other liquids. The problem of maintaining contact between a liquid quenching medium and the object to be quenched is one of keeping gases from adhering to the surface of the object. Gases may be carried into the quenching medium by the object itself (adsorbed on the surface or trapped in pockets); or may come from the quenching medium by liberation from solution—for example, air dissolved in water—or by vaporization of the liquid itself. Gases arising from these sources and adhering to the surface of the object, insulate the object from the liquid and thus retard cooling. Circulation of the liquid against the surface helps to remove gases, and also tends to prevent the liberation of gases or vapors from the liquid, by preventing the overheating of the liquid in contact with the surface. When water is boiled before it is used for quenching, a negligible amount of air remains in solution.

If it is desired to cool certain portions of an object more slowly than the rest, as with holes and keyways in steel to be hardened, these portions may be shielded from the full action of the cooling medium by the application of clay, asbestos, sodium silicate, or other insulation.

The effect of a quenching medium on the properties of a metal depends on the rate of cooling produced. Except when the cooling rate is affected, there is no evidence of any special effect caused by the composition of certain local waters, extraordinary aqueous solutions, or odd mixtures of oils that have been used or proposed.

It should be noted, however, that the *average* rate of cooling from the quenching temperature to that of the quenching medium is not a sufficient indication of the effect on the metal. The rate of cooling at all temperatures on the way down must be considered. For example, if a certain object made of an alloy tool steel is found to crack when quenched in cold water for hardening, slower cooling is indicated. The object may be quenched successfully in a certain oil without cracking. Equally slow cooling through the higher temperature range, may be obtained by quenching in boiling water, but the object may still crack, because the cooling rate is too rapid at lower temperatures, possibly from 700 to 300 F.

Careful studies have been made concerning the rates at which steel, in particular, can be cooled by various quenching mediums.[10, 11] Detailed data concerning rates and other factors that influence the process of quenching, are in-

cluded in other articles in this Handbook (pages 615 to 629).

When the ratio of the surface of an object to the volume is large, as in wire and thin sheet, extremely rapid cooling can be obtained by a quenching method that cools the surface rapidly; for example, a jet of cold water of ample volume and under high pressure. With heavier sections, however, the cooling rate is limited by the rate of conduction of heat from the interior to the surface. Hence, the center of a large section of steel cannot be cooled rapidly by any method. If the composition of the steel is such that rapid cooling is necessary for full hardening it is impossible to cool the center of a large section rapidly enough for such hardening. This is called "mass effect".

Different quenching mediums may be used in sequence to produce different rates of cooling. For example, to reduce distortion and strains, a tool may be cooled in air for a short time before being quenched in water; or a crankshaft of alloy steel may be quenched in water for a measured time and then be removed and allowed to cool in air or oil, in order to prevent cracking.

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Recrystallization

By Robert F. Mehl*

METALS that have been strained by cold working are not stable, but tend to revert to a strain-free state. This article will consider the processes by which the effects of cold work may be relieved; among them recrystallization is the chief. The cold working of metals in industrial practice is familiar to the engineer; so is the annealing of cold worked metals for softening, either to facilitate further working or to provide more suitable properties for use. The examples are exceedingly numerous; for instance, the annealing of cold rolled low-carbon steel sheet (see the article on "Effect of Cold Work on the Properties of Iron"). In order to understand the processes by which metals hardened through cold work may thereafter be softened by annealing, it will first be necessary to consider the effect of cold work on the nature of metals.

The Nature of Cold Worked Metals. Cold work consists in the plastic deformation of a metal at such temperatures and at such rates that no recrystallization occurs during the deformation process. Under such conditions the metal is strain hardened. The compression of iron at room temperature, for example, is cold work; the compression of iron at higher temperatures in the absence of recrystallization is also cold work. Only when such temperatures are reached that recrystallization (which leads to softening) occurs during the working process, can the term "hot work" be properly employed. In general, these temperatures are high in metals melting at high temperatures and low in metals melting at low temperatures—occasionally as low as room temperature or below. Since permanent plastic deformation is required (for metals do not recrystallize without prior cold work), it will be obvious that the deformation must be beyond the yield point.

Such deformation produces fundamental structural changes in the metal. At low degrees of deformation, slip lines appear in those grains in which the slip planes are most favorably oriented for yielding under the resolved shear stress; in metals which readily form mechanical twins, like zinc at ordinary temperatures or iron at low temperatures, twin bands also appear. As the degree of deformation becomes greater, slip lines appear in an increasing number of grains, the grains tend to rotate, the crystal planes to become curved, and the grains to become sensibly elongated in the direction of flow. It is a result of the fact that the directions in the crystal grain by which flow can take place during deformation are determined by crystal symmetry and are therefore not random, that cold and hot deformation are accompanied by the generation of preferred orientations, which may be described in crystallographic terms, accompanied by corresponding directional properties. This deformation is accompanied by an increase in the strength properties: hardness, yield point or strength, tensile strength; and a decrease in the ductility properties: elongation to fracture, reduction of area at fracture, drawing capacity, impact strength. Deformation is accompanied also by a slight decrease in density, a slight decrease in electrical conductivity, and a decrease in maximum permeability, as well as by an increase in electrode potential and the general tendency to corrode, an increase in coercive force, a slight increase in the coefficient of thermal expansion, and a slight increase in compressibility.

The atoms in an annealed metal are in a continuous state of thermal vibration about mean positions that are symmetrically disposed on a crystal structure. Apart from relatively minor imperfections, this is a geometrically perfect arrangement. The perfection of arrangement, however, is grossly altered by deformation. The crystallographic planes become curved and twisted; atoms no longer have precise mean positions on the crystal lattice, but are distorted to positions less symmetrically disposed, with resultant distortion of atom shapes and energy distribution, and increase in the internal energy of the metal.

The nonhomogeneous character of cold deformation creates a pattern of residual strains. In commercial forming operations, the friction of rolls or of dies, or the complexities introduced by multiple types of deformation or by heat treatment, create residual "macroscopic stresses" (Heyn stresses). These macroscopic stresses are characterized by a gross distribution in such a way that one section of a piece may be in tension while another is in compression; thus, for example, the center of a cold drawn copper wire is in compression while the outside is in tension. Furthermore, a pattern of stresses on a fine scale, "microscopic stresses", characterized by minute regions in which tensile (and compression) stresses occur, also are formed as a result of slip on atom planes, of the bending of slip planes, of slip on intersecting slip planes, and of the impedence to normal slip at grain boundaries. Such a pattern of stresses will obviously be characterized by points of unusually high energy peaks, which are the points of least stability in the cold worked metal where processes relieving the effects of cold deformation presumably will originate. The greater the amount of cold deformation, the greater will be the number of such peaks, and presumably the greater the number of peaks of extremely high energy.

The heating of cold worked metals results in a softening and accordingly a renewed ability to suffer cold work. This heating also relieves both microscopic and macroscopic residual stresses, either of which may be harmful in special cases, though generally cold worked materials find widespread and wholly satisfactory applications. Macroscopic

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stresses can measurably decrease the fatigue strength of materials when such stresses are tensile on the surface, can increase fatigue strength when such stresses are compressive on the surface, and in a wholly similar way can be conducive to failure in stress corrosion as in season cracking; and can lead to the yielding of structural members at loads below the normal yield strength. Any softening process that will obviate these effects is important practically; it will be seen that both the process of recovery and that of recrystallization will perform this task.

The Effect of Annealing on Cold Worked Metals. The changes in properties that follow upon annealing are in the direction of the restoration of the properties obtaining before cold deformation. But the ways in which the various properties change on annealing are not simple.

Three types of mutually distinguishable processes occur on annealing a cold worked metal. These are: (1) recovery, (2) recrystallization, and (3) grain growth, as illustrated in Fig. 1. Recovery is a change in the properties—particularly those determined by the state of strain—of a cold worked metal at low annealing temperatures; a change unaccompanied by any detectable change in the microstructure of the cold worked metal. Recrystallization, occurring at higher temperatures, is a process of the formation and growth of new unstrained grains, supplanting entirely the cold worked structure. Grain growth, occurring in completely recrystallized metals, is merely a continued growth of recrystallized grains.

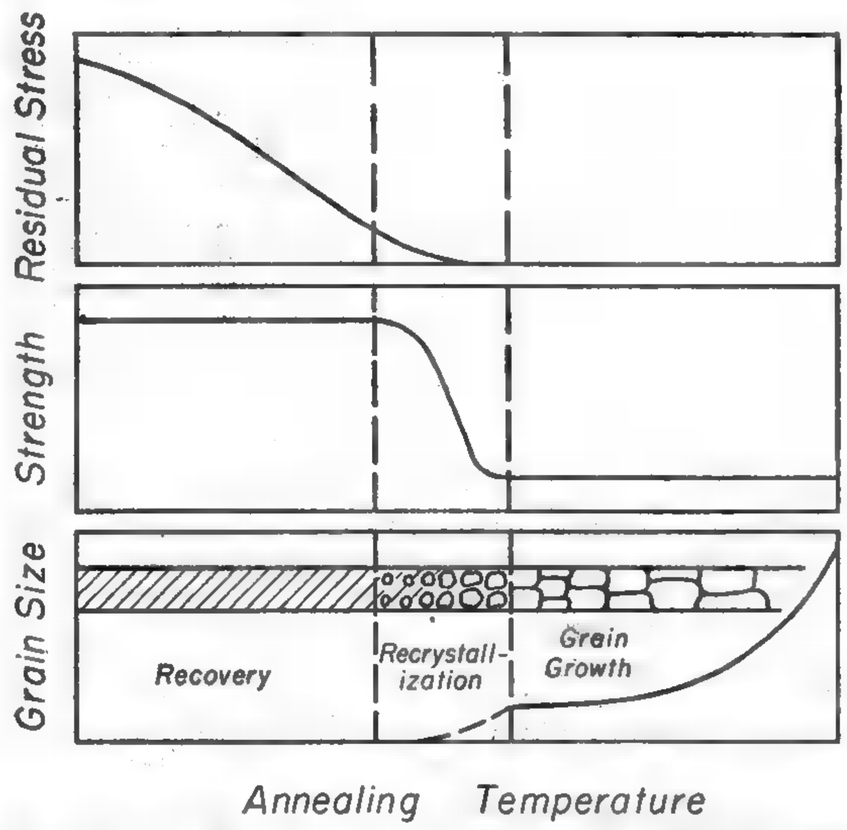

Fig. 1 Schematic representation of recovery, recrystallization and grain growth (adapted from Sachs).

These three processes all depend on time; they are not instantaneous. The rate at which each operates increases with increasing temperature, following an exponential law. When the temperature to which a cold worked metal is subjected is sufficiently high, these processes operate with such rapidity as to appear to be instantaneous, but at lower temperatures the time dependence is readily detected. The rates, however, vary widely from metal to metal and depend greatly on composition, purity, grain size of the sample before deformation, and the amount of deformation. Generally, metals with low melting points exhibit high rates at low temperatures, as in the case of tin. Furthermore, the three processes sometimes overlap and are difficult to distinguish, while in other cases they can be clearly separated. The accompanying changes in properties are not always parallel, that is, the properties do not change concomitantly (Fig. 5), and this fact often permits the production of unusual property combinations.

Recovery, recrystallization, and grain growth are all processes leading to softening. It is conventional to study these by heating cold worked samples to a series of increasingly elevated temperatures and holding for a certain time period, usually between 15 min and 2 hr, and subsequently measuring the properties at room temperature.

The selection of a constant time period of annealing eliminates time as a variable, and the results must be viewed with this limitation. In a narrow temperature range the change in properties is rapid, as shown in Fig. 2 for copper of various degrees of purity, but this range may readily be displaced to lower temperatures by increasing

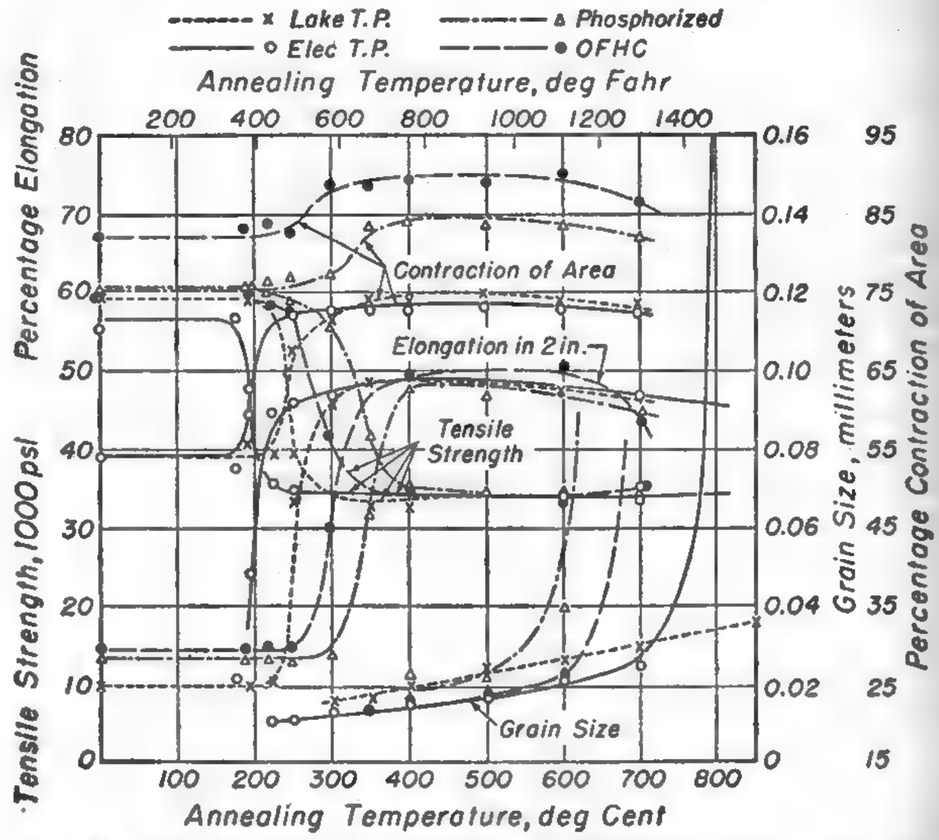

Fig. 2 Effect of annealing on tensile properties and grain size of tough pitch lake, tough pitch electrolytic, phosphorized (0.02% P), and oxygen-free high-conductivity copper. Wires cold drawn to 62.5% reduction in area and annealed one hour (Pratt). Tested at room temperature.

the time of annealing (Fig. 3). Doubling the annealing time lowers the softening temperature by approximately 10 C. The temperature of rapid softening is also decreased by an increasing degree of cold work (Fig. 4).

These curves of softening do not distinguish with absolute certainty the three processes described above. Of the three processes, recovery should be considered first, since it is the process which occurs first on heating.

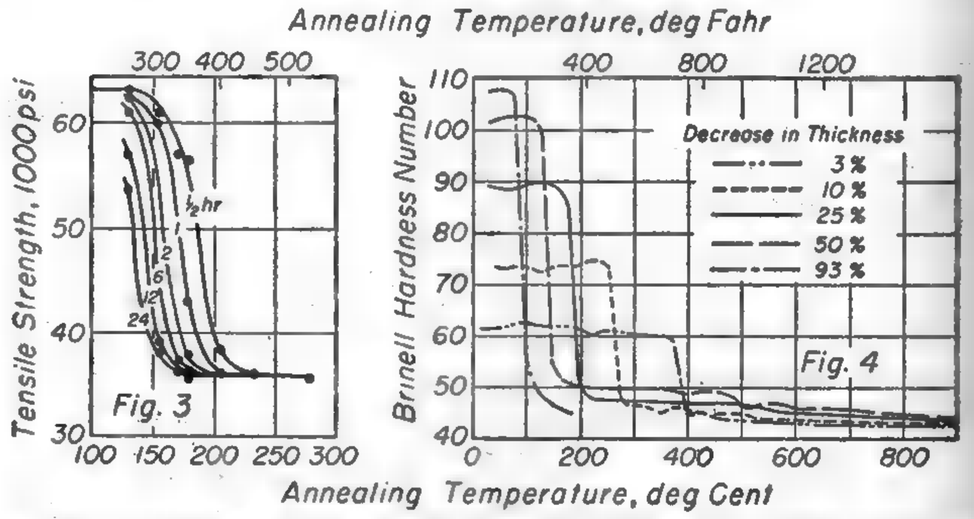

Fig. 3 Influence of annealing time on softening of copper wire, reduced 93% by cold drawing to 0.26-mm diam (Alkins and Cartwright) Tested at room temperature.

Fig. 4 Influence of percentage reduction in thickness on the softening temperature of cold rolled, high-purity copper (Köster). Annealed for one hour at temperatures shown. Tested at room temperature.

Recovery. The elongation of single crystals is characterized by a steadily rising stress-strain curve. If the load is removed and immediately reapplied, the stress continues from the point of interruption. However, if time elapses between release and reapplication of load, or if the piece is slightly heated, the stress begins at a low value; that is, some strain hardening has been lost, though no recrystallization has taken place. This is recovery, sometimes termed "crystal recovery". The process is most striking in single crystals but occurs also in aggregates.

The effect of recovery on several physical and mechanical properties in iron is shown in Fig. 5. The Brinell hardness decreases rapidly upon recrystallization, and only a very slight decrease as a result of recovery occurs before this, but the thermoelectromotive force and the electrical conductivity decrease at much lower temperatures, and the

change in these is complete before there is any detectable change in grain structure, any recrystallization. This behavior, then, illustrates a change which occurs on heating cold worked metals without recrystallization. It will be seen that the properties do not change in a parallel way.

Recovery is especially marked in the relief of residual stresses, as shown by the curve for "spring-back" in Fig. 5. The tendency to season-crack in brass, the magnitude of macroscopic stresses, and the general tendency to crack on treatment are greatly decreased by annealing to induce recovery without recrystallization. Such stresses in cold worked steel can be largely eliminated by annealing at 850 F, at which temperature steel does not recrystallize. Stress relief can be more completely attained by annealing at higher temperatures, and this is the usual commercial practice. (*See* "Relief of Residual Stresses", page 237.)

The process of recovery in metals is doubtless widespread, though experimental studies have not been sufficiently extensive to say when recovery may be separated from recrystallization and when these two processes overlap. If overlapping occurs, recovery cannot be distinguished from recrystallization. In iron, nickel, palladium and platinum, recovery may be readily distinguished from recrystallization, for the changes in properties on heating are not parallel (Fig. 5); but in copper, silver and gold, the properties change more nearly simultaneously during annealing. Whatever may be the underlying cause of these differing behaviors, it is evident that the type of crystal structure is not important, but that the position in the periodic table is.

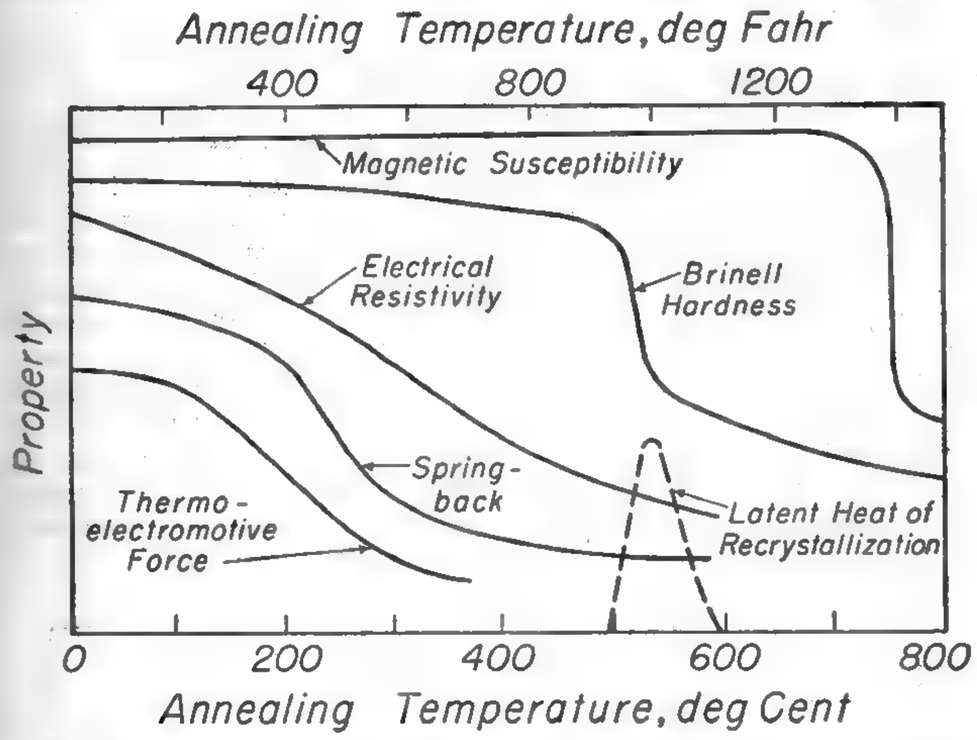

Fig. 5 Recovery and recrystallization in iron. Annealing time one hour; cold rolling 95 to 98%. "Spring-back" is the increase in diameter of a roll of strip after removing from mandrel around which it has been held (adapted from Tammann).

The causes for recovery are not clear. Recovery is doubtless a change in the residual stresses in worked metals, affecting primarily the elastic properties, and also the electrical, magnetic, and miscellaneous properties, like velocity of solution in acids, but having relatively little effect on the properties involving strength and ductility. This reduction in stress may be associated with the straightening of bent slip planes, and perhaps with the healing of microscopic cracks adjacent to points of severe curvature of slip planes; however, it cannot be pictured as a complete relief of stress, but only as a partial relief of some special sort of stress, since a metal which has recovered does not lose its capacity to recrystallize, and in some instances an entirely undiminished capacity for recrystallization has been demonstrated. The reasons for strain hardening in cold working are not well understood, and until the cold worked condition itself can be more adequately described, it is unlikely that recovery and the types of stresses causing recovery and recrystallization can be understood clearly.

Recrystallization. When a cold worked metal is heated to a sufficiently high temperature, or for a sufficiently long time at a somewhat lower temperature, new grains appear and grow, until ultimately a new grain structure has completely replaced the old. This is recrystallization. The changes that accompany recrystallization are in the direction of the restoration of the properties characteristic of the metal before cold deformation, though these properties may not be exactly reproduced, because the final grain size may be different from the initial grain size. The softening temperatures illustrated in Fig. 2, as shown by the rapid increase in elongation and decrease in strength, are temperatures at which recrystallization occurs, and generally such changes in properties can be safely considered as evidence of recrystallization; but when the material has partially recovered before recrystallizing, the changes in strength properties do not sharply define the beginning of recrystallization; and when grain growth after recrystallization is pronounced, the strength properties continue to change after the completion of recrystallization and thus do not sharply define the completion of recrystallization. In such instances microscopic studies are required, in order to define the beginning and the ending of recrystallization, though frequently X-ray diffraction methods are superior.

The complete removal of the effects of cold work and the possibilities of controlling grain size, and thus particularly the behavior of the material toward further working, make recrystallization a process of immense practical importance. Unusually large grains are often highly undesirable, for they lead to an unattractive rough appearance of drawn objects (for example, the familiar "orange peel" effect), and to tears in large worked sections. It is therefore of the greatest importance to know what factors govern the temperatures and times of recrystallization and what factors govern the final grain size.

The process of recrystallization involves continuous formation of nuclei of new crystals and the growth of these nuclei until the system is constituted entirely of the new grain structure. The rate of formation of nuclei and the rate of growth of these nuclei are thus the basic factors determining the rate of recrystallization, and it is necessary to inquire how these may vary with temperature, with time, with initial grain size, with degree of deformation, and with composition and purity.

Recrystallization is thus not an instantaneous process but one with a time dependence. It is, in this sense, similar to the formation of pearlite from austenite, giving rate curves of a completely analogous form. Most recrystallization data, however, have been obtained by employing short and fixed annealing times, as stated above, and thus give no clue to this time dependence.

The new nuclei appear to form at grain boundaries, slip lines, deformation markings of various sorts, and twinning planes, as may be seen in slightly deformed samples, though this is probably also true in heavily deformed samples. Recrystallization can thus be detected most conveniently metallographically, but the sharpening of X-ray diffraction spots and the appearance of new sharp spots has frequently been used as a trustworthy criterion. The mechanical properties are not always trustworthy, as stated above.

Apart from composition and purity, four factors determine the grain size after recrystallization: (1) the amount of cold deformation, (2) the temperature to which the cold worked metal is heated, (3) the time for which the metal is held at this temperature, (4) the original grain size.

Several fundamental laws of recrystallization are now well recognized: (1) Recrystallization occurs at a higher temperature, the smaller the degree of deformation or, more accurately, the smaller the degree of strain hardening. (2) Increasing time of annealing displaces recrystallization to a lower temperature. (3) The final grain size depends chiefly on the degree of deformation and to a lesser extent on the annealing temperature; the final grain size is larger, the smaller the degree of deformation. (4) The larger the original grain size, the greater the amount of cold deformation to give equivalent recrystallization temperatures and times. In addition to these major factors, it should be noted that (*a*) the rate of heating to the recrystallization temperature is a further variable, and (*b*) the amounts of cold work to give equivalent strain hardening vary with the temperature at which deformation is performed.

The first law may be illustrated by a diagram in which the beginning of recrystallization is plotted against an-

nealing temperature for hot worked iron (Fig. 6). Here it may be seen that recrystallization does not occur below 460 C, and that the temperature of beginning of recrystallization increases with decreasing deformation until the A_3 temperature is encountered. This diagram, obtained for deformation at the temperature of recrystallization, differs only in degree from a diagram for deformation at room temperature and recrystallization at the designated temperature; the general form is the same, as indeed it is for all metals and alloys. Therefore, for degrees of deformation and annealing temperature to the left of and below the curve of beginning recrystallization, no recrystallization occurs, no change in the grain structure can be detected; in this range recovery occurs.

The exact position of such a curve will vary with a number of factors: with the type of deformation, with the original grain size, and with purity. Even slight differences in purity have a wholly disproportionate effect. Data on recrystallization are given elsewhere in this Handbook; see, for example, the article on the "Effect of Cold Work on the Properties of Iron", and other articles on the properties of various metals and alloys. It is ordinarily difficult to determine the applicability of published data to a given material, since important variable factors have frequently been disregarded.

When samples are heated which have been deformed to increasing degrees, the grain size developed is especially instructive (Fig. 7). It is seen that a deformation of approximately 7% is required before any change in grain size occurs; this degree of deformation at which grains suddenly grow to a large size, is known as the "critical deformation".

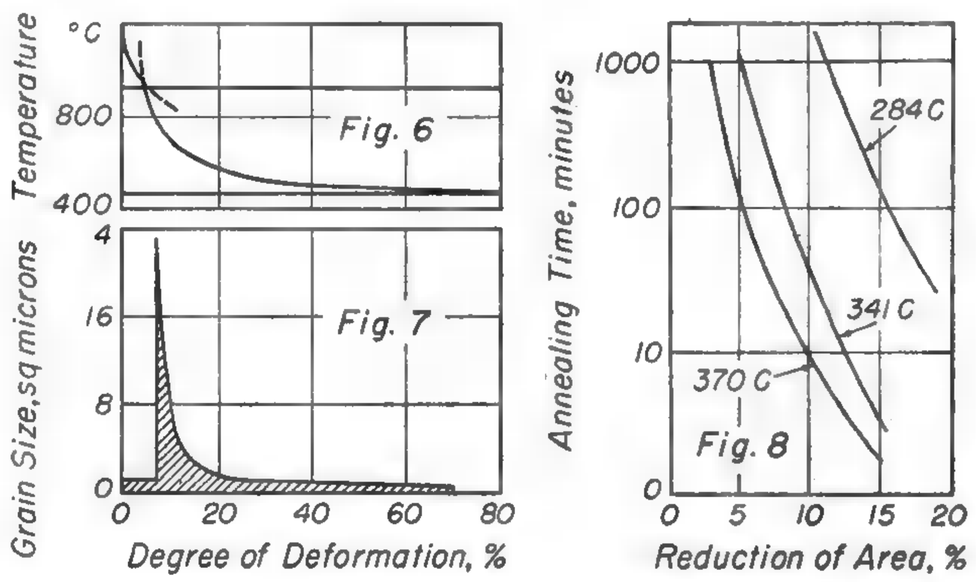

Fig. 6 Influence of temperature and degree of deformation at temperature on curve of initial recrystallization of low-carbon steel (Hanemann).

Fig. 7 Influence of degree of deformation on grain size developed at 950 C in low-carbon steel (Hanemann).

Fig. 8 Influence of degree of deformation and time of annealing upon recrystallization temperature of copper deformed by elongation in tension (adapted from Sachs).

The formation of large grains during recrystallization at the minimum deformation is caused by the occurrence of a minimum of recrystallization nuclei during the time available for recrystallization. At degrees of deformation smaller than this, the number of recrystallization nuclei becomes disappearingly small. With increasing degrees of deformation, an increasing number of points of high stress (high energy) are present, leading to recrystallization from a greater number of nuclei, and finally to a greater number of grains, and thus to a continually smaller grain size. The degree of deformation at which very large grains form, the "critical deformation", will be displaced to lower deformation for increasing times of annealing, because increased time will permit the formation of nuclei in lower ranges of deformation; and it will be displaced to higher deformation for larger original grain size, because, as stated elsewhere, a larger original grain size suffers less strain hardening for an equal degree of deformation and thus provides a lower rate of nucleation and rate of growth on recrystallization.

The influence of degree of deformation on the recrystallization temperature and time is illustrated in Fig. 8. This figure shows that, for a constant annealing temperature, shorter times are required for recrystallization at higher degrees of deformation, and shows also that with increasing temperatures, lower degrees of deformation and shorter times are required for recrystallization. Such generalizations are applicable when the type of deformation is simple, as, for example, increasing amounts of compression; but when several types are superimposed, or when reversed deformation occurs—alternate compression and elongation, bending and unbending—the recrystallization tendency is decreased even though reversed deformation may continue to work harden. The reason is not clear.

The effect of original grain size on recrystallization can be readily understood. The amount of strain hardening which a given amount of compression, elongation, or torsion introduces into a metal increases as the grain size decreases. When, in a given metal at a single temperature, equivalent amounts of strain hardening are introduced, requiring large amounts of deformation for large-grained metals and small amounts of deformation for small-grained metals, the recrystallization behaviors are apparently identical.

The relationships among degree of deformation, annealing temperature, and resultant grain size have frequently been assembled into a three-dimensional chart, of which Fig. 6 and 7 are sections. Such a diagram for iron is given in the article on the "Effect of Cold Work on the Properties of Iron", elsewhere in this Handbook. Charts of this sort are commonly derived from data obtained by using constant (and short) annealing times, and do not show the time variable; furthermore, the factor of original grain size is not represented. A five-dimensional chart would be required to show all these relationships. This limitation of three-dimensional diagrams, the occasionally extreme effects of minor amounts of impurities, and the complications introduced by the complexities of industrial forming processes with resultant complexities in residual stress distribution, render such charts of little direct practical use. They should be used only to indicate the recrystallization behavior of a material in a qualitative way. Such charts frequently show the grain size of the recrystallized metal to be the greater, the higher the temperature of recrystallization; but at least in some cases this effect is associated with grain growth following recrystallization, for since the rate of recrystallization increases very rapidly with increasing temperature, increasing time is left available for grain growth at the higher temperature.

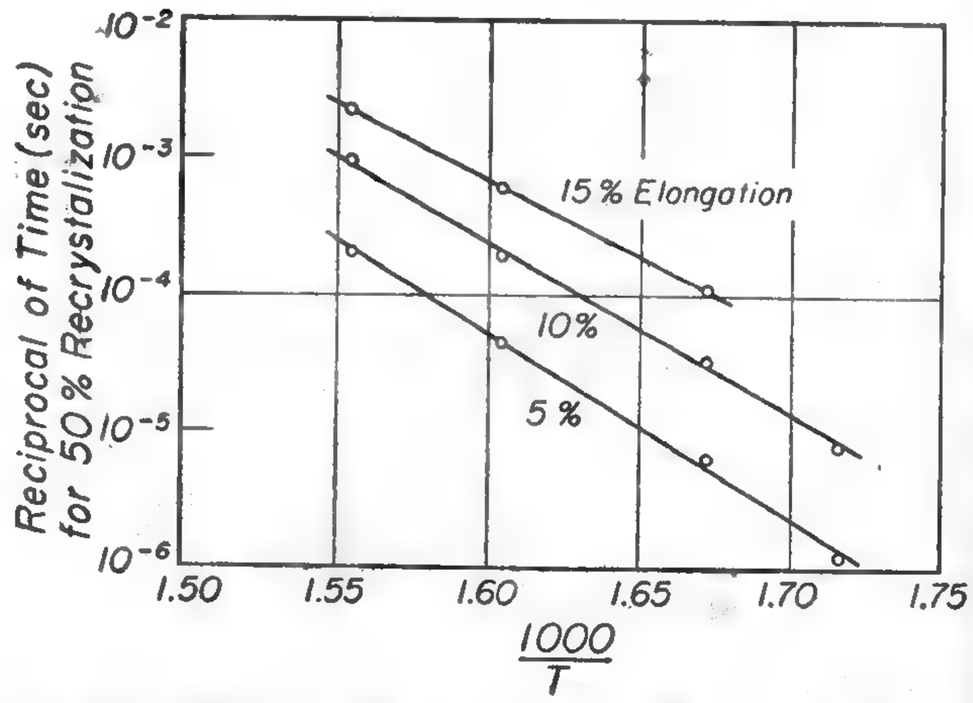

Fig. 9 Plot of reciprocal time for 50% recrystallization versus reciprocal of the absolute temperature for high-purity aluminum for 5, 10, and 15% cold work by tensile elongation. (Compare with reference article by W. A. Anderson and R. F. Mehl.)

The effect of temperature on the rate of recrystallization may be given either in diagrams of the form of Fig. 6, 7 or 8, or may be expressed more fundamentally in terms of rates of nucleation and growth. Whether the times for beginning recrystallization, or half or full recrystallization, or rates of nucleation and growth are employed, it is always observed that the rates vary exponentially with the reciprocal of the absolute temperature; that is, a plot of the logarithm of the rate versus the reciprocal of the abso-

lute temperature is a straight line. The slope of this curve, which is the temperature coefficient of the process, furnishes the "energy of activation of recrystallization". Figure 9 shows a plot of the logarithm of the reciprocal of the time required for 50% recrystallization—thus a measure of the rate of recrystallization—plotted against the reciprocal absolute temperature. This is for high-purity aluminum. The rate is evidently higher with increasing amounts of deformation. This fundamental law is widely applicable. Since time, percentage deformation and original grain size are variables, each determining the occurrence of recrystallization, it is evident that metals do not possess a "recrystallization temperature" of the nature of a physical constant; therefore the term should be avoided.

Recrystallized metals, like cold worked metals, can exhibit preferred orientations and directional properties, though they may not be identical with those which characterized the cold worked metal before recrystallization. Relatively little is known concerning the inheritance of preferred orientations during recrystallization, and no generalizations can be made.

Impurities in solid solution exert a pronounced effect upon recrystallization temperatures. The relatively minor variations in composition in the several varieties of copper represented in Fig. ▮ can be seen to have caused a difference of 100 C in the softening temperatures, and more extreme cases have been noted. Increasing concentrations in solid solution become increasingly less effective until, in a completely isomorphous system, a maximum recrystallization temperature is reached at an intermediate composition, which may be several hundred degrees Centigrade above those of the component metals. It has frequently been stated that impurities which do not form solid solutions have little effect on softening and recrystallization temperatures. This generalization is somewhat doubtful, for at least in the case of aluminum alloys, such impurities are employed to raise the temperatures required for recrystallization, and when present in a sufficiently fine state of subdivision are more powerful in this respect than elements in solid solution.

Grain Growth. Figure ▮ shows softening and recrystallization to have been completed at 400 C, but shows also an increasing grain size on heating beyond this temperature. This phenomenon in an essentially completely recrystallized and strain-free structure is known as grain growth. Presumably there is a tendency for the grain boundary area and thus the internal energy to decrease, or perhaps, as suggested recently, for certain relationships to obtain among the angles formed by the grain facets of maximum stability. Grain growth proceeds by the absorption of grains, usually of smaller by larger grains, and undoubtedly accompanies and overlaps recrystallization, at least to some degree. It is especially noticeable following the recrystallization of severely deformed aggregates, for the grain size after recrystallization in this instance is small and grain growth is readily noted; whereas in samples recrystallized after slight deformation, the grain size is large and the subsequent grain growth is minor. Grain growth continues with time, with the grain size increasing linearly with the logarithm of the time; and the rate of grain growth increases with increasing temperature, as may be inferred from Fig. 2, but the laws are not well known and need systematic study. Slow heating favors the growth of large grains, which under some circumstances may become very large.

Impurities in solid solution have a minor effect on grain growth, but undissolved impurities exert a pronounced effect. In very pure substances, grain growth proceeds steadily, with the average grain size increasing with increasing annealing temperature (Fig. 2.). But if undissolved impurities, such as ThO_2 in tungsten, iron in aluminum, lead in zinc, are present in the proper amount, the grain size is then small at low temperatures and suddenly increases in a narrow temperature range, forming unusually large crystals; when the amounts are larger, grain growth may be entirely obviated. Thus immiscible impurities may be used either to suppress grain growth at relatively low temperatures or to create unusually large grains at higher temperatures.

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The bibliography on recrystallization is extraordinarily voluminous. It is unnecessary to reproduce all of it here. The most complete summary of this subject is the excellent and comprehensive monograph by W. G. Burgers, Rekristallisation Verformter Zustand und Erholung, III, "Handbuch der Metallphysik", lithoprinted by Edwards Brothers, Ann Arbor, Michigan, 1944. An extensive bibliography on the recrystallization of iron and steel has been given by H. F. Kaiser and H. F. Taylor: The Effect of Cold Deformation on the Recrystallization Properties of Armco Iron, Trans ASM, 27, 227 (1939). Recent work may be illustrated by the following papers: W. A. Anderson and R. F. Mehl, Trans AIME, 161, 140 (1945); L. W. Eastwood, R. W. James and R. F. Bell, Trans AIME, 133, 124 (1939); R. S. French, Trans AIME, 156, 195 (1944); D. Harker and E. R. Parker, Trans ASM, 34, 156 (1945); J. K. Stanley, Trans AIME, 162, 116 (1945).

The Martensite Transformation

By A. R. Troiano* and A. B. Greninger*

THE TERM "martensite" was proposed in 1895, by F. Osmond[1] in honor of the German metallurgist A. Martens, and at that time was used to designate the "constituent or structure" found in hardened steel. Later, as it became known that the hardness of quenched steel is a property of a needlelike constituent formed when austenite is allowed to transform at low temperatures, the use of the term was reserved for the constituent itself. During recent years it has been demonstrated that martensite results from a particular type of transformation completely unlike the normal transformation of phases by nucleation and growth. Furthermore, this martensite type of transformation has been found in a number of alloy systems, including nonferrous alloys, and undoubtedly occurs also in pure metals and compounds. The transformation has thus come to be recognized as a basic type of reaction in the solid state, and it is logical that investigators, both in this country and abroad, have adopted as general terms for any alloy, "martensite transformation" and "martensite" to designate the process and product respectively. The matter is therefore no longer confined to the metallurgy of steel.

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It is the intent of this article to describe the known salient characteristics of the martensite transformation and to show how it differs basically from the more familiar process of transformation by nucleation and growth.

Transformation by Nucleation and Growth. It is desirable to review briefly the main facts concerning nucleation and growth. For binary alloys, phase transformations in the solid state are of four types, each associated with a characteristic region of the phase diagram. These four types of transformation are as follows: allotropic, precipitation, eutectoid and peritectoid. All these transformations proceed by (*a*) formation of *nuclei,* and (*b*) subsequent *growth* of these nuclei. They all depend on *time* and *temperature.* If they occur in an alloy, composition changes and diffusion are necessarily a part of the transformation process.

These transformations, especially the eutectoid, are most conveniently studied by allowing the reaction to proceed isothermally at some temperature below the equilibrium level. Under these conditions the reaction-rate curve (percentage transformed versus time) has a characteristic S-shape, although in certain instances the incubation period may be very short. The curves of beginning and end of transformation, plotted on temperature–log time coordinates have equally characteristic C-shapes, as shown

in Fig. 1. In this figure, the reader may note (*a*) that at temperatures just below the equilibrium temperature, the transformation begins only after a long delay; (*b*) that as the reaction temperature is lowered, the isothermal reaction rate increases to a maximum value (corresponding to the "nose" or "knee" of the curve); and (*c*) that

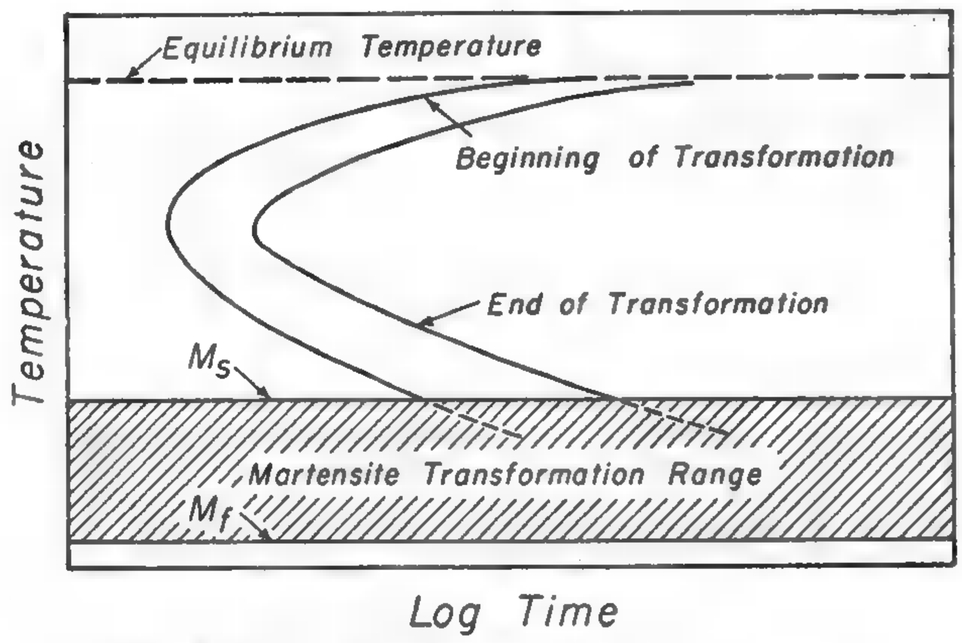

Fig. 1 Schematic representation of simple C-curve and martensite temperature range

for temperatures below the nose, the reaction rate is lower, the lower the temperature, approaching a zero rate at low temperatures, where diffusion for most alloy systems is negligible. It is in this temperature range, below the nose of the C-curve, that in certain alloys the martensite transformation, a diffusionless process, makes its appearance to complicate the simplified picture of the decomposition of a metastable phase.

Whether or not a solid solution, stable at high temperatures, may be retained intact at lower temperatures depends on the minimum incubation time—that is, the time interval at the nose of the C-curve during which no transformation occurs. The slowest cooling velocity (measured at the temperature of the minimum incubation period) that will accomplish this result, is termed the "critical cooling velocity" for the alloy. Actual values of this velocity for different alloys, range from the maximum to the minimum that can be produced experimentally. For example, in a 0.1% C iron-carbon alloy, this velocity is greater than 5000 °C per sec; for eutectoid beta copper-aluminum, approximately 1 °C per min; and for many alloys, furnace cooling will exceed the critical cooling

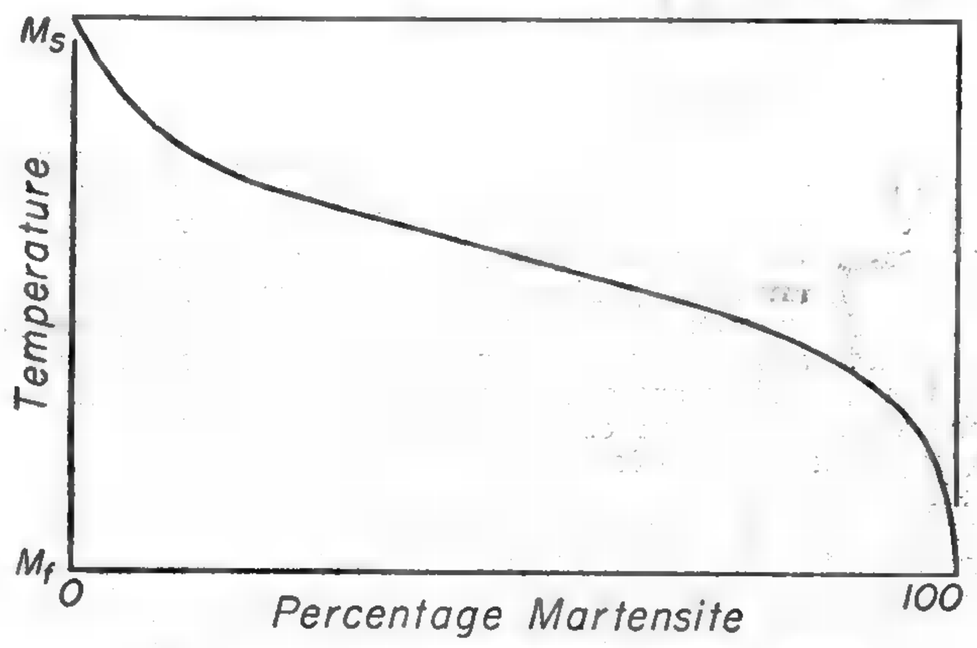

Fig. 2 Schematic representation of percentage of martensite formed as a function of temperature

velocity. For a given alloy, the critical velocity is also sensitive to variations in grain size of the parent phase.

Characteristics of the Martensite Transformation. The behavior of the martensite transformation is in sharp contrast with the diffusion type of transformation described above. The salient characteristics of the martensite transformation are the following:

1 The transformation is diffusionless and involves no change in chemical composition. A large array of evidence supports this fact. Measurements of the lattice constant indicate that the martensite has the same composition as the parent solid solution in both steel[2,3,4] and other alloys.[5,6] There is no nucleation followed by growth; rather, small discrete volumes of the parent solid solution suddenly change crystal structure. The most recent measurements[7] of the speed of formation of martensite have determined the time of formation of a single plate of martensite in an iron-nickel alloy to be approximately 7×10^{-5} sec. Goniometric measurements have shown that the transformation occurs by a process of homogeneous shear.[8] It follows (as shown also by X-rays[8]) that each platelike volume, after transformation, is a single crystal of martensite. All martensite crystals have a typical acicular microstructure. The regularity of the structure depends more on the temperature of formation than on the composition.[9] In general, the lower the temperature of formation, the more perfect is the acicular microstructure.

2 The transformation progresses only while the specimen is cooling; that is, more and more discrete volumes of the parent solid solution suddenly transform. The transformation ceases if the cooling is interrupted.[10,11,12] Thus, the transformation is independent of time[13] and depends for its progress only on the decrease in temperature. The amount of martensite existing at a given temperature in the martensite range is characteristic of the temperature and independent of the time at temperature.

The amount of martensite formed per degree of decrease in temperature is not a constant. The number of martensite needles produced at first is small. As the temperature continues to decrease, this number increases; and finally, near the end, it decreases again.[14,15,45] (Fig. 2)

3 The martensite transformation for a given alloy cannot be suppressed nor can the temperature of its beginning be depressed by the maximum cooling velocity obtainable.[11,12,16,17,18*] In other words, the temperature range of formation of martensite is characteristic of a given alloy and cannot be lowered by increasing the cooling velocity. The thermal arrest associated with the temperature of the beginning of formation of martensite in steel, has been known generally as Ar″. More recently the term M_s has been applied to the temperature of the start of martensite formation; and correspondingly the term M_f indicates the temperature of the finish. Both of these "critical" temperatures are of immediate commercial as well as fundamental importance, especially in steel. The variation of M_s with composition, in both plain carbon and alloy steels, has been the subject of considerable fruitful research in recent years. A few data exist concerning the effect of composition on the M_f temperature;[19,20] more are needed. The influence of composition on M_s and M_f in iron-carbon and copper-aluminum alloys is shown in Fig. 3. The influence of common alloying elements in steel on the M_s temperature is considered in the article on page 611.

4 All recorded martensite transformations have been shown to be reversible below the equilibrium temperature, except those in plain carbon and relatively low-alloy steels. In the steels mentioned above, the speed of the decomposition of the martensite is probably too great to allow an observation of reversibility by ordinary experimental means. However, reversibility has been observed[21] in the martensite of a high-nickel steel in which M_s was below room temperature. Apparently, in this alloy, the nickel content was high enough and the temperature low enough to slow down the decomposition of martensite sufficiently to allow it to go back into the original single crystal of austenite.

Some of the other systems in which reversibility has been definitely observed include the copper-aluminum,[22,23] the copper-zinc,[11,24] the copper-tin,[23] the iron-manganese,[17] and the iron-nickel[25] systems. In these and other systems, a single crystal of the parent solid solution will transform, in part at least, to many regularly oriented crystals of martensite, and during rapid reheating, will transform back again to a single crystal of the same initial orientation. A hysteresis effect is associated with this phenome-

* For a summary of the publications on this subject for steel, the reader may consult reference 16.

non; two examples are epsilon martensite in iron-manganese alloys,[17] and gamma-prime martensite in copper-aluminum alloys.[22]

■ All metastable phases that have M_f appreciably below room temperature, will also produce martensite during deformation at room temperature. This phenomenon is quite consistent with the fact that martensite forms by a process of homogeneous shear. Two well-known alloys in which this behavior is utilized extensively in industry are 18-8 Cr-Ni stainless steel and Hadfield's manganese steel. In addition, certain martensitic structures may themselves be transformed to a different crystal structure by deformation. This has been demonstrated clearly for epsilon martensite in the iron-manganese system,[17] and for beta-prime martensite in the copper-aluminum system.[26] In fact, it is apparently possible in some alloys to form more than one martensite structure directly from the metastable parent solid solution, by deformation.[17,26]

6 Martensite is probably never in a condition of real equilibrium, although many martensitic structures may persist indefinitely at or near room temperature. In general, the structure can be considered as a transition between the unstable phase and the final equilibrium condition. More than one transitional (martensitic) structure may exist at the same time. As illustrated above, it is possible, by deformation, to go from one transitional structure to another. Also, more than one martensitic structure can be formed directly from the parent solid solution and can coexist, as the result of quenching as well as of deformation; for example, iron-manganese alloys that contain approximately 15% Mn will form both alpha martensite and epsilon martensite during quenching.[17]

Examples of martensite crystal structures are the body-centered tetragonal martensite of the iron-carbon and related alloy steel systems,[27] the close-packed hexagonal gamma-prime and pseudohexagonal beta-prime structures of the copper-aluminum system,[26,28] the face-centered tetragonal structure of the copper-zinc[11] and the beta-prime structure of the copper-tin systems.[11,12]

In some instances, such as the gamma-to-alpha martensite in iron-nickel[6] and iron-manganese[17] alloys, the crystal structure is body-centered cubic, the same as the phase in equilibrium at low temperature, but is supersaturated, except for the relatively dilute solid solutions where the alloy has a composition within the homogeneous alpha-phase field.

7 The martensitic structure always has a greater hardness than the parent solid solution from which it is formed. However, extreme hardnesses are associated with martensite only in steel that contains appreciable amounts of carbon. The martensite structures often age harden during tempering. In steel it is possible to increase slightly the hardness of the as-quenched martensite.[29] For Fe-Co-W alloys, the increase in hardness on tempering is most striking.[30]

8 The martensite plates always form parallel to a given crystallographic plane of the parent lattice, and there is always a unique relationship between the lattices of martensite and the parent phase. Rarely does the martensite plate delineate a plane of low indices in the parent lattice. For example, in medium-carbon steels martensite delineates the {4 4 10} planes of the austenite; [31] in copper-tin, the {266} planes of the beta phase;[11] in copper-zinc, the {2 10 10} planes of the beta phase;[11] in copper-aluminum, the {244} and {266} planes of the beta phase.[26] In the copper-zinc system, the martensite plates possess the same orientation regardless of whether they are formed by quenching or by deformation.[11] The orientation habit is independent of the temperature of formation of the martensite for a given alloy; in other words, the martensite plates formed near M_s delineate the same plane of the parent lattice as those formed near M_f.[31]

Stabilization. In certain alloys, particularly alloy steels, the aging of the metastable solid solution (austenite, in steel) will result in a lowering of M_s. In alloy steels, where M_f is near or below room temperature, this effect will manifest itself further in an increase in the amount of austenite retained at room temperature. This phenomenon has come to be known as "stabilization", which may be defined as a lowering of the temperature range of martensite formation (or of a part of that range), resulting from aging, without change in composition of the parent solid solution.*

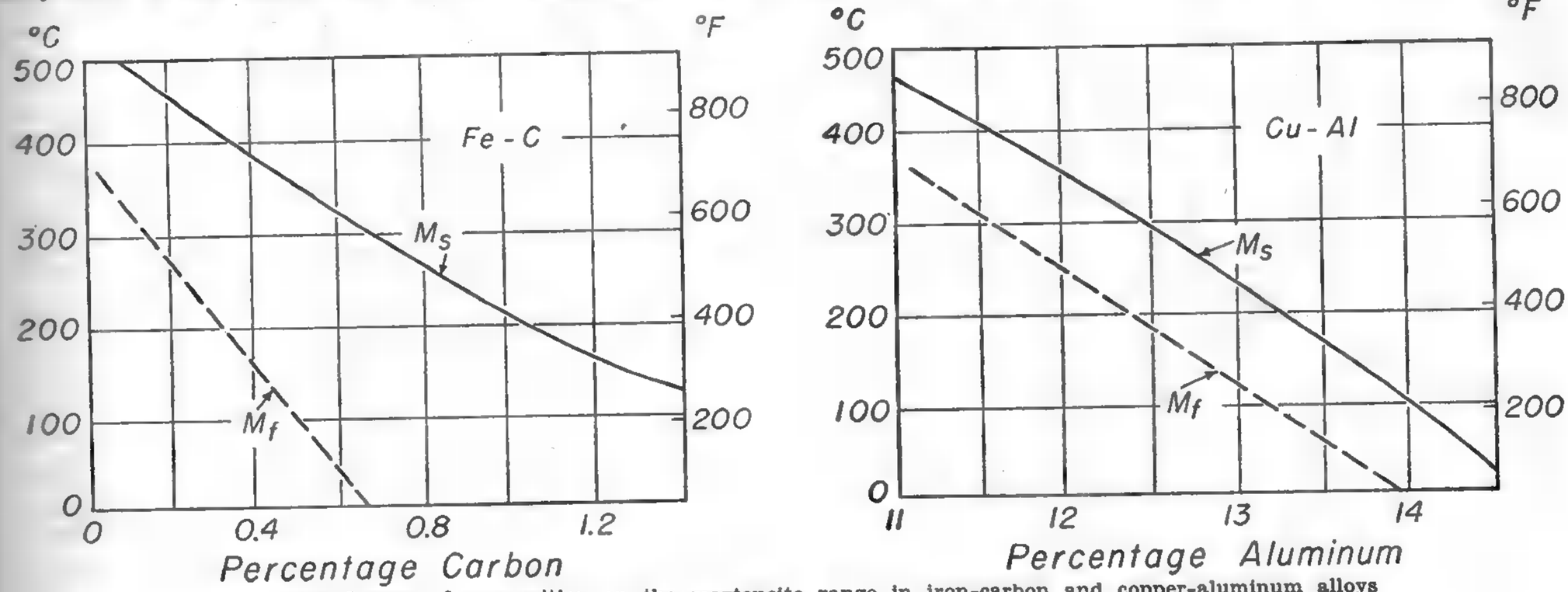

Fig. 3 Influence of composition on the martensite range in iron-carbon and copper-aluminum alloys

In steel, the time and temperature may or may not involve partial transformation of the austenite. Specifically, stabilization of austenite has been observed under the following conditions:

1 After partial transformation to martensite, followed by aging with or without further decomposition of the austenite to bainite, the subsequent formation of martensite during further cooling does not begin immediately, but starts at some lower temperature.[32,33] The amount of lowering is a function of the aging temperature and time.

■ After partial transformation to bainite, the M_s point is lowered.[31,34,35] The amount of lowering depends on the duration of holding at the bainite transformation temperature. In this connection, it is important to note that further aging in alloy steels, after the partial transformation to bainite has ceased, will continue to lower M_s.[36,37]

3 After aging at temperatures in the bainite range, but before any observable decomposition of austenite occurs, the M_s temperature is lowered in certain steels.[9,38] As in the previous citations, the amount of lowering depends on the temperature and duration of aging.

4 In certain systems where reversibility can be observed, such as iron-nickel[39] and copper-zinc alloys,[11] it has been found that heating and cooling several times

* Certain data (for instance, concerning high speed steel[37]) indicate that there is no appreciable effect of stabilization on M_f; while other data indicate that stabilization will lower M_f. For example, 3% Cr ferrite, after stabilizing, will retain gamma at room temperature,[19] yet M_f is well above room temperature.

through the martensite transformation temperature range will result in greater retention of the parent solid solution at any given temperature. This may also be considered evidence of stabilization of the parent solid solution.

There is similarity in the effect of temperature and time in all examples of stabilization. Qualitatively, for a given alloy, long times at low temperatures enhance stabilization. It appears logical to assume that the primary factors influencing stabilization are the temperature and duration of aging, and that the role of any decomposition is fortuitous and at most can exert only a secondary effect.

Martensite Transformation in Single Metals. Martensite transformations have been observed in many systems and they undoubtedly exist in many others where they have not yet been detected or where their presence has not been recognized by the investigator. There is ample reason to believe that even allotropic transformations of pure metals and compounds may occur by the martensite mechanism; for example, hexagonal cobalt can be formed by deformation of face-centered cubic cobalt at room temperature.[40,41,42] In addition, high-temperature X-ray work on cobalt shows (*a*) that the proportion of the cubic and hexagonal phases depends only on the temperature, and not on the time at temperature, and (*b*) that the transformation is reversible (with hysteresis) below the equilibrium temperatures.[43] Another example is hexagonal zirconium, which can be formed by deformation of the metastable body-centered cubic phase at room temperature.[42] The time for transformation of a given discrete volume of beta to alpha zirconium has been measured as approximately 3×10^{-4} sec.[7] In addition, published micrographs of metals that have allotropic modifications (for example, titanium[44]) suggest the existence of a martensite transformation.

In discussing the effects of combined shear and high hydrostatic pressure on phase transformations, Bridgeman states:[46] "It is also probable that there are certain reversible transitions which occur only under shearing stress, and will not occur at all with pure hydrostatic pressure; lithium is a probable example of one of these." It is further stated in this article that under conditions of constant, continuously applied shearing force the flow is sometimes interrupted by "snapping". Recently a low-temperature transformation has been found in lithium.[47] Normally body-centered cubic lithium, plastically deformed near minus 196 C, will partially transform to a face-centered cubic modification. The transformation is accompanied by audible clicks and exhibits reversibility with hysteresis.

It is apparent from the above discussion that the martensite type of transformation is an important mode of transformation in the solid state. Despite the relatively large amount of reliable data concerning this transformation, its characteristics and general ubiquity are not fully appreciated.

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INDUSTRIAL HEATING

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Fuels and Fuel-Heated Industrial Furnaces

By M. H. Mawhinney*

THIS section is a discussion of fuel-heated furnaces that operate at temperatures up to about 2400 F, and the fuels that are used in such furnaces. The classification includes furnaces for heat treating and for heating for rolling and forming operations, but does not include furnaces for the melting of metals.

Principles of Combustion. The combustion of fuel—solid, liquid or gaseous—consists of the rapid oxidation of the combustible portion to produce heat. The heat energy theoretically available depends on the net calorific value of the combustible content, and the temperature produced (theoretical flame temperature) depends on the gaseous products of combustion, which must be heated by this available energy. When the combustible elements (usually carbon and hydrogen) are combined with the theoretically correct amount of air, the resulting products of combustion are confined to carbon dioxide, water vapor and nitrogen (from the air). Any oxygen in the flue gases serves as a measure of the fuel-air mixture on the lean side (excess air), and carbon monoxide in the flue gases indicates the richness (excess fuel) of the mixture.

Fuels are usually sold on the basis of the "higher heating value" in Btu per unit of volume or weight, which is the gross chemical energy in the fuel. The "lower heating value" is the net useful Btu available after subtracting the heat which is necessary to convert the water in the flue gases to steam.

For most fuels (except producer gas and blast furnace gas) the amount of air required for combustion is about 1 cu ft for each 100 Btu of lower heating value. Table I shows the physical characteristics of the principal fuels used in heating furnaces.

Fuels for Heating Furnaces. Where metallurgical requirements are rigid, the most suitable fuels are clean gases and light fuel oil. The gaseous fuels are the most satisfactory for control of temperature and for maintenance of proper atmosphere in the furnace, but almost equal results are obtainable with light fuel oil, if care is used in furnace design and in supervision of operation.

For rougher forms of heating (forging, forming and rolling) solid fuels, heavy fuel oil and dirty gases may be used, although the specifications in this class of heating

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Table I. Properties of Fuels[a]

Fuel	Average Chemical Composition by Weight for Solids and Liquids; by Volume for Gases — S	H_2	C	N_2	O_2	CH_4	C_2H_6	CO	CO_2	Ash	C_6H_6	Lower Heating Value, Btu per unit of fuel[b]	Density, lb per unit (standard conditions)	Cold Combustion Air, cu ft per unit (perfect combustion)	Cold Flue Gases, cu ft per unit	Density of Flue Gases, lb per cu ft	Ultimate CO_2 in Flue Gases, per cent
Lignite	0.9	6.8	41.3	0.7	40.7	...	...	...	...	9.6	...	7,189	40	71	82	0.0760	16.1
Sub-bituminous coal	0.6	5.9	60.1	1.0	27.0	...	...	...	...	5.4	...	10,557	to	103	112	0.0782	17.0
Bituminous coal	0.6	5.2	78.0	1.3	11.5	...	...	...	...	3.4	...	14,134	50	137	143	0.0790	17.4
Semibituminous coal	0.5	4.8	84.6	1.0	5.1	...	...	...	...	4.0	...	14,669	lb/cu ft	148	153	0.0795	17.5
Cannel coal	1.0	6.8	73.3	1.3	8.3	...	...	...	...	9.3	...	14,251	piled	139	146	0.0782	16.0
Fuel oil, 24 Bé	..	13.0	83.7	2.0	1.3	...	...	...	...	..	...	140,000	7.55	1410	1505	0.0760	13.4
Coal tar	0.8	6.0	86.7	0.1	3.0	...	H_2O is 3.3		...	0.1	...	150,000	9.49	1500	1560	0.0785	16.7
Natural gas (Ohio)	..	...	...	5.0	..	80.3	14.7	...	...	..	...	970	0.0491	10.11	11.19	0.0730	12.1
Coke-oven gas	..	53.0	...	12.1	..	28.1	...	6.0	0.8	..	...	425	0.0288	4.08	4.79	0.0708	11.1
Blast furnace gas	..	...	...	65.0	0.1	...	...	27.8	7.1	..	...	90	0.0767	0.66	1.52	0.0830	23.8
Raw producer gas (bituminous)	..	12.5	...	56.5	..	3.0	...	20.5	7.5	..	...	138	0.0674	1.07	1.91	0.0780	19.0
Clean producer gas (bituminous)	..	13.5	...	54.8	..	3.0	...	19.0	9.7	..	...	128	0.0677	1.06	1.90	0.0780	...
Coal gas	..	47.0	...	2.3	..	34.0	...	9.0	1.1	..	6.6	569	0.0313	5.51	6.23	0.0715	10.7
Blue water gas[c]	..	52.9	...	4.7	..	2.2	...	36.8	...	(c)	...	287	0.0342	2.35	2.87	0.0740	22.3
Carbureted water gas	..	35.2	...	1.8	..	14.8	...	33.9	1.5	..	12.8	535	0.0454	4.88	5.54	0.0750	17.2
Oil gas[c]	..	58.4	...	3.8	..	28.8	...	4.4	1.2	(c)	...	440	0.0226	4.23	4.88	0.0705	10.7
Butane gas	..	...	...	...	C_4H_{10} is 93.0;		C_2H_6 is 7.0		...	..	...	2,977	0.1480	30.47	32.93	0.0755	14.0
Propane gas	..	...	...	...	C_3H_8 is 100.0		...	...	...	..	...	2,371	0.1162	23.82	25.99	0.0750	13.7
Raw producer gas (anthracite)	..	16.6	...	50.0	..	0.8	...	27.1	5.0	..	0.1	142	0.0654	1.12	1.90	0.0775	19.5
Raw producer gas (coke)	..	9.3	...	55.4	..	0.7	...	31.0	3.6	..	...	132	0.0680	1.03	1.85	0.0778	...

(a) Reprinted from "Practical Industrial Furnace Design", by M. H. Mawhinney, with permission of John Wiley & Sons, Inc.

(b) Units are for lb for coals, gal for oil and tar, and cu ft for gases.

(c) 3.4% illuminants

are becoming more exacting, so that considerable care and supervision are needed to meet the requirements when the fuels used are unsuited to steady automatic control.

Solid Fuels. In the United States almost all the solid fuel used in heating furnaces is bituminous coal. This fuel may be hand-fired, stoker-fired, or fired in powdered form. Both stokers and powdered coal can be automatically controlled to maintain a satisfactory temperature in a furnace for heating steel in preparation for any forming operation. The principal objections to the use of stokers and powdered coal are the ash content that is carried into the furnace and the labor required for handling the coal and the ashes produced. For metallurgical furnaces, coal in any form should always be fired with forced draft from a fan, in order to maintain proper control over the furnace atmosphere and pressure.

Liquid Fuels. The principal liquid fuels for heating furnaces are oil, coal tar and pitch (topped coal tar). Properties of these and other fuels are given in Table I.

Industrial fuel oils may be conveniently divided into two classes, light fuel oil (No. 3) and heavier oils. The lighter grades of industrial fuel oils are recommended for all types of heat treating furnaces at temperatures below 1700 F (quenching, tempering, normalizing and annealing) and for any other furnaces where individual burners are required to burn less than 10 gal of oil per hr. The heavier oils can be used where the consumption is more than 10 gal per hr per burner in furnaces heated to temperatures higher than about 1700 F (for forging, rolling and so on).

In general, light fuel oils can be used without any preheating, except in the storage tank, but heavy oils require additional preheating to reduce viscosity (resistance to flow) below about 200 Saybolt-Universal seconds (about 200 F for Bunker C).

By-product tar is in approximately the same classification as the heaviest fuel oils, and requires considerable preheating. Pitch, which results after approximately 15% of the lighter oils have been distilled from by-product tar, is exceedingly heavy and very difficult to use satisfactorily in any heating furnace. It is ordinarily used in the open hearth furnaces for steel melting, where temperatures and rates of firing are high, and is preheated to about 350 F.

A recent development in fuels is the so-called colloidal fuel, made by mixing finely powdered coal with heavy fuel oil. A mixture containing 40% by wt of coal will weigh about 10 lb per gal and have a heating value of about 170,000 Btu per gal. The handling of this fuel is similar to that of heavy fuel oil, except that corrosive action, power required for pumping, and clogging of burners are somewhat increased by the coal content.

Dirty Gases. This classification includes blast furnace gas, coke-oven gas, and hot producer gas made from either bituminous or anthracite coal.

Blast furnace gas is not used alone as an industrial furnace fuel, but is sometimes mixed with coke-oven gas to produce a useful fuel (about 250 minimum Btu per cu ft of mixture for annealing and 350 Btu for heating billets). The supply of gas from the blast furnace is not steady; another disadvantage is that large pipes are required for its transportation. It contains considerable moisture and much dust; ordinary wet cleaning leaves 0.25 grains of dust per cu ft of gas and cyclone cleaning leaves 0.10 grains. Delivery pressure of this gas from the blast furnace is between 2 and 6 in. of water pressure.

Coke-oven gas is widely used in the steel mills for all types of heating, in spite of its dust and tar content. It is delivered from the coke ovens at a uniform rate and at a pressure of about 2 to 3 psi. The sulfur content is 500 to 550 grains per 100 cu ft, which is objectionable in some cases. The tar content seriously interferes with the use of devices for automatic control of furnaces.

Producer gas made from bituminous coal is exceedingly dirty and is used only in soaking pits and large heating furnaces in modern plants. Large brick-lined mains are required, which must be burned out regularly (about once a week) to remove the accumulation of tar and soot. Hot gas made from anthracite coal is entirely different, containing dry dust in considerable quantity, but no tar or soot. About 50% of the original sulfur content of the coal is removed in the ashes from the gas producer, but approximately 60 to 80 grains of sulfur remain per 100 cu ft of hot producer gas made from either bituminous or anthracite coal.

Clean Gases. This group includes natural gas, artificial gases made from coal or oil, liquefied petroleum gases and clean anthracite producer gas.

All these fuels can be controlled accurately and are ideal for heat treating furnaces at all temperatures, for operations requiring close regulation of temperature and furnace atmosphere. With the exception of clean anthracite gas (30 grains of sulfur per 100 cu ft) all these fuels have a sulfur content of less than 15 grains per 100 cu ft of gas.

The liquefied petroleum gases are shipped and stored in liquid form under relatively high pressure. Butane and propane are the common industrial fuels in this group. The gas may be withdrawn from the top of the container or liquid may be withdrawn and vaporized by controlled heat. The gases are handled and burned in the same manner as the other clean fuel gases, except that since butane requires 30.47 and propane, 23.82 volumes of air per volume of gas burned, high-pressure injector burners are not suitable, unless the gases are first mixed with air. Such a mixture is usually preferable to straight gas for distribution in a plant, because utilization is more efficient and condensation in the mains is reduced by mixture with air.

Methods of Applying Heat. Methods of heating furnaces by combustible fuels include:

1 *Recirculation.* A recirculating system is used for lower temperatures (usually lower than 1300 F) where gas or oil is burned in a separate chamber and the resulting products of combustion, together with air, are circulated vigorously in the furnace by a fan; or where circulating fans are arranged below the arch of a direct-fired furnace with suitable alloy baffles to provide circulation around the metal.

2 *Indirect Firing.* Indirect firing is used extensively for temperatures up to 1900 F, where combustion chambers are located below the heating chamber (underfired), beside (sidefired) or above (overfired), and are separated from the heating chamber by suitable baffles.

3 *Direct Firing.* Direct firing is almost always used for temperatures higher than 1900 F, with the burners firing directly into the heating chamber, usually above the charge. When the clean gaseous fuels are used, direct

Table II. Burner Systems for Heating Furnaces

Fuel	Designation	Approximate Pressure per sq in. Fuel	Air	Comments
Oil and tar	Steam atomizing	10 to 40 lb	½ to 4 oz	Steam at 60 lb min
	Low-pressure	10 to 40 lb	8 to 16 oz	40 to 50% induced air
Hot producer gas	Mixing type	2 in. water	4 oz to 5 lb	Scrapers or steam jets for cleaning tar and soot
Blast furnace gas	Proportioning	3 oz	8 to 16 oz	Automatic air-gas mixing
Clean gases	Blast type or nozzle mixing	4 to 8 oz	3 to 16 oz	Separate air and gas control
	Luminous or radiant	3 to 8 oz	3 to 8 oz	Separate air and gas control
	Low-pressure proportioning	3 oz	8 to 16 oz	Air inspirates gas at zero pressures
	High-pressure	10 to 25 lb	Atmosphere	Gas injects combustion air
	Complete premix	4 to 8 oz	Atmosphere	Mixture is supplied to burner from premix blower

firing is often employed for temperatures lower than 1900 F and as low as 1000 F with satisfactory results.

4 *Full Muffles and Retorts.* Either full muffles or retorts of metal, surrounding the heating material and heated from the outside, are employed to permit the use of a protective atmosphere around the charge while it is being heated. The words "muffle" and "retort" are frequently confused in furnace engineering. Generally, a muffle is defined as a permanent container within the furnace, into which work is introduced for heating; while a retort is a container loaded outside the furnace and then charged into the furnace or covered by a bell-type furnace.

■ *Radiant Tubes.* Radiant tubes of alloy or refractory, with combustion inside the tubes, are used in conjunction with tightly sealed furnace casing and openings in order that protective gas may be introduced into the furnace around the heating material. This arrangement of fuel-heated furnace competes directly with electric furnaces employing resistor elements.

6 *Cup Burners.* Patterned combustion, employing special cup-shaped burners of high-temperature radiant design, sometimes replaces large furnaces in special heating processes and competes with electric induction heating.

Burner System for Heating Furnaces. The various types of burners commonly used are given in Table II.

Muffles. Carbofrax muffles are used for high-temperature annealing of stainless steel in an atmosphere of air; but where a protective atmosphere is used at lower temperatures, as in the bright annealing of metals, a tight muffle or retort of heat-resisting alloy is usually employed. The construction and maintenance of such muffles in any size is seriously complicated by warpage from uneven expansion and contraction.

The use of a muffle decreases the heating capacity of a furnace about 20%, as compared with an open-fired furnace, and the fuel consumption is increased by the necessity of higher temperatures outside the muffle, with consequently higher losses by radiation.

Pot Furnaces. Pot furnaces are frequently used for heat treating. Although costly and troublesome because of the necessity for pot replacement and because of losses of liquid heating medium, pot furnaces have the advantages of ability to heat steel without oxidation of the charge, to heat rapidly and uniformly and, if desirable, to treat only a portion of the work piece, without affecting the remainder. Heat treating salts and lead are commonly used as the heating mediums.

Pot furnaces are being heated to an increasing extent by electric induction current; electrodes are immersed in the salt. In this arrangement the heat is not forced through the walls of the pot, as in fuel-heated pots; therefore the life of the pot is greatly increased. At high temperatures the pot can be eliminated and the salt can be held directly within the brick lining of the furnace chamber.

Material Handling in Furnaces. The selection of the best method for conveying material through furnaces involves difficult problems. The rules listed below should always be followed:

1 The method of conveying material must not interfere with the heating characteristics of the furnace.
2 The advantage of simplicity of design of hot conveyers should not be overlooked in a desire to save labor.
3 In the selection of means for conveying, those which will damage the material under consideration must be eliminated. There must be no scratching, damage to threaded parts, sagging or denting of coils and tubular products.

The various furnaces for industrial heating include:

Batch. The batch types include stationary hearth, solid bottom; stationary hearth, roller bottom; car bottom; bell type, round or rectangular; and pit type.

Semicontinuous. These include stationary hearth or car-bottom furnaces in conjunction with handling forks or peels or special cranes to reduce the interval between charges to a few seconds or minutes, so that virtually continuous operation is obtained from a series of batch-type furnaces.

Continuous. These include pushers, direct or on pans or shoes; tunnel kiln with cars; chain conveyer or moving fingers; mesh belts; slat conveyers; walking beam; roller hearth; rotating hearth; rotating retort; strand or strip furnaces; and miscellaneous special types.

Furnace Materials. For estimating comparative operating costs of different designs of fuel-heated furnaces, it is safe to assume that firebrick linings will last for 5 yr at temperatures below 1900 F and for 1 yr above 2000 F. This does not apply to doorjambs, piers, and bridgewalls, which will require additional patching. The life of metal parts that are properly designed for stress and for usual furnace conditions will be approximately as follows:

Working Temp, deg Fahr	Cast Iron	Heat-Resisting Alloys
Below 1400	5 yr	....
1700	1 yr	3 yr
1800	5 mo	2 yr
1900	1 mo	1½ yr
2000	not used	6 mo

The nickel and chromium contents of certain heat-resisting alloys commonly used in furnace parts include:

Furnace Temp Below 1400 F		Furnace Temp Above 1400 F	
Nickel, %	Chromium, %	Nickel, %	Chromium, %
25	20	68	18
18	8	60	12
8	18	38	18
..	28	35	15
..	18	30	10
		12	28
		11	25

Remainder, iron

All doors and other openings in furnaces should be surrounded by iron castings protected from the heat by refractories. The doors are usually iron castings lined with brick or plastic insulation and should be counterweighted. In small sizes the doors may be operated by hand. Large doors should be operated by motor, air pressure, or oil-hydraulic pressure cylinders.

Flues are provided in a fuel-heated furnace to permit the escape of the products of combustion of the fuel. The size of these openings should be such that they can be adjusted to maintain a slight pressure (about 0.010 in. water) in the furnace to exclude air. Required flue area varies with the rate of firing, temperature, arrangement and location of flues. The best plan is to provide ample flue area and damper regulation to permit control of the furnace pressure under all conditions. Flue areas may be determined with the aid of the following table:

Table III. Flue Areas, in Square Inches per Unit of Fuel Burned per Hour

Fuel and Unit	Furnace Temperature, deg Fahr 1000	2000
Bituminous coal, lb	1.47	2.01
Fuel oil, gal	14.20	19.40
Butane or propane, cu ft	0.30	0.41
Natural gas, cu ft	0.11	0.15
Coke-oven gas, cu ft	0.05	0.06
Artificial gas, cu ft	0.06	0.08
Raw producer gas, cu ft	0.02	0.02

The use of stacks with heating furnaces has been almost entirely discontinued, because modern burners do not require stack draft and because the usual failure to control the stack draft by proper damper operation, results in large quantities of excess air in the furnace at low fuel rates.

Determination of Furnace Size.* The size of furnace required depends on the amount of material to be heated per hour, the heating time required, the size of the pieces to be heated, and the amount of heat that can be liberated without excessive damage to the furnace. The efficiency and refractory life obtained depend on the correctness of the furnace size.

The heating time in the furnace depends on the nature of the heating process. For thorough heating only, the time may be estimated from such rules as 5 min for each ⅛ in. of thickness of flat plates of steel (heated from one side) and 20 min per in. of diam for round steel bars. These rules apply when the furnace temperature is above 1400 F. At 800 F, without forced circulation, the time is

* From Combustion Furnace Section, by M. H. Mawhinney, "Marks' Mechanical Engineers' Handbook", 3rd Ed, McGraw-Hill Book Co.

increased about 100%, and below 800 F it may require as much as three times as long to heat thoroughly as it does above 1400 F. The time required for heating varies also with the material to be heated. Brass requires about one half as long as steel to heat, and copper requires 40% as long. The above rules represent the time in which the material will conduct heat to its interior; they can be misleading in that they do not express the ability of the furnace brickwork to transmit the necessary heat. The rules also assume that the material is fully exposed to the heat of the furnace. Piling of material in a furnace lengthens the heating to an extent that cannot be estimated numerically, but must be determined by actual trial. Besides simple thorough heating, additional time is frequently required for holding at temperature.

The weight of material in the furnace at any time is the product of the weight of material discharged per hour, multiplied by the heating time in hours. When the weight and sizes of pieces involved are known, the area required in the furnace can then be fixed. The width and length of the furnace to produce this hearth area are determined by the method of firing to be used and the method of manipulating the material.

The life of a furnace at a given temperature and the size required in some applications depend on the rate of heating, which may be expressed in pounds per square foot of hearth area per hour. The maximum rate allowable for heating steel is about 40 lb per sq ft per hr for heat treating furnaces and about 80 lb per sq ft per hr for furnaces used for heating steel for rolling or forming. These are upper limits which should not be exceeded if satisfactory life is to be obtained from the refractories. These rates are for the heating of mild steel, and may be about twice as great for heating brass, 2½ times as great for copper, and only 0.7 as great for certain alloy steels with low conductivity. These maximum allowable rates should be used for checking the calculation of furnace size from physical dimensions and heating time, because material cannot be heated properly at higher rates.

Example of Calculation. If a furnace is required to heat 20 pieces per hr, weighing 30 lb each and requiring a heating time of ½ hr, the furnace must be large enough to hold ½ × 20 = 10 pieces. If each piece requires a hearth area of 2 sq ft, the area of the hearth will be 2 × 10 = 20 sq ft for a single layer of pieces in the furnace. If the furnace is of the batch type, a size of 4 ft wide by 5 ft deep would probably be about right for convenient handling. Checking the rate of heating, 20 pieces per hr × 30 lb ÷ 20 sq ft = 30 lb per sq ft per hr. For this rate an underfired furnace would be satisfactory, but with direct heating a smaller furnace could be used, if the pieces could be more densely piled without interfering with satisfactory heating.

The allowable rate of heating, expressed in lb per sq ft of hearth area per hr, varies with the temperature. At lower temperatures of about 1000 F, the usual rate in a directly heated furnace is about 25 lb per sq ft per hr, compared with the allowable rate of 40 lb given above for heat treating at 1500 to 1600 F. When forced circulation is utilized, this rate may be increased to equal the rate at higher temperatures in either fuel-heated or electric furnaces. At heat treating temperatures of 1500 to 1600 F or higher, forced circulation will not increase the rate of heating sufficiently to be worth while, because the amount of heat transferred by convection at these temperatures is relatively small.

Economy of Furnaces. The heat input to a heating furnace is distributed in various ways, depending on the type of furnace. Ordinarily, the heat balance includes useful heat to the material; heat to conveyer, shoes or pans; radiation and absorption by the furnace lining; radiation through openings; sensible heat in waste flue gases; and heat in unburned fuel in fuel-heated furnaces. Miscellaneous additional items include heat to water-cooled parts, radiation from cars of car-bottom furnaces while charging, or conduction from metal parts extending out of the furnace.*

* The methods of calculating these various losses may be found in "Industrial Heating Furnaces", by W. Trinks, and "Practical Industrial Furnace Design", by M. H. Mawhinney, both published by John Wiley & Sons, Inc.

It is customary to line electric furnaces with a greater quantity of insulation than is used in fuel-heated furnaces, on account of the higher cost of electric current per unit of heat. However, because of the absence of waste gases in electric furnaces, this smaller amount of radiation appears in the heat balance as a greater percentage of the heat input.

Table IV gives the average fuel economies for typical heating furnaces, expressed in Btu per pound of material heated in fuel-heated furnaces, and in kilowatt hours per ton for electric furnaces. The values given represent good operation at efficient rates of production, and are for operation without recuperators or other heat-saving devices. To estimate the fuel consumption, divide the economy given in Btu per pound by the lower heating value of the fuel under consideration (from Table I). The values of Table IV are typical figures and will vary for different furnaces.

Table IV. Fuel Economies for Heating Furnaces

Operation	Average Temperature, deg Fahr	Average Economy Good Operation Fuel, Btu/lb	Electric, kwhr/ton
Tempering, Batch type	1000	700	120
Chain conveyer	1000	500	110
Hardening, annealing, normalizing	1500 to 1700	...	...
Batch type	....	1250	300
Rotary hearth	....	850	210
Pusher, direct	....	900	225
Pusher, pans	....	1400	340
Chain conveyer	....	1000	245
Car type	....	1200	290
Roller hearth, sheet steel	....	850	...
Box anneal, sheets	....	1300	...
Carburizing in boxes	1650	...	...
Batch type	....	1500 (a)	400 (a)
Pusher, straight	....	1200 (a)	325 (a)
Pusher, counterflow recuperative	....	750 (a)	150 (a)
Enameling			
Batch, sanitary 3 coats	1750	2150	...
Continuous, flatware	1500 to 1650	...	...
Ground coat	....	2500	320
Finish coat	....	1750	220
Lead pots	1500	1500	225
Heating for forming	1900	...	...
Batch	....	1750	...
Continuous pusher	....	1600	...
Plate reheating	....	1800	...
Forging	2200	...	...
Batch	....	2800	500
Continuous pusher	....	1400	...
Rotary hearth	....	1600	...
Wire patenting	1850	1500	...
Heating for rolling	2400	...	...
Batch, 4 to 6 doors	....	1800	...
Continuous pusher	....	900	...
Soaking pits for hot ingots	2400	600	...
Copper billet heating	1700	500	...
Annealing brass and copper	1000 to 1200	...	...
Pan-type batch	....	400	...
Continuous, pans	....	350	110
Continuous chain	....	350	110
Continuous, counterflow	....	160	50
Heat treating aluminum			
Continuous forging	880	...	140
Pit type, 21-hr heating	960	...	265
Car type	975	...	200

(a) Economies for carburizing furnaces are fuel per gross weight, including boxes and compounds. The values will vary with the depth of case required.

Furnace Atmospheres. Atmosphere in a fuel-heated furnace may be the products of combustion of the fuel; in an electric, muffle or radiant-tube furnace, it may be a special protective atmosphere surrounding the work.

Atmosphere in Fuel-Heated Furnaces. In general, it has been found that scaling or oxidizing gases in a furnace atmosphere are carbon dioxide, water vapor, and oxygen (resulting from an excess of combustion air or infiltration from the outside), while reducing constituents are carbon monoxide, hydrogen and unburned hydrocarbons from the fuel. The scaling action of the atmosphere for any temperature and for any duration of contact depends on the relative amounts of these two types of gases in the atmosphere of the furnace. The so-called neutral atmosphere, where the theoretically correct quantity of air is introduced with the fuel, resulting in the complete absence of oxygen or carbon monoxide in the atmosphere, is in reality a scaling atmosphere, because the proportions of carbon

dioxide and water vapor are high. To reduce the scaling of carbon steel to 50% of that resulting with this atmosphere requires an excess of fuel necessary to produce about 2% CO in the flue gases at 1700 F and about 14% CO at 2300 F. To eliminate scaling in a combustion furnace is practically impossible. Sulfur in the fuel also increases the amount of scaling of steel.

Besides causing scaling, the atmosphere of a fuel-heated furnace will also frequently decarburize steel. Moist hydrogen and water vapor are principally responsible, with carbon dioxide and infiltrated air contributing to this result. Where decarburization of steel is to be avoided as much as possible, an oxidizing atmosphere is usually the best, with about 3% O_2 in the flue gas. The reasons for this are that all hydrogen is converted to water vapor in this atmosphere (eliminating the moist hydrogen combination) and that the additional scale formed on the steel not only inhibits decarburization but removes a part of the decarburized skin when scale is removed from the steel after heating.

The conditions which reduce scaling and decarburization, in their probable order of importance include: (1) minimum temperature in the furnace, (2) minimum time in the furnace, (3) positive furnace pressure, to exclude free air, (4) low hydrogen content in fuel burned, (5) air-fuel ratio slightly oxidizing.

Factors 4 and 5 must necessarily be considered together, because the nature of the different industrial fuels is so variable. The best fuel for heating steel is that which contains a minimum of hydrogen and at the same time can be accurately controlled. Table I shows that coal is very low in contained hydrogen; but coal in most forms (hand-fired, powdered, or in raw producer gas) is difficult to control, particularly at low and intermediate temperatures, so that the desired ratio of air to fuel cannot be consistently maintained. Washed producer gas from anthracite coal and coke satisfies both requirements. Coke-oven gas is high in hydrogen and contains large amounts of objectionable sulfur which, together with some difficulty in control, makes it an undesirable fuel in its usual form. Artificial gases, natural gas and liquefied petroleum gases are relatively high in hydrogen, but this disadvantage is largely offset by their accuracy of combustion control. Light fuel oil is relatively low in hydrogen and is a very desirable fuel, if care is taken in the control of combustion.

Heating in Protective Gas. The heating of steel while it is surrounded by a protective gas atmosphere is a highly important development in furnace design. This is accomplished in electric furnaces with sealed outer shells, alloy muffle or retort furnaces, or furnaces heated by radiating tubes instead of electric elements.

Protective furnace atmospheres are discussed in the article on page 294, where the principles involved in the preparation and purification of atmospheres are described.

Automatic Control of Furnaces. Automatic control of furnaces involves control of temperature, fuel-air ratio, and furnace pressure.

Automatic temperature control comprises a thermocouple or other measuring device at the furnace, a controlling pyrometer operated by the thermocouple, and a fuel valve operated by the pyrometer. The pyrometer may be indicating only or recording, and may be arranged for two-position (high-low) operation or for proportioning (multi-position) control, if it is desirable to eliminate the fluctuation between maximum and minimum control temperature, which is characteristic of two-position control. There are many different types of controlling instruments from which to choose and the accuracy of these instruments is being constantly improved by the application of electronic and other new principles to their operation.

The methods of fuel and air control commonly used for fuel-heated furnaces include:

1 Manual adjustment of fuel and air valves for high and low settings with two-pipe burner systems, using oil or gas fuel, and having two-position control.
2 Proportioning valves depending on constant air and fuel pressure and a constant ratio of air and fuel orifices at all settings. These are used with two-pipe burner systems, oil or gas fuel, and with either two-position or proportioning controllers.
3 High-pressure gas burners or injectors, where the gas injects a constant ratio of air for combustion. A control valve is required for gas only; the system can be used with any type controller.
4 Low-pressure proportioning systems for gas, which is reduced to zero pressure and automatically inspirated at constant ratio by the air flow. A control valve for air only is required and all types of controllers can be used.

Table V. Comparison of Fuels

Fuel and Unit of Measure	Furnace Temp, deg Fahr	Net Btu per Unit	Cost per Unit Prepared or Delivered, cents	Units Equiv to One Kwhr	Cost Equiv to One Kwhr, cents	Cost per Million Btu As Delivered, cents	Cost per Million Btu Left in Furnace after Flue Gas Losses, cents
Electricity	all	3415	1.0	1.0	1.0	293	293
Bituminous coal, lb	1000	14000	0.25	0.294	0.074	18	27
	1500	....	...	0.338	0.085	...	25
	2000	....	...	0.397	0.100	...	30
Fuel oil, gal	1000	140000	5.0	0.029	0.145	36	44
	1500	....	...	0.034	0.170	...	50
	2000	....	...	0.040	0.200	...	60
Natural gas, cu ft	1000	1020	0.04	4.03	0.161	40	48
	1500	....	...	4.63	0.185	...	56
	2000	....	...	5.45	0.218	...	66
Artificial gas, cu ft	1000	475	0.08	8.65	0.692	168	202
	1500	....	...	9.96	0.798	...	234
	2000	....	...	11.70	0.935	...	276
Butane, cu ft	1000	3020	0.19	1.38	0.262	64	77
	1500	....	...	1.59	0.302	...	89
	2000	....	...	1.87	0.355	...	105
Propane, cu ft	1000	2371	0.15	1.72	0.258	63	76
	1500	....	...	2.01	0.301	...	88
	2000	....	...	2.37	0.355	...	103
Coke-oven gas, cu ft	1000	510	0.01	8.06	0.081	20	24
	1500	....	...	9.26	0.093	...	28
	2000	....	...	10.90	0.109	...	33
Producer gas bituminous, cu ft	1000	150	0.003	30.3	0.091	20	26
	1500	....	...	37.3	0.112	...	33
	2000	....	...	46.9	0.141	...	41
Producer gas anthracite, cu ft	1000	140	0.007	32.4	0.227	46	61
	1500	....	...	39.9	0.279	...	75
	2000	....	...	50.2	0.351	...	94
Blast furnace gas, cu ft	1000	90	0.0023	57.0	0.131	26	40
	1500	....	...	79.4	0.183	...	54
	2000	....	...	126.5	0.290	...	87

5 Cross-connected control, in which air pressure in the air line beyond the control valve is transmitted to a governor in the fuel line (gas or oil fuel) to regulate the fuel in constant proportion to the air. An air valve only is required and may be actuated by any type of control.
6 Balancing systems, in which a change in flow of air or fuel through an orifice causes a change in pressure drop, which is transmitted by one of many devices to the valve controlling the other medium (fuel or air) to bring the pressure drop into balance. One control valve is required with any type of controller.
7 Premixing of fuel (gas) and air in a compressor, with proportioned air and gas valves in the suction inlet. By this arrangement, an air-gas mixture is transmitted through all manifolds, and the control valve controls the mixture.

Automatic control of pressure involves the control of a flue damper to maintain a constant pressure in the furnace at all times, in spite of fuel rate variation, door operation or other changes. Equipment is available for this purpose, which operates on a number of different principles to accomplish the same result.

Control of furnace temperature is discussed more fully in the article on page 174.

Comparative Costs of Fuels. In comparing the costs of furnace operation, the major items for consideration are fuel, furnace efficiency, charges on the investment, labor and maintenance.

The last four items depend largely on the construction of the furnace, the type of conveyer or other mechanism used for handling, and the type of combustion equipment employed. An accurate comparison of fuel cost must include a consideration of the percentage of heat lost in the flue gases. For example, all the heat liberated in an electric furnace at all temperatures goes to heating the metals, the furnace lining, radiation through openings, and such losses. In contrast, a fuel-heated furnace involves an additional loss in the flue gases leaving the furnace. Table V gives the amounts of different fuels which equal 1 kwhr of electric heat at different temperatures, after correcting for flue gas losses. The comparative cost is also shown in the table, based on assumed fuel costs which are given. The Btu equivalent of 1 kwhr used in this table is 3415.

The figures in Table V afford a comparison of the cost of heating with various fuels, assuming perfect combustion and the same furnace construction in all instances. In actual practice, more insulation is generally used on electric furnaces because of the relatively high Btu cost of electricity, so that in many instances the relative cost of electricity as compared with other fuels is slightly less than is indicated by the table.

The cost of fuels is a guide in their selection, but should never be used alone to determine the best fuel for any given conditions. The relative convenience and cost of preparation should be carefully studied. Of even more importance is the kind of heating possible with various fuels, including accuracy of control and nature of surface obtainable. The fundamental purpose of a furnace is to heat a given material properly, and frequently the savings from the use of a cheap fuel are quickly lost in the cost of material spoiled by improper heating. The nature of subsequent operations, such as cleaning and machining, the probable percentage of rejections in finished work, and the continuity of service obtainable with the different fuels must all be taken into account, if fuel costs are to be compared accurately.

Fuel to Heat Cold Furnace. It is often desirable to know the approximate quantity of fuel required to heat a furnace from cold to operating temperature. This may be calculated from the data in Table VI. These values are based on the usual practice of firing hard at the start and cutting down on the fuel rate as the furnace comes up to temperature. The values vary somewhat with furnace design.

The following illustrates the use of Table VI for calculating the quantity of fuel oil required to heat a firebrick furnace having 1000 sq ft of interior area, from cold to 1500 F in 4 hr.

$$\frac{4 \text{ hr} \times 6800 \times 1000 \text{ sq ft}}{140{,}000 \text{ Btu per gal}} = 194 \text{ gal oil}$$

Furnaces lined with the so-called "light refractories" which are made to combine a part of the advantages of both firebrick and insulating bricks, will heat in about one half the time required for firebrick, with the same rate of heat input.

Table VI. Rate of Heat Liberation (Btu fired per sq ft of interior per hr) Required to Heat Firebrick-Lined Furnace to Temperature in Given Time

Hours to Final Temperature Ready for Operation	Operating Temperature, deg Fahr		
	1000	1500	2000
2	6000	12000	....
4	4200	6800	13500
6	3300	5100	8000
8	2700	4300	6000
10	2200	3800	5200
12	1800	3300	4800
14	1600	3000	4500

Operation of Gas and Oil Burners. There are several fundamental facts that are important to remember when lighting furnaces equipped with oil or gas burners. For all fuel-heated furnaces, observe the following rules:

1 Open all doors before lighting the furnace.
2 Always purge the furnace by means of air from the blower before lighting, making sure that all fuel valves to the furnace are closed during this purging cycle.
3 When lighting oil burners or gas burners of the blast type (two pipe), turn the air on first, then the fuel.
4 When lighting gas burners of the proportional-mixing, low-pressure type, always open the gas supply valve wide; all regulation of fuel is by the air flow and the ratio-adjusting screw on the mixer.
5 When shutting off an oil burner or a gas burner of any type, always shut off the fuel first.

Because of rapid ignition of most gaseous fuels, there is generally little difficulty in keeping gas burners lighted. However, care must be taken when lighting oil burners. When the finely divided atomized oil strikes cold surfaces in the furnace, condensation takes place and separated carbon, burning with insufficient air, causes dense smoke. Small quantities of oil should be burned with excess air, until the burner block becomes red hot, in order to assist in vaporization of the oil and to maintain ignition. A baffle in the form of a steel bar inserted from the outside and projecting in front of the burner will assist in lighting most oil burners, because it keeps the velocity of the atomized oil below that of ignition, and affords the mixture an opportunity to light before passing through the furnace chamber.

When lighting a furnace that has several burners, it is best to light properly one or two at a time, rather than to attempt to light all burners at once. The reason is that unburned combustion gases constitute an effective fire extinguisher, and several improperly adjusted burners will interfere with the lighting of the others.

A newly constructed furnace should be slowly dried out with gradually increasing temperature to avoid spalling and cracking. This process should take two or three days, while the moisture in the brick and clay is slowly converted to steam and released without damage to the brick structure. When a large furnace is to be heated to 2000 F, a good schedule of drying is as follows: 10 hr below 500 F; 11 hr below 1000 F; 8 hr below 1500 F; and 8 hr below 2000 F, giving a total time of 34 hr.

After the furnace has been heated to the required temperature and the doors have been closed, the total flue area should be partially closed until a pressure of about 0.01 in. water exists in all parts of the furnace. Temperature uniformity may be partially controlled by closing the proper flues when regulating to the proper pressure. In general, the flues at the hotter portions of the furnace should be closed to force more gas and heat toward flues left open in the colder portions of the furnace.

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Electrically Heated Industrial Furnaces

By R. M. Cherry* and William Adam, Jr.*

ELECTRIC FURNACES may be classified according to the medium in which the work material is heated, or according to the design of the heating chamber, of the electrical arrangements, and of the method of moving the work material into, through and out of the furnace. In the metal industries the heating medium is usually a gas or a liquid salt, either of which may be heated by the resistance of a conductor ("heating unit") through which an electric current is passing. Liquid salt frequently is heated by an electrode that is immersed in the bath.

Resistance Furnaces. The resistance furnace consists essentially of a heating chamber containing heating units that may be mounted on the furnace walls, roof, floor or door, depending on the application; means for controlling the amount of heat; means for supporting the work pieces in the furnace, or conveying them through the furnace; an inside lining of insulating refractory backed by suitable heat insulation; and frequently a cooling chamber and protective atmosphere.

The heat is transmitted to the work by radiation and convection; the higher the temperature, the greater the amount of radiant heat.

Resistance furnaces are used for annealing, normalizing, hardening, tempering, carburizing, nitriding, brazing,

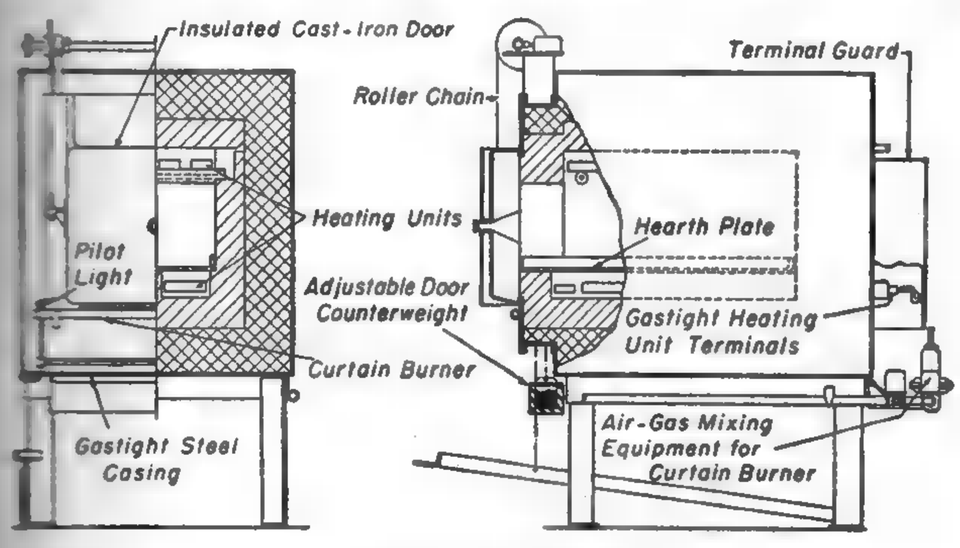

Fig. 1 Typical box furnace

porcelain enameling, hot dip galvanizing, sintering and other treatments.

Heating Units. The heating units are made of metal in ribbon, rod or cast form, or of a nonmetallic material such as silicon carbide, usually in the form of a round bar.

Nickel-chromium and nickel-chromium-iron alloys are used for the heating units of furnaces that operate at temperatures up to 2100 F, with or without protective atmosphere. For temperatures up to 2500 F, the silicon carbide

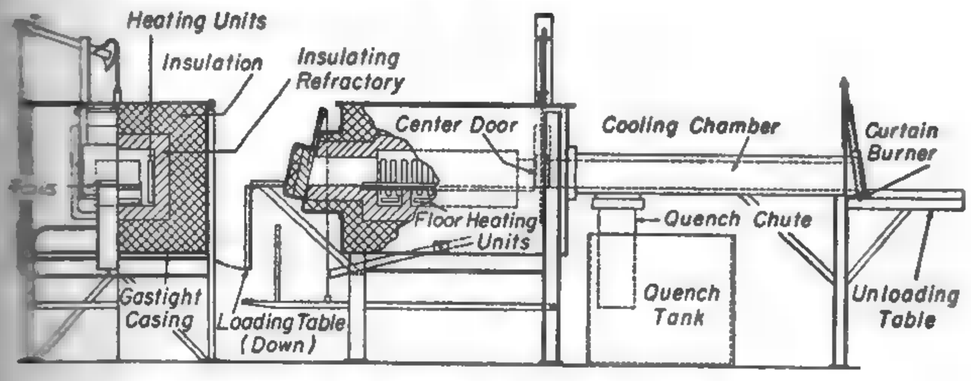

Fig. 2 Typical box furnace with a cooling chamber

heating unit may be used with or without a protective atmosphere.

Pure molybdenum is suitable material for units where a protective atmosphere is used and where operating temperatures above 2100 F are required. Large production furnaces are made for temperatures up to 2500 F, and small laboratory furnaces for temperatures up to 3000 F.

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Most resistance furnaces are used at temperatures below 2100 F, and the nickel-chromium and nickel-chromium-iron alloys are used for the heating units.

The design of these metallic heating units is important since it involves supporting, placing and spacing the heating units, and also the thickness of material to be used for these units and the amount of heat to be dissipated per unit area. The life of these heating units is determined largely by the thickness and by the maximum temperature of the heating unit at its hottest point. The maximum temperature at any point on the unit, for a given furnace temperature, will depend on the amount of heat dissipated per unit area (watts per square inch of heater surface), the shape and spacing of the heating unit, and the muffling effect of the supports used. The less the supports for the heating unit interfere with radiation and convection, the lower the temperature of the heating unit at points of support.

The nickel-chromium and nickel-chromium-iron alloys depend on a coating of oxide as protection against further oxidation. Therefore the heating unit must be thick enough so that the oxide coating that is formed, will be thin in comparison with the thickness of the unit.

The allowable heat density, or watts per square inch, will depend on the operating temperature and on whether or not forced convection is used.

Types of Furnaces. There are many standard types of furnaces. The differences depend largely on requirements for charging metal into the furnace and discharging.

The selection of the size and type of furnace for a given application, depends primarily on the particular heating process involved, the expected rate of production, and the most efficient means of moving the given parts to,

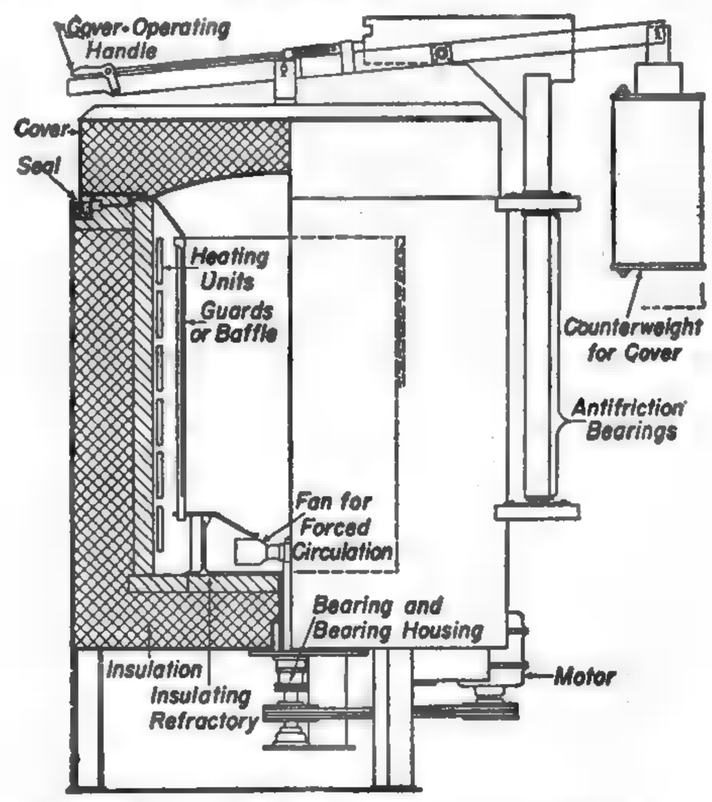

Fig. 3 Typical cylindrical pit furnace with a fan

through, and from the furnace. Some of the common types of furnaces are discussed below.

Box Furnace (Fig. 1 and 2). This type has a heating chamber in the shape of a box, a door at one or both ends, and a hearth for supporting the work pieces. The furnace may be provided with a cooling chamber and with a fan for heating by forced convection. The parts to be treated are charged and discharged manually, either individually or in containers.

Box furnaces are used principally in the hardening of carbon and alloy steels, in the preheating and hardening of high speed steel, and in annealing, normalizing, pack carburizing, porcelain enameling, brazing and tempering.

Pit Furnace (Fig. 3). This type of furnace may be either circular or rectangular with the opening in the top and with an insulated cover. The furnace may be equipped with a fan at top or bottom for circulating the atmosphere

or for heating by forced convection, and may have a retort.

The work may be supported on a load platform in the bottom of the furnace, or may be suspended from the top of the furnace or loaded in containers.

Pit furnaces are used chiefly for the hardening, tempering, annealing, normalizing and gas carburizing of steel, and the heating of aluminum and magnesium alloys.

Car Furnace (*Fig. 4*). The car furnace is essentially a large box furnace with the bottom and hearth mounted on wheels so that the car can be withdrawn for loading and unloading.

Car furnaces are used chiefly for the annealing and tempering of alloy steel bar stock, tubes and forgings; the annealing of steel castings; the annealing and aging of iron castings; the stress relieving of welded structures;

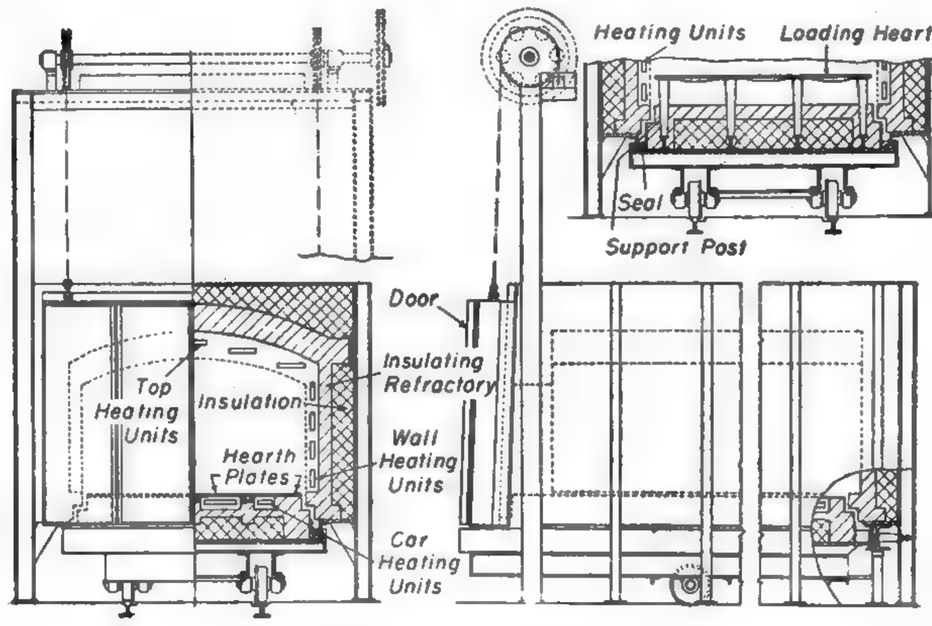

Fig. 4 Typical car furnace

and for nitriding with fan circulation in a retort mounted on the car.

Bell Furnace (*Fig. 5*). The bell furnace may be either circular or rectangular and may be provided with a fan for heating by forced convection.

The material to be heated is loaded on bases and the heating chamber of the furnace is raised and moved from base to base; or the furnace may be lifted and the bases moved. This furnace may be used with or without an inner retort, depending on the application. When an inner retort is used, three or more bases are ordinarily required to provide for heating, cooling and loading or unloading.

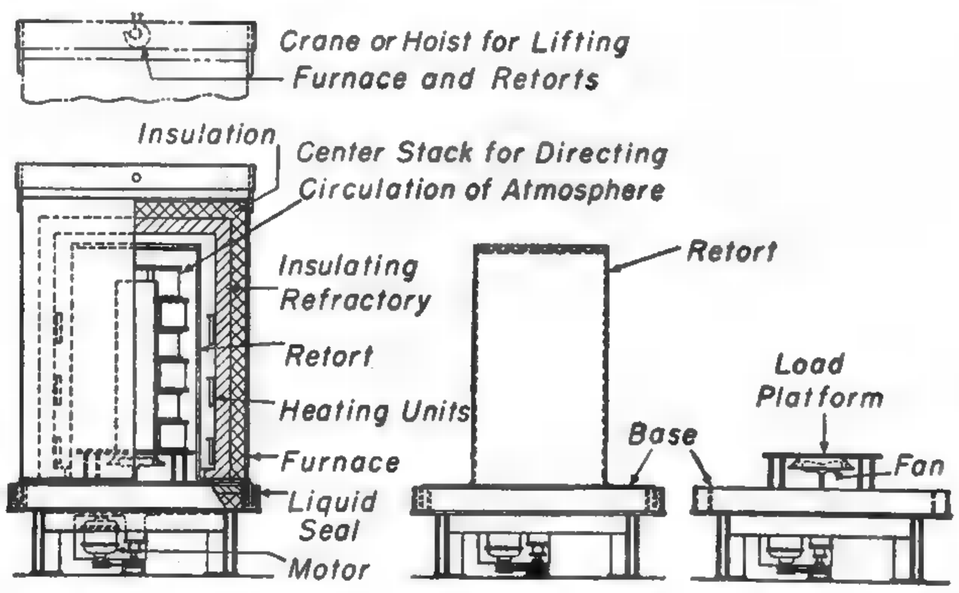

Fig. 5 Typical cylindrical bell furnace

Bell furnaces are used for the annealing of steel strip in coils, steel wire in coils, copper and brass wire and strip in coils or on spools, and miscellaneous parts loaded in baskets. These furnaces are used also for nitriding. The larger rectangular bell furnaces are used for the annealing of sheets and alloy bar stock.

Elevator Furnace (*Fig. 6*). The elevator furnace is usually rectangular but may be circular and may be provided with a fan or fans for heating by forced convection. The parts are loaded on a car, which is then elevated into the heating chamber. Where the headroom permits, the design allows a loaded car to pass under the furnace when a car is in the furnace, thereby saving the amount of floor space required for switching cars. Also, two or more furnaces may be located over the same car tracks.

Elevator furnaces are used principally for the annealing of steel castings, malleable iron castings, cast iron, steel

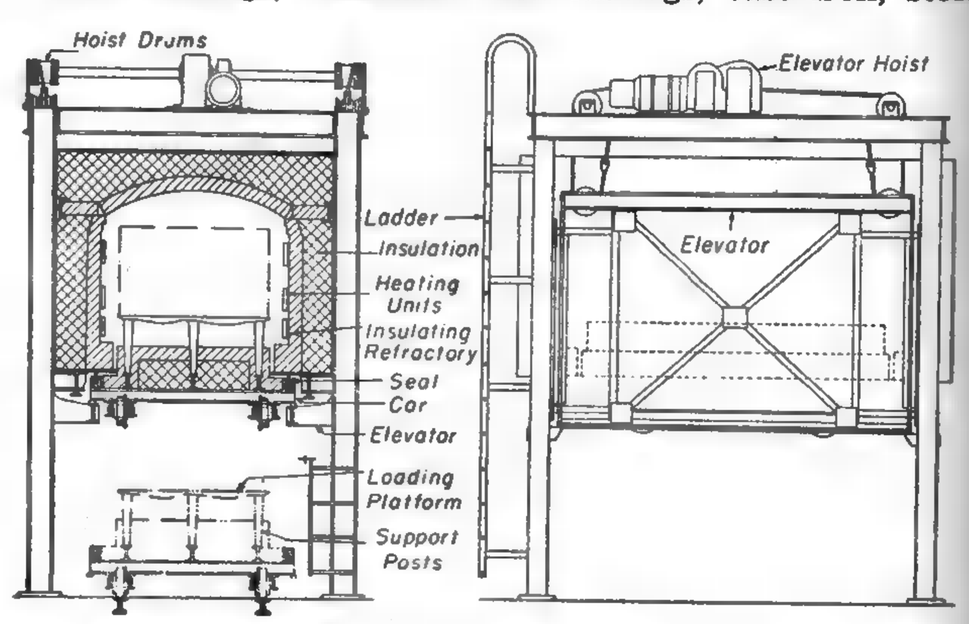

Fig. 6 Typical elevator furnace as used for annealing

bar stock, steel tubes, steel sheets and flat punchings; for the heat treating of aluminum alloys and magnesium alloys; and for pack carburizing.

When used for the heat treating of aluminum alloys, the elevator furnace is located over a tank employed for quenching parts in water. The parts to be treated are suspended from a loading rack, and the rack and charge are elevated into the heating chamber. When the work has been heated and the charge is ready to be quenched, the bottom door is moved quickly to one side and the charge is lowered rapidly into the quench tank. With this arrangement the shortest possible interval elapses between the

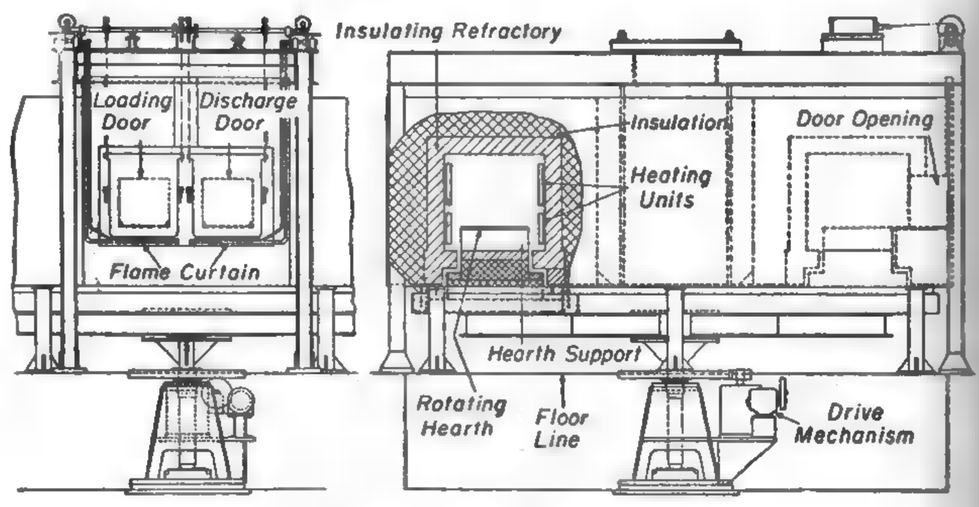

Fig. 7 Typical rotary hearth furnace

time when the work leaves the heating chamber and the time when it enters the quenching medium.

Rotary Hearth Furnace (*Fig. 7*). This type of furnace has a hearth in the shape of a doughnut; the hearth is rotated and sand or liquid steels, or both, are provided between the rotating table and the stationary part of the furnace. In small furnaces the rotating hearth may be supported from a central point and rotated within the heating chamber.

The parts are charged and discharged at one central place through the same door or adjacent doors. The furnace may have fans for heating by forced convection.

Rotary hearth furnaces are particularly suitable for heating parts that are to be handled individually. Typical applications are the heating of gears, shells, cylinders, and other parts that are fixture-quenched or individually han-

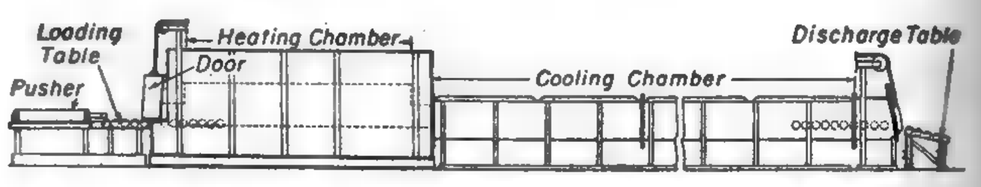

Fig. 8 Typical pusher furnace with heating and cooling chambers

ded; the heating of smaller parts loaded in lightweight trays; pack carburizing; and the heating of aluminum alloys for forging.

Pusher Furnace (*Fig. 8*). The work is pushed through this type of the furnace, one piece against another, where the parts are of such shape and size as to permit handling in this manner; or the parts are loaded on trays or stools that are pushed through the furnace, from one predetermined position to another. The furnace may be provided with a cooling chamber.

Pusher furnaces are used for the hardening and tempering of parts that may be pushed one against another—shells, cylinders, pins and the like. Other applications in-

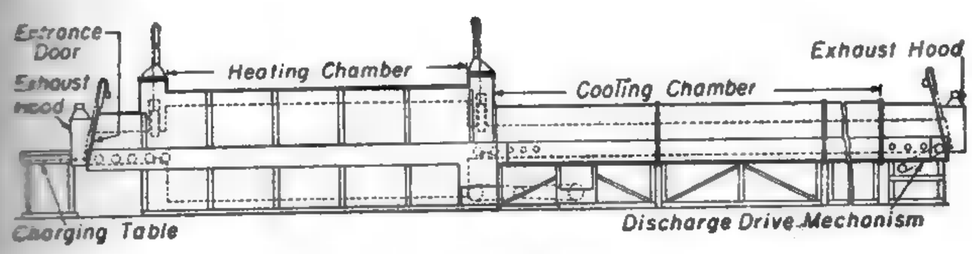

Fig. 9 Typical roller hearth furnace, with heating and cooling chambers, as used for bright annealing and furnace brazing.

clude the annealing of castings and forgings and pack carburizing, where the parts are loaded in trays.

Roller Hearth Furnace (*Fig. 9*). In this type of continuous furnace, the conveyer consists of driven rolls made of heat-resistant alloy. The ends of the rolls extend through the walls of the furnace to suitable bearings and are driven through sprockets and chain.

The parts to be heated are either loaded directly on the roll table (for tubes, bars, large sprockets and the like) or loaded in trays or on rails.

The charging and discharging, the transfer of the work rapidly from one section of the furnace to another, and the return of the trays to the front of the furnace, may all be done automatically.

The furnace may be provided with a cooling chamber, quenching tank, or fans for heating by forced convection, all depending on the application.

The roller hearth furnace is a high-production continuous furnace that is inexpensive to operate and maintain.

This furnace is widely used for: furnace brazing; bright annealing of ferrous and nonferrous products, such as tubes, stampings, drawn parts, and strip; normalizing, annealing, hardening and tempering of steel bar stock; annealing of malleable iron castings, small steel and iron castings and forgings; annealing and solution heat treating of aluminum alloy bar stock and structural shapes;

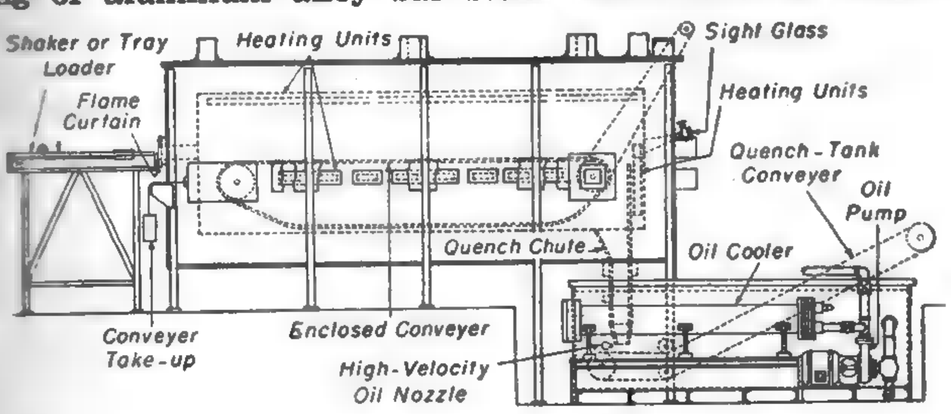

Fig. 10 Typical belt conveyer furnace for hardening

sintering of pressed parts made of metal powder; hardening and tempering of miscellaneous steel parts that are loaded directly on the roll table or on trays.

Belt Conveyer Furnace for Hardening (*Fig. 10*). This furnace has a conveyer, usually made of an assembly of cast alloy links. The furnace is used for the hardening of steel parts that may be dumped from the conveyer into the quenching tank. A discharge chute is provided for connection between furnace and quenching medium.

The furnace is usually equipped with a loading mechanism (shaker or tray loader) but parts may be loaded by hand. A suitable quenching tank is also part of the equipment.

Belt conveyer furnaces are widely used for the hardening of such parts as bolts, screw-machine products, bearing races, business-machine parts, small gears and forgings.

Shaker Hearth Furnace (*Fig. 11*). This furnace is of the continuous type for hardening small parts made of carbon and alloy steels. The parts are loaded on the hearth at the front of the furnace and are conveyed along the hearth by means of its reciprocating shaker motion, until they fall

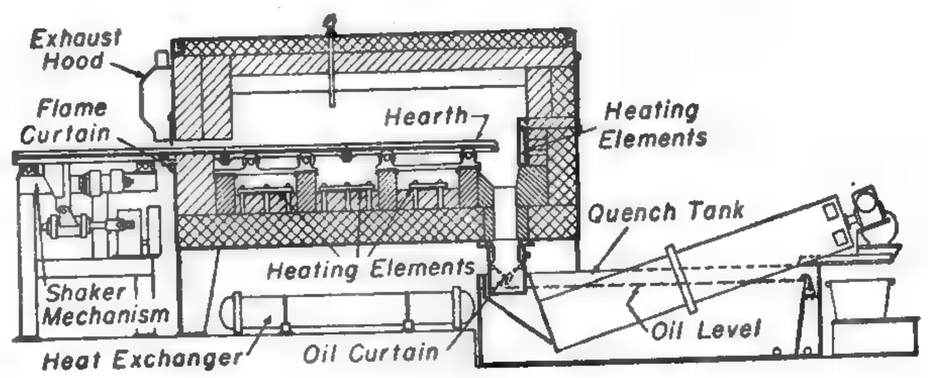

Fig. 11 Shaker hearth furnace

off the discharge end of the hearth, down the quench chute and into the quenching liquid.

Mesh-Belt Conveyer Furnace (*Fig. 12*). This furnace is usually provided with heating and cooling chambers and has a conveyer made of woven wire. The parts are loaded directly on the conveyer, which returns under the furnace.

The mesh-belt conveyer furnace is used principally for furnace brazing, bright annealing and sintering.

Tower Furnace. This type of furnace, used for the continuous heating and cooling of strip, consists of one or more vertical heating chambers and may be equipped with one or more vertical cooling chambers. Each chamber has supporting drums at top and bottom.

Catenary Furnace (*Fig. 13*). This furnace consists of heating and cooling chambers for the continuous annealing of strip in a protective atmosphere. Rolls located outside

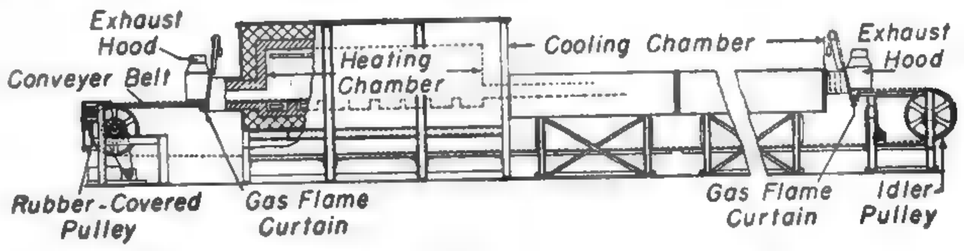

Fig. 12 Typical mesh-belt conveyer furnace with heating and cooling chambers

the heating chamber support the strip so that it hangs in a catenary having no contact with supports in the heating chamber.

Oil Bath (*Fig. 14*). The oil bath consists of a steel tank suitably insulated and equipped with immersion heaters. The oil bath is used for the tempering of steel parts.

Lead Hardening Pot Furnace (*Fig. 15*). This furnace consists of a heating chamber that contains an alloy crucible. The parts to be heated are immersed in molten lead. This furnace is used for localized heating of steel parts.

Salt Bath Furnaces. In a salt bath, the heat is transferred from the source to the work pieces by convection through the liquid bath. Since this convection is very rapid and the bath has a high heat capacity, the rate of heating the work is limited in practice only by the ability of the work to conduct the heat. For example, the rate of heating steel between 1500 and 1750 F is four to six times

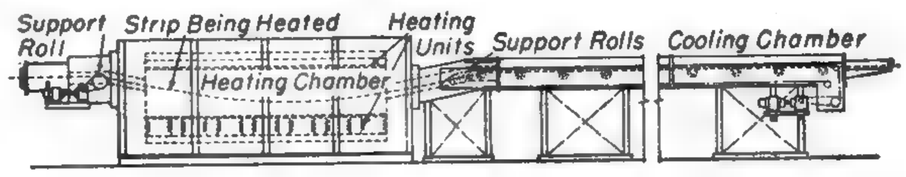

Fig. 13 Typical catenary furnace with heating and cooling chambers

faster in a salt bath than in a furnace that depends on radiation for heating the work. When cold metal is immersed in a liquid salt bath, a layer of frozen salt is formed instantly and encases the entire piece. This is because the melting point of the salt compounds used is always only a few hundred degrees (200 to 600 F) below the operating temperature of the bath. This characteris-

tic serves to preheat the work, and when the layer of frozen salt is melted (usually within 1 min) the piece is heated to the bath temperature by conduction. As a result, salt bath furnaces are designed to operate with considerably faster time cycles. See page 283 for specific

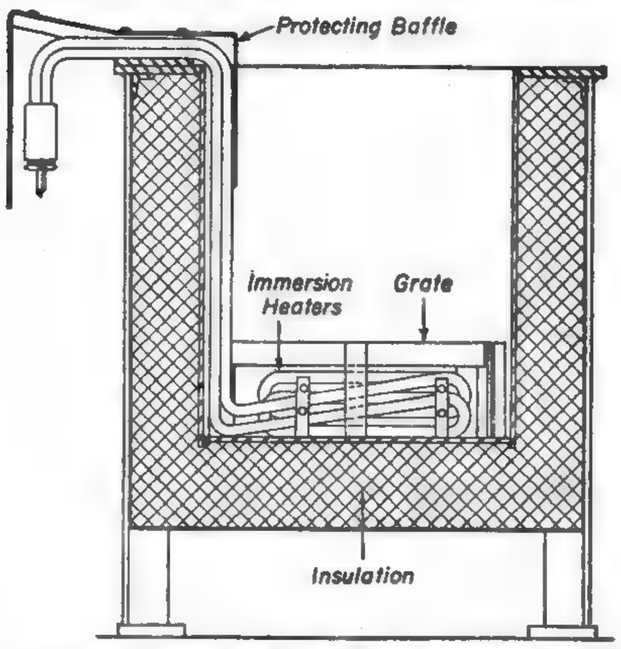

Fig. 14 Typical oil bath heated by immersion heaters

data regarding types of salts and operating techniques recommended for various heat treating applications.

There are three types of electrically heated salt bath furnaces; namely, the externally heated type, the immersion heating-element type and the immersed-electrode type.

Externally Heated Type (*Fig. 15*). The resistance heating elements that are mounted on the walls of this type of furnace, radiate heat to the outside surface of the pot.

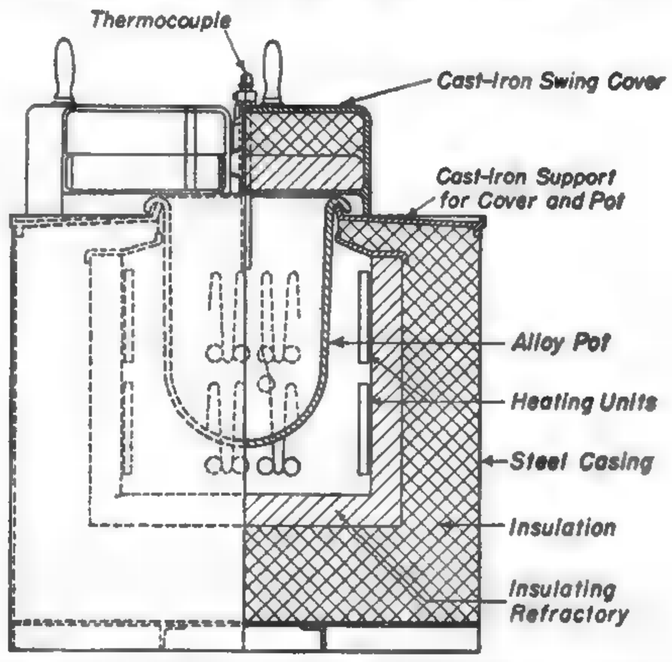

Fig. 15 Typical pot furnace with external heating for lead and salt bath hardening

The pot must be made of metal—usually of a heat-resistant alloy—in order to conduct the heat efficiently from the heating chamber to the salt bath. A temperature gradient of several hundred degrees must be maintained between the heating elements and the bath so that the energy will be transmitted through the wall of the pot. Therefore, externally heated salt bath furnaces are limited to a maximum operating temperature of approximately 1650 F. These furnaces are used for tempering, neutral hardening, cyanide hardening, and carburizing.

Immersion Heating-Element Type. This type of furnace is heated by electric immersion heaters that consist of a resistance wire embedded in refractory insulation, all

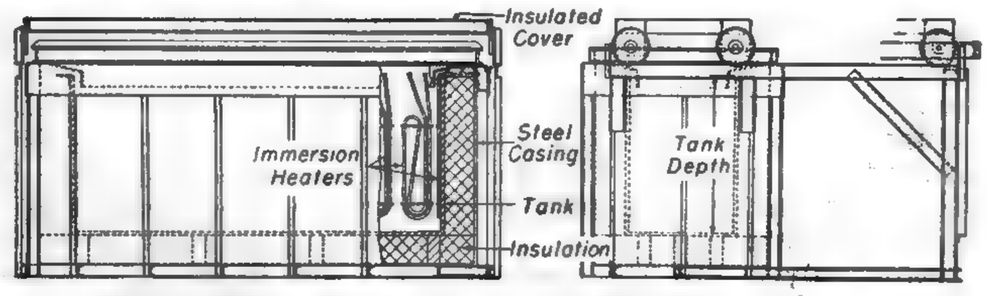

Fig. 16 Typical salt bath heated by immersion heaters

within an outer metallic sheath. Here again, a temperature gradient exists between the heating element and the outer sheath in contact with the bath. These immersion heaters are used for bath temperatures up to 1100 F. The pots are usually made of steel and suitable insulation is placed between the walls of the pot and outer casing. This type of furnace is used for the tempering and coloring of steel parts, the heat treating of aluminum alloys and interrupted quenching of steel parts in connection with austempering and martempering treatments (Fig. 14 and 16).

Immersed-Electrode Type. This type of furnace—probably the oldest electric heat treating furnace in commercial use—was introduced about 1906. Though all salts are good insulators in the solid state, they become fairly good conductors when melted. This electrical characteristic is utilized in the operating principle of the electrode type of furnace. Ordinary shop voltage, such as 220 or 440 v, from an alternating-current source, is reduced to a low voltage (5 to 25 v) by means of a transformer adjacent to the furnace. This low voltage is impressed on the electrodes immersed in the salt bath, causing an alternating current of

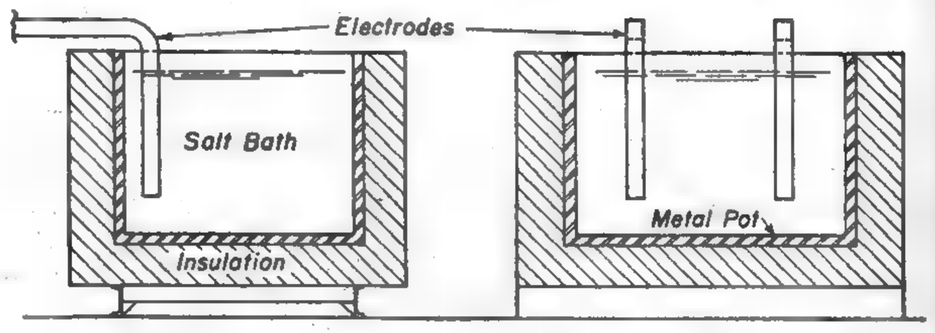

Fig. 17 Immersed-electrode type of furnace with suspended electrodes widely spaced

rather high amperage to flow through the liquid salt. The salt is heated by its own resistance to this flow of current. Direct current cannot be used because it would electrolyze and decompose the bath. The electrode salt bath furnace consists of a thermally insulated container made either of metal or refractory and usually called the "pot", with immersed electrodes to heat the salt bath internally. The operating temperature is limited only by the heat resistance and chemical resistance of the materials used for the electrodes and pot. This type of furnace is used for virtually all heat treating operations that involve operating temperatures from 325 to 2400 F, such as the following: tempering of steel parts; isothermal or interrupted quenching; heat treating of aluminum alloys; annealing of carbon and alloy steels, copper alloys, stainless steels, aluminum alloys and silver; neutral hardening of all types of steels, including martempering and austempering; carburizing and cyanide hardening; hardening of high speed steel tools; nitriding of high speed steel tools; brazing of

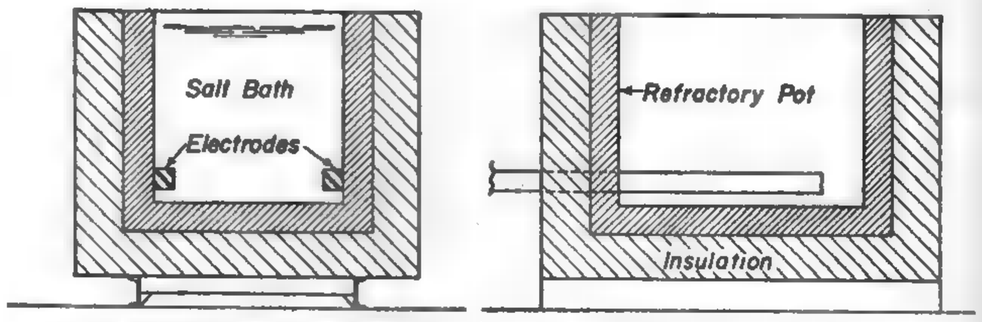

Fig. 18 Immersed-electrode type of furnace with submerged electrodes

steel, copper and aluminum assemblies using silver, brass, aluminum or copper brazing solders; heating for forging; descaling of stainless and alloy steel wire, shapes, forgings and castings.

Electrode-type furnaces now in use are of three general designs characterized by (1) suspended and widely spaced electrodes, (2) submerged electrodes, and (3) suspended and closely spaced electrodes.

In the earliest type of immersed-electrode furnace, electrodes were located on opposite sides of the bath and were suspended in it from the top. The pot or container for the salt was made of refractory. The path of current from one electrode to the other must pass through the charge, a circumstance that may lead to serious difficulties. Since the

metal charge is always a better conductor of electricity than the bath, the current density will rise abnormally in the area where the current enters and leaves the work pieces. Overheating and partial melting may result, while the temperature of the bath itself remains unaltered.

The defect in this design is overcome in an electrode type of furnace in which the pot is of metal and has the electrodes arranged along one of its walls, as shown in Fig. 19. The current passes from one electrode to the pot wall, through the pot, and then across a gap of liquid salt back to another electrode. Thus the current is confined to the electrode area and cannot enter the metal charge.

In the submerged-electrode design, a refractory pot is used and the electrodes penetrate through the pot wall at or near the bottom of the bath, as shown in Fig 18. If the charge is not too deep, the path of the current is confined to the area between electrodes. The electrodes are usually water-cooled in order to freeze and seal any leaks from the bath. Since all the heat is generated at the bottom of the bath, thermal circulation is effected by virtue of the difference in temperature between the bottom and top of

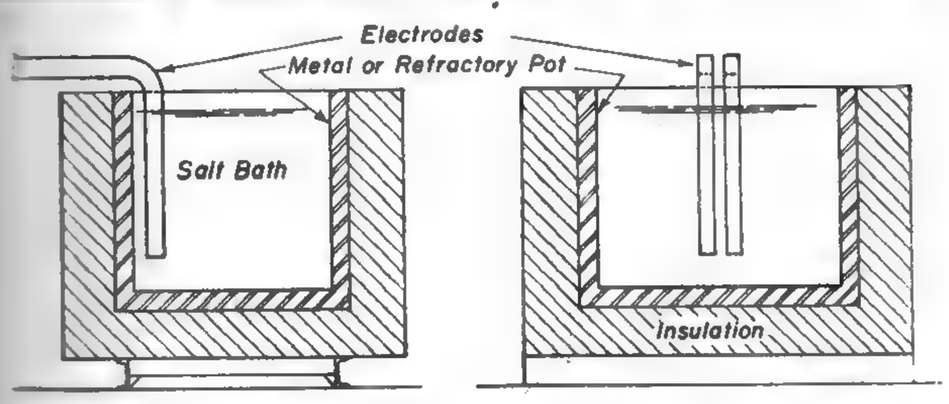

Fig. 19 Immersed-electrode type of furnace with closely spaced electrodes

the bath. The hot salt at the bottom is less dense than the colder salt at the top and naturally rises to be displaced by the colder and denser salt. The advantage of this design is primarily in the reduction in the area of the exposed surface of the bath. It is difficult, if not impossible, to replace the electrodes when the furnace is in operation. The heavy sludge that forms in most salt baths and collects at the bottom, may also present difficulties. The conductivity of this sludge varies greatly from that of the salt and if such sludge accumulates in the area traversed by the current, the power input can be affected greatly. If the bath should freeze for any reason, such as an interruption of power or failure of electrical control, the furnace could

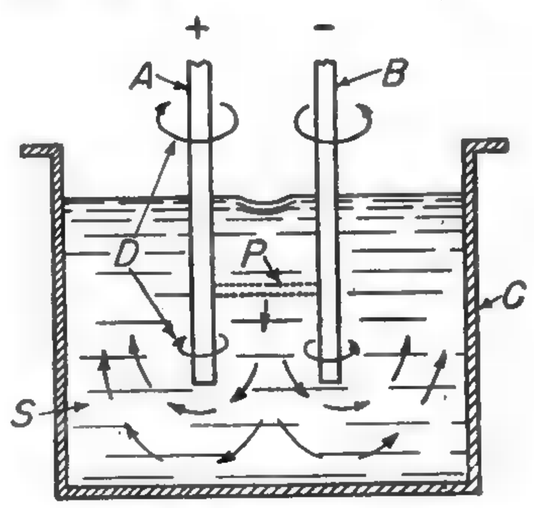

Fig. 20 Theory of electromagnetic circulation in immersed-electrode type of salt bath furnace

not be started again because of the inaccessibility of the bottom electrodes. Therefore, in this type of furnace it is necessary to anticipate such an occurrence and to insert a resistance coil from the top, to restart a solidified bath.

The third type of immersed-electrode furnace in prevalent use, has suspended and closely spaced electrodes, as shown in Fig. 19. The pot is made either of metal or refractory, whichever lends itself better to a particular operation. The main distinguishing feature of this design is that the electromagnetic field created by the current in the electrodes is utilized to circulate the liquid salt. So that these electromagnetic forces can be used to best advantage, the electrodes are grouped in pairs along the pot wall and are placed relatively close together. The gap between the electrodes is only from 1 to 2 in. so the current is confined to the electrode area and cannot be short-circuited through the charge with consequent overheating, as in furnaces that have the electrodes more widely separated.

With the electrodes arranged thus along one side of the bath, the heating zone is kept distinct from the working space. The electromagnetic circulation causes the liquid salt to be drawn into the gap between the electrodes and sucked downward, or opposite to the direction of flow that might be obtained by thermal convection. This electromagnetic circulation removes the heat as fast as it is generated between the electrodes, and ensures uniform temperature throughout the bath.

Figure 20 explains the theory of this electromagnetic circulation. Any conductor that carries current, when placed in a magnetic field, tends to move at right angles to the direction of the magnetic field and at right angles to the direction of the current. Applying this rule to the salt bath, electrodes *A* and *B* are immersed vertically and close together in a molten salt *S*, and a current of high magnitude, 3000 amp for example, is passed between them. Each electrode is surrounded by approximately circular lines of force *D*. Current of high density flows between the electrodes at all points from the surface of the bath to the ends of the electrodes. If a current element *P* is considered, midway between the two electrodes, and some distance down from the surface, and the current is traveling at any instant from *A* to *B*, then with the resultant electromagnetic field between the two electrodes extending outward from the plane of the figure at the point *P*, the con-

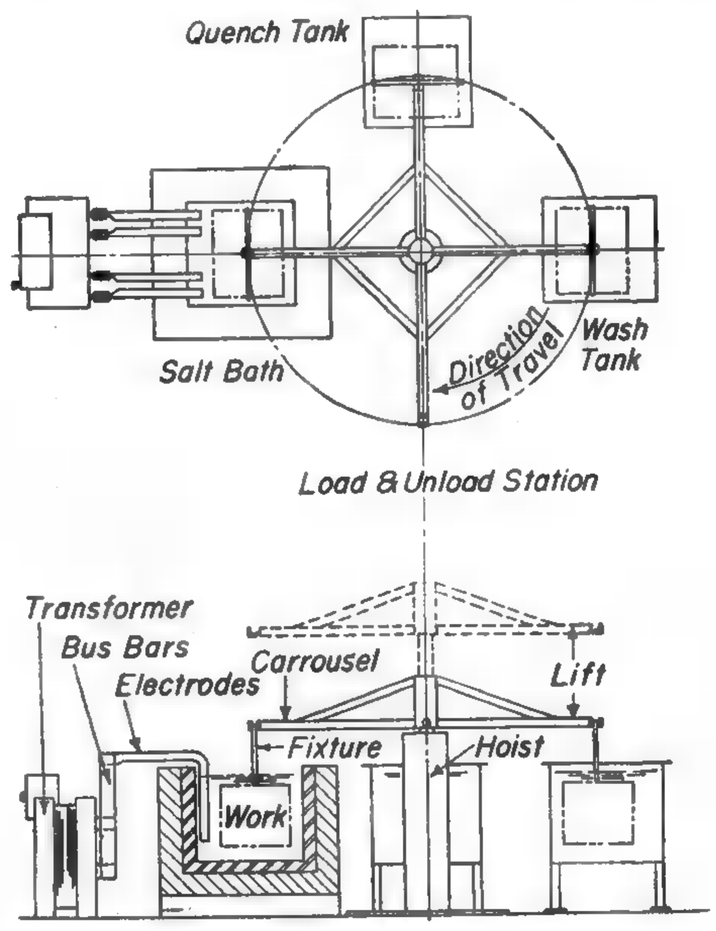

Fig. 21 Carrousel type of mechanism applied to immersed-electrode type of salt bath furnace

ductor, or element of the liquid salt that is carrying the current, will be forced downward between the electrodes in the direction of the arrow. This is according to the well-known electromotive laws of Maxwell. If the direction of current is reversed, the direction of the magnetic field also reverses, and the direction of movement is still downward.

Automatic control of temperature for salt baths is provided by means of the usual apparatus; that is, a thermocouple, pyrometric controller and magnetic contactor.

Electrodes are made of various metals such as iron, chromium-iron or nickel-chromium-iron alloys, depending on the temperature and chemical nature of the bath in which they are used. Pots for low-temperature baths to be operated at 1300 F or less, are usually made of welded steel plate. For the higher temperatures, up to 2400 F, refractory pots, made of preformed and prefired ceramic shapes, are commonly used. This is invariably good practice for neutral salts, but where carburizing baths are involved, plain welded steel pots are ordinarily used in the temper-

ature range from 1500 to 1750 F. In spite of the poor "refractory" properties of steel, these pots give long service when employed with such carburizing baths, because the ebullition of carbon monoxide gas (formed in the bath when the sodium cyanide decomposes) protects the steel from severe oxidation, which would otherwise occur.

The salt for a particular application is determined primarily by the highest temperature to which it will be heated and by whether or not a chemical reaction is desired on the surface of the metal being treated. Mixtures of nitrates and nitrites are generally used for temperatures below 1100 F. Chlorides of barium, sodium and potassium are used for the medium-temperature range from 1200 to 1750 F, and barium chloride is most commonly used for the high-temperature range from 1750 to 2400 F. Rectifiers such as borax, silicon carbide, organic cyanides, silica and carbon, are used as additions to the baths for controlling the "neutrality" of the solutions so that decarburization, pitting and other surface reactions may be inhibited. Salts that contain from 8 to 35% sodium cyanide, along with chlorides and carbonates, are used for carburizing and case hardening. The decomposition of the cyanide evolves carbon monoxide and nitrogen, which react with the surface of the steel to produce the carburized case.

The connected load of a furnace is determined by the following factors:

1 Power required to heat the charge and fixtures
2 Heat lost from the furnace
  (*a*) from bath surface
  (*b*) through sides, bottom and cover
  (*c*) by electrodes
  (*d*) by transformer

The heat lost from the surface of the bath is the largest factor in the total loss. Therefore, the designer of the furnace should try to keep the exposed area of the bath as small as possible.

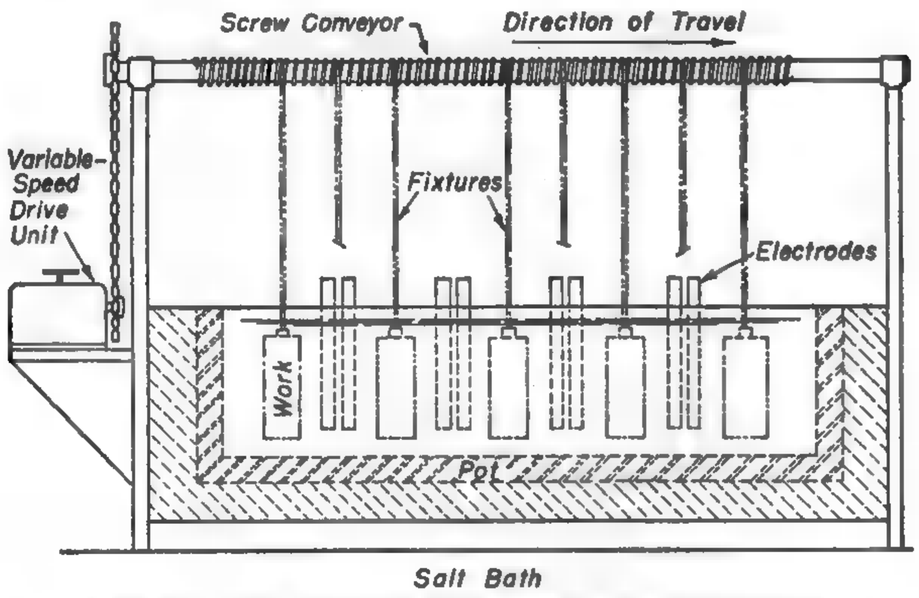

Fig. 22 Salt bath equipped with screw conveyer mechanism

The ingenuity used in devising a method for arranging the work on fixtures or supporting it in the bath, can have an important bearing on the surface area required and therefore on the efficiency of operation. Small parts, such as pins, rivets, studs, nuts and bolts, are heated in baskets made either of wire mesh or of perforated metal. Larger pieces require fixtures to support the work—in many instances simply a piece of wire passing through a hole in the work piece and attached or hooked to a supporting rod above the bath. Other fixtures, either weldments or castings, resemble trees and the pieces are hung on the "limbs". The choice of material from which to construct the basket or fixture depends on the temperature required in the bath and on whether the fixture is to be quenched.

The immersed-electrode type of furnace permits the design of any size or shape of bath, and because of its internal heating principle, ensures very long life for the pot. These factors, plus the ability to generate virtually any desired power within the bath, make it feasible to mechanize such furnaces so that work material may be sent through continuously on conveyers. One commonly used mechanized design is the "carrousel" type (Fig. 21), wherein the work pieces, suspended from fixtures, are rotated by a device located in the center of a circle that has two or more salt baths equally spaced around its periphery. The work pieces are moved progressively from one bath to the next (including quenching or washing stations if desired) for the cycle of treatment and then, after complete processing, are returned, for unloading, to the same point where they were loaded.

Another design, known as the "screw conveyer", comprises a motor-driven worm located directly over the salt bath (Fig. 22). The fixture or basket containing the work, is hung on this revolving screw, which moves the work through the bath at any desired speed, thus controlling the time-temperature cycle. In some instances the work is removed manually from the screw conveyer, but this operation also lends itself to mechanization.

The "jack rabbit" design (Fig. 23) provides perhaps the most flexible means of mechanizing a series of heat treating operations involving one or more salt bath furnaces and then quenching, washing and drying.

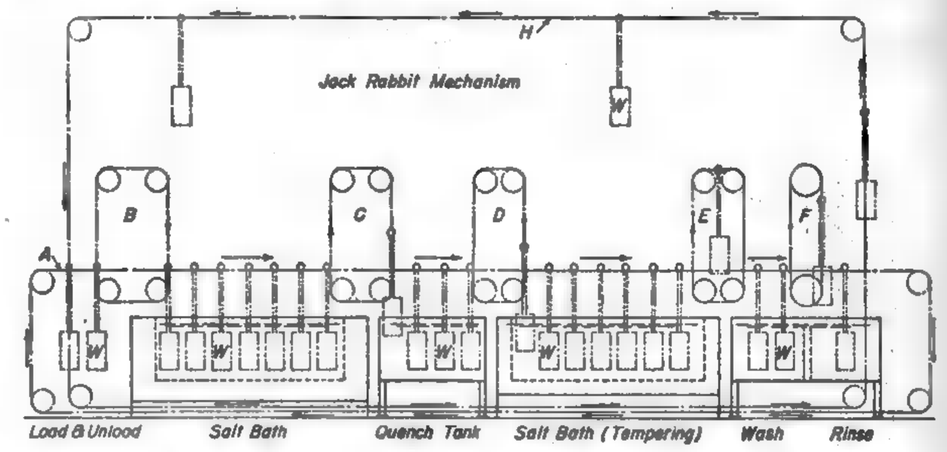

Fig. 23 Jack rabbit type of mechanism applied to a series of salt bath heat treating operations

Horizontal racks, holding the work-laden fixtures *W*, rest on two constantly moving conveyer chains *A*, on the top of the furnaces but away from the heat of the bath. Chains *A* return beneath the furnaces. When the racks of fixtures approach the entry or exit of any operation, vertical chain transfer mechanisms, *B*, *C*, *D*, *E*, *F* and *G*, actuated by limit switches, either lower or raise the fixture as required and transfer the work rapidly to the next bath. These transfer stations consist of two matched chains and are motor-driven. The separate pair of return chains *H*, powered by the main drive that also runs conveyer *A*, picks up the racks after the washing operation and conveys the work overhead, back to the starting end of the unit, where the operator unloads and reloads the fixtures.

Atmosphere for Resistance Furnace.* When this type of furnace is used for the heating of metal parts, protective atmosphere is ordinarily required in the heating and cooling chambers to protect the surface of the parts.

In almost all these procedures for heating, it is necessary to prevent oxidation of the metal. There may be other requirements also, such as preventing the removal of carbon, adding carbon, or eliminating discoloration from sulfur.

Most metals can be bright annealed without decarburization. Carbon steels, alloy steels and high speed steels can be hardened without decarburization or scaling.

Such materials as stainless steel and high-zinc brass are not strictly bright annealed in the usual production furnace unless the material being annealed is such that the furnace atmosphere can be maintained at high purity and the time at temperature is relatively short.

Before selecting the type of atmosphere equipment for a given application, a study should be made of all the atmosphere requirements for nearby furnaces. One centralized atmosphere equipment will usually entail lower first cost, lower cost of maintenance and less supervision.

Typical atmosphere equipments are:

Atmosphere Gas Converter (Fig. 24). This is an equipment for the re-forming of the available city or natural gas (or tanked butane or propane). The air and gas (in proper proportion for the application) are mixed, compressed and then fed into the combustion chamber. The composition of the output gas can be varied, within limits, by changing the air:gas ratio. The output gas contains H_2, CO, N_2, CO_2 and water vapor.

* See also the article on page 294.

This gas is suitable for the bright annealing of low carbon steels, for furnace brazing where decarburization is not a factor, and for sintering.

Additional purification of this gas may be necessary, such as removal of sulfur (if present), removal of water vapor and of CO_2.

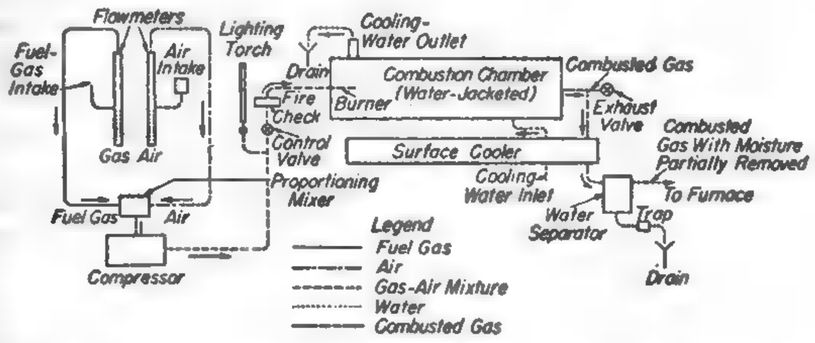

Fig. 24 Flow diagram of a typical atmosphere gas converter

Nondecarburizing Atmospheres (*Fig. 25*). To be nondecarburizing, the protective gas atmosphere must be free from CO_2 and water vapor. Such an atmosphere may be provided by passing air or products of combustion (that is, combustion of a controlled mixture of air and gas) over hot charcoal, or by combining air with a gas high in methane and heating to the range between 1900 and 2000 F. The resultant gas is CO and N_2.

Another means of providing a dry gas free from CO_2, is the use of a chemical CO_2-remover and a dryer, which may be an activated alumina dryer, or a combination of a refrigerated gas cooler and activated alumina dryer. The products of combustion (that is, combustion of air and gas under controlled conditions) are passed through an absorbing tower where the gas comes in contact with the circulated liquid absorbent. The CO_2 is absorbed by the liquid and the remaining gas passes on to the dryer where the moisture is removed. The CO_2-laden absorbent is heated to drive off the CO_2 and the liquid is recirculated.

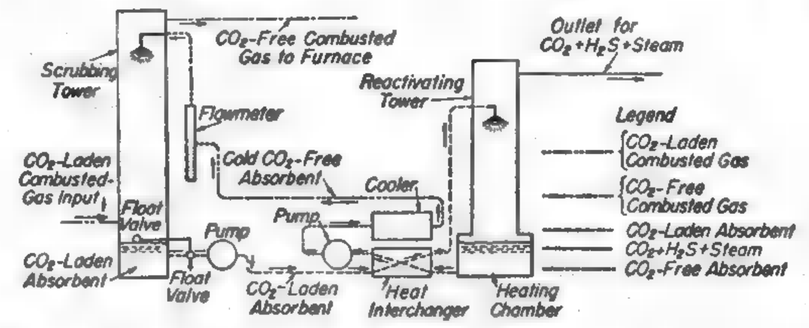

Fig. 25 Typical flow diagram of equipment for removing CO_2

In another type of equipment for producing a gas very low in CO_2 and water vapor, the air:gas ratio is low. Since the amount of heat generated at the low ratio is not sufficient to maintain the temperature required in the combustion chamber, some auxiliary heating is used. This auxiliary heating may be obtained by preheating the air-gas

Table I. Principal Applications of Electric Furnaces

Process	Material	Type of Furnace	Fig. No.	Approx Energy Consumption, lb net per kwhr[a]
Annealing and heat treating	Aluminum and aluminum alloys	Box	1	Aluminum, 8 to 14
		Pit	3	
		Car	.	
	sheets	Elevator	6	Aluminum alloys, 6 to 12
	forgings	Rotary hearth	7	
	castings	Roller hearth	9	
	stampings	(All the above furnaces with air recirculation)		
	rivets	Salt baths	15 to 23	.....
Annealing	Copper and brass, Silver alloys	Bell	5	Copper wire or strip in coils or on spools, 25 to 40
		Box	1	
		Pusher tray	8	
		Roller hearth	9	
		Mesh belt	12	Brass wire or strip in coils or on spools, 15 to 25
		Salt baths	15 to 23	.....
	Malleable iron castings	Elevator	6	5 to 7
		Roller hearth	9	5 to 7
		Pusher tray	8	5 to 7
	Steel bar stock and tubes	Car	4	6 to 8
		Pit (rectangular)	.	7 to 10
		Elevator	6	6 to 8
		Roller hearth	9	7 to 11
	Steel sheets	Elevator	6	Sheets stacked,
		Bell (rectangular)	.	9 to 12
	Steel strip	Bell	5	In coils, 10 to 14
		Roller hearth	9	Continuous, 8 to 12
		catenary	13	Continuous, 8 to 12
		tower		Continuous, 8 to 12
	Steel wire	Bell	5	In coils, 10 to 12
		Pit	.	
		Salt bath	17 to 23	.....
	Steel castings and forgings	Car	4	6 to 10
		Elevator	6	6 to 10
		Roller hearth	9	6 to 10
		Pusher tray	8	6 to 10
		Salt bath	17 to 23	.....
	Stainless steels	Tube	.	.....
		Box	2	.....
		Mesh belt	12	4 to 7
		Roller hearth	9	6 to 10
		catenary	13	6 to 10
		tower		6 to 10
		Salt bath	17 to 23	.....
Brazing (copper, brass, silver solder)	Steel	Box	2	4 to 6 copper brazing
	Copper	Mesh belt	12	3 to 5 copper brazing
	Aluminum	Roller hearth	9	5 to 7 copper brazing
		Salt bath	17 to 23	.....
Carburizing	Steel	Box	1	Pack method, 2 to 4
		Elevator	6	Pack method, 2 to 4
		Pusher tray	8	Pack method, 3 to 4
		Pit	.	Gas carburizing, 3 to 6
		Salt bath	17 to 23	
Case hardening	Steel	Pit	.	.....
		Pusher	.	.....
		Belt conveyer	10	.....
		Roller hearth	9	.....
		Salt bath	17 to 23	.....
Tempering	Steel	Box	.	At approx 400 F, 40 to 60
		Pit	3	At approx 800 F, 20 to 25
		Pit	3	At approx 1200 F, 10 to 15
		Oil bath	14	.....
		Salt bath	15	.....
		Salt bath	16	.....
		Salt bath	17 to 23	.....
Galvanizing	Steel	Pot	.	Hot dip, 12 to 20
Hardening	Steel, carbon and alloy	Box	1	
		Lead pot	15	
		Pit	.	Hardening at 1500 F, 7 to 11
		Belt conveyer	10	
		Pusher	8	
		Rotary hearth	7	
		Roller hearth	9	
		Shaker hearth	11	
		Salt bath	15	
		Salt bath	17 to 23	
	High speed steel	Box	1	.....
		Pit	.	.....
		Salt bath	17	.....
Nitriding	Steel	Pit	3	.....
		Bell	5	.....
		Car	4	.....
		Salt bath	17 to 23	.....
Porcelain enameling	Steel	Box	.	Single coat
	Cast iron	Monorail conveyer	.	
Sheet steel. In box furnace, 5 to 8; In continuous furnace, 10 to 15. *Cast iron.* (wet process) In box furnace, 6 to 10; In continuous furnace, 12 to 15.				
Sintering	Pressed metal powders	Bell	5	.....
		Box	2	.....
		Pusher	8	.....
		Mesh belt	12	.....
		Roller hearth	9	.....
Austempering, patenting and cycle annealing	Steel	Belt conveyer	10	.....
		Roller hearth	9	.....
		Lead pot	15	.....
		Salt bath	15	.....
		Salt bath	16	.....
		Salt bath	17 to 23	.....

(a) These are approximate figures. The energy consumption for a given application will vary, depending on production, type and size of furnace, efficiency of loading and the time-temperature cycle.

mixture or by surrounding the combustion retort with a heated chamber.

The type of equipment selected to produce a nondecarburizing atmosphere will depend on the application and the quantity of gas atmosphere required.

Ammonia Dissociator. The ammonia dissociator consists of an electrically heated chamber containing a coil of heat-resistant alloy tubing. While being passed through this coil, the anhydrous ammonia is heated and dissociated, giving a resultant gas that consists of 75% H_2 and 25% N_2. This atmosphere is used for the bright annealing of high-carbon and chromium (including stainless) steels, and as a source of hydrogen for atomic hydrogen welding and for chemical processes.

The dissociated ammonia may be mixed with air and burned to obtain a mixture that is low in hydrogen and high in nitrogen.

Temperature Control. The temperature is controlled by means of a thermocouple, working in conjunction with a standard instrument for control of temperature and a control panel. The methods of control that are used, are discussed in the article on page 174 of this Handbook.

Selection and Application of Electric Resistance Furnaces. *Selection of Heat Source.* In selecting the type of furnace and source of heat (electricity, gas, oil or coal) to use for a given application, a thorough analysis should be made of the over-all costs involved.

Some of the major factors that should be covered in the analysis of costs are: (1) heat source, (2) subsequent operations (such as cleaning, or machining), (3) transportation of parts to and from the furnace, (4) floor space, (5) labor and supervision, (6) maintenance, (7) working conditions, (8) continuity of service, and (9) acceptability of products.

Selection of Type and Size of Furnace. The differences among types of furnaces are largely differences in the handling of material and the method of applying the heat, by radiation or forced convection.

Too frequently the selection of the correct size and type of furnace is limited by a few parts of special size or a few parts that require a different heating cycle. In such instances it is well to consider a separate furnace for these few parts, or to send them to a commercial heat treating company and then to select the type and size of furnace best adapted to the requirements of the production items.

The size of furnace selected for a given application and production will be governed by the efficiency of loading (pounds per square foot, per cubic foot, and the like), the temperature gradient permissible, the weight of conveyer, trays, and other fixtures that must be heated, and the shape and size of parts to be heated.

As an example, when a belt conveyer furnace (Fig. 10) is used for the hardening of bolts, or a similar product, at approximately 1500 F, the production will be approximately 25 lb net per hr per sq ft of belt in the heating chamber. For a production of 1000 lb net per hr, the furnace should have a belt with loading area of approximately 40 sq ft in the heating chamber.

When the same type of furnace is used for hardening lightweight parts (such as typewriter parts), the production may be less than 15 lb net per hr per sq ft.

Another example is the annealing of brass stampings at approximately 1100 F in a mesh-belt conveyer furnace (Fig. 12). When annealing to reasonably constant grain size, the production may be 25 to 30 lb net per sq ft of conveyer in the heating chamber. However, if grain size is not very important and a temperature gradient can be used, production may reach 50 lb net per hr per sq ft.

When steel stampings are bright annealed (at 1650 F) between drawing operations, in a roller hearth furnace (Fig. 9) where the parts are loaded on lightweight trays, the production may vary from 40 to 80 lb gross per hr per sq ft of hearth in the heating chamber, depending on the uniformity of anneal desired. The net production will depend on the ratio of net weight to gross weight.

The principal applications of electric furnaces are summarized in Table I, on the preceding page.

Induction Heating

BY THE SUBCOMMITTEE ON INDUCTION HEATING*

THE discussion of this subject will be confined to the heating of materials by electromagnetic induction.

In recent years, the heating of metals by induction has gained such widespread acceptance and importance that it merits careful consideration in the following applications: (1) heating for hot working as in forming and forging; (2) heating for hardening or other changes in physical properties; (3) heating for joining metals by fusion, as in soldering, brazing or welding; (4) heating for sintering, for shrink fitting and for special effects. The melting of metals in induction furnaces is not discussed here; for information on this subject, see "The Induction Furnace Process of Steel Melting", page 332.

Although possibly the greatest number of applications have been made in processes mentioned in items 3 and 4, undoubtedly the greatest amount of power has been consumed in processes listed as items 1 and 2. Certainly the greatest technological developments have occurred in the processes of heating for hardening. The scope of such development has been described in detail in technical articles and scientific literature.

Heating for selective hardening (that is, localized heat treatment) has assumed major importance although a number of successful applications exist in which continuous through-hardening and tempering are carried out by induction; for instance, the heat treatment of long bars and tubes.

The principal requirements for such types of induction heating depend on the operation of the following equipment: (1) a source of alternating or pulsating current, (2) a device for transferring energy to the work piece, (3) precise methods for control of the operation, that is, rate of energy input, duration of input, and rate of cooling.

The available sources for alternating current can be classified under these commercial types:

1 *Motor-generator sets*
Frequencies: 60; 1000; 3000; and 10,000 c. A few higher steps are possible.
Capacities: a to several thousand kilowatts

2 *Vacuum-tube oscillators*
Frequencies: 200,000 to 5,000,000 c
Frequencies most used: 450,000 c and higher
(Frequencies to 15,000,000 c or more are possible.)
Capacities: 5 to several hundred kilowatts

3 *Mercury-arc converters*
Frequencies: 400 to 1500 c
(Frequencies to 3000 c may be possible.)
Capacities: 300 to several thousand kilowatts

4 *Spark-gap oscillators*
Frequencies: 20,000 to 300,000 c
Capacities: 2 to 40 kw

In application, the first problem is the choice of frequency. The following essential factors should be considered:

1 Material (ferrous and nonferrous)
2 Size (diameter or section) of the work piece
3 Depth of section to be affected by heating
4 Result desired (forging, hardening, tempering, brazing, or other processes)
5 Properties of the work piece (magnetic, electrical, thermal and such)
6 Closeness of electrical coupling (the necessary width of insulating gap between work piece and inductor)
7 Final cost of work

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The high-frequency converters in the motor-generator range of frequencies are capable of having current conducted at some distance from the source. In one instance 600 kw of 3000-c power was conducted a distance of 1000 ft by use of coaxial cable.

Heating for Forging, Upsetting and Hot Coining. The rapid heating of bar surfaces for localized hardening, undoubtedly suggested and gave impetus to heating for hot working. Many large forging plants that were built during World War II depended entirely on induction heating for supplying hammers and headers.

The recommended heating times for bringing various carbon steel billets to a uniform forging temperature of approximately 2200 F are shown in Fig. 1.

If the applied power is kept at the average level, as was the practice for the curves shown, the temperature gradient in the charge piece is low, the load factor on the generator approaches a maximum and the equipment can be of the simplest design.

The heating times shown can be shortened appreciably if the power density is kept at a high level, holding the surface of the charge at the maximum temperature while the heat soaks inward. In equipment adapted to this

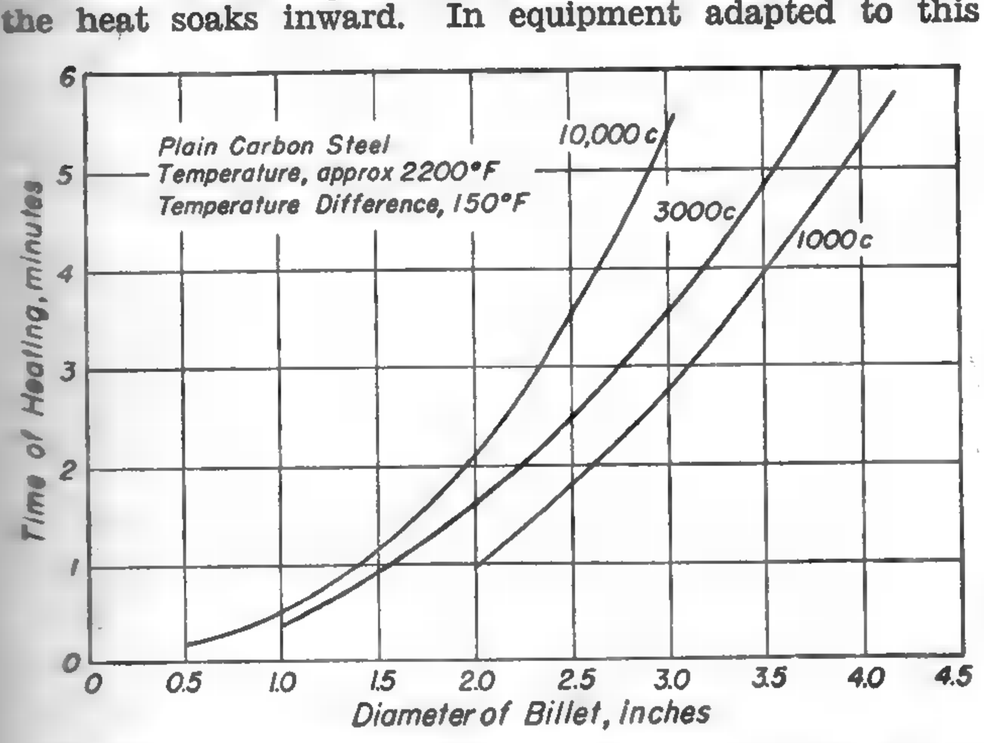

Fig. 1 Recommended time for induction heating of carbon steel billets for forging

practice, the power plant and the controls would be somewhat more elaborate than those adequate for obtaining the conditions illustrated in Fig. 1. However, the heating time would be the shortest attainable.

When several heaters, drawing average power, are connected in parallel, virtually full power is drawn from the feed lines at all times, thus enabling heated billets to be supplied to the forging equipment at the same rate as billets heated singly at a faster heating rate.

As is evident from Fig. 1, the time of heating will depend not only on the diameter of the piece being heated, but also on the frequency. Figure 2 shows the *minimum* frequency required for satisfactorily heating carbon steel bars of various diameters to forging temperature.

In general, if a lower frequency can be used, the power density can be maintained at a higher level than when a higher frequency is used, and heating time can therefore be shortened. As shown in Table I, for stock sizes less than ½ in. in diam, frequencies higher than those obtained from motor generators are needed; for stock from ½ to 1 in. in diam, a frequency of 10,000 cycles is usually employed; for 1 to 2 in., 3000 cycles; and for more than 2 in., 1000 cycles. Figure 3 shows how inductor efficiency varies with frequency and bar size.

In heating for forging, 5 to 6 lb of steel per kwhr (energy measured at the generator terminals) is usually obtained. However, the over-all efficiency of the motor-generator set should be considered in computing total power requirements.

Although the first costs and energy costs of induction heating equipment are usually higher than for conventional forging furnaces, the expense is offset by distinct advantages, such as: lower loss from scale formed (a saving equivalent in some instances to the energy cost), better die life, less forging flash, and less metal lost in machining.

The induction heating unit requires much less floor space and heating can be almost as rapid as desired, limited only by the time required for the surface and center of the billet to reach a satisfactory forging temperature.

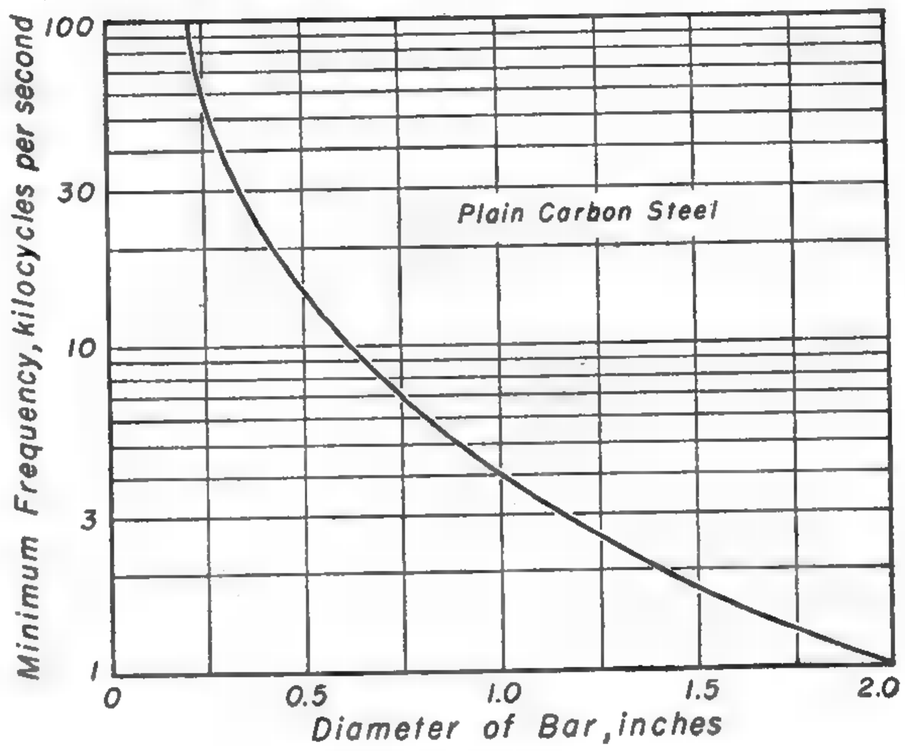

Fig. 2 Minimum frequency to heat various diameters of plain carbon steel bars to forging temperature. All diameter-frequency combinations lying to the right of the curve are satisfactory.

Higher rates of production, uniform temperature for forging, improved working conditions, lower maintenance costs, and flexibility, are difficult to evaluate on the basis of pounds of forgings produced, but the total may result in large over-all savings.

In Table I are shown the frequencies and types of equipment recommended for various applications of induction heating. Melting has been included for comparison.

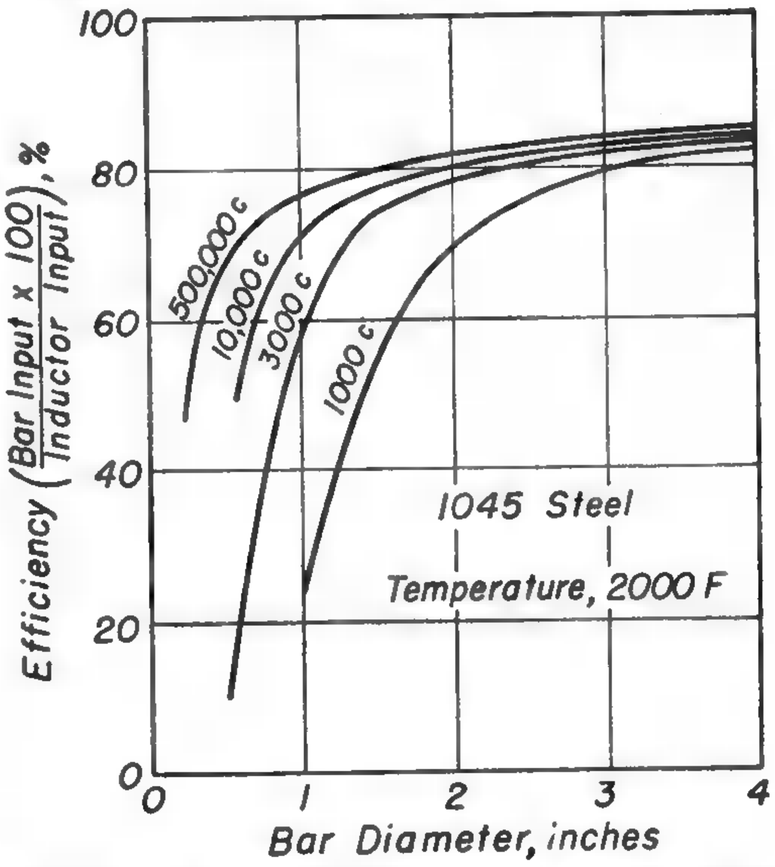

Fig. 3 Calculated variation of inductor efficiency with frequency and bar diameter for a constant air gap of 0.56 in.

Heating for Hardening, for Tempering and for Stress Relieving. As a broad generalization, it may be said that the instantaneous heating effect of an inductor varies inversely as the square root of the frequency. Thus, 10 kc heats instantly seven times deeper than 500 kc. Irregular contours are more readily followed by higher frequencies.

In obtaining desirable results, due care must be given to (1) the chemical composition of the work piece, (2) the metallographic structure of the work piece, (3) the final grain size and structure required, (4) control of stress, desirable and otherwise, (5) freedom from cracking, and (6) surface conditions of the work piece.

To illustrate, the chemical composition determines the thermal properties while the work piece is being heated. Conductivity is very high in most copper alloys, and relatively low in cast iron. Resistivity is relatively high in nickel alloys and low in aluminum alloys. The rate of solution of carbon is slow in high-chromium steels and rapid in sorbitic carbon steel.

Malleable iron is difficult to harden without a preliminary heating to bring necessary carbon into solution. Spheroidal carbon is slow to redissolve. "As-cast" structures are slower to respond to hardening than wrought structures.

A coarse-grained steel is more susceptible to cracking than a fine-grained steel. Grains excessively coarsened in heating will crack readily in severe quenching. In general, the finest grained martensite is the toughest structure in fully hardened steel.

A surface put in tension by hardening may quickly fail in service under bending loads. Residual stresses may prove sufficiently unfavorable to impair the integrity of the work piece. Beneficial stresses may make the work piece more resistant to wear and impart over-all toughness—for example, to a surface under compression opposing shearing stress. A prior slow stress-relieving of hardened parts is advisable to avoid cracking while reheating by induction. Refer to "Induction Heating", ASM, 1946. See also the article on page 243 in this Handbook.

Many parts are tempered selectively by induction heating, but low power inputs and much longer time is necessary than in heating for hardening. Stress relieving of welded joints (for example, in pipe or cumbersome assemblies) can be carried out conveniently by this method, and usually with frequencies in the lower end of the range.

If a work piece is heated too long or attains too high a temperature in air, it may scale or decarburize and thus defeat the purpose of induction hardening. Manifestly, a work piece initially decarburized will not harden by induction beyond the carbon limitation of the surface. Great care must be taken to insure obtaining the proper composition *at the surface.*

Slight seams and other surface imperfections are very injurious in drastic heating and hardening. They become "stress-raisers" which induce overheating, burning and cracking.

The shape of the work piece often determines the feasibility or desirability of induction heating or hardening.

Even more important than the ability to heat a work piece for hardening, is the ability to abstract the heat uniformly in quenching. Spotty surface hardening may result from improper jet impingement or steam pockets.

In general, the insulating gap between the inductor and the work piece should be as small as practicable, thus promoting efficiency and speed of heating. Coupling can be so remote that heating will be scarcely noticeable.

Considering over-all cost, the choice of frequency, type of equipment, and method of applying the heating and cooling often depend on other factors more important than the initial cost, the ratio of power input to cost, or the efficiency of the heat transfer. A minimum frequency might be a limiting factor; shape of the work piece might be another; type of material, another. The range of sizes and shapes to be hardened might indicate a compromise.

A comparison of the affected depth and hardened depth for the various prior structures when using power of 3000, 10,000 or 500,000 c, is shown in Table II for given power densities based on the maximum inductor input during the heating cycle. The values shown are for the minimum time of heating that will give a satisfactory microstructure for SAE 1045 steel.

Materials That Can Be Hardened by Induction. Plain carbon steel (0.15% C or more), constructional alloy steel, hardenable stainless steel, plain and alloyed cast steels, plain and alloyed cast iron, pearlitic and malleable iron.

Quenching Methods. Water, oil, air, gas, or self-quench.

Advantages of Induction Heating. Although the initial cost of installing appliances for induction heating may be several times greater than the cost of conventional methods for accomplishing a similar result, yet the advantages and economies may easily offset the first cost. Certainly, when selective hardening or continuous hardening, as by

Table I. Power Source and Frequency for Various Applications of Induction Heating[a]

Applications	Power Lines 60 c	Motor Generators 20 to 1200 Kw (Up) 1000 c	Motor Generators 20 to 1200 Kw (Up) 3000 c	Motor Generators 20 to 1200 Kw (Up) 10,000 c	Spark Gaps 2 to 40 kw 20 to 300 kc	Tubes 5 to 100 kw (Up) Under 1.5 mc	Tubes 5 to 100 kw (Up) Over 1.5 mc
Forging, Upsetting, and such							
Pieces to ½-in. diam	..	..	..	B	A	A	C
1-in. to 2-in. diam	..	..	A	A	A_2	B_2	C
2-in. to 4-in. diam	..	A	A	B	C_2	C_2	..
4-in. diam and more	..	A	B	C	..	..	..
Hardening—Very Thin	..	..	..	..	..	A	A
Hardening—Average Case							
Pieces to 1-in. diam	..	..	C	A	A_2	A	B
1-in. to 2-in. diam	..	..	A	A	C	B	..
2-in. diam and more	..	B	A	B	..	C	..
Hardening—Deep Case							
2-in. to 4 in. diam	..	A	A	B	B	..	..
4-in. diam and more	..	A	B	C	..	..	..
Through-Hardening and Tempering							
Sheet, thin-wall tubes	..	..	..	C	A	A	B
Pieces to ½-in. diam	..	..	..	B	A	A	B
½-in. to 2-in. diam	..	..	A	A	B	C	..
2-in. diam and more	..	A	A	B	..	..	..
Brazing, Soldering, Welding							
Small irregular parts	..	..	..	B	A	A	B
Large regular parts	..	A	A	A	..	..	..
Sintering Metal Powders	..	A_1	A_1	B	A_2	B_2	..
High-Temperature Work							
In general				See note (b)			
Graphitizing carbon	..	A_1	A	B	A_2	B_2	..
Vaporization processes	..	A_1	A	A	A_2	B_2	..
Vat and Autoclave Heating	A	B	B	B	..	..	..
Degassing Vacuum Tubes	..	..	..	..	B	A	..
Sheet-Heating, Tin-Reflowing	..	..	..	C	A_2	A	B_2
Shrink-Heating	A_1	A_1	A_1	A_1	A_2	A_2	B_2
Annealing and Stress-Relieving				See note (b)			
Baking and Drying Finishes				See note (b)			
Die Heating				See note (b)			
Muffle Heating				See note (b)			
Melting							
Charges to 50 lb	..	..	..	A	A	..	..
50 to 500 lb	..	B	A	B	..	..	..
500 lb and more	..	A	B	..	..	..	..
Vacuum and pressure	..	A_1	A	A	A_2	..	..

(a) A = Best, B next and so on. A_1 and A_2 = Large and small scale work, respectively.

(b) Where the field of application is quite diversified as for annealing, baking of finishes, heating of dies or muffles, or heating to high temperatures, any certain frequency might be best suited for the job. Each application must be judged on its merits.

Table II. Data for Induction Hardening

A comparison of affected depth[a] and hardened depth[b] for the various prior structures with 3000, 10,000 and 500,000 cycles power, for given power densities based on the maximum inductor input during the heating cycle. The values shown are for the minimum heating time that gives a satisfactory microstructure.

Maximum Inductor Input Per Unit of Hardened Surface Area, kw per sq in.	Prior Treatment	Affected Depth, inches[a]			Hardened Depth, inches[b]			Heating Time, seconds		
		3000 cycles	10,000 cycles	500,000 cycles	3000 cycles	10,000 cycles	500,000 cycles	3000 cycles	10,000 cycles	500,000 cycles
5	Annealed	0.170	0.156	0.126	0.148	0.132	0.096	6.8	7.8	10.5
	Annealed	0.153	0.122	0.063	0.105	0.108	0.057	3.3	2.8	3.5
10	Normalized	....	0.112	0.062	....	0.100	0.057	3.2	2.6	4.0
	Quenched and tempered	0.079	0.072	0.029	0.058	0.061	0.026	3.2	2.3	2.5
	Annealed	0.148	0.099	....	0.096	0.090	....	2.5	1.5	...
15	Normalized	....	0.090	....	....	0.082	....	2.5	1.3	...
	Quenched and tempered	0.071	0.055	....	0.052	0.044	....	1.9	0.97	...

(a) The minimum depth below the surface where there has been no appreciable change in prior structure

(b) The depth below the surface where the hardness has decreased to Rockwell C 50

(c) Determinations made with solid single-turn inductor, 0.060-in. air-gap and SAE 1045 steel

scanning, may be applied to a part, induction heating should be given consideration. These special advantages are available from induction heating for hardening: (1) rapid processing, (2) clean operations, (3) little or no scaling or decarburization, (4) attainment of maximum hardness, (5) less noisy operation, (6) freedom from radiation of heat and hazards of hot handling, (7) easy reproducibility of hardness pattern and dimensions, (8) lower cost per piece, (9) low resultant distortion, (10) reduced floor space, (11) use of less costly material for same part, (12) location of heating equipment in production line and synchronization with the line.

Heating for Soldering, Brazing or Welding. Brazing and soldering present many suitable applications for induction heating. Because of the ease of control and the high rate of output, many highly mechanized devices have been employed for such purposes.

Continuous soldering or brazing, on a progressive belt or feeding mechanism, can be combined with the continuous flow of power through an inductor coil, or the power may be interrupted intermittently as the work pieces appear in the inductor loop. For soldering, sufficient time must be allowed in the heating period to permit liquation and capillarity to operate, which usually requires from 3 to 4 sec. By this means, less waste of solder results and no unnecessary heat is generated in the work piece.

In some instances, under sufficiently high temperature and under suitable fluxes or atmosphere, complete fusion may be obtained without the use of filler material.

Heating for Sintering. Induction heating has gained wide acceptance in sintering of pressed metal powder compacts. The compacts are placed within a muffle of graphite or high-melting material. The muffle is heated by induction; the compacts are heated by conduction and radiation. In some instances, the compacts have electrical conductivity high enough to absorb energy directly from the inductor, and the muffle may be omitted. Special atmospheres can be provided as required.

Heating for Shrink-Fitting. Annular pieces, such as rings and cylinders, are particularly suitable for induction heating operations. A simple inductor can be placed inside or outside such a piece, or a transformer core may be linked through the piece, thus heating the work quickly. When the ring is heated, it expands and can be placed around a prepared base piece and shrunk to fit. Ring gears for engine starters, tires for railroad car wheels, and cylinder muffles are commonly assembled thus.

Since differential heating is not required, low-frequency current from a commercial circuit may be used.

When the ring or cylinder has shrunk on, it may be removed by differential induction heating before the base piece is heated. This, however, requires higher input of power and generally much higher frequency. Hardening and shrink-fitting are often accomplished simultaneously.

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Salt Baths

BY THE SUBCOMMITTEE ON SALT BATHS*

TECHNOLOGICAL improvements made since 1937, in both furnace equipment and bath composition, are largely responsible for the present widespread commercial use of salt baths for virtually all heat treating operations. The term "salt bath" means a bath compounded by melting one or more chemical salts to form a liquid medium for immersion of the material to be treated. The chemical nature of such baths varies according to the temperature at which they are to be used.

Salt baths possess certain inherent characteristics that have a discernible and beneficial effect on the work material being treated in them. When a cold piece of metal is immersed in the salt bath, a "cocoon" of frozen salt is immediately formed, encasing the entire piece. This layer of frozen salt acts as a temporary insulator, preventing temperature shock and too sudden heating of the work. After this layer has melted, which usually occurs in a minute or less, the piece is heated rapidly to the temperature of the bath. The rate of heating is limited only by the conductivity of the metal itself and by the ability of the furnace to supply energy at a rate fast enough to maintain the bath temperature. The rate of heating in salt baths is

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considerably faster than in furnaces heated by radiation or gaseous convection, because the charge is heated by conduction only. For most work, time cycles can be employed that are from one-fourth to one-sixth as long as those normally used for heating the same objects in furnaces of the atmosphere type.

Since the immersed parts are not in contact with the atmosphere during the heating cycle, the problem of avoiding scaling or decarburization is simplified. However, it is important to prevent secondary chemical reactions in the bath itself, because of possible deleterious effects on the metal being treated. When the part is withdrawn from the bath, a film of liquid salt adheres to it. This serves to protect the surface during transfer from one bath to another or to the quench.

Another inherent feature of salt baths is the buoyancy caused by the bath. Although less dense than any of the metals, so they readily sink in it, the bath nevertheless "supports" the charge somewhat. In effect, the metal weighs appreciably less when immersed than it did previously; thus there is less tendency to distort or warp. All material treated in salt baths must be hung on fixtures and wires or placed in baskets or trays. The degree of ingenuity used in this preliminary arranging can have an important bearing on the cost of the entire operation.

For problems involving partial or selective heating, the salt bath offers special advantages. Because of the rapid rate of heating, only the portion of metal that is immersed, is heated, with a rather sharp line between the heated and unimmersed portions.

The salt bath processes described in this article are the following: carburizing, cyanide hardening, neutral hardening, austempering, martempering, cycle annealing, heat treating high speed steel tools, annealing, brazing, heat treating aluminum and beryllium-copper alloys, descaling alloy steels, removing sand from castings, cleaning steel parts, tempering steel parts, coloring, removing enamel, heating for forming and forging, and cleaning molds.

Salts. Table I presents typical compositions of baths used for various heat treating operations. The designations listed in the first column of this table are used throughout the present article to identify the various types of salt mixtures.

All salts should be stored in closed containers in a dry place to prevent absorption of moisture. The advice of salt manufacturers should be followed in regard to correct operation and maintenance of salt mixtures. Low-temperature salts L-1, L-2 and L-3 should never be permitted to come in contact with cyanide baths, such as L-4 and C-1 to 10, since the mixture is explosive.

Equipment.* Table II presents the various available types of salt bath furnaces, together with the ranges of temperature in which they operate.

Steel pots, either welded, pressed or cast, are generally used in all furnaces for temperatures up to 1000 F. Above this temperature it is necessary to use cast heat-resisting alloy pots for externally heated furnaces, whether fuel-heated or electric. Ceramic or refractory pots, employed only with the immersed-electrode type of furnace, offer special economic advantages when operated with neutral salt baths in the temperature range from 1500 to 2400 F, because these relatively cheap ceramic pots last from two to five years.

Table II. Types of Furnaces for Salt Baths

Type of Furnace	Temperature Range, deg Fahr
Externally heated, gas or oil	350 to 1650
Externally heated, electric	350 to 1650
Internally heated, gas immersion tube	350 to 750
Internally heated, electric resistance element	350 to 1000
Internally heated, electric immersed electrode	350 to 2400

It is not necessary to hood furnaces operating with nitrate baths at temperatures up to 1000 F, but since all other baths that are operated above 1000 F fume more or less, it is good practice to provide a fume-exhaust system or a hood, and sometimes both.

Baskets, racks and fixtures for holding the metal to be treated, are made of steel for low-temperature operations, and of heat-resisting alloys for medium and high temperatures. Welded structures made of rolled shapes last longer than castings. This equipment, as well as tongs used in handling, should be made of solid material, to avoid the possibility of water or oil from the quench being carried into the salt bath, where it could readily cause serious spattering or eruptions. For the same reason, all equipment and the parts to be treated should be completely dry before being placed in the bath.

For best results, all salt bath furnaces should be provided with automatic temperature control. For operations at low and medium temperature, bimetal thermocouples are satisfactory. However, for high temperatures (2000 F and above) pyrometers of the radiation type are preferred. These may be equipped with a closed-end target tube made either of ceramic or of heat-resistant metal. The tube is immersed in the bath and the lens of the pyrometer is focused on the bottom of the tube.

* *See also* the articles concerning furnaces, pages 267 and 273.

Table I. Nominal Compositions of Salts for Heat Treating

	Weight Percentage										Approximate Melting Point, deg Fahr	Recommended Heating Range, deg Fahr
Designation[a]	NaCl	KCl	$BaCl_2$	$NaNO_3$	$NaNO_2$	KNO_3	$CaCl_2$	NaCN	Na_2CO_3	KCN		
L-1	.....	.....	.....	*	40 to 50	50 to 60*	.....	.....	.....	.....	290	325 to 1200
L-2	.....	.....	.....	40 to 50	.....	50 to 60	.....	.....	.....	.....	440	500 to 1200 [c]
L-3	.....	.....	.....	96 min	.....	.....	.....	.....	.....	.....	700	750 to 1200 [c]
L-4	30 to 40*	*	.....	.....	.....	.....	.....	15 to 40	30 to 50	.....	1020	1150 to 1500
L-5	15 to 25	.....	25 to 35	.....	.....	.....	45 to 55[b]	.....	.....	.....	900	950 to 1400
I-1	45 to 55	45 to 55	.....	.....	.....	.....	.....	.....	.....	.....	1250	1350 to 1650
I-2	15 to 25	20 to 30	50 to 60	.....	.....	.....	.....	.....	.....	.....	1100	1250 to 1700
I-3	20 to 30	.....	70 to 80	.....	.....	.....	.....	.....	.....	.....	1300	1400 to 1700
I-4	10 to 20	.....	80 to 90	.....	.....	.....	.....	.....	.....	.....	1400	1500 to 2000
H-1	.....	.....	98 min	.....	.....	.....	.....	.....	.....	.....	1800	1900 to 2450
H-2	4 to 8	.....	92 to 96	.....	.....	.....	.....	.....	.....	.....	1600	1750 to 2300
C-1	4 max	.....	.....	.....	.....	.....	.....	96 min	4 max	.....	1150	1450 to 1750
C-2	*	.....	.....	.....	.....	.....	.....	.....	4* max	96 min	1150	1450 to 1750
C-3	*	5 to 10*	40 to 50	.....	.....	.....	.....	35 to 40	.....	.....	1150	1550 to 1750
C-4	15 to 25	.....	.....	.....	.....	.....	.....	45 to 50	20 to 30	($BaCO_3$)	1150	1500 to 1750
C-5	20 to 30	.....	15 to 25	.....	.....	.....	.....	30 to 40	20 to 30	.....	1150	1450 to 1650
C-6	10 to 15	.....	.....	.....	.....	.....	.....	70 to 80	10 to 15	.....	1150	1500 to 1750
C-7	15 to 25	.....	.....	.....	.....	.....	.....	60 to 70	15 to 25	.....	1150	1500 to 1750
C-8	40 to 50	.....	.....	.....	.....	.....	.....	40 to 50	5 to 10	.....	1150	1500 to 1750
C-9	.....	60 to 70*	.....	.....	.....	.....	.....	30 to 40	*	.....	925	975 to 1250
C-10	.....	.....	.....	.....	.....	.....	.....	55 to 65	.....	35 to 45	925	975 to 1250

* Either of the two materials marked by an asterisk in this line, or any mixture of the two materials, may appear in the percentage shown under the one material.

(a) These designations are used to identify the salt mixtures throughout the present article.

(b) This material is hygroscopic and should be added to molten salt with great care.

(c) The materials should not be operated above 1100 F in a fuel-heated pot.

Liquid Carburizing.* Liquid carburizing is a method of impregnating steel surfaces with carbon and small amounts of nitrogen to improve the strength and resistance to wear. As distinguished from plain cyanide-chloride mixtures, liquid carburizing baths are used for production of deep cases of high carbon, low nitrogen content. In composition these baths differ by the presence of alkaline earth metals (Ba, Ca, Sr), which function as catalysts to increase the rate of absorption of carbon. The presence of nitrogen in amounts produced by liquid carburizing baths is beneficial in improving the wearing properties of the case.

The economical operating range of liquid carburizing baths is from 1550 to 1750 F. Below this range such baths produce shallow, high-nitrogen, low-carbon cases comparable with those obtained in plain cyanide baths. Operations above 1750 F are not economical because of the rapid increase of cost for maintaining equipment, the necessity for preheating the work material, and the problem of selecting a suitable steel.

Baths compounded to operate within the range from 1550 to 1650 F belong to the "accelerated" or "activated" type. Operating with cyanide content of 17 to 23% and cyanate limit of 1% max, they produce carbon-nitrogen cases economically, as deep as 0.030 in.

"Deep-case" baths are characterized by lower cyanide content (7½ to 12%), presence of two catalysts, and ordinarily a higher content of catalyst. Operating within a range from 1600 to 1750 F, with cyanate limitation of 0.3%, the baths produce economically cases up to 0.250 in. deep. Nitrogen content diminishes at higher temperatures.

Though most of the carburizing baths contain sodium cyanide as the active element, a proprietary bath of calcium cyanide has been used successfully for many years. This bath gives good metallurgical results for medium case depths of 0.035 in. or less, and it is noteworthy that the percentage of calcium cyanide in the bath to produce such case depths is approximately 0.5%, or a small fraction of the percentage of sodium cyanide required to give comparable results in the other types of baths. The most serious drawback of the calcium cyanide type of bath is the necessity for using approximately 70% calcium chloride. This highly hygroscopic salt requires special precautions to avoid rusting of the finished work and also adds materially to the costs of furnace maintenance.

Liquid carburizing offers the following advantages: freedom from distortion; absence of "oxygenation" of case (often present in pack carburizing); close control of depth and characteristics of case; economy and flexibility of operation (since several batches of steel may be carburized simultaneously, each to a different case depth); and adaptability to mechanization and mass production.

Liquid carburizing baths are simple to operate if certain precautions are observed:

1 Formation of a carbonaceous cover is inherent in liquid carburizing baths. If this cover is inadequate, a natural flake graphite of high purity (1% SiO_2 max) should be used, or artificial graphite powder that contains not more than 2% ash.
2 In the bath a thick sludge forms, consisting of carbonates that have a high content of metal (reduced iron oxide from work, fixtures and pot; nickel and chromium from electrodes and thermocouple tubes; copper and other impurities). This sludge should be removed periodically by scraping the bottom of the pot with suitable tools.
3 For selective carburizing, high-density cyanide copper plating should be used on the surfaces not to be carburized. Copper-base paints are also frequently used to inhibit carburizing.
4 A nonsaponifiable oil should be used for quenching; otherwise drag-out salt may cause formation of soap and gumming.
5 Hot-spray washing with emulsion-type cleaners should be used to remove salt from the steel pieces and fixtures. To remove salt from deep recesses, the steel may be dipped for 2 to 10 sec in a 10% solution of inhibited hydrochloric acid, and then washed thoroughly in water and immersed in warm oil or a hot alkaline bath containing 4 oz of soda ash per gallon. In order to prevent the evolution of HCN gas that would result from the reaction between sodium cyanide and hydrochloric acid, the salt remaining on the work should be removed as thoroughly as possible before the steel is dipped in the solution of hydrochloric acid.

Two general types of furnaces are available for liquid carburizing: in one, the salt-filled pot is heated externally; in the other, the salt bath is heated by immersed electrodes. See page 275 for a description of batch and continuous salt bath furnaces.

Cyanide Hardening. Cyanide hardening produces a thin hard case on steel surfaces heated in molten cyanide salts and subsequently quenched. This case is caused by the absorption of both carbon and nitrogen from the salt. The presence of nitrogen in the case imparts greater hardness than is found in surfaces that contain additional carbon only. *See* page 694, in the CASE HARDENING SECTION, for a discussion of the chemistry of cyanide baths.

This method of heat treatment is used for the case hardening of finished or semifinished parts that require a case depth up to 0.008 in., and is widely used for all types of carbon and alloy steel parts. Cases deeper than 0.008 in. cannot be obtained economically with plain cyanide-chloride-carbonate salts. (*See* Liquid Carburizing, above, for cyanide baths used for deeper cases.)

The salts used for cyanide hardening are mixtures of sodium cyanide, sodium chloride and sodium carbonate. The sodium cyanide content, determined by operating conditions, varies from 15 to 30%; salt C-4 is typical.

Temperatures used in cyanide hardening range from 1300 to 1550 F. The temperature used depends on the material being treated, as well as on the core hardness desired. In general, parts are cyanided at temperatures just above the Ac_3 point, because at this temperature the penetration of carbon is more rapid and optimum mechanical properties are developed in the core when the metal is quenched.

The time cycle for cyaniding varies from a few minutes to approximately one hour. For most applications a time longer than one hour proves uneconomical, since the increase in case with increase in time is very slight. Usually the type and thickness of the case can be varied by varying the temperature, the cyanide concentration of the bath, and the time at temperature. High temperature and high concentrations of cyanide produce cases with high carbon and lower nitrogen content, while low temperature and low concentrations of cyanide produce cases with lower carbon and higher nitrogen content.

All cyanide mixtures are extremely toxic and great care should be taken lest these salts enter the human body. All parts being treated in molten cyanide baths should be clean and dry. Nitrates and nitrites, as well as other oxidizing agents, react explosively with cyanide; therefore it is imperative that all salts containing these materials be kept separate from cyanide mixtures.

In general, the same rules are followed for the maintenance and operation of cyaniding equipment as for any other salt bath equipment.

The maintenance of a correct cyanide concentration in the bath is extremely important. For the average case hardening application, a cyanide content from 20 to 30% has proved most economical. The optimum cyanide concentration for any particular application is governed by the specifications to be met. A periodic analysis should be made for sodium cyanide content, and salt of the proper cyanide content should be added in an amount sufficient to restore the predetermined concentration of the bath. Where drag-out is at a minimum, it will usually be found necessary to replenish with 96 to 98% sodium cyanide. Where drag-out is at a maximum, replenishing with a 45% cyanide salt will be sufficient. In most applications it will be necessary to use both a 45% salt and 96 to 98% sodium cyanide for replenishing the baths.

Neutral Hardening. The object of hardening carbon and alloy steel parts in a neutral salt bath is to develop a desired set of mechanical properties with no deleterious effect on the surface, such as scaling, decarburizing and pitting. Heating in a salt bath, followed by a water, oil or salt bath quench, can be used for the neutral hardening of all grades of carbon and alloy steels. The process is now in common use for gears, shafts, springs, screw-machine products, forgings, tools, dies and many other parts. However, this procedure may not prove economical for parts designed in such a way that they cannot be removed from the bath without excessive drag-out of salt.

Both fuel-heated and electric pot types of furnaces are used. However, the immersed-electrode type of furnace is generally preferred for neutral hardening, because the cost of maintenance is low. Pots externally heated by gas or

* For information concerning the chemistry of liquid carburizing and for data on the effect of duration of carburizing on the case depth, the reader may refer to page 692, in the CASE HARDENING SECTION.

oil must be made of heat-resisting alloys. Such pots can be produced only in relatively small sizes and the scale from them contaminates the bath. On the other hand, the immersed-electrode furnace ordinarily employs a refractory pot, built to any desired size or shape. These refractory pots have a long life, measured in years, and do not contaminate the bath. Neutral hardening is frequently obtained without the use of rectifiers in the bath.

Salts I-1, I-2, I-3 and I-4 are in common use for neutral hardening. Sometimes small amounts of sodium cyanide, silicon carbide or borax are added as a rectifier in order to avoid decarburization. It is important that the neutral salts should be stored in airtight containers, so that the moisture content before use will not exceed 0.5% by weight. Otherwise, an appreciable percentage of hydrochloric acid will be formed in the bath, not only affecting the work metal but also causing premature failure of electrodes and other metal parts in contact with the bath.

For neutral hardening, the bath should be free from sulfides, sulfates, oxides and carbonates and should contain no fluorides, especially where a refractory pot is used. The bath should never be overheated, since this may cause secondary reactions that will break down the solution.

A powdered graphite cover may be used on top of the bath to reduce both loss of heat and the amount of oxides forming in the bath. However, unless care is taken in removing the parts, this cover may introduce a cleaning problem.

A quick check that can be used to determine whether a bath is satisfactory, is to heat treat a high-carbon steel rod in the bath and to measure the hardness on the Rockwell 15-N and Rockwell C scales. If both scales check the same hardness, the bath can be considered satisfactory for most applications. A more accurate method is to take turnings, approximately 0.005 in. deep, off the surface of the rod and to determine the carbon content of the turnings. If the carbon content is the same as that of the bar before heat treating, the bath is neutral. Also the bar can be cut into sections and examined under the microscope to determine whether the surface has the same carbon content as the core.

Austempering, Martempering and Cyclic Annealing. Isothermal transformation diagrams, "S-curves", for certain commercial steels have been used as the basis for the interrupted quenching methods known as austempering, martempering and cyclic annealing. The quenching techniques employed in these heat treating processes are described in the article "The Quenching Process", page 620.

Quenching-bath temperatures and holding times are selected on the basis of the transformation diagram for the steel being treated. It is always necessary that means be provided, in the quenching bath, for cooling rapidly enough to remove heat from the piece at the desired rate, as determined by hardenability and mass, and to keep the temperature of the bath constant.

The quenching bath may he heated internally by gas or electricity. For dissipation of heat during quenching, a jacketed tank is often used. The bath is cooled by circulation of air at low pressure through the jacket, or by a spray of water against the outer surface of the quenching tank. Maximum speed of quenching is obtained by one or a combination of the following: an agitator that has a motorized propeller, a pump that forces salt against the work pieces at high pressure, or compressed air forced through the bath.

The salt that has proved most effective is a mixture of nitrates and nitrites that melts at approximately 290 F and has a working range from 350 to 1100 F, such as type L-1 in Table I.

Austempering involves quenching from the austenitizing temperature to a selected temperature above the M_s point and below the knee of the S-curve. The work material is held until transformation is complete, and then is cooled to room temperature.

Martempering consists in quenching to a temperature just above the martensite transformation range, and holding at this temperature long enough to equalize the temperature throughout the section (but not long enough to cause transformation to bainite); then cooling in air to room temperature.

Austempering and martempering offer special advantages where it is important to eliminate quench cracking and excessive distortion, which can readily occur during quenching in water or oil.

In any of the above procedures, it is important to select a steel with sufficient hardenability to ensure that the cooling rate of the quenching bath is greater than the critical cooling rate of the steel. Often the interrupted quench fails because of the selection of ■ steel with insufficient hardenability.

Mechanized salt bath furnaces are in operation for heat treating various sizes and shapes of steel forgings and castings. Generally these units consist of a neutral salt bath for austenitizing, and low-temperature salts for the quenching medium and for tempering if necessary. Both heating and quenching salts are water-soluble and are easily cleaned off after heat treating. *Caution.* Parts heated in a cyanide bath should never be quenched directly in the low-temperature nitrite-nitrate salts. Parts that have been liquid-carburized in cyanide baths should be transferred to a neutral salt bath before being placed in the low-temperature quenching bath.

In the hardening of steel, the formation of the softer structures should be avoided at the higher subcritical temperatures. In cyclic annealing, these soft constituents are formed intentionally by allowing transformation of austenite to take place at or above the knee of the S-curve. If a piece remains in the bath long enough to permit complete transformation, it may be cooled further at any rate desired.

Cyclic annealing in salt baths consists in heating the work pieces in a neutral salt to austenitizing temperature, then transferring them to another neutral bath and subsequently holding at a constant temperature until transformation has been completed. This process is practicable for annealing high-carbon and alloy steels when saving time is important. Salt baths also permit better control during annealing than the long-cycle, furnace-cooling process, and promote uniformity, more consistent results and a minimum of decarburization.

Heat Treating High Speed Steel Tools. Molten salts of various compositions are well adapted to all the operations in the complete heat treatment of high speed steel parts.

The critical operation in the hardening of high speed steel has always been the high-temperature heating. For salt baths to meet the requirements of this operation successfully, two major developments have been necessary.

1 The selection of a salt or mixture which will remain fluid and operable at the operating temperature, and which can be kept inert to the steel surface and can be washed easily from the treated work.
2 The design and construction of pot-type furnaces to hold the salt and serve reasonably long with a minimum of maintenance, at the extremely high temperatures involved (2200 to 2400 F).

The three chemical reactions possible in a salt bath at high temperatures are oxidation, carburization and decarburization. Most salts operable in the high-temperature range have little tendency either to oxidize or to carburize; in fact, they protect the steel from oxidation by blanketing it against contact with the air. The main problem then is decarburization.

The modern high-temperature baths are basically anhydrous barium chloride ($BaCl_2$) such as H-1 and H-2, contained in ceramic pots and heated by electrical resistance between two or more metal electrodes immersed in the molten salt. When freshly melted, this salt is inert to high speed steel surfaces and possesses the other characteristics necessary for operation at high temperature. After some use, however, the bath may become decarburizing because of accumulation of soluble and insoluble metallic oxides. When this occurs, deoxidation (rectification) may be accomplished by one of the following methods:

Silica. The periodic addition of sufficient silica (SiO_2) to the bath, in any desired manner, will keep the harmful oxide content down to a safe working level. The silica combines with the oxides to form silicates, which settle to the bottom of the pot in the form of a heavy viscous sludge that can and must be removed frequently. Addition of too much silica can be harmful to electrode life and safe operation of the furnace. Usually satisfactory additions of make-up salt contain between ½ and 5% of silica by weight.

Graphite Rod. A reasonably pure graphite rod, approximately 2 in. in diam, reduces the oxides in the bath to pure metal, which adheres to the rod. The exact method of using a graphite rod varies

somewhat, depending on the construction of the furnace. In some furnaces the rod is placed in special recesses in the pot walls and is submerged completely; in others, the rod is held by some clamping device above the top of the bath and is immersed vertically. In any type of furnace the rod should be withdrawn periodically, cooled to room temperature, and scraped to remove picked-up metal globules. This method is slower and less effective than the use of silica, but has the advantages of producing very little sludge, of being harmless to electrode life, and of maintaining higher fluidity in the bath.

Combination Method. A graphite rod used alone in straight barium chloride may not always be sufficient to prevent decarburization completely. In such instances very small amounts of silica may be added regularly to supplement the action of the graphite rod. This arrangement may prove to be the most generally acceptable method of rectification, since it combines the features of a minimum amount of sludge and bath viscosity with the excellent deoxidation characteristics of silica.

As a check on the decarburizing tendency of the high-temperature bath, test specimens should frequently be hardened by quenching in oil. A file-soft surface indicates a need for more rectification. This test may be supplemented by chemical analysis.

The soluble barium oxide (BaO) content (alkalinity) of the bath is considered the most active decarburizing agent and should be kept less than 3% by adequate rectification. For determining the content of BaO a 5-g sample from the bath may be dissolved in water and then filtered. The filtrate is titrated with N/10 hydrochloric acid, using a phenolphthalein indicator. The percentage of BaO can then be calculated:

$$\frac{\text{cu cm N/10 HCl} \times 0.00765}{5} \times 100 = \%\ \text{BaO}$$

The insoluble metallic oxides (of iron, chromium, nickel and such) have a slighter decarburizing effect and in general are kept automatically at less than the safe maximum of about 5%, by rectification based on the above test for BaO.

One of the most desirable features in the use of salt baths for hardening high speed steel is the fact that the work pieces can be supported, so that a minimum of distorting stress is applied, both while the material is in the bath and while it is being transported from one bath to another. This fact alone tends to reduce greatly the amount of distortion that occurs otherwise in heating tools of delicate shape to the very high temperatures required.

During salt bath operations small tools may be handled conveniently in baskets. For best results, it is recommended that the baskets be equipped with some means of separating individual pieces to avoid packing them together in a tight mass. Long slender parts, which may not need to be hardened throughout their length, may be supported by fixtures of the screw or clamp type, so that the work pieces hang vertically in the bath. Other types of work material may be wired, either singly or in groups, and suspended from long-handled hooks that can be laid across the top of the furnace. Since they must go through the high-temperature bath continuously, some fixtures for high production are made of heat-resisting alloys, although usually cheaper material, such as plain iron wire or low-carbon steel, is satisfactory for holding the work pieces.

In the hardening of high speed steel, several baths are used in sequence. The salts in these baths should be so related that among other factors, the carry-over from one to another will not be harmful. If there is doubt concerning possible reactions caused by carry-over, correct information should be obtained from the manufacturers of salts.

The bottom of the pot that contains the bath should be scraped periodically with a long-handled, perforated ladle to remove sludge. Dry powdered salt should be added as needed to maintain the bath level. When rectifiers are used, the removal of sludge will be necessary more frequently than otherwise.

All salt baths should be kept molten as much of the time as possible. During nights and week ends, the temperature is set down to a point just above the melting temperature of the salt and the pot is covered. Very little input of heat will be required to hold the baths in this condition.

Preheating. Either salt I-1, I-2, or I-3 may be used. Rectification is usually unnecessary where a ceramic pot is used. The operating temperature is usually between 1500 and 1600 F.

High-Temperature Heating. Either salt H-1* or H-2* may be used in a ceramic pot heated by internal electrodes made of 28% Cr iron, pure nickel, or a high-nickel alloy.

Electrodes that contain nickel will have the longest life but will cost more than the iron-chromium alloy and will cause nickel to be deposited either in or on the surface layers of the work pieces. If the silica content of the bath is held to a very low value and deoxidation is accomplished by a graphite rod, this tendency to coat the work with nickel may be minimized but whether it can be eliminated altogether is doubtful.

The hardening temperature depends on the grade of steel being treated. It is recommended that the control instrument be set about 25 to 40 degrees *lower* than in radiant furnaces to get equivalent results, because the charge will actually come closer to the control temperature in salt baths than in gaseous atmospheres. The steel is usually brought just to the operating temperature and not soaked. It is generally agreed that the temperature of the charge will become equalized with the salt temperature before the bath comes back to the control point. Therefore it is customary to consider that when the control instrument throws off the power, the steel is at the operating temperature and ready to be quenched.

Quenching. Moderately small pieces might be hardened successfully by quenching in oil or by cooling in still air from the high temperature, but a molten salt bath is recommended for parts of all sizes for three reasons: (1) to ensure that cooling through high temperature ranges is sufficiently rapid, (2) to equalize the temperature throughout the part before cooling further (principle similar to martempering), and (3) to wash off the $BaCl_2$, which is less easily dissolved in water than are most quenching salts.

Salt L-4 or a modification thereof is ordinarily used for quenching. The use of cyanide is largely a matter of preference. The presence of cyanide results in easier washing and somewhat greater fluidity at low temperatures. It also produces a file-hard carbon-nitride case about 0.002 to 0.003 in. deep on the surface of the material. This case-forming characteristic of cyanide is sometimes considered good insurance that any soft surface caused by decarburization at the high temperature, will be counteracted in a quenching bath that contains cyanide; others doubt the desirability of such cases, especially on unground tools.

Quenching baths should be operated below 1200 F, with 1250 F as an absolute maximum. The maintenance of correct temperature is complicated by the fact that most suitable salts when fresh have a melting point not lower than 1000 F, and this melting point rises when $BaCl_2$ is introduced. Consequently, the tendency is to keep increasing the temperature to keep the bath fluid. In baths that contain cyanide, high temperature may cause a crust to form on the surface, from reaction of the cyanide with $BaCl_2$. The remedy is *not* to raise the temperature further in an attempt to melt the crust, but rather to bail out salt and lower the temperature to 1150 F, keeping the bath fluid at this temperature by frequent additions of fresh salt.

All quenching baths accumulate considerable sludge of $BaCl_2$ in the bottom. Unless this sludge is removed frequently, it will become caked and difficult to scoop out.

The time required for holding the steel in the quench is usually about the same as during the high-temperature cycle. It is recommended that pieces of normal size be cooled to room temperature from the quench by hanging in still air.

All work-holding devices that enter the quenching bath, should be washed thoroughly and dried before being put back into the preheating bath.

Tempering. Either salt L-2 or salt L-5 may be used.

Tempering temperatures may vary between 1000 and 1200 F, depending on the hardness desired. The duration of tempering depends on the temperature and the results desired, but in general should be about 1½ to 2 hr total time for each tempering operation. After having been tempered, the work should be air-cooled to room temperature before the salt is washed off in water. If calcium chloride ($CaCl_2$) is present in the salt, special precautions

* Rectified in a suitable manner

should be taken to guard against subsequent rusting. The first washing should be followed by a short pickling treatment in an inhibited mineral acid or 10% acetic acid, plus one or two more rinsing operations with a final dip in an alkaline cleaning solution.

"Nitriding". This operation may be performed in any one of a variety of mixtures that contain fairly large percentages of cyanide. Salt C-10 is commonly used.

These "nitriding" baths are usually not very effective until they have aged by standing molten for a period of time to permit the formation of at least 5% cyanate. The bath should be operable at this stage and the cyanate content should be kept at more than 5% during operation, by periodic bailing out and additions of fresh NaCN or salt mixture. Occasionally it may be necessary to remove excess carbonate salts by cooling the bath to just above the melting point (about 850 F) and scooping the precipitate out of the bottom.

The "nitriding" operation is usually performed on finished or nearly finished tools. The usual temperature for the operation is 1000 to 1050 F and the duration of immersion may vary from 10 min to 1½ hr, depending on the type of tool and the results desired. The main purpose of this treatment is to produce an extremely hard, wear-resistant case on the ground surface, but it must be understood that this may cause some brittleness in tools of small size or delicate shape.

Annealing. As a means of heating both steel and nonferrous alloys for annealing operations, the salt bath is steadily widening its field of usefulness, principally because of the rapid rate of heating and the preservation of the surface of the metal. The principal application in this field lies at present in the stress relieving or process annealing operation, in which the metal or alloy is recrystallized after cold work and is thus softened for further cold forming or finishing operations. In the wire industry, salt bath annealing is used for softening low-carbon, high-carbon, high-alloy and stainless steels between passes, and is currently employed in heating austenitic stainless steels for the final softening quench. In the nonferrous field, salt baths have the following typical uses: the annealing of sterling silver at various stages in the forming operations, in order to soften it for further processing; and the annealing of aluminum alloy wire and shapes, as well as cupro-nickel condenser tubing and the like.

The salt bath method of process annealing has these advantages: elimination of all atmosphere and of the accompanying problems of oxide, pitting, decarburization and the like; almost no alteration of the surface condition; uniform heating of all parts of the charge; a very rapid rate of heating in comparison with other methods, and consequent reduction in floor space required for a given installation. Disadvantages include the rinse necessary to remove adhering salt; the maintenance of electrodes, pot and salt in a suitable condition for operation; and the need for a continuous flow of material at all times to ensure economical operation.

The newer installations for salt baths are entirely of the internally heated, immersed-electrode type, having metal pots for low-temperature service, and refractory pots for high-temperature service. In the annealing of wire, the tightly bound coils are strung on a horizontal bar, if the annealing temperature is low and the gage of wire heavy. If there is danger of sagging into an oval shape, a condition known as "horsecollaring", the coils are strung on a saddle fixture that supports the upper half. For handling partially formed articles, trays made of coarse wire mesh or special fixtures are employed. Immediately after removal from the furnace, material is immersed in a strong stream of hot water, which rapidly dissolves the adhering salt. Light pickling is generally necessary before the next drawing or cold forming operation.

The actual cycle employed in process annealing depends on the material being handled, the amount of prior cold working and the amount of softening required for subsequent processing. In annealing practice for steel, the carbon and engineering alloy grades are heated to a temperature just below the transformation range and are removed from the salt bath as soon as the entire charge has reached temperature. Temperatures range from 1250 to 1325 F, depending on the gage of the wire and the duration of heating (from 30 to 40 min in typical installations, depending on the weight and tightness of the coil). From four to six 250-lb coils are annealed in a batch and handled together through the subsequent rinsing, pickling and liming operations in preparation for further drawing.

The intermediate grades of stainless steel are treated in the same temperature range, but are generally held at temperature for time intervals up to 30 min before removal from the bath; for example, type 430 stainless steel is heated to 1325 F and held 30 min before discharge, while type 416 is held 10 min at 1275 F. The austenitic stainless steels and certain nickel alloys are process annealed at about 1850 F; austenitic stainless steels may be quenched finally from 2100 F after being heated in such a bath. The temperatures and time periods that are used in the stress relieving of nonferrous alloys cannot be stated precisely since they depend largely on composition, amount of prior cold work, and the next operation to be performed. Sterling silver, for example, is completely softened at 1225 F; the total heating cycle for tableware and other small articles does not exceed 10 min. For other operations, however, temperatures ranging from 700 to 900 F are used satisfactorily.

The carbon and engineering alloy steels are usually heated in a molten salt mixture composed of equal parts of Na_2CO_3 and KCl. The same salt may be used as successfully if the intermediate grades of stainless steel are processed through the same installation. This salt does not break down rapidly and requires no rectification. The bath should be sludged regularly and the pot should be drained and cleaned about twice yearly in continuous operation. The H-2 salt mixture is used for the high-temperature treatment of austenitic stainless steels and nickel alloys. The low-temperature carbonate-chloride mixture is widely used in the annealing of most nonferrous alloys.

Brazing Steel and Copper Assemblies. The molten salt bath may be used as a medium for joining steel or copper metals by nonferrous brazing, simply by dipping the assembly into the bath. This process is recommended only for brazing assemblies that can be washed readily, after the brazing operation, in order to remove the traces of solidified salt adhering to the joint area. The process is satisfactory for brazing with almost any bonding agent, such as silver solder, bronze, brass or copper, but is not satisfactory for low-temperature solders that flow below 900 F. Although all the bonding agents mentioned above may be used, silver and copper alloys have proved most satisfactory and efficient when a salt bath is employed as the heating medium.

During the operation, the assemblies to be brazed should be fitted tightly together with not more than 0.004-in. clearance and with a shim of brazing metal between the parts. A wire of small diameter may be wound around the outside of the joint, instead of the shim between the parts. During the melting, the wire is drawn into the joint by capillary action. It is important that the assembly remain in correct alignment while heating; this sometimes requires special fixtures.

The dip brazing in the salt bath is accomplished in seconds rather than the minutes required by other processes; hence a rather small furnace will produce a large output. Moreover, no cooling chamber is required after the brazing cycle, because the work material is either cooled in the air or quenched directly from the brazing temperature, thus reducing requirements for floor space to a minimum.

If the assembly is large or long and brazing is required only on one end, the salt bath has the definite advantage of local heating, making it unnecessary to heat more than the section to be brazed. This feature accounts for the present general use of salt baths for brazing the return bends on heat exchangers. Each end of such a unit may have 20 to 100 joints, which are brazed simultaneously, in one minute or less, by immersing the end of the assembled unit in the bath.

The operation of the process is relatively simple. Because of the high temperatures necessary for copper brazing, salt furnaces that have internal electrodes are recommended; the preferred salt is H-2. When the carbon

rod is used as a rectifier (*see* section on Heat Treating High Speed Steel Tools, page 286) the salt is rendered nondecarburizing for an indefinite period. The temperature should be controlled closely, according to the size of the assembly and the parent metal used.

A temperature of 2050 F is recommended for the copper brazing of steel. After heating long enough to "flow" the copper, it is advisable to quench the assembly in another salt bath (L-4 or L-5 salts) operating at 1000 to 1150 F. Occasionally this quenching bath is used for preheating also. By selecting the proper transformation temperature and time in the quench, it is possible to anneal the parent metal to any desired pearlitic structure isothermally.

The same process may be employed for all other bonding metals, except that the "flow" temperature will vary according to the metal used. When brass is used as the bonding metal, very close temperature controls must be employed. The zinc in brass may oxidize at a temperature slightly above the melting point. This results in a bond of low quality; furthermore the zinc oxide contaminates the bath. For brazing the metals that melt at lower temperatures, salts I-1, I-2 and I-3 are recommended.

Another interesting use for salt baths is in the simultaneous carburizing and brazing of a steel assembly. An activated carburizing bath, such as salt C-5, is used and operated at about 1675 F. When the brazing material—usually Muntz metal (60% Cu, 40% Zn)—is assembled at the joints, the steel assembly is immersed in the bath and left there for the time required in order to produce the desired depth of case. During this time, the brass melts and enters the joints. The assembly is then removed and quenched in water. By this method, brazing and carburizing are accomplished in a single operation.

Brazing Aluminum and Aluminum Alloys. For dip brazing, aluminum or aluminum alloy parts are assembled on a suitable rack, when the filler material is in place, and are then dipped into a molten salt bath held at the correct temperature to melt the filler material and cause it to flow into the joints. The process is peculiarly adapted to the joining of thin-gage aluminum or aluminum alloy assemblies, including aircraft heat exchangers, thin tubing, radiators and similar assemblies that permit complete drainage of the molten flux after brazing.

The advantage in dip brazing lies in the fact that many joints, particularly line-contact joints such as exist in heat exchangers, can be made in one operation. The chief disadvantage is the drag-out of flux. Parts to be dip-brazed should be designed so that alignment during brazing is obtained by the fit of the parts rather than by holding the pieces in jigs or fixtures.

It is important that the flux be held in a container that will not cause contamination. Certain ceramic linings have been found suitable and nickel pots are satisfactory, but a service life of about six months is all that can be expected from the nickel.

The flux may be heated either externally by gas or internally by immersed electrodes. Control of temperature within 5 F of the brazing temperature, is essential. The bath should be large enough so that the chilling effect from immersing the parts to be brazed, does not decrease the temperature too much. Increased speed and smoother joints are obtained if the parts are preheated to the range between 900 and 1000 F before they are dipped into the molten flux. This preheating, usually a separate operation, prevents local freezing, distortion, inconsistent joining and entrapment of flux in small openings. In some installations the work is preheated directly over the salt bath and is then lowered into the molten bath at the proper temperature, as shown in Table III.

The assembled parts are dipped from 30 sec to 3 min, depending on the shape and thickness.

The flux bath consists of a mixture of chlorides and fluorides having suitable melting point, density and fluxing characteristics. Two fluxes are now available as No. 34 and No. 53 brazing fluxes.

Addition of flux, to replace drag-out or to increase the depth, will introduce moisture. A coil or piece of aluminum sheet dipped into a freshly melted bath of flux, will eliminate the moisture before the brazing operation. As long as moisture is present, hydrogen, evolved by reaction of the water with aluminum, will ignite on the surface, producing small flames. The source of this moisture is water chemically combined in the flux constituents, and unless the bath is dehydrated, the moisture will attack the aluminum parts. During the period when a dip-brazing bath is in use, metallic impurities may enter the bath, making periodic cleaning necessary. For this purpose aluminum sheet is dipped into the bath at intervals determined by the appearance of discoloration on the work material during brazing. Since a certain amount of flux is lost by drag-out, partial purification results from the continuous addition of flux to the bath.

Table III. Brazing Temperatures for Some Aluminum Products

Brazing Material	Temperature, deg Fahr
2 S	1160 to 1185
3 S	1160 to 1185
No. 1 Brazing sheet	1160 to 1185
No. 2 Brazing sheet	1160 to 1185
53 S	1060 to 1090
61 S	1060 to 1090
No. 11 Brazing sheet	1090 to 1140
No. 12 Brazing sheet	1090 to 1140
No. 21 Brazing sheet	1090 to 1120
No. 22 Brazing sheet	1090 to 1120

Often the filler material for the assembly is supplied by special brazing sheet. A thin coating of filler metal is bonded to one or both surfaces of the sheet in the mill. Parts formed from this sheet can be joined to coated or uncoated sheet by dip brazing. The sheet is available as an alloy that cannot be heat treated (No. 1, 2, 11 or 12 brazing sheet) and also as an alloy that can be heat treated (No. 21 or 22 brazing sheet). The heat treatment may be accomplished directly by quenching from the dip brazing bath or, if the design is such that direct quenching will result in breakage or distortion, the heat treatment may be conducted as a separate subsequent operation.

After the brazing operation, it is always essential that the joints be properly cleaned in order to remove flux residue that might cause corrosion during subsequent exposure to moist environments. The first step in cleaning is immersion in water—preferably boiling—which will remove the major portion of the flux. Then the work is dipped into concentrated nitric acid for 5 to 15 min, depending on the design, drainage and accessibility of the parts of the assembly. The acid is removed by a rinse in hot water. An alternative cleaning method is to dip the work material for 5 to 10 min in a solution of 10% nitric acid plus 0.25% hydrofluoric acid at room temperature and then to rinse with water. Brazed parts with thin sections, 0.010 in. and lighter, and also parts where maximum resistance to corrosion is important, should be immersed in hot water and then dipped in a solution of 10% nitric acid and 10% sodium dichromate for 5 to 10 min, before a final rinse in hot water.

Heat Treatment of Aluminum and Beryllium-Copper Alloys. Salt baths are employed as the heating medium in the solution heat treatment of certain aluminum alloys, and are also used extensively in the precipitation or aging treatment of beryllium-copper alloys. These baths heat the alloys rapidly and uniformly.

The use of salt baths is more desirable for the heat treatment of wrought products than for castings, since castings are generally irregular in shape and have relatively rough surfaces that greatly increase losses of salt through drag-out. Also, removal of salt from the surface of a casting is difficult and sometimes impossible; hence severely corrosive conditions may result.

Because of the more rapid heating and the consequently short cycles used in a salt bath, clad aluminum objects can be heat treated with a minimum of diffusion of the pure aluminum coating into the base alloy; thus such work retains its resistance to corrosion. The complete immersion of the parts prevents bare aluminum alloy from blistering as it sometimes does in air-convection furnaces.

When parts such as stampings and extruded and formed shapes are treated in salt baths, distortion is noticeably less, because of the uniform heating and the possibility of quenching the parts individually. A further advantage is

that salt baths permit parts that have widely varying gages to be treated simultaneously.

Because of the widely varied shapes and sizes of aluminum aircraft parts to be heat treated, and because most of these parts are given further forming operations after solution heat treatment, the use of elaborate fixtures is not practical. Ordinarily, parts are suspended individually or on small racks and are handled manually.

Small beryllium-copper parts, hardened in salt, are commonly held in steel fixtures, particularly if they are formed parts and if dimensional stability is of prime importance.

Aluminum. Time-temperature cycles for the solution heat treatment of aluminum in salt baths depend on the alloy and gage. The range from 880 to 980 F includes satisfactory temperatures for virtually all the wrought alloys heat treated in salt baths. Time cycles range from 10 min to 1 hr, depending on the gage. The time in the bath may be considered the time "at temperature" under normal operating conditions.

The salt generally used is sodium nitrate (L-3). However, if the salt bath is to be used for both annealing and heat treatment, a mixture of sodium nitrate and potassium nitrate (L-2) is used, because it has a lower freezing point. Commercial grades of these salts are suitable for heat treating baths. The addition of about ½ oz of sodium dichromate or potassium dichromate per 100 lb of nitrate, is recommended for inhibiting corrosion from residual salt. After continued use of the salt bath, the heat treated material may show evidence of etching or corrosive attack, when removed from the quench water; this is a warning that more dichromate should be added. An alternative method is to check the nitrate bath and add potassium dichromate so that the pH of a 1% solution never exceeds 7.5. Care must be taken to ensure that the potassium dichromate is thoroughly dry before it is added.

Several fatal and disastrous explosions* have occurred during the heat treatment of aluminum alloys in nitrate baths, while relatively few explosions have been reported in the use of nitrate baths for ferrous products, probably because lower temperatures are used for ferrous products. Since nitrate salts are highly oxidizing, special precautions must be taken to prevent any reducing salts, such as cyanide, from being added by mistake, with explosive results. A bath of nitrates should never be used at temperatures above 1100 F, because of the possibility of violent reactions. The reaction with iron may start at a temperature as low as 1100 F and is vigorous at 1600 F. This danger from iron pots is caused particularly by local overheating, which sometimes results when sludge or sediment accumulates at the bottom of the pots and the heating is applied externally through the bottom. This kind of attack is less serious when the pots are made of certain alloy steels.

Aluminum is reported to react vigorously with the nitrate at 1500 F and in some instances as low as 1350 F. Under no circumstances should magnesium-base alloys ever be heat treated in nitrate, nor should aluminum alloys that contain more than a few per cent of magnesium, be heat treated in this manner.

Beryllium Copper. Precipitation hardening of beryllium copper is accomplished between 600 and 700 F. Time periods may range from 1 to 3 hr at 600 F, to as low as 15 min at 700 F. Salts used in these treatments are nitrate-nitrite mixtures (L-1).

The temperature of the bath and the duration of immersion must be controlled carefully. At the higher temperatures, control becomes more critical. After the heating cycle, parts are quenched in water to remove salts and allow handling, but not for any metallurgical reason other than to control definitely the length of the heating cycle.

Cleaning and Descaling Processes. Sodium hydride, a strong reducing agent, is employed in this process to reduce metallic oxides, such as annealing scale and mill scale, thereby expediting the cleaning of metals and alloys during the processing and fabrication into finished articles. When the reducing reaction stops, there is no further action; consequently there is no attack on the base metal. All metals and alloys are amenable to this treatment except those that react with fused caustic soda or that have physical characteristics which are affected adversely by the temperature of the bath (700 F plus or minus 20 F). Materials that react slowly with fused caustic soda, may be treated during short cycles if satisfactory results are obtainable. The scale produced in oxidizing atmospheres is reduced quite readily; on the other hand, it is reported that the scale produced on some high-chromium irons in highly reducing atmospheres is sometimes difficult to remove. Most oxides that form scale are reduced to the metal. Oxides of metals that form acid radicals are only partially reduced, but the action is sufficient to produce entirely satisfactory results.

Fused caustic soda is used as a carrier bath for the sodium hydride. The concentration of sodium hydride is kept within the range of 1.5 to 2% by weight and is produced "in place" by metallic sodium and hydrogen reacting in open-bottom chambers partially immersed in the bath. These chambers, called "generators", are arranged where convenient on the sides or ends of the carbon steel tank that contains the descaling liquid. Sodium bricks, weighing either 2½ or 5 lb, are fed at regular intervals to the generators into which hydrogen or dissociated anhydrous liquid ammonia is introduced near the bottom, at a rate adjusted to the rate of adding sodium.

No pitting occurs during descaling and it is not possible to overtreat the work material. Pickling losses are eliminated since there is no attack on the metal in the descaling bath. The working temperature (700 F) is below the transformation range of most steels, which makes treatment possible without changing the structure of alloys.

The process has been used commercially to descale the following metals and alloys:

SAE and AISI steels	Chromium-nickel stainless steels	Inconel
Carbon steels	High speed tool steels	Silver
Cast iron and steel	Silicon steels	Copper
Chromium stainless steels	Nickel	Stellite

Sodium hydride descaling baths are also being applied to iron castings, since this type of bath readily removes any sand entrapped in recesses or adhering to the surface. Installations have been made for cleaning steel stampings, such as the frames for automobile windows and autobody trim. Here the function is not descaling, but rather the rapid and effective removal of surface dirt or stain caused by previous manufacturing operations.

Sodium and hydrogen react directly to form sodium hydride, as shown by the following equation: $2Na + H_2 = 2NaH$. Theoretically, each pound of sodium requires 7.8 cu ft of hydrogen. When dissociated ammonia is employed as the source of hydrogen, approximately 12 to 15 cu ft of the dissociated gas is required (75% H_2 and 25% N_2 by volume). The sodium hydride that is formed, is dissolved in the fused caustic carrier bath and emerges from the bottom of the generator. The sodium hydride is then distributed uniformly throughout the bath by the convection currents, without auxiliary means. Since the sodium hydride bath is quiescent and does not give off irritating fumes or vapors, hooding is unnecessary.

Reactions between sodium hydride and scale are illustrated in the following equations:

$$4NaH + Fe_3O_4 = 3Fe + 4NaOH \quad (1)$$
$$NaH + CuO = Cu + NaOH \quad (2)$$
$$NaH + Cr_2O_3 = 2CrO + NaOH \quad (3)$$

Complete reduction is shown by equations (1) and (2) while partial reduction is shown by equation (3). The sodium hydride reduces the scale in all these examples to the metal or lower oxide, simultaneously forming caustic soda. Since the carrier bath is caustic soda, no undesirable materials are made that necessitate replacing the bath.

A typical treating cycle consists of the following steps: sodium hydride treatment, water quench, water rinse, acid dip and water rinse.

Work to be processed is placed in baskets or on suitable racks; careful arrangement is unnecessary provided the bath has free access to and from the surfaces that require treatment. Optimum duration of treating may be established readily by experiment and usually ranges from 8 to 20 min for large batch operations.

When the scale has been reduced completely, the work

* For a discussion of Safety Precautions in the Use of Salt Baths, the reader may refer to the February 1947 issue of *Metal Progress*.

is removed from the bath, is allowed to drain and, while still hot, is immersed in water. A large portion of the reduced material is dispelled during this operation.

A high-pressure water hose is used in rinsing away loosely adhering material and washing off any caustic soda that remains.

A short dip in acid produces bright surfaces, such as are required for drawing, rolling and forming operations. This dip may be eliminated when parts are cleaned before inspection, machining and the application of hot dip coatings.

A high-pressure water hose is used in rinsing away smut and acid that remain after the brightening dip. A clean bright surface is obtained by this operation.

Other salt-bath processes that do not employ sodium hydride as the active element are now in commercial use for descaling, cleaning, and preparing the surface of metals. In one of these processes, the bath consists essentially of sodium hydroxide. When a direct current is passed through this bath, oxidation is effected at the positive pole and reduction at the negative pole. The metal to be processed becomes one pole of the electrical circuit, and the tank becomes the other. By means of a reversing switch, the polarity of the work material can be changed from positive to negative. The timing and sequence of oxidation and reduction depend on what material is being processed and what kind of surface is desired.

Another bath, for descaling stainless and alloy steels, as well as nonferrous metals, consists essentially of caustic soda. No sodium hydride is used, but a still undisclosed addition is made, and the bath is operated at 900 to 1000 F, instead of at 700 F as in the sodium hydride process.

Miscellaneous Applications. In addition to the foregoing applications, salt baths are used for various other purposes.

Tempering Carbon and Alloy Steel Parts. For this application a bath composed of nitrates and nitrites is usually employed, such as L-1 or L-2. The eutectic mixture has a melting point of 275 F, and the useful operating range of the bath is from 300 to 1100 F.

Coloring Steel Parts. When nitrate baths, with or without the addition of manganese dioxide, are used in the temperature range from 600 to 1000 F, they impart the characteristic blue colors to prefinished parts. The time of immersion varies with the temperature and with the size of the pieces, but rarely exceeds 6 min. Care must be taken not to leave the metal in the bath longer than necessary to produce the blue color desired. Otherwise the color will be destroyed, changing to black.

Removing Enamel. The formed steel shapes from defective enamelware, can be recovered for re-enameling. This is accomplished by immersing the pieces in a molten bath of sodium hydroxide, kept at a temperature of approximately 900 F. The enamel is removed in a matter of minutes by the reaction of the caustic soda. However, the removed enamel does not dissolve in the caustic bath. Instead, the bath is allowed to remain quiescent for a period, during which the suspended enamel settles to the bottom, where a pan is provided to collect it.

Heating for Forming and Forging. The use of salt baths for heating steel shapes before forming or forging, is of recent origin and the true merits of the practice have not yet been clearly established. During World War II certain salt baths were used successfully for heating selectively the ends of high-explosive shells, for the nosing or closing-in operation. The selectively heated portion of the hollow forging was then subjected to combined upsetting and forming operations by dies in a press. Salt baths are also used occasionally for certain forming operations. The problem presented by the accumulation of salt in the dies, must be solved before the salt bath can be utilized for any forging application.

Cleaning Metal Molds. Another recent innovation is the use of a nitrate bath in the temperature range from 600 to 800 F, for removing residual rubber, carbon black and lubricants from rubber molds, both cast iron and aluminum. The molds to be processed are simply immersed in the bath from 10 to 30 min and then quenched in water.

Lead Baths

By R. B. Schenck*

THE various liquid heating mediums employed in the heat treatment of steel fall into three general classes: metals, salts and oils. Of all the metals, lead is the only one that has proved suitable as a commercial bath material. Lead is used for this purpose in its commercially pure form, without the addition of other metals. The salt bath materials are usually mixtures of two or more different salts and cover a wide range of composition. The oils are limited to low-temperature applications well below the melting point of lead and will not be discussed here.

Lead has little, if any, application in the heat treatment of nonferrous metals and alloys, many of which are actively attacked by molten lead.

Properties of Lead

Melting point, deg Fahr	621
Heat to raise metal from 60 F to melting point, Btu per lb	18
Latent heat of fusion, Btu per lb	11.3
Mean specific heat, liquid state	0.034
Boiling point, deg Fahr	3170
Unit weight, solid, lb per cu in	0.41
Unit weight, liquid, lb per cu in	0.37

Comparative Properties of Lead and Salts.* *General Comparison.* In comparing the properties of lead with those of the commercial salt bath materials, there are certain marked characteristics which differentiate the two. Lead is higher in specific gravity, higher in thermal conductivity, higher in electrical conductivity, lower in specific heat and lower in latent heat of fusion. The melting point of lead is lower than that of any of the salts used for hardening, but higher than that of most of the tempering salts. Lead has a total working temperature range of about 650 to 1700 F. The salts, as a class, have a range of approximately 350 to 2400 F. Lead oxidizes readily but is otherwise stable and has no appreciable chemical action on the metals with which it comes in contact. Many of the salts tend to decompose and some have various chemical effects on the metals. Lead does not adhere unless the stock is impure or oxidized, but the salts cover the work metal with a film of bath material. Lead is not hygroscopic, whereas the salts all possess this property to a greater or lesser degree. Lead has a much higher heating rate than any of the commercial salt bath materials.

Specific Gravity. Steel sinks in all of the salts, but floats on lead unless immersed by suitable fixtures. The specific gravity of molten lead is approximately 10, while that of the salts is about 2.

Thermal Conductivity. The high thermal conductivity of lead is one of its most valuable properties, tending toward rapid heating, high output, uniform temperature throughout the bath, and high thermal efficiency.

Electrical Conductivity. Because of its high electrical conductivity, lead does not lend itself to internal resistance heating by immersed electrodes. The salts, however, are readily heated by this method, which offers greatly increased pot life and improved temperature control as advantages over external heating. Both metal and ceramic pots are used in electrode heating.

Specific Heat. Because of its low specific heat, the thermal capacity of lead is less than that of most of the salts even on the basis of volume. Low thermal capacity results in greater temperature drops where cold stock is intro-

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*For information concerning the use of salt baths in heat treating operations, see the article on page 283.

duced, and decreases thermal stability. Low thermal capacity also tends to reduce time and fuel in bringing a cold pot up to temperature; also it probably increases thermal efficiency in batch operation, and maintains a greater average temperature differential between the pot and the source of heat.

Latent Heat of Fusion. The low latent heat of fusion of lead tends to cause the formation of heavier layers of solidified bath material when cold stock is placed in the pot. Independent of melting point and other considerations, these layers actually form more extensively in all salt baths, as a result of the much lower thermal conductivity of the salts. On the basis of volume, the number of heat units involved is less for lead than for most of the salts; consequently, less time and fuel are required in bringing a cold pot up to temperature.

Melting Point. The melting point of a bath material not only determines the minimum temperature of operation, but also has a pronounced effect on the heating rate when cold stock is charged. The solidified layer of bath material that forms on cold stock, in lead and salt baths, must be completely melted before the temperature of the stock can rise above the melting point of the bath. The lower the melting point, the less will be the weight of frozen material formed. The greater the difference between the melting point and the bath temperature, the more rapidly this layer will be removed. Heat conductivity plays an important part in this connection, with the result that, for the same temperature differential, the frozen layer melts much more rapidly in lead than in salt baths. Therefore, lead can be used satisfactorily at temperatures closer to the melting point, and the heating rate is less adversely affected at higher temperatures. Other factors being equal, a bath operating at 1500 F with a melting point of 700 F will heat more rapidly than one operating at the same temperature with a melting point of 1300 F. In some instances where intricate parts would otherwise be inclined to warp or crack in hardening, the retardation of heating because of the solidified layer is distinctly advantageous. Preheating the stock to temperatures below the melting point will decrease the amount of frozen material, and temperatures above the melting point will, of course, eliminate the solidified layer.

Temperature Range. The wide temperature range of lead, approximately 650 to 1700 F, makes the lead bath available for the majority of hardening and tempering operations. The lower limit depends primarily on the melting point; the upper limit is determined by the ability of the pots to stand up and the ability of the coverings to give adequate protection against oxidation.

Some of the salt mixtures are used as high as 2400 F for the hardening of high speed steel, and others are employed for tempering as low as 350 F. All intermediate ranges can be covered by selecting proper salt mixtures.

Oxidation and Decomposition. Molten lead is readily oxidized by the air at all temperatures and must be protected by a suitable covering to prevent excessive formation of dross. Lead oxide is sufficiently insoluble in molten lead to preclude any appreciable contamination of the bath as a whole. Aside from this tendency to oxidize, lead is inherently stable in composition when used as a bath material, and seems to be free from any tendency to pit or decarburize the work metal.

Many of the salts tend to oxidize or decompose after continued use, and require the addition of so-called "rectifiers" to prevent changes in the properties of the bath, sometimes resulting in troublesome sludge deposits and pitting and decarburization of the work material.

Rusting of the Stock. Lead leaves no corrosive agent on the stock after heat treatment. Certain salts, especially the chlorides, rust steel very readily in the presence of moisture, so that cleaning with hot water or hot sal soda solution is frequently necessary to remove all the salt.

Chemical Action on Pots. Lead seems to have no appreciable chemical action on the commercial pot materials, but some of the salts are troublesome in this respect. The nitrates and nitrites attack metals violently when slightly overheated, and the cyanides are detrimental to chromium-nickel alloy pots if permitted to enter the combustion chamber. Most of the other commercial salt mixtures normally have little chemical action on the pots and, in comparison with lead, the shorter life frequently obtained is probably more the result of local overheating from external firing than of any other cause. Local overheating is much more prevalent with salts because of their lower heat conductivity. Sludge formation may also be a contributing factor of considerable importance.

Adherence to the Stock. The tendency of lead to oxidize is a troublesome feature, resulting in loss of lead and dirty stock. Suitable coverings must be used, but at low temperatures even the best coverings may be inadequate and special means are often required to clean the work. Above 850 F, however, lead can be well protected and the bad effects of oxidation kept to a minimum.

Salts cover the stock with a continuous film of the bath material, resulting in large mechanical losses, but because of the solubility of these materials in water, the work is easily cleaned. The adhering film of salt may be an advantage where it is important to have a fine finish, since this film effectively prevents oxidation by the air when the metal is removed from the bath. The thickness of the film and, consequently, the mechanical loss, depend largely on the fluidity of the bath.

Affinity for Water. The fact that lead does not absorb water is a decided advantage. Some of the salts are objectionable in this respect and require careful handling in order to avoid dangerous explosions when they are added to a molten bath. All the salt bath materials have more or less affinity for water and should be shipped and stored in airtight containers.

Heating Rate. The heating rate, or time required to bring a piece of steel of a given size up to the temperature of the bath, depends mainly on heat conductivity and melting point. Lead so greatly excels in heat conductivity that, for any temperature within its range of operation, few other bath materials approach it in rate of heating.

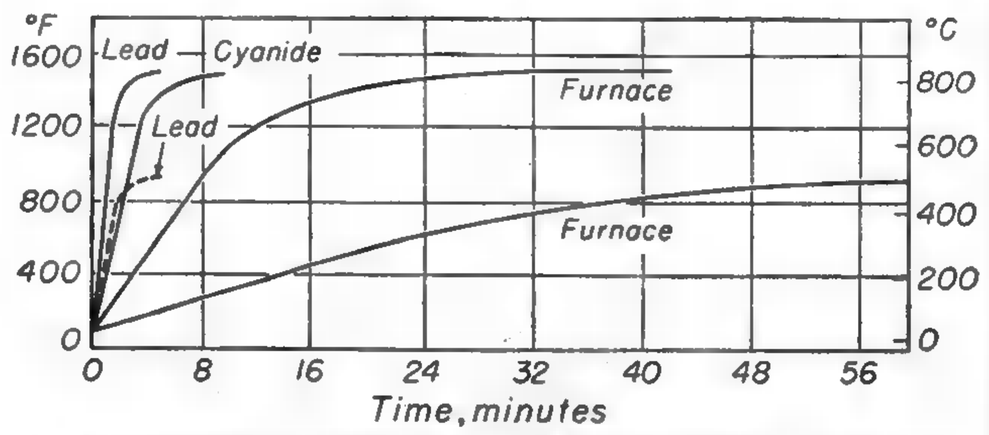

Fig. 1 Comparative heating rates of steel in different mediums

Figure 1 shows the comparative heating rates of steel in a lead bath, a cyanide bath, and an oven furnace. The test piece consisted of a cylinder of low-carbon steel with a stem on one end bored to admit a thermocouple. All the units tested were of sufficient size to prevent more than slight temperature drops when the cold test piece was introduced. The lead and cyanide baths were of exactly the same size. The baths and furnace were constant in temperature and remained nearly so, without firing, throughout the duration of the test. By analysis at the time the test was performed the cyanide mixture showed a composition of approximately 14% NaCN, 14% NaCl, and 72% Na_2CO_3. The extremely rapid rate obtained in lead is clearly shown. It is also interesting to note that lead heats to the required temperature in the same time at 900 and 1500 F, while the oven furnace takes longer to heat to the lower temperature.

Quality of Lead Used. The grade of lead purchased for baths is not of great importance. Ordinary pig lead seems to answer every requirement. Special grades, claimed to be superior for lead pot work and marketed at a higher price, apparently give no better results than the regular commercial pig. Tin is to be avoided since, even in small percentages, it tends to cause lead to stick to the work. Tin contamination is sometimes encountered in lead which has been refined from dross. Sulfur also is claimed to be an objectionable impurity.

Pot Materials. In general, there are three classes of pot materials: cast iron, steel, and the special alloys.

Cast Iron. Cast-iron pots, if properly made, usually give good service at temperatures below 1300 F. At higher temperatures, cast iron has not been found satisfactory, except in small units operated at low output. The composition of such pots ranges from ordinary gray iron to the so-called "alloy iron", made with additions of steel scrap and containing small quantities of alloying elements.

Steel (Cast and Pressed). Cast steel is used for all temperatures throughout the range of lead. Below 1300 F it gives excellent results. At higher temperatures the life depends largely on the conditions of service. The chemical composition varies considerably, and within certain limits is of much less importance than freedom from porosity.

Pressed steel pots are also successfully used throughout the temperature range of lead. Their advantage lies in light weight and freedom from porosity. Unfortunately they do not possess the flexibility of design attainable with cast steel and, on account of die cost, are confined for the most part to standardized shapes and sizes.

Special Alloys (Cast and Pressed). Most of the special alloys come under three general classifications: high nickel-chromium, low nickel-chromium, and chromium. These materials are all much higher in price than steel and, to prove economical, must give correspondingly longer service. They are always used at temperatures above 1300 F, since they cannot compete with cast iron and steel in the tempering range.

Special alloy pots are usually cast, although certain compositions are obtainable in pressed form. As with cast steel, the composition of a cast alloy pot is often of less importance than its freedom from porosity. The advantages and the limitations of design of the pressed steel pot apply in greater degree to the pressed alloy pot.

Pot Design. An important factor in obtaining efficient service is the design of the pots. Sharp corners and abrupt changes of section should be avoided wherever possible. Large radii in corners below the lead level are especially important. Thickness of section is a much disputed point. As a rule, the cast special alloys do not require such heavy bottoms and sidewalls as cast steel. Extremely thin sections tend to cause failure because of bulging followed by cracking; thick sections often fail to give service in proportion to their greater cost, especially when operated at high temperatures and high output. In other words, the life of a pot is not directly proportional to its thickness, except possibly within narrow limits. Probably the premature failure of thick pots often results from the greater temperature difference between the inner and outer surfaces. Pressed pots, either of steel or of special alloy, are necessarily of quite uniform section throughout.

Furnace Design. Lead baths are generally fuel-heated with either oil or gas. Also in use are electrically heated units, in which the heat is applied by means of resistors surrounding the pot. The principal advantages of electric heat consist of exceptionally long pot life and cleanliness. Electric heat is especially well adapted for use in the machine shop. The following discussion, however, is confined to fuel-heated baths. The design of the furnace, and especially of the refractory setting which supports the pot and forms the combustion chamber, should receive the most careful consideration. Proper location of burners and vents, adequate combustion space, correct vent area, length of flame travel, location of splash brick, and height of combustion chamber are all items which, if neglected, may result in unsatisfactory and costly operation. For information on fuel-heated and electrically heated furnaces see the articles on pages 267 and 273 of this Handbook.

Lead Bath Coverings. As previously stated, molten lead is readily oxidized by the air at all temperatures and must be covered with some suitable material in order to avoid excessive lead loss and dirty stock.

Solid Coverings. Wood charcoal, corncob charcoal, charred nut shells, charred leather, coal coke and petroleum coke are some of the materials which have been used as pot coverings. One of the best coverings is hardwood charcoal, size No. 3, also used in the manufacture of carburizing compounds, but this covering is not always the most economical. In determining the most suitable covering, a great deal depends on the nature of the work and the temperature of the operation. In hardening transmission gears, the best covering obtainable is generally none too good; but in hardening axle shafts later to be tempered in lead, a covering of coal coke or the cheapest grade of charcoal screenings will answer the purpose.

The action of the carbonaceous coverings is both chemical and mechanical. Their efficiency depends, to a great extent, on the rapidity with which they burn and the temperature at which burning starts, sometimes called the "kindling temperature". The chemical action is caused by the reducing effect of carbon monoxide gas generated by the combustion of the covering. Below the kindling temperature no carbon monoxide is formed and the protective effect becomes entirely mechanical. Coal coke has such a high kindling temperature that it is virtually useless in the tempering range, although it makes an excellent covering for some classes of work at the higher temperatures. Wood charcoal has a much lower kindling temperature, somewhere in the neighborhood of 850 F, and will protect the lead much less effectively at 800 than at 900 F in spite of the fact that the tendency of lead to oxidize increases rapidly with temperature. The size of the covering, which must also be considered, depends largely on the nature of the job. Sizes much larger than No. 3 charcoal are generally unsatisfactory.

Depending on the nature of the work, the kind of covering employed and the temperature of operation, the bath must be skimmed more or less frequently. The coverings burn to an ash, which collects rapidly and interferes with the action of the carbon monoxide gas. Moreover, the protective effect is never perfect and a certain amount of oxide will always form, even under the best conditions. This ash and oxide must be removed and replaced with new material every so often or trouble will result.

At temperatures below the kindling point of the covering, the problem of cleaning the stock often becomes serious. This difficulty has been overcome by dipping the stock into molten caustic soda immediately after its removal from the lead, and then quenching in water. The result is perfectly clean work and a large saving in lead. The caustic soda pot is held at a temperature slightly below that of the lead. Sodium nitrate has been successfully used for the same purpose.

Liquid Coverings. Molten salts of suitable composition make effective coverings, but are generally more expensive than solid coverings. Cyanide mixtures are very efficient but their cost for large production is prohibitive. Mixtures of NaCl, Na_2CO_3 and K_2CO_3 have been used successfully on small units. Salt coverings have the advantage of producing exceptionally clean work and keeping the lead loss extremely low. The salt consumption, however, is usually a source of considerable expense. Many salts, other than those mentioned above, have been tried without success. Caustic soda causes a gradual oxidation of the lead; sodium nitrate is still worse in this respect. Most of the mixtures of chlorides and carbonates tend to decompose and form infusible products which are very undesirable.

A decided objection to the use of salt covering on large pots is the great amount of heat radiated from the surface of the bath, resulting in bad working conditions for the operators and lowering thermal efficiency. The solid coverings have a marked blanketing effect; the salts have almost none.

Pot Failures. With properly designed and operated units, pot failures result from three general causes: porosity, cracking and oxidation. Cast iron almost always fails by cracking. Cast steel usually fails from porosity and from oxidation, as a secondary effect, when blowholes open up as the metal scales away. Failures with cast steel pots are seldom caused by cracks. Cast alloy pots usually fail from cracking, and in many cases from porosity. They suffer very little from the effects of oxidation except where metal segregation occurs. Pressed steel pots nearly always fail from oxidation, and pressed alloy pots usually fail from oxidation or cracking.

Lead Poisoning. In order to insure protection from lead poisoning, all lead pot installations should be provided with suitable ventilating equipment to prevent lead and its compounds, in the form of fumes and dust, from being inhaled by the operators. Hoods should be designed to collect the products of combustion as well as the fumes and

dust arising from the surface of the bath. For further information on lead poisoning, see the article on "Industrial Poisoning by Metals", page 755.

Caution. To be immersed in a lead or salt bath with any degree of safety, material must be entirely free from moisture. When moist material is immersed in a molten bath the moisture is instantly changed into steam, thus causing a violent eruption of the bath, which may burn the operator severely.

Methods of Operation. Lead pot furnaces may be operated by either the batch or continuous method. For tempering, the former is the more satisfactory, but for hardening, both methods are successfully employed. In the batch method, the pot is filled to capacity and the work material is all removed as soon as the desired temperature is reached. It is usually necessary to shut off the burner before removing the work, but in some hardening operations, if charging and discharging are sufficiently rapid, the burner may be allowed to remain open. With the continuous method, the bath is held at the desired temperature by removing part of the work material and replacing it with cold work at stated intervals. Automatic handling of the stock has been employed in lead baths with a certain degree of success but many difficulties have been encountered which are not met in oven furnaces. Parts requiring local heating may be handled with rotary fixtures in round pots, or with chain conveyers in oblong pots.

Applications. Although at one time the lead bath had a wide range of utility, it has been largely superseded in recent years by the salt bath, the controlled atmosphere furnace, and flame and induction heating. It is still used to some extent for local hardening and tempering and for other special applications where rapid heating to a definitely controlled temperature is required.

Protective Furnace Atmospheres

By A. G. Hotchkiss* and H. M. Webber*

PROTECTIVE furnace atmospheres are usually employed to perform one or both of two important functions for the purpose of insuring better quality in metals that are heated in a furnace. These functions are prevention of oxidation, commonly recognized as bluing or scaling, and prevention of decarburization, commonly recognized as a loss of surface carbon in ferrous metals. When surface oxidation is eliminated, cleaning methods such as pickling and sandblasting are unnecessary. When decarburization is eliminated, ferrous alloys are hard at the surface instead of having a soft skin, and thus have high strength and good resistance to wear, without requiring machining or grinding to get down to the hard metal.

A wide variety of gases and mixtures of gases are used for protective furnace atmospheres. Bottled hydrogen, nitrogen, carbon dioxide, and sulfur dioxide are commonly available. Of these, hydrogen is perhaps the most widely used and will be discussed briefly below. Dissociated ammonia serves as a high-quality, low-cost substitute for hydrogen in numerous instances. Products of combustion of hydrocarbon gases, sometimes purified, sometimes reacted in a special manner, are by far the most widely used gases for protective furnace atmospheres.

Table I gives the characteristics and costs of various protective furnace atmospheres. Table II lists processes for heat treatment in which protective furnace atmospheres are advantageous and, in the right-hand column, specifies recommended atmospheres.

Typical chemical reactions that are possible among furnace-atmosphere gases, iron, carbon, and cementite (Fe_3C), at elevated temperatures, are listed in Table III. Generally the reactions proceed to the right, but equilibrium conditions vary with the temperature and with complex mixtures. Many of these reactions are included in the following text, where the use of furnace atmospheres is discussed.

Hydrogen. Because of excellent properties and ready availability, hydrogen has been a standby for furnace atmospheres for more than 40 years. It is commonly produced by the dissociation of water into hydrogen and oxygen in a battery of electrolytic cells. Although hydrogen is sometimes taken directly from holders fed by the cells, it is more commonly purchased in bottles holding 220 or 440 cu ft of hydrogen measured at atmospheric pressure and compressed to between 1800 and 2000-lb pressure. A typical composition is 99.8% H_2, 0.2% O_2, saturated with water vapor. When the gas is compressed to 2000 lb, the moisture is condensed and the dew point of the gas is lowered to about minus 30 F. This gas is highly reducing when in contact with iron and copper oxides at elevated temperatures.

The H_2O/H_2 ratios for equilibrium with iron are shown in Fig. 1. To the left of the curve the atmosphere is reducing; to the right of the curve it is oxidizing. At high temperatures the hydrogen atmosphere is reducing with relatively high amounts of moisture; at low temperatures less moisture is permissible to maintain reducing conditions. Since metals heated in a hydrogen atmosphere are generally cooled in the same protective gas, and it

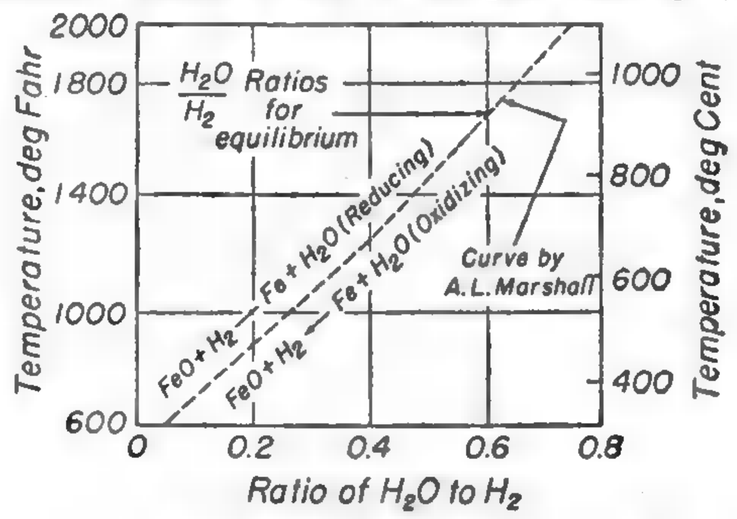

Fig. 1 Theoretical equilibrium relations among iron, iron oxide, hydrogen, and water vapor

is desired to avoid oxidation during this cooling cycle, the content of moisture must be reasonably low to avoid crossing the line into the oxidizing range during the cooling period. In practice, this offers no problem because the minimum H_2O/H_2 ratio of 0.05 at 600 F, shown at the bottom left of the chart, or 5% H_2O by volume, is considerably higher than ordinarily encountered. This explains the ease with which iron can be brought out bright from hydrogen atmospheres. However, at elevated temperatures, oxygen and water impurities in hydrogen will form selective oxides with chromium, manganese, silicon, vanadium, zinc, aluminum, beryllium, titanium and certain other metals. Accordingly, when metals containing these constituents are being treated in a furnace, it is sometimes necessary to purify the entering hydrogen.

Removal of Oxygen. Two methods are commonly used for removing oxygen from hydrogen. One of these is to pass the hydrogen over copper, heated to about 1100 to 1200 F. The copper serves as a catalyst to convert the oxygen with hydrogen into H_2O, completely removing the oxygen except for traces. The remainder can be removed by passing the hydrogen over hot ferromanganese, ferrotitanium or ferrosilicon, at 1650 to 1850 F.

In the other method for removal of oxygen, the hydrogen is passed through a palladium-catalyst purifier. This method is superior to the one using copper chips as a purifier, not only because it is less expensive but also because it is more convenient and more economical to operate. The palladium-catalyst purifier is simply a small tower that contains the catalyst, which operates effectively

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Table I. Approximate Composition and Cost of Producing Typical Furnace Atmospheres

Item	Furnace Atmosphere	Type of Reaction	Ratio of Air to Natural Gas	Composition, % CO_2	O_2	CO	H_2	CH_4	N_2	Dew Point, deg Fahr	Cost per M cu ft, (a) dollars
I	Hydrogen	Electrolytic									
	A Unpurified										
	1. From Cells		.....	0.0	0.2	0.0	99.8	0.0	0.0	Saturated	1.50 to 3.00
	2. From Bottles		.....	0.0	0.2	0.0	99.8	0.0	0.0	−30 to −10	5.00 to 10.00
	B Purified										
	1. From Cells		.....	0.0	0.0	0.0	100.0	0.0	0.0	−60	1.52 to 3.02
	2. From Bottles		.....	0.0	0.0	0.0	100.0	0.0	0.0	−60	5.01 to 10.01
II	Dissociated Ammonia	Endothermic		0.0	0.0	0.0	75.0	0.0	25.0	−60	0.95 to 3.50
	A Untreated										
	B Burned with Air										
	1. Partly burned		1/1	0.0	0.0	0.0	24.0	0.0	76.0	Saturated	0.57 to 2.10
	2. Completely burned		1.75/1	0.0	0.0	0.0	1.0	0.0	99.0	Saturated	0.72 to 2.70
III	Combusted Fuel Gas	Exothermic									
	A Unpurified										
	1. Partly burned		6/1	5.0	0.0	10.0	15.0	1.5	68.5	Saturated	0.10
	2. Completely burned		10.25/1	11.5	0.0	0.7	0.7	0.0	87.1	Saturated	0.08
	B Purified										
	1. Partly burned										
	a. Dry and free from CO_2		6/1	0.0	0.0	10.5	15.5	1.5	72.5	−40	0.14
	2. Nearly completely burned										
	a. Dry and free from CO_2		9.5/1	0.0	0.0	2.0	2.0	0.0	96.0	−40	0.13
	3. Completely burned										
	a. Dry and free from CO_2		10.25/1	0.0	0.0	0.7	0.7	0.0	98.6	−40	0.13
	b. Converted with charcoal (No H_2O removed)		10.25/1	0.0	0.0	30.0	16.0	0.0	54.0	−15	0.32
	c. Converted with charcoal (H_2O condensed)		10.25/1	0.0	0.0	20.0	3.0	0.0	77.0	−20	0.22
IV	Reacted Fuel Gas	Endothermic									
	A With air over catalyst										
	1. Completely reacted		2.25/1	0.0	0.0	19.0	38.0	1.5	41.5	−10	0.22

(a) Costs include only materials consumed, such as power, gas and water. They do not include factors for obsolescence, installation, maintenance, and the like. The estimates have been based on the following unit costs: power, 1 cent per kwhr; natural gas, 50 cents per M cu ft; water, 5 cents per M gal; charcoal, 3 cents per lb; ammonia, 3½ to 15 cents per lb.

at room temperature. The purifier is connected in the gas line and functions much as a filter would. Like the copper-chip unit, it converts oxygen plus hydrogen into H_2O. However, it is more effective than the copper-chip unit since it removes the oxygen completely, giving purity equivalent to that obtained by the combination of the copper-chip and ferromanganese purifiers; in fact, the extremely high purity of less than one part oxygen per million parts hydrogen is claimed for this type of unit. Hydrogen delivered from the purifier contains H_2O, so if dry gas is necessary, removal of moisture is also required.

Removal of Moisture. The dew point and moisture content of gases, and the extent of moisture removal by various methods, are shown in graphic form in Fig. 2, indicating that most of the moisture can be removed by refrigeration. For example, with a dew point of 70 F and moisture content of about 2½%, refrigeration will reduce the dew point to about 40 F with a moisture content of 0.8%; thus 67% of the moisture is removed in this one step. With a higher initial dew point and the same final dew point, the ratio would be even greater.

A typical refrigerated cooler for gases consists of a condensing unit and a finned-tube evaporator.

Combusted gases, to be discussed later, are sometimes partially dried by refrigeration for batch annealing of low-carbon steel sheets or coils, to assure brightness of finish. The need for refrigeration of gases generally arises in summer, when water for cooling is warm and

Table II. Heat Treatment Processes and Furnace Atmospheres Recommended for Them

Heat Treatment	Metal to be Processed	Requirements: Metallurgical	Requirements: Surface	Temperature Range, deg Fahr	Furnace Atmospheres Recommended(a)
Annealing	Low-carbon steel		Bright	1200 to 1350	IIIA1, IA1, IA2, IIB1
	Medium-carbon or high-carbon steel	No decarburization	Bright	1200 to 1450	IIIB1, IIIB2
	Alloy steel, medium-carbon or high-carbon	No decarburization	Bright or clean	1300 to 1600	IIIB1, IIIB2
	High speed tool steel	No decarburization	Clean	1450 to 1650	IIIB1, IIIB2
	Stainless steel		Bright	1800 to 2100	IB1, IB2, IIA
	Copper		Bright	500 to 1200	IIIA2
	Copper-nickel alloy		Bright	800 to 1400	IIIA1, IA1, IA2, IIB1
	Brass		Clean	800 to 1400	IIIA2, IIIB3a
Normalizing	Low-carbon steel		Bright or clean	1600 to 1850	IIIA1, IA1, IA2, IIB1
	High-carbon alloy steel	No decarburization	Bright or clean	1500 to 2000	IIIB1
Hardening	High-carbon or carburized steel	No decarburization	Bright or clean	1400 to 1750	IIIB1, IIIB3b, IIIB3c, IVA1
	Alloy steel, medium-carbon or high-carbon	No decarburization	Bright or clean	1400 to 1750	IIIB1, IIIB3b, IIIB3c, IVA1
	High speed tool steel	No decarburization	Bright or clean	1800 to 2400	IIIB1, IIIB3b, IIIB3c, IVA1
Brazing	Low-carbon steel	Copper braze	Bright	2050	IIIA1, IA1, IA2, IIA, IIB1
	Medium-carbon or high-carbon plain or alloy steel	Copper braze, no decarburization	Bright	2050	IIIB1, IIIB3b, IIIB3c, IVA1
	Stainless steel	Copper braze	Bright	2050	IB1, IB2, IIA
	Low-carbon steel	Silver braze	Bright	1100 to 1600	IIIA1, IA1, IA2, IIB1
	High-carbon steel	Silver braze	Bright	1100 to 1600	IIIB1, IIIB3b, IIIB3c, IVA1
	Copper or brass	Silver braze	Bright or clean	1100 to 1600	IIIA2, IIIB3a
Sintering	Low-carbon ferrous metals	Sintering	Bright or clean	1800 to 2100	IIIA1, IA1, IA2, IIA, IIB1
	High-carbon ferrous metals	Sintering, no decarburization	Bright or clean	1800 to 2100	IIIB1, IIIB3b, IIIB3c, IVA1
	Stainless steel (with Ti or Cb)	Sintering	Bright or clean	2150 to 2500	IB1, IB2
	Copper, copper-lead, copper-tin, graphite	Sintering	Bright or clean	1300 to 1900	IIB1, IIIA1, IIIA2
	Tungsten	Sintering	Bright or clean	2150 to 2500	IB1, IB2, IIA
	Molybdenum	Sintering	Bright or clean	2150 to 2500	IB1, IB2
	Alnico magnets	Sintering	Bright or clean	2150 to 2500	IB1, IB2, IIA

(a) See Table I for approximate composition and cost of furnace atmospheres.

the surface cooler of the atmosphere-gas converter becomes less effective; this allows too much moisture to stay in the combusted gas. Refrigeration reduces the moisture content and establishes the proper H_2O/H_2 ratio for brightness.

When refrigeration is inadequate for certain applications, additional drying is necessary for good results. In these situations, the gas can be passed through a regenerative dryer. Such units in daily operation are known to reduce the dew point of gases to as low as minus 100 F. It is a rather common practice to dry the gas in two steps, first by refrigeration and then by adsorption, for the sake of economy both in initial cost and in operating cost.

Hydrogen from a palladium-catalyst purifier, when passed through a regenerative dryer of adequate capacity, has sufficient purity to reduce oxides of chromium; to bright anneal 18-8 stainless steel; to sinter 18-8 stainless steel compacts, Alnico, 80 Ni – 20 Cr and similar alloys.

High-purity gas is of little value if it is allowed to become contaminated in the furnace by oxygen or H_2O, or both. Air that infiltrates while the doors are open during the charging and discharging of the work, air and H_2O entrapped in the work and in the furnace lining, H_2O and CO_2 from flame curtains and such, are all sources of these impurities. To be sure of maintaining the high purity of the hydrogen surrounding the work material the most certain and successful method is to enclose the material in a well-sealed metal retort or box that has a pipe inlet for the purified hydrogen and a small outlet to allow circulation of the pure gas. A modification of this method sometimes used successfully is to have a metal retort running throughout the heating and cooling chambers, with well-sealed furnace ends through which the charge travels. In this manner, strands of nickel-chromium wire and strip are bright annealed, and trayloads of Alnico compacts are sintered.

Table III. Typical Reactions of Furnace Atmospheres With Ferrous Metals

Reaction	Effects when proceeding to the right
$CO_2 + Fe \rightleftarrows FeO + CO$	Oxidizing
$H_2O + Fe \rightleftarrows FeO + H_2$	Oxidizing
$H_2 + CO_2 \rightleftarrows CO + H_2O$	(Water gas reaction)
$CO_2 + Fe_3C \rightleftarrows 3Fe + 2CO$	Decarburizing
$H_2O + C \rightleftarrows CO + H_2$	Decarburizing
$CH_4 + 3CO_2 \rightleftarrows 4CO + 2H_2O$	Decarburizing
$2H_2 + Fe_3C \rightleftarrows 3Fe + CH_4$	Decarburizing
$CH_4 + 3Fe \rightleftarrows Fe_3C + 2H_2$	Carburizing
$2CO + 3Fe \rightleftarrows Fe_3C + CO_2$	Carburizing

Dissociated Ammonia. Dissociated ammonia, a well-known high-purity gas mixture that is sometimes used as a low-cost substitute for hydrogen, is obtained by cracking anhydrous ammonia (NH_3) at about 1650 F over a catalyst. The chemical composition of dissociated ammonia is 75% H_2, 25% N_2, with traces of NH_3 as an impurity. The dew point is about minus 60 F.

Because of the relatively high purity of dissociated ammonia it has a wide field of application. There are few alloys for which it cannot be used successfully as a furnace atmosphere. In general, it is employed for the same applications as pure hydrogen. Exceptions are those where unwanted nitriding might take place, because of the nitrogen in dissociated ammonia, as in the sintering of compacts made of stainless steel powders that contain small percentages of titanium and columbium; in the sintering of compacts made of molybdenum powders; and in other heat treatments involving molybdenum.

One pound of liquid ammonia gives about 45 cu ft of dissociated ammonia gas, consisting of about 33.7 cu ft H_2 and 11.3 cu ft N_2. Thus 22.2 lb of liquid ammonia is required to produce 1000 cu ft dissociated ammonia. Dissociated ammonia can be burned with air to reduce cost and inflammability. When dissociated ammonia is given this treatment, the hydrogen content can be controlled within a range of 24 to 1%, leaving 76 to 99% of nitrogen, saturated with H_2O.

Combusted Gas. The most common gas used for furnace atmospheres is combusted gas, resulting from the partial or complete combustion of hydrocarbon fuel gases with air in atmosphere-gas converters. Industry has used such atmospheres for years, and the characteristics and advantages of them are now well known.

Coke-oven, natural and propane gases are commonly employed for burning in atmosphere-gas converters. The chemical composition of the gas product depends on the

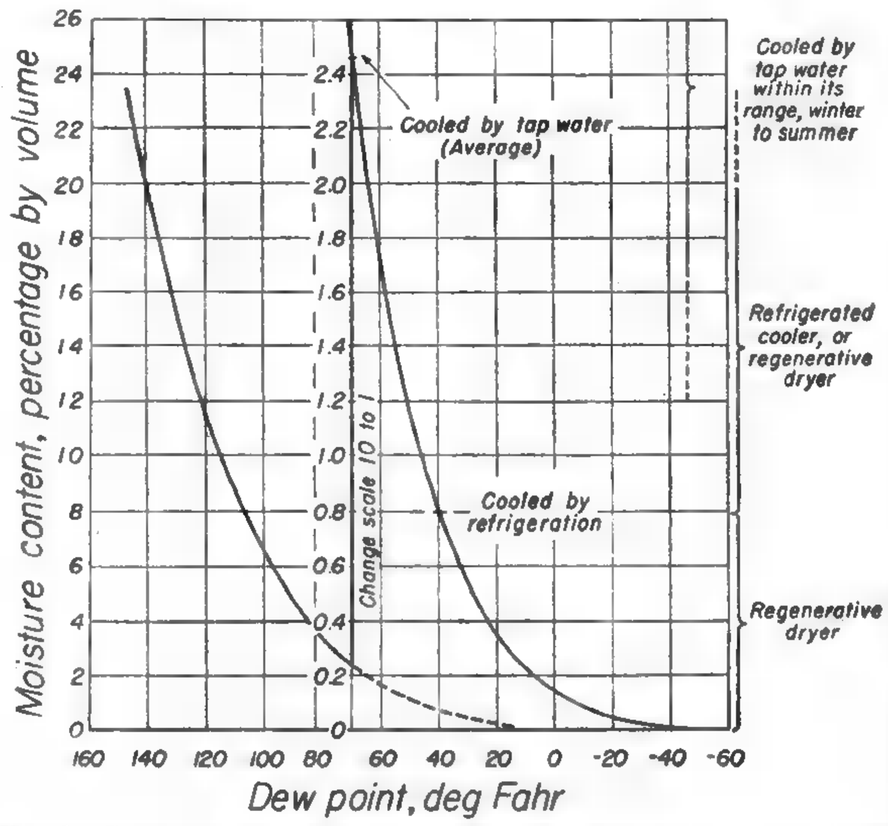

Fig. 2 Curves showing relation between dew point and moisture content of gases and the extent of moisture removal by various methods

ratio of input air to gas, as indicated in Fig. 3. For example, a 6–to–1 ratio of air to gas (at *A*), when natural gas is burned, gives approximately 5% CO_2, 10% CO, 14% H_2, 1.5% CH_4 (methane), and 69.5% N_2. The gas is saturated with H_2O at a dew point approximately 10 F above the temperature of the cooling water used in the surface cooler. This mixture (at *A*) is commonly used for various treatments of ferrous metals, such as hardening, bright annealing, furnace brazing, and sintering. When burning natural gas at almost complete combustion, or 10.25–to–1 ratio (at *C*), the composition is about 11.5% CO_2, 0.7% CO, 0.7% H_2, 0.0% CH_4, and 87.1% N_2. This gas (at *C*) has wide application in the bright annealing of copper.

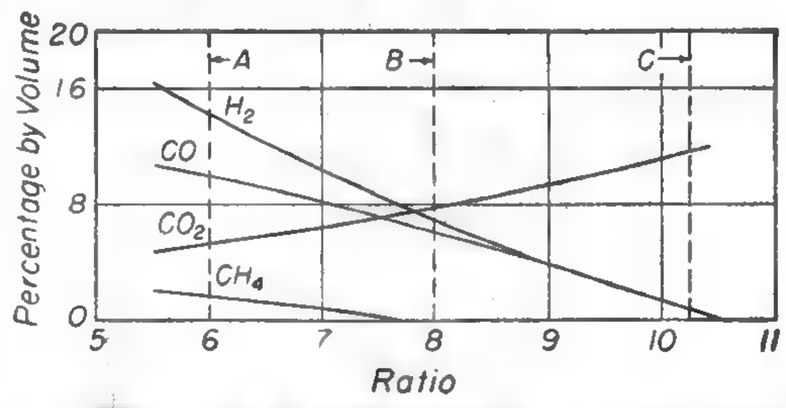

Fig. 3 Products of partial combustion of natural gas consist largely of nitrogen. The above curves show the remaining constituents for various input ratios of air to gas. *A* is the ratio commonly used for atmospheres employed in hardening, bright annealing, furnace brazing, and sintering ferrous metals; *B*, for sintering bronze compacts; *C*, for bright annealing copper.

A typical atmosphere-gas converter consists of air and gas flowmeters, a proportioning mixer, a compressor, a fire check, a burner, a combustion chamber, and a surface cooler, with condensate separator and trap.

The complexity of the combusted gas mixtures at various ratios, and the resulting effects with respect to oxidation of iron during heating and cooling, have frequently been explained by the equilibrium curves shown in Fig. 4. The H_2O/H_2 equilibrium curve at the left will be recognized as the one shown in Fig. 1. The area to the left of the curve is reducing to iron; that to the right is oxidizing. For example, when treating iron at 2000 F with the low-ratio gas mentioned above, having an assumed dew point of 70 F (2.5% H_2O), and containing 14% H_2, the H_2O/H_2 ratio is 2.5/14 or 0.18. The ratio of

0.18 is indicated on the chart by the dotted line *A–A′*. At 2000 F, *A-A′* is predominantly reducing to iron and no oxide would form. On the contrary, any oxide present (FeO) would be reduced to iron plus H_2O. However, during the cooling of the metal along the line *A–A′*, the curve is intersected at about 860 F; and at temperatures lower than 860 F the work pieces would be in the oxidizing range. Thus during slow cooling, the iron parts could be oxidized. However, many parts are relatively thin in section and cool rapidly enough so that oxidation within this range is slight. In addition, the extra effect of the CO_2/CO ratio in this complex gas should be considered. The right-hand curve in Fig. 4 is the equilibrium curve for CO_2/CO ratios with respect to iron. To the left of this curve the gas is reducing; to the right it is oxidizing. With the low-ratio gas above, containing 5% CO_2

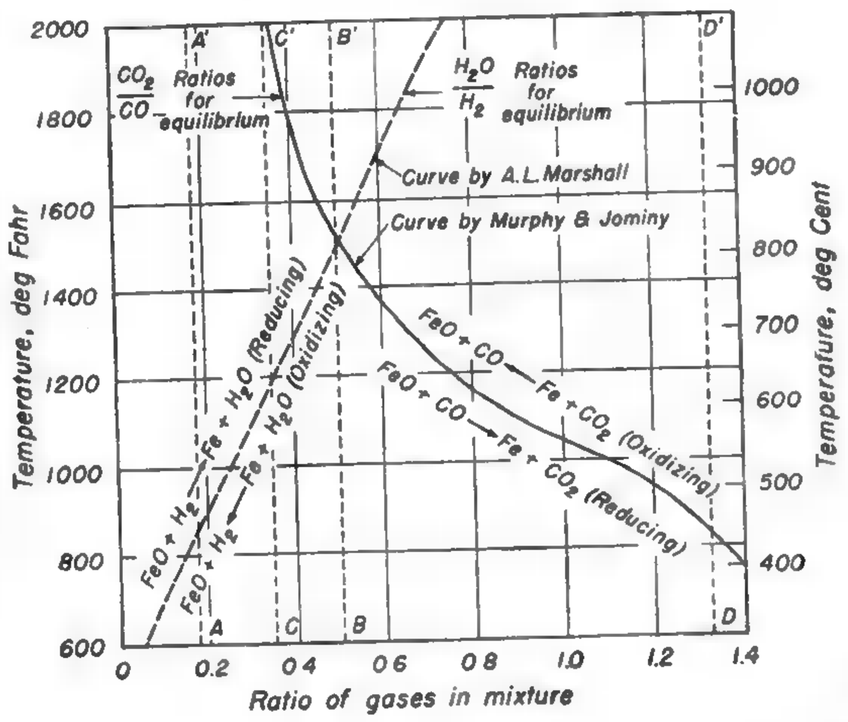

Fig. 4 Theoretical equilibrium relations among iron, iron oxide, hydrogen, and water vapor and among iron, iron oxide, carbon monoxide, and carbon dioxide

and 10% CO, the CO_2/CO ratio is 1 to 10, or 0.5; and as indicated on the chart by the dotted line *B–B′*, at 2000 F the work would be in a slightly oxidizing atmosphere with respect to CO_2/CO; but the predominantly reducing effect of the H_2O/H_2 ratio overcomes this and the net result is that the atmosphere is definitely reducing. During cooling, the work crosses the CO_2/CO curve at about 1525 F, and at any lower temperature the action is reducing. At 860 F it is predominantly reducing, and increases somewhat even below that point. Thus during the cooling cycle, this reducing effect overcomes the slightly oxidizing effect of the H_2O, and gives reasonable assurance that the work pieces will come out bright.

With the higher air-gas ratios, conditions are less favorable for iron, because the atmosphere is definitely oxidizing; an explanation will indicate why high ratios are therefore not used for iron. When an 8–to–1 ratio is assumed (at *B* in Fig. 3), and 70 F dew point, the H_2O/H_2 ratio is 2.5 to 7, or 0.35 and is indicated by the dotted line *C–C′*. This atmosphere at *C′* (at 2000 F) is not so reducing as the one at *A*; and the oxidizing effect is more pronounced after crossing the curve at about 1200 F. The CO_2/CO ratio is 8 to 6, or 1.33, indicated by dotted line *D–D′*. At 2000 F this atmosphere is so predominantly oxidizing for iron that it would overcome the slight reducing effect of the H_2O/H_2 ratio. Also, the oxidizing effect continues until the temperature drops to about 830 F, and adds to the oxidizing effect of the H_2O/H_2 ratio at less than 1200 F. Thus the work material would be thoroughly oxidized before it encountered the feeble reducing effect of the CO_2/CO ratio below 830 F. In consequence, from the standpoint of oxidation, it is impractical to treat iron parts in the 8–to–1 gas, unless the H_2O and CO_2 are removed or greatly reduced:

Removal of Sulfur. Copper-base and nickel-base alloys are subject to discoloration, embrittlement, or both, if the combusted gas contains sulfur. Coke-oven gas commonly contains sulfur, but natural gas and propane are generally free from it. Where removal of sulfur is required, it can be accomplished easily. First the combusted gas passes through a water-spray tower which removes sulfur dioxide (SO_2). Then it passes through a tower containing iron oxide on wood shavings, called "lux", which removes hydrogen sulfide (H_2S). From here the gas goes to the furnace completely free from sulfur.

A simple test can be used to detect whether sulfur is present in combusted gas. Chemically pure zinc is placed in the bottom of a beaker; then 1 to 20% solution of hydrochloric acid is poured in. One or more parts that have been treated in the furnace atmosphere suspected of contamination are then placed in the beaker, the beaker is covered with a piece of filter paper that has been soaked in lead acetate solution, and the filter paper is covered with a glass plate. If sulfur is present, the lead acetate paper will turn brown or black within a minute or so; if no sulfur is present, the color will remain unchanged.

Removal of CO_2. Combusted natural gas, partially burned at a 6–to–1 ratio, or the equivalent of such gas, is commonly used for heat treatment of iron or steel products. The highly reducing characteristic is responsible for obtaining good appearance with little or no oxidation of the work pieces. However, this gas has a strongly decarburizing effect on medium-carbon and high-carbon steels. It removes carbon from the surfaces at elevated temperatures, causing a soft skin to be present after heat treatment and thus impairing the resistance to wear and decreasing the strength. To get down to the hard metal, machining or grinding is necessary, which is costly and time-consuming. There are many instances in which such surface decarburization is not considered objectionable; but there are also numerous instances in which it is highly desirable to have the metal hard at the surface after heat treatment. Fortunately, it is possible to eliminate this decarburizing action simply by removing two constituents from the gas — H_2O and CO_2. This combusted gas, free from CO_2 and H_2O, is being used very successfully for various heat treatments on medium-carbon and high-carbon steels and carburized steels, without surface decarburization.

Because of the reducing and carbon potential requirements, low-ratio dry combusted gas, free from CO_2, is specified for short-cycle annealing, clean hardening, and furnace brazing of medium-carbon and high-carbon steels. This atmosphere consists of approximately 10.5% CO, 15.5% H_2, 1.5% CH_4, 72.5% N_2, with a dew point of minus 40 F. Other uses for this low-ratio gas are the hardening of high speed steels (in both the preheat and high-temperature furnaces); the sintering of high-carbon ferrous metals; the restoration of carbon to decarburized surfaces; and use as a carrier gas for propane or natural gas in gas-carburizing work. On the other hand, a high-ratio (9.5 to 1) dry combusted gas, free from CO_2, is required for long-cycle annealing of low-carbon, medium-carbon and high-carbon steels, and for annealing brass, in bell-type furnaces. This atmosphere is approximately 2% CO, 2% H_2, and 96% N_2, with dew point minus 40 F.

Carbon dioxide is usually removed from combusted gas by means of an absorption chemical which is reactivated by heat and recirculated to provide continuous operation. The remover of CO_2 can be supplied as a separate unit in conjunction with the atmosphere-gas converter; but a combination of the two units is available which effects economies in cost and floor space by having the combustion chamber of the converter built into the boiler of the reactivating tower of the equipment for removing CO_2. Thus heat, otherwise wasted from the combustion chamber in its water jacket, is utilized to boil the chemical to drive off the CO_2, which saves about 18 kwhr per M cu ft processed. For drying the gas, refrigerated gas coolers and driers of a regenerative type, as previously described, are commonly employed.

The need for dry combusted gas, free from CO_2, to prevent surface decarburization is graphically illustrated by Gonser[1] in Fig. 5. Steel samples containing carbon varying from 0.10 to 1.0% or higher were treated for 3 hr at 1740 F, unless otherwise noted on the chart. The furnace atmosphere was low-ratio combusted gas, with

or without purification. For two samples (11 and 12), the CO_2 was removed to 0.0%; for the other samples (10 to 1), the CO_2 was gradually increased to 5.3%. For most samples the gas was completely dry but for a few it was undried. Usually the CH_4 content was less than 1%. It will be noted that the best results were obtained with 0.0% CO_2 (curves 11 and 12); regardless of the amount of carbon in the steel, parts were slightly carburized as indicated by the weight increases, and there was no sign of decarburization. However, as soon as CO_2 was introduced, and in some instances H_2O, decarburization became evident, as indicated by loss in weight; this loss in weight increased with the increase in CO_2 and, in some samples, H_2O. This comparison shows the superiority of dry combusted gas, free from CO_2, over raw or incompletely purified combusted gas.

Figure 6 shows results of weight-change tests on SAE 1060, 1090, and 52100 steels, held for 1 and 2 hr at 1500 F in low-ratio dry combusted gas atmosphere, free from CO_2, and in low-ratio untreated combusted gas atmosphere. The samples treated in dry combusted gas, free from CO_2, showed a slight increase in weight, indicating some carburization, but the samples treated in raw combusted gas showed quite a sharp decrease in weight, indicating decarburization. The samples that were treated in the purified gas were within the generally acceptable range of weight change from minus 20 to plus 50 g per

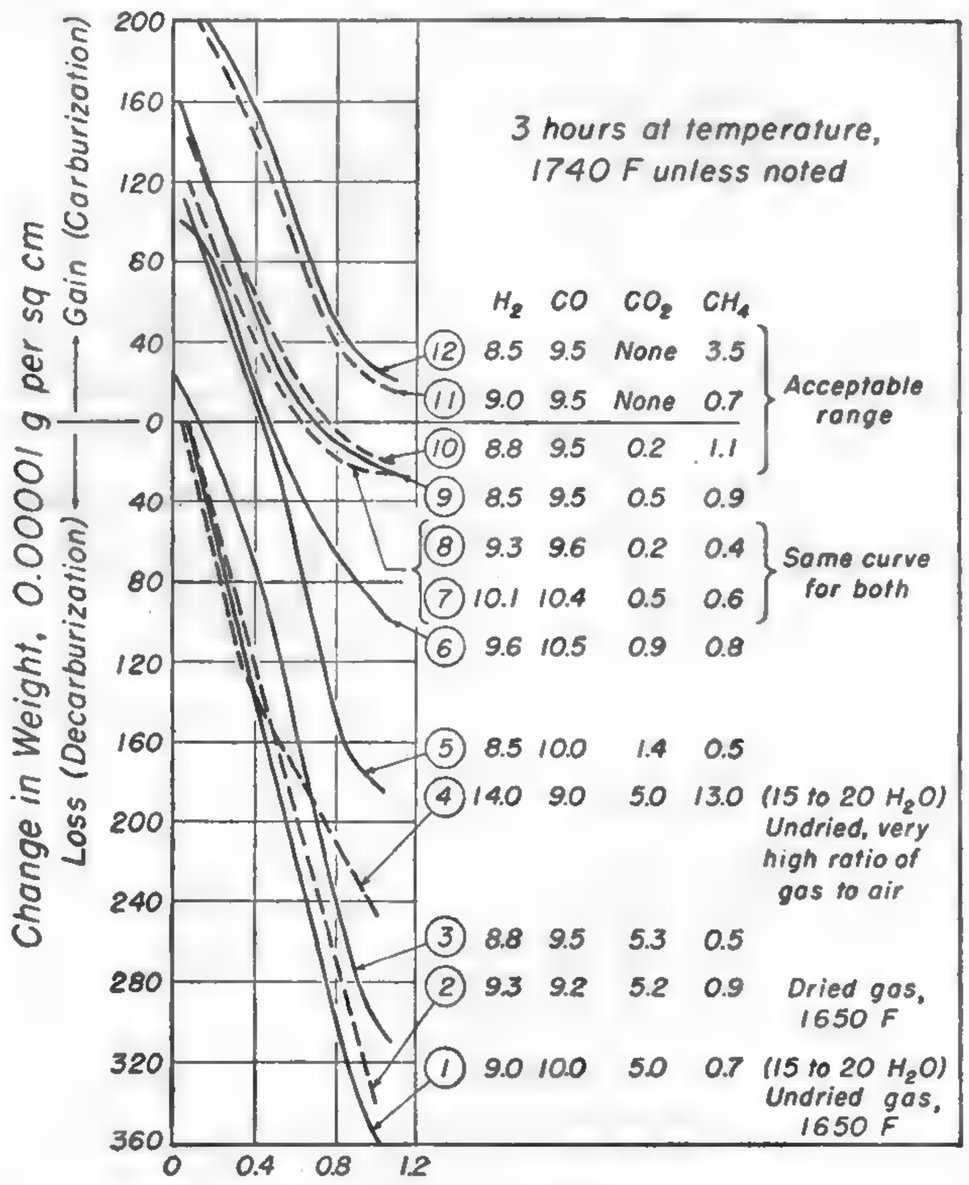

Fig. 5 Curves showing slight carburizing action of dry combusted gas, free from CO_2 but including methane (CH_4), and the increasing decarburizing action with increasing CO_2 and, in some instances, H_2O (Gonser[1])

sq cm times 100,000, as indicated by the bracket at the extreme right of Fig. 6. However, if the slight carburization on the SAE 1060 and 52100 steels should be considered objectionable, this effect can be reduced (1) by changing the combustion ratio of air to gas, or (2) by passing some moist combusted gas around the dryer to increase the dew point of the gas within the furnace.

Rockwell hardness tests on the weight-change samples, after hardening, confirm the data concerning changes in weight. Rockwell 15-N readings converted to the C scale, on samples treated in dry combusted gas, free from CO_2, were greater than the direct C readings, indicating that no decarburization, but actually carburization, had occurred. A similar comparison of samples treated in raw, partially combusted gas under the same conditions gave the reverse effect in hardness readings, indicating that decarburization of the surface had occurred.

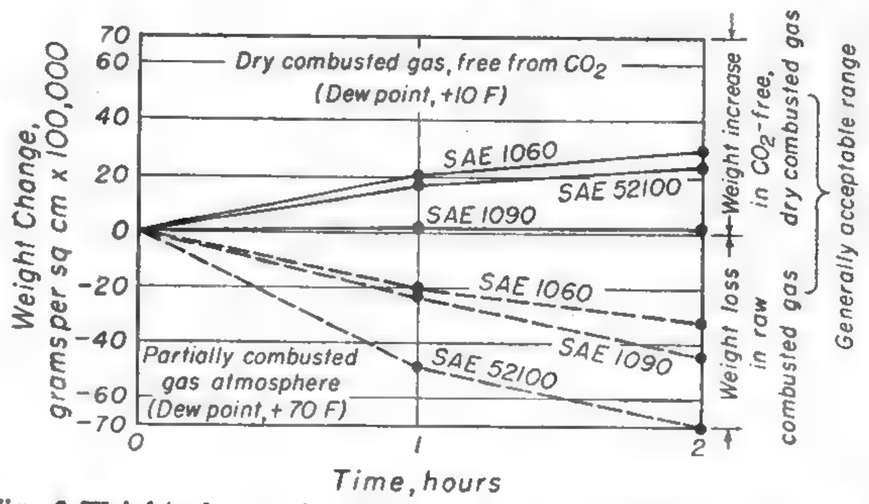

Fig. 6 Weight-change tests on samples of three different types of steel, treated in atmospheres of dry combusted gas free from CO_2, and in raw combusted gas. Slight carburization occurred in the dry combusted gas and serious decarburization in the raw combusted gas.

Charcoal-Converted Combusted Gas. Another type of equipment is available for making nondecarburizing gas, combining the production and purification stages in one unit. In this unit, products of combustion of hydrocarbon gas are passed through incandescent charcoal to convert the H_2O and CO_2 into H_2 and CO. Most of these units are operated at complete combustion, some with water removed from the products of combustion before conversion by the charcoal, and others without the water removed. The chemical composition of a typical gas from a unit with water removed is 0.0% CO_2, 20.0% CO, 3.0% H_2, 0.0% CH_4, 77.0% N_2, with a dew point of minus 20 F. The composition when all the water vapor is being converted by charcoal is approximately 0.0% CO_2, 30.0% CO, 16.0% H_2, 0.0% CH_4, 64.0% N_2, with dew point minus 15 F.

Catalyst-Converted Fuel Gas and Air. Another method of producing a nondecarburizing atmosphere is to react mixtures of air and hydrocarbon gases at very low ratios, such as 2.5-to-1 air-to-natural gas, over a heated catalyst. Just enough air is used to furnish oxygen for converting all the hydrocarbons to CO. The reaction is endothermic and gives gas with approximately the following composition: 0.0% CO_2, 19.0% CO, 38.0% H_2, 1.5% CH_4, 41.5% N_2, with a dew point of minus 10 F.

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SURFACE TREATMENTS

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Solvent and Vapor Cleaning of Metals

By Walter R. Meyer*

THREE methods of cleaning metals contaminated with oil, grease or buffing compositions are discussed here: simple solvent cleaning, emulsifiable solvent cleaning and vapor degreasing. All these methods of cleaning are employed for degreasing metals prior to organic finishing. However, metals that are to be electroplated should be cleaned with alkaline solutions after preliminary cleaning by one of the three methods mentioned above.

Solvent Cleaning. Solvent cleaning usually employs special naphthas with flash points above 100 F, such as "Stoddard Solvent" used in the dry cleaning industry. Solvents of this type are preferred to kerosene and VM & P naphtha because there is much less residue left after evaporation of the solvent. The work material is immersed in the solvent or scrubbed with it and is usually dried with sawdust or corncob drying meal.

Chlorinated solvents are sometimes used instead of naphthas, but they are more likely to cause skin irritation and physiological harm to the operator although fire hazard is reduced or eliminated. Chlorinated solvents used most commonly are trichlorethylene and ethylene dichloride. Ethylene dichloride is a better solvent than trichlorethylene, but it is more volatile and burns weakly. Occasionally, buffing compounds containing tallow and stearic acid must be removed by simple solvent washing; cyclic hydrocarbons such as toluol and xylol are used for this purpose because of their good solvency. Proper ventilation should be provided when using these solvents because they are more noxious than naphthas.

Emulsifiable Solvent Cleaning. Naphthas and other hydrocarbon solvents are made emulsifiable by the addition of emulsifying agents. These emulsifiable solvent cleaners may be used in two ways. They may be added to water, particularly in power-spray washing machines, usually in the ratio of 1 to 5 volumes of emulsifiable cleaner to 100 volumes of water, with the operating temperature between 130 and 160 F. Aqueous emulsions of this type are used most advantageously with pressure spray or agitation. Emulsifiable solvent cleaners may also be used without dilution with water, then followed with a water rinse. This method is more effective for removal of pigmented drawing compounds and oils containing solid dirt. Occasionally different solvents, such as xylol or ethylene dichloride, may be used for specific applications. The work to be cleaned is immersed and occasionally agitated in the emulsion cleaner so that oil and grease are dissolved and each solid particle is wetted thoroughly by the cleaner. Then the work material is drained and rinsed with running water, or preferably with a pressure spray. For organic finishing, a second rinse in hot water will suffice, but for electroplating, the work is transferred from the hot water to an alkali cleaner.

Emulsion cleaning decreases the length of the time required in the alkali cleaner and insures removal of solid dirt. The best emulsifiable solvent cleaners contain emulsifiers and penetrants that neither harm alkali cleaners nor react with acid to form insoluble fatty acid films. The advantages of cleaning with emulsifiable solvent are: use at room temperature for removal of solid and organic dirt; no harmful action on active metals such as aluminum and zinc; lower toxicity than chlorinated hydrocarbons.

Vapor Degreasing. The vapor degreaser may be likened to the chemist's reflux condenser. A nonflammable solvent, such as stabilized trichlorethylene, is heated to boiling, by electricity or by steam coils, in a chamber around the top of which are cooling coils or compartments to recondense the hot vapors and to prevent escape of the solvent. The work material to be cleaned is hung in the hot vapor, which condenses on the work and washes off the grease and oil. Because the oils removed are only slightly volatile at the operating temperature of the degreaser, the hot vapor will be essentially that of clean solvent although the liquid solvent itself may be badly contaminated. The volume of solvent condensing on the work to be cleaned, and consequently the effectiveness of cleaning, is determined by the weight of the metal, the specific heat of the metal, the rise in temperature necessary to bring the work to the temperature of the solvent, and the latent heat of condensation of the solvent. For a given metal and cleaner, the amount of vapor condensed will depend on the weight of the metal to be cleaned. It is obvious, therefore, that light metal sections with heavy films of oil will be cleaned poorly, whereas heavy metals with comparatively heavy grease films may be cleaned effectively. The vapor cleaner cannot completely remove solid dirt from the surface, and frequently, though well cleaned of oil, the work may be covered by a cloud of solid dirt, which necessitates a subsequent wiping operation.

To overcome the difficulties mentioned, spray cleaning, combinations of two solvents, or a sequence of boiling liquid, cold liquid, and hot vapor may be employed. In the last-named sequence, the work material is first immersed in the boiling solvent where most of the solid dirt and oil are removed. (This cleaner soon becomes contaminated but the cleaning efficiency of the system is not seriously affected.) The work metal is transferred from this chamber to a chamber containing relatively cleaner cold solvent that is formed by the condensation of the vapor from the first cleaner. In the second chamber, the work material is cleaned of dirt that was not removed in the previous chamber; and the solvent in the second chamber is kept relatively clean by the constant condensation of the clean hot vapor and the run-off of excess condensate into the first compartment. The work material is withdrawn from the cold chamber and held above the hot compartment where the hot clean vapor condenses and removes any residue of oil not removed in the cold chamber. This sequence, although more laborious than simple vapor clean-

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ing, makes possible the cleaning of thin, badly contaminated work pieces.

In designing vapor degreasers it is essential that sufficient heating capacity be provided; otherwise the vapor line in the cleaner will drop too low when the cold pieces are immersed, and the cleaning process will be seriously retarded. Improper height of the vapor column and poor condensing facilities permit large loss of solvent and a decrease in the amount of heat that can be applied to the boiling solvent. The equipment should be designed to meet the requirements of size and volume of work as closely as possible, because too large units allow higher ratios of solvent lost by diffusion to amount of work cleaned, and too small units permit large loss of solvent by displacement of vapor when the work material is immersed.

Vapor degreasing has several specific advantages: (1) After cleaning, the drying of the work is rapid, a feature of particular value for recessed work or where water stains might be objectionable; (2) the high temperature of operation softens the solid fats and lowers the viscosities of the oils, allowing rapid penetration and removal of material in holes or crevices (removal which would be difficult with alkaline aqueous cleaners); (3) metals such as aluminum or zinc that are attacked by many alkaline cleaners may be cleaned by vapor degreasing with almost no visible effect on the finish. The installations may be made automatic and are cleaner than alkaline cleaning methods. Vapor degreasing is particularly valuable for cleaning metals prior to lacquering, japanning, enameling, or general organic finishing; however, an alkaline cleaning that removes all traces of organic matter still remaining on the surface, should follow vapor degreasing before a metal is plated.

The disadvantages of vapor degreasing include cost of materials greater than for alkaline cleaning, difficulty in removing solid dirt, toxicity of the solvent (troublesome in poorly designed equipment), and the need for subsequent alkaline cleaning preceding plating operations.

Blast Cleaning of Metals

By Victor F. Stine*

IN the process of blast cleaning metals a metal abrasive (grit or shot) or sand, propelled by centrifugal or air force, is directed at the surface to be cleaned. The method of application varies with the requirements of the material to be cleaned. During the past 10 years, the centrifugal process has come into wide use, although there are still many applications where it is desirable and necessary to use the compressed-air method. However, with the centrifugal process, only metal abrasives can be used, since the specific gravity of sand is too low for centrifugal force to clean as efficiently as is possible with the much heavier metal abrasives.

Centrifugal Method. In this process the abrasive is thrown against the work at approximately 250 ft per sec by means of a bladed wheel, running at approximately 2200 rpm. The wheel units are capable of throwing as much as 60,000 lb (30 tons) of steel abrasive per hour, using as high as 50 hp. It is said that as much work can be cleaned by using the centrifugal method with 25 hp as can be cleaned by using 150 hp with the compressed-air method.

Three types of machines are used with the centrifugal method—barrels, tables and special cabinets. Where work can be cleaned in a barrel, by batch handling, this is the most economical way. For flat and fragile work, tables are used. For parts such as cylinder blocks, cylinder heads, bath tubs, and other large pieces, cabinets with monorails are ordinarily used for handling the work material. For cleaning steel rods, steel plates, steel sheets and the like, the flat type of conveyer is used to conduct the work pieces through the blast cabinet.

Types of Air-Pressure Blasts. Two major types of blast are used in air-pressure blasting: (1) the direct pressure type and (2) the induction type, based on either the gravity principle or the suction principle.

Direct Pressure Type. When the principle of direct pressure is applied, the full pressure of compressed air is carried all the way to the tip of the nozzle. In order to introduce the abrasive into this high-pressure line, it is necessary to provide a pressure storage tank in which a certain amount of abrasive is also under pressure. Through an orifice in the bottom of the tank, the abrasive is permitted to flow by gravity into the high-pressure abrasive line; the pressure in the tank and line are equal. In actual practice, the apparatus is often complicated by the introduction of adjustable orifices, means for shutting off the abrasive and air, and double-chamber arrangement for obtaining continuous operation.

Gravity Type. The gravity method provides an overhead abrasive storage, or other means of supplying abrasive by gravity to an induction type of gun in which air is introduced through a jet that is in definitely spaced relationship to a nozzle. The air rushing from the jet into the nozzle creates a partial vacuum in the space surrounding the gap between jet and nozzle. The abrasive introduced into this gap is sucked into the nozzle and mixed there with the compressed air, which accelerates the movement of each grain. At the nozzle tip, the air suddenly expands, pressure is transformed into velocity and the grains receive a last and quite effective shove. Although less effective than the direct pressure blast, the gravity principle is frequently used, mainly because of lower initial and maintenance costs.

Suction Type. The use of suction is similar to the use of the gravity type of blast and, though somewhat less effective, finds even more frequent application, particularly in the design of automatic equipment for treating materials easily cleaned. An air jet and a nozzle are again in definitely spaced relationship but, as distinguished from the open hopper or funnel type of mixing chamber used in the gravity type of outfit, these parts are enclosed in a body commonly called a gun. An outlet is provided at some point with an arrangement for attaching an abrasive hose or pipe line that leads to an abrasive feeding device, often many feet away. The partial vacuum inside the gun creates a strong suction in the abrasive line, sufficient to lift the abrasive entering the end of the hose or line for considerable distances. However, to lift this abrasive, energy is required that is lost from useful work; consequently this principle is the least effective of the three.

Blast from Blower. The medium of force in another method of blast cleaning is generated by a specially designed blower that blows air at approximately 30,000 fpm through a nozzle into which approximately 10 times as much abrasive is fed as when using compressed air through a standard ⅜-in. nozzle. Surfaces are cleaned by a scouring action. It is claimed that the power and maintenance costs are very low. However, the cleaning efficiency may not be so great as that of high-pressure air blasting or centrifugal blasting.

Nozzles. A small but important part of all air-pressure blast cleaning equipment, the nozzle, is subject to wear at the inlet as well as at the outlet. The wear at the inlet is of concern because the size of the inlet controls the air and power consumption.

A new ⅜-in. nozzle, for instance, permits the flow at 90-lb pressure of about 211 cu ft of free air, requiring 40.5 hp. If the nozzle is permitted to wear at the inlet to $\frac{7}{16}$ in., the air flow increases to 286 cu ft or 35½%, and the power to 54.9 hp (also 35½%). Clearly it may prove to be bad economy to use a nozzle too long, particularly in equipment using multiple nozzles. The wear at the nozzle tip is much more rapid than at the inlet because of the expansion of the air, which carries a certain amount of abrasive

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with it, forcing the abrasive against the nozzle walls. This explains why abrasives of lighter specific gravity will wear down a nozzle faster than the heavier abrasives. Each moving abrasive particle has a certain kinetic energy directly proportional to its weight or mass. If it were possible to fire a cork ball and a lead ball simultaneously from a double-barrel gun during a windstorm, the cork ball would be deflected from its course much more rapidly than the lead ball. Similarly, the side thrust exerted by the expanding air acts more quickly on the lighter grains than on the heavier ones.

Another reason for the rapid wear on nozzles by the lighter abrasives (such as sand or artificial abrasives) is the fact that the light abrasives travel through the nozzle faster than the heavier steel abrasives, because it is easier for the compressed air to accelerate a lighter particle than a heavier one. This higher velocity causes a larger volume of abrasive to flow in a given time, resulting in more frictional wear.

It goes without saying that granular abrasives (meaning abrasive grains that have sharp corners) wear away a nozzle more quickly than globular grains of essentially spherical shape, such as metal shot. The explanation of nozzle wear applies also to the wear of all other parts through which abrasive flows. The least wear is encountered when metal shot or grit is used. A long nozzle will give a more concentrated stream, whereas a short nozzle covers a larger area but shows a slightly higher abrasive velocity.

Recent years have brought the development of nozzles made from boron carbide, which give more than 750 hr of service using sand abrasive, and 1500 hr of service using steel abrasive.

Finishes. Almost any desired finish can be produced by using the proper abrasive or mixture of abrasives.

Types and Sizes of Blast Cleaning Equipment. There are various types and sizes of blast cleaning equipment. Proper selection among them depends on the work to be cleaned and the rate of cleaning desired.

Air Pressure. For ferrous metals the pressure used ranges from 60 to 100 lb, depending on the extent of cleaning required and the condition of the work. For nonferrous metals the pressure is from 10 to 60 lb, also depending on the nature of the work and extent of cleaning. In blast work for design or frosting effect, the air pressure is usually from 3 to 15 lb.

Health Precautions. Blast cleaning is applied both to rough castings to which core sand is adhering and to finished products (free from sand) prior to painting, dipping, and lacquering. Whether the abrasive is silica sand, steel grit or shot, the sandblaster must be protected by a helmet supplied with air, special gauntlets, apron and often special spats. The blasting equipment and the blasting room have been brought to a high degree of efficiency and include ventilation involving as many as 12 air changes per min, with cleaning and recirculation of the air that is withdrawn. The air supplied the worker (about 6 cu ft per min) should be from a separate source and must be clean, odorless, dry and free from gaseous contaminants. If taken directly from the compressed-air receiver, it is likely to be wet and malodorous.

The health risk from blast cleaning is silicosis, a disease resulting from the breathing of very fine silica particles. In past years, sandblasting improperly done has been the cause of many cases of silicosis, the effects of which can be permanently disabling and even fatal. No matter how good the equipment may be, the blaster should be X-rayed before he is employed and at least once a year thereafter. The films should be read by a physician specializing in this particular field.

Sandblasting of sand-free steel or iron castings, and shot blasting of sandy castings will both produce enough fine silica to make the air dangerous to breathe. The standard equipment with which the blaster is provided will keep him comfortable and insure his breathing good air. However, the men who blast and clean are usually unskilled workers with no conception of health risks, even if warned. It is not unusual for such men, on finishing a cleaning job, to turn off the blast, remove their helmets and blow the loose sand from the casting. Every safety director knows that such practices are wrong, but the dusty air is not unpleasant to breathe and the worker may be wholly unaware of his physical peril.

The purpose of this note is simply to emphasize that blast cleaning jobs can be done without health risks to the workmen, but that such work is safe only if the advocated precautionary measures are followed rigorously.

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Tumbling, Rolling, and Barrel Burnishing

By R. W. Mitchell*

METAL PARTS, after fabrication, are often cleaned, rinsed, rolled, ball burnished and dried, all in one sequence of operations. The words "tumbling" and "rolling" are often used synonymously. There is, however, some distinction between the two processes, and the words may be used to differentiate between two operations, similar in general but differing in detail.

"Tumbling" is an operation in which the work pieces (usually castings or forgings or stampings) are rotated in a barrel, drum, or chest, together with stars, jacks, slugs, metal punchings, or some abrasive such as sandstone or granite chips, slag, silica, sand or pumice. Ordinarily in this operation the work is packed tight and the barrel is nearly filled.

"Rolling" consists in rotating a barrel containing a load of work pieces and abrasive, so that the load rolls over and over upon itself in a continuous flowing motion. Rolling may be done in either horizontal closed barrels or open tilt barrels. In open barrels the load is lighter and much more free to move within itself or to roll as the barrel rotates. Work pieces may be rolled with any one of a large number of abrasives of varying particle size, sharpness and hardness, such as ground slag, sand, silex, pumice, volcanic ash, emery, carborundum, alundum, Vienna lime, crocus, or rouge. The abrasive is generally finer in size than any used in tumbling.

Both tumbling and rolling may be done either dry or wet, depending on the results desired. The amount of "bite" to the abrasive, and the resultant cut are affected considerably by the amount of water present. The water may contain dissolved chemicals such as muriatic or oxalic acid, acid salts such as sal ammoniac, or cyanide, to aid in removal of scale.

"Ball burnishing" is a method for putting a high finish or luster on metal parts, by rolling them in a revolving barrel with polished hardened steel balls (or a modification of these) and some lubricant. In tumbling and rolling, metal is removed from the surface; in ball burnishing it is not. The continuous rolling pressure and rubbing action of the heavy load of balls flowing over the metal surfaces of the work, peens and smooths out minute surface inequalities to produce the luster characteristic of an even reflecting surface. In some instances, small parts such as buttons and rivets can act as a self-burnishing load. Surface irregularities are cold worked or flowed to a more even plane; they are not cut down. Ball burnishing can be successful only on a surface properly prepared for this final finishing operation.

Tumbling might be compared with snagging or grinding; rolling is analogous to polishing or cutting down; and

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burnishing corresponds to buffing. Tumbling removes sand, "skin", scale, and fins from castings, and scale from forgings. Rolling removes flash and burrs, wire edges, pits, rough spots, scale and rust, and cuts down a metal surface to an even and uniform condition. Both processes, unfortunately, also remove corners and round off edges. Barrel burnishing puts a lustrous finish on a clean and smooth, but dull, metal surface.

Tumbling. Foundries use a "rattler" for removing sand, rough "skin" and fins from castings. Scale and rust have long been removed by tumbling metal parts in acid; the mechanical action greatly aids the pickling effect.

Modern tumbling equipment removes dust and dirt by means of exhausted air circulation and dust filters, automatically loads and discharges the work material, and then separates the work from the stars, sawdust and other materials.

Tumbling is the least expensive method of cleaning castings. It is claimed that tumbling increases the strength of castings, since the peening action during tumbling evens the surface and neutralizes residual strains. On some classes of work material this has the same effect as annealing. Liberal use of stars or jacks is essential for quick and thorough cleaning, in order to reach every pocket and corner of the castings and to produce an even finish.

Barrel Rolling Operations. Rolling, a cutting down operation, is done in open tilt barrels or in horizontal closed barrels. Depending on time and abrasive, the cut may be light or heavy. This method can be applied to objects that will form a rolling load in a slowly rotating barrel. Generally this means small parts and parts that will not entangle, nest or interlock; that are not so thin in any cross section as to become bent; and that do not require the holding of sharp edges or corners. In some instances it is possible to have a little extra metal at edges or points subject to the greatest cutting down effect, to make the barrel rolling method acceptable. Hollow or drilled pieces are not suitable if the rolling abrasive cannot readily be rinsed from them. Ordinarily this process is not used for pieces that have a dimension much greater than 6 in. An exception is long straight work, such as curtain rods, tools and handles, which can be rolled in a horizontal barrel in such a way that their long axes are always parallel.

The tilt barrel, designed for rolling small parts, has an open top and hence is readily loaded and discharged. It can be inclined at different angles for varying effect.

The rolling action increases in intensity as the axis of revolution is lowered toward the horizontal. Speed of rotation varies between 20 and 60 rpm, usually the slower the better. Speed should suit the requirements of the work material, and should never be great enough to cause the pieces to "throw" or move in any but a gentle rolling motion. The barrel should be from 40 to 50% full. An advantage of the open tilt barrel is that the operator can watch the progress of the work and avoid excessive rolling, which not only wastes time but also may damage the work material.

Types of Barrel Construction. Barrels are made of wood, rubber and most of the metals, in a number of shapes, both round and polygonal, with angle-cornered or round-cornered bases. These different shapes provide different rolling actions. The polygonal form affords more effective rolling, carrying the load farther up the side of the barrel and allowing it to roll down a steeper slope. Barrels may be left smooth inside or may be fitted with cleats, fins, steps or similar devices to effect a more complete movement of work in the load. The individual pieces in the load should not only roll over and over but should rotate in more than one plane and move back and forth slowly, in a direction parallel with the axis of the barrel.

Wooden barrels are used for rolling comparatively light articles, either wet or dry—particularly articles made of nonferrous metals such as brass and nickel silver. Wooden barrels are not suited to withstand the wear of rolling rough or heavy articles in sand or other coarse abrasives.

The metal used in construction should be such as to avoid galvanic action with the load.

Cast barrels are used for either wet or dry tumbling, or for rough work involving the use of abrasives such as coarse sand and gravel, and for finer work requiring fine pumice or emery.

Barrels made of nonferrous metal are used for tumbling articles in certain acids that would corrode iron, and for rolling high-grade brass articles, which might become discolored by rubbing against cast iron.

Sheet metal barrels are used to tumble heavy articles that have sharp corners, since these might chip a cast barrel and wear it away rapidly.

It is usual to set up the barrels with a water pipe arranged so that water will run into the open head. For washing and rinsing the work pieces in the barrel before rolling, or for rinsing them in solutions after rolling, a piece of hose connected to the water line is run to the bottom of the barrel. A running rinse then displaces the solution by overflowing.

The usual method of discharging the work pieces is by tilting the barrel so that the load slides into a sieve-topped box, which serves to separate work from jacks, balls or abrasive. When sturdy sieve caps on metal frames are used, locking tight into the head of the barrel, the barrel is lowered and run in this position for a few minutes, allowing separation of work pieces and rolling medium, the work being retained in the barrel temporarily.

Horizontal Barrels. Larger articles, or those with one long dimension, roll more evenly in horizontal barrels, which afford more uniform cutting down and polishing. In the tilt barrel such parts would roll end over end, and produce too much action on the end faces or corners. Horizontal barrels are also better suited structurally for large and heavy loads. The horizontal barrel is more generally used for "rough work"—grinding and smoothing up—and the tilt barrel for light finishing.

Horizontal barrels with the axis of the barrel a little out of line with the axis of rotation, are used to give the most effective motion to the load.

Horizontal barrels are made with one or more multiple compartments. They are usually of metal, often cast iron, although other metals may be used to meet special requirements. They may be lined with wood for rolling soft or easily discolored metals. Barrels should be designed to balance and run without jerks.

When wet work material is tumbled in closed barrels, the barrels must be vented every few hours, because finely divided metal reacts with water, forming hydrogen gas, and the frictional heat generated by the mechanical working of the load, builds up dangerously high gas pressure.

The open-ended horizontal barrel is quite different. It is able to handle large loads and has been highly developed expressly for automatic operation. These barrels are designed to be self-loading and, by means of spiral fins on the inside surface, are self-discharging when the rotation is reversed. Some have a device for separating work pieces from stars, balls or slugs, and automatically returning the tumbling agent to the barrel.

Abrasives and Duration of Rolling. The abrasives commonly used are slag, cinders, sea sand, sharp sand, or builders' sand, pumice, limestone, and granite chips, broken glass, silex, emery, alundum and carborundum. Particle size, hardness and sharpness are factors affecting the time required for rolling. Pumice is a sharp but light and soft abrasive used mostly on brass and soft metals in finish smoothing. Hard metals require hard, quick-cutting abrasives such as emery, alundum and carborundum.

To provide a more uniform action, to add weight, or to carry the abrasive with a rubbing motion into depressions or corners, an auxiliary load is often added, such as wood blocks, jacks, slugs, punchings, steel balls or steel wool.

Where the surface of the work material is soft or where a brightening action is desired rather than a cutting down action, milder or finer abrasives are used. Silica, chalk, lime, crocus, polyroth, and rouge are suitable. Leather scrap or meal, felt, and hardwood sawdust (maple, boxwood, or lignum vitae) are also used, ordinarily dry, and sometimes with fine abrasive mixed in. After an abrasive roll, sawdust is employed to scour fine abrasive from the metal surface.

Greater cutting action is obtained in the wet process. The amount of water present has a great effect on the success of the process. For maximum action, the amount should be just sufficient to make a wet paste or mud. If too dry, the abrasive will stick to and coat the work material and interior of the barrel, preventing the desired action. If too much water is present, most of the abrasive particles will go to the bottom of the load and will not work evenly through the rolling mass.

Water evaporates during rolling and must be replaced or the abrasive will pack and ball up. Chemicals may be added to the water. Dilute sulfuric or muriatic acid, or ammonium chloride aids in removing scale. In the rolling of steel, alkali and cyanide in small amounts are often added to improve color. Cream of tartar or cyanide improves the color of copper alloys. Soap solutions are not used in cutting down or polishing operations, but are applied later during the burnishing. Oil may be employed for rolling with sharp abrasives; kerosene is often used with emery.

Proper speed of the barrel should carry the load of work and abrasive up the side of the barrel to approximately three-fourths of the inside diameter. The mass should then have a slope that causes the top of the load to fall over and roll backward upon itself.

Dry rolling, using sawdust, is preferable to wet rolling for brightening screw-machine products. Fine sawdust should be used to avoid the clogging of threads and slots. The dry roll gives a better color in the allowable time and has a less injurious effect on the threads. If sufficient sawdust is used (several times the volume of the work load) to keep the screws or bolts spaced well apart and away from the barrel surface, the work material may be rolled as long as 2 hr without appreciable dulling of thread edges. This is sufficient to give a high finish. To remove any oil, the work pieces should be rolled in sawdust about 15 min; then the sawdust should be changed. It is not possible to bring the objects out entirely free from sawdust, but in some instances this is not essential.

To obtain high finishes—that is, smooth, even and bright surfaces—a long rolling is required. Coarse abrasive used at the start, is gradually broken down; consequently as rolling proceeds, the cut becomes finer and finer.

The length of time required obviously depends on the quality of surface desired, and on the condition, shape and hardness of the metal surface. The softer a metal, the faster it is cut down.

For brass and bronze castings the average duration of rolling is 10 to 15 hr; for malleable iron castings, 30 to 40 hr; for gray iron castings, 70 to 80 hr. For stampings or automatic screw-machine parts, the necessary time varies from 1 to 100 hr, depending on the quality of the stock and the extent of die marks, scoring, or rough edges, brought from the machine operations. Ordinarily when hot rolled and pickled stock is being prepared for ball burnishing, the parts are rolled for about 48 hr. Often 80 to 90% of forging scale is removed by rolling for a few hours. A much longer time would be required to remove scale entirely.

Often much time is saved and a net economy is effected by performing one wheel operation before barrel rolling and burnishing. Sprues, parting fins, or any gross surface irregularities, should always be removed by an abrasive wheel or belt. Deep scratches or score marks should also be polished out on a wheel before rolling.

Barrel Burnishing. The purpose of barrel burnishing is to develop high luster on parts otherwise unfinishable because of size or shape, or to provide this finish at a lower cost than possible with hand labor. Barrel burnishing allows the finishing of small parts in bulk. The process can replace buffing on a wheel in many instances, and may be used as a preliminary to electroplating and as a finishing process afterward.

Burnishing has no cutting or abrading action; it must avoid these. In burnishing, rubbing pressure flattens and spreads all minute surface irregularities to a perfectly even surface. This action also reduces the porosity in plated surfaces.

Burnishing will not remove visible surface irregularities, scratches or pits. It will not improve color. These conditions must be treated before the burnishing operation (*see* Barrel Rolling).

In barrel burnishing, the rubbing action that produces the burnishing may be between pieces of the work itself (self-burnishing), or between hardened steel balls (ball burnishing), or other suitable forms—cones, slugs or pins—and the work. The rubbing pressure varies with the weight and depth of the load, and is influenced by the speed of rotation. A lubricant solution prevents abrasion from metal-to-metal contact in the rubbing, prevents heating of the load, and promotes the development of the high luster that is the object of the process.

In general, about two volumes of burnishing agent (balls and the like) should be used to one volume of work material. For some work, a ratio of one to one suffices. The proper ratio is influenced by the type of barrel, by whether it is run full or only partly full, and by the form of the work objects. The weight of the burnishing mass provides most of the pressure. There must be plenty of balls to space off and surround each piece of work entirely. Hollow or recessed work requires a larger proportion of balls than solid articles. Stampings require more balls than do castings or forgings. It is better to use too many balls than too few.

Work that floats or rides on the burnishing mass is obviously under no pressure and hence does not burnish. Work cannot float on the balls if no free space is left above the burnishing load.

Burnishing Agent. Round steel balls are ordinarily the most satisfactory burnishing agent because they can be hardened and they supply best the fundamental combination of half-rubbing and half-rolling action. Pressure is a necessary factor in burnishing; however, too much pressure between ball and work might result in grooving or rubbing off metal. When excessive pressure might occur because of some resistance in the load, grooving is avoided by the natural tendency of the ball to roll. The balls need not be perfectly spherical but they must be hard, smooth, and too tough to fracture.

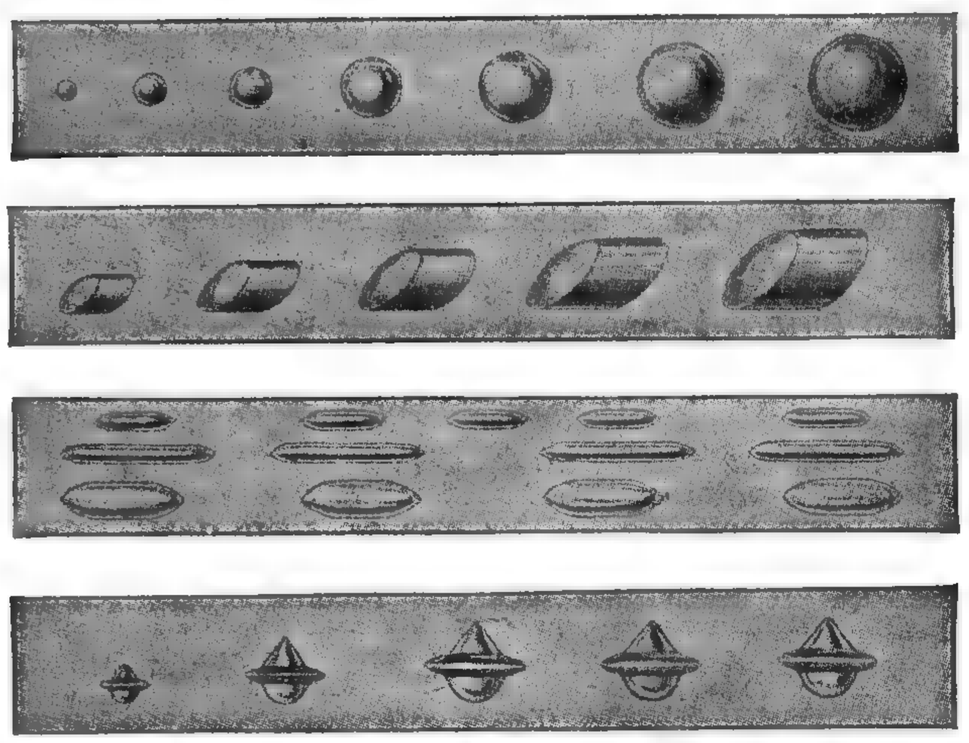

Fig. 1 Balls, slugs, pins, and ball cones for burnishing operations (Hartford Steel Ball Co.)

A ball will not burnish in corners and angles. It cannot enter an angle, slot or indentation smaller than its own diameter. In such places, or where the surface of the work material is figured, the use of other shaped pieces is required. Slugs, diagonals, burnishing steels, cones, ball cones, fin balls, pins or "oats" (Fig. 1) burnish into angles, corners or grooves not reached by balls. These forms are generally used in admixtures with balls. Too high a ratio of pins or "oats" may cause a stippling effect on flat work. "Balls" should be understood to mean either balls, some of the modified forms, or mixtures of these.

The unit size of burnishing agent is important. Small balls obviously provide more contacts with the work, but they give lighter pressure. Large balls are less expensive and less readily lost while handling. It is common practice to mix two sizes of balls.

For drilled, slotted or recessed work pieces, it is advisable to choose balls larger than the holes or slots into which they might otherwise wedge.

On soft metals small balls are necessary to avoid too much pressure in rubbing. Balls ⅛, 3/16, and ¼ in. in diam are the sizes most commonly used.

Much time and labor are expended in making the surface of burnishing balls mirror smooth, and successful burnishing depends on keeping the balls this way. Steel ordinarily rusts easily, and balls with surfaces roughened or pitted are seriously impaired. Steel does not rust when kept immersed in a solution of pH 9.5 or more. A dilute soap solution, or a dilute solution of soda or alkali will have a pH of at least 9.5; hence steel balls kept under such solutions are protected.

Balls pick up dirt or scum and become dull or even black. The dirt may have been brought in on the work pieces, or it may be an accretion of the sticky, insoluble lime soaps formed from the burnishing soap and the small amount of "hardness" usually present in water. Balls should be kept clean and bright at all times. Dirty balls are ordinarily cleaned by rolling with a warm solution of sodium cyanide, about one ounce per gallon in concentration. They may also be cleaned by rolling with metal cleaner and rinsing thoroughly afterward.

Surfaces to Be Burnished. Before the burnishing operation, the metal surface must be in proper condition to attain the final quality of finish desired. Burnishing will not remove metal or take out surface blemishes. It is absolutely impossible to secure good results without a good surface in the beginning. If the natural surface is not good, it must be prepared by rolling with abrasive.

In addition to being smooth, the work must be clean of all dirt, rust, scale or tarnish.

Burnishing will improve luster but it will not improve color. To provide good color, brass, copper, bronze and nickel silver, are often bright dipped and thoroughly rinsed before burnishing. Annealed drawn brass, or brass that has acquired an uneven color or perhaps actual tarnish from standing around or being handled, must be either bright dipped or dipped in cyanide. A dip commonly used is made by pouring 3 volumes of sulfuric acid (1.84 sp gr) into 3 volumes of water, and then adding 1 volume of nitric acid (sp gr 1.4).

A pinch of salt (sodium chloride) or about 1% of hydrochloric acid (conc) added daily, makes the dip more effective. The temperature of the dip should not rise above 95 F. Enough lampblack is usually added to bright dips to form a thin covering film on the surface.

Aluminum and particularly aluminum die castings are ordinarily dipped first into hot dilute caustic soda solution (about 3 to 4% conc) for 5 to 10 sec. Then they are rinsed, and are finally bright dipped in a solution made by mixing 3 volumes nitric acid (sp gr 1.4) and 1 volume hydrofluoric acid (48%), for use at room temperature. To find a suitable container for this solution entails some difficulty. A lead-lined vessel is recommended, painted inside with a mixture of 1 part beeswax and 4 parts paraffin. Avoid personal contact with the liquid, and do not breathe the fumes from it.

Hydrochloric acid (20 Bé or sp gr 1.16) is used for brightening steel or iron and for removing rust. Acid ammonium citrate in warm dilute solution will remove light rust without roughening a polished steel surface.

Sometimes, after a short period of burnishing, a dark scum will appear on the solution covering the load. If this occurs, the solution should be run out, the load rinsed, and fresh water and burnishing lubricant added.

The load of work pieces and balls is usually just covered with water, the burnishing lubricant is added, and the barrel is closed and set in rotation. Enough burnishing soap should be used to build and hold a heavy cushion of suds in the barrel throughout the run.

Importance of Hardness. The harder the surface of the work material, the higher the finish it will take. Many small steel parts that are finished by ball burnishing are hardened especially for this reason. It takes longer to develop luster on the hardened metal, but higher quality and more permanent results are obtainable.

Soft metals, however, can be ball burnished to a good luster. When small balls and low speeds are employed to avoid excessive pressure, even die castings can be brought to a high finish. Brass, soft nickel plate and nickel silver can be given a beautiful luster. Because die castings are soft, they must be ball burnished with a relatively small burnishing ball, at a low speed, and with more than the ordinary amount of lubrication.

A plated surface can be ball burnished as well as a solid metal. A hard plate will develop a better luster than a soft electrodeposit.

Zinc and aluminum die castings can usually be brought to a good finish in about 60 min. Sometimes overburnishing is detrimental. A 60-min burnishing period is also usually sufficient for nickel or for brass.

For steel, burnishing time varies greatly, depending on the quality of the surface, the result desired, and above all on the hardness of the steel. Burnishing may require from 15 min to 100 hr or more.

Chromium plate is harder than nickel plate and, under similar conditions, should be burnished about twice as long.

Chromium solutions have what is known as a "bright range". Occasionally parts will be dark or "burned" in some spots because of too high local current density and will be dull in other parts because of too low local current density. Ball burnishing evens up the finish by giving a more uniform brightness to such surfaces.

Speed for Burnishing. The speed of rotation depends on the nature of the work material and also on the diameter of the barrel. The smaller the diameter of the barrel, the faster the allowable speed. The faster the rotation, the more movement in the load and the greater the number of burnishing rubs. On soft metals, too great pressure may develop, causing deformation of the surface. Small or regularly shaped pieces can be run faster than large or irregularly shaped pieces. Articles with edges or sharp corners must be run slowly. If the work shows scratches, dents or peen marks, the speed must be reduced.

Racking and Work-Holding Barrel. For pieces that scratch or dent one another, or pieces with large smooth areas that must be free from rubbing marks, racking is essential. A framework is needed into which the parts can be locked by clips, or by clamping the frame together after loading. Some shapes can be slid on rods with spacers between the parts. The racks are designed to slip closely into an open-ended barrel.

Sometimes it is important to keep parts from nesting together. This can also be done on racks. On studs and other parts where only the head should be finished, threads can be protected by tightly fitting covers made of short pieces of elastic rubber tubing.

Unloading the Barrel. After the burnishing has proceeded long enough to produce the required luster, the solution is run off and the load of balls and work pieces is *thoroughly* rinsed with clean water. Any soap film left on the work material will dim the luster. On brass, or similar alloy, residual traces of soap cause rapid tarnish and change of color. The next step is to separate the balls from the work pieces and to dry the work pieces. The customary procedure is to dump the load on a riddle or sieve of mesh that will permit the balls to fall through to a tray or box. The upper box is arranged to slide on cleats. After the balls have been riddled through the screen bottom, the upper box is removed to carry the work to a sawdust or hot air drier. The bottom box can be arranged with a bottom sloping toward the front. The balls collecting there can be returned to the barrel by a portable loading machine.

Work removed from the barrel is commonly dried by tumbling or rubbing with clean dry sawdust; maple or boxwood sawdust is preferred. The work pieces are sometimes passed through a hot air drier, employed for those parts that retain sawdust; for example, split or tubular rivets, threaded or slotted screw-machine products.

Sawdust is the best drying medium where it can be used. It serves as a cushion between pieces and prevents scratching or marring. Only good hardwood sawdust is suitable and it must be dry since moist sawdust clings to the work material and is likely to leave water marks. Sawdust is kept dry by circulation through a fanning mill or by storage in a box or bin with a steam coil in the

bottom. Cob meal (ground corncobs) is an excellent alternative for sawdust.

Burnishing Lubricants. Many kinds of material have been used for burnishing solutions. Soap, soap bark, blackstrap molasses, stale beer, alkalies, alkaline cleaners, cyanide, and cream of tartar are the most important. Foremost among these is soap, at least in extent of use.

Soaps may be made neutral, acid or alkaline, depending on whether alkali base and fatty acid are present in exact chemical equivalents or not. Small percentages of free alkali, or of free fatty acid, greatly influence the properties of soap solutions. Commercial soaps often contain added filler or builder (alkaline salts or silicate), rosin, or solvents. Depending on the method of saponification, glycerine may be either removed from or left in the soap.

Soaps used in commerce vary greatly in solubility, gelling power, ability to produce lather, ease in rinsing, alkalinity and viscosity. The differences in properties are important in barrel burnishing.

High-titer soaps give the best lubrication and burnishing action. However, they may not be used where good rinsing is a controlling factor, or in a tubbing machine where their solutions would gel. Lower-titer soda soaps are best where rinsing is difficult because of the nature of the work material.

For nickel, brass or other copper alloys, or aluminum, a neutral soap is required. A small amount of borax or bicarbonate of soda (both less alkaline than soap) or of cream of tartar is used with the soap. On aluminum, use of the proper nonalkaline soap means the difference between success and complete failure.

For steel, the presence of free alkali is desirable. The use of cyanide with soap is also desirable on steel, since this combination increases the speed of burnishing and keeps the color white and free from a dull or leaden appearance.

The use of rosined soaps, or those containing silicate, should be avoided.

Where burnishing is done on a large scale, it is convenient to prepare a soap solution in a tank or barrel, and to add a measure of the liquid soap to the burnishing barrel instead of throwing in dry soap. In this way the soap gets to work as soon as the barrel is started. Where other ingredients are used with soap, this liquid soap is particularly desirable.

Enough soap or soap mixture should be added to build and maintain a heavy suds in the barrel throughout the burnishing period. To use more than this amount is wasteful. The solution should just cover the load.

Soap bark is often used for burnishing brass and other copper alloys that are sensitive to alkaline tarnishing. Soap bark and cream of tartar, or "tartar substitute", is a favorite combination.

A good formula for use on steel is made by dissolving 30 lb of high-titer burnishing soap in 50 gal of hot water, together with 15 lb of alkali (such as trisodium phosphate or soda ash) and two "eggs" of sodium cyanide. This mixture sets, becoming a soap jelly. About one quart is enough to use with the average load.

Dry burnishing is sometimes carried on where, for some particular reason, the wet method must be avoided. Dry burnishing ordinarily takes several times as long. Steel is dry burnished with cocoa butter and lime, or sometimes chip soap and rouge; nickel is burnished with leather meal and rouge; aluminum is burnished with leather meal and whiting; zinc die castings are burnished with boric acid crystals.

After brass has been burnished and rinsed thoroughly, a dilute solution of bichromate is sometimes applied to hold the color. The work is then thoroughly rinsed again and dried.

Burnishing Barrels. Widely differing designs and constructions of burnishing barrels are in common use. Barrels may be single or in tandem. They may have single, double, or triple compartments, or a single barrel may be built with a number of different pockets, each a separate sector of the barrel. In these pockets, a number of different small lots of work pieces can be run at one time without mixing. The barrel may rotate evenly about its axis or, with some designs, it may rotate eccentric to its axis, giving the load a combined rotational and oscillating movement.

Barrels are commonly made with cast shells. Articles should not be rolled against cast iron because it has a tendency to deaden color. Hence, these barrels are lined with hard maple wood. When not in use, a wood-lined barrel should be kept wet and the cover should be on, to prevent the lining from drying out and shrinking. For a similar reason, wood barrels made for dry rolling should not be run wet. They will swell and buckle, or burst the bands. Since wood is somewhat porous, it is essential for wooden barrels to be kept scrupulously clean. After use with any solution containing chemicals, wooden barrels should be thoroughly rinsed several times. Strongly alkaline solutions rapidly disintegrate wood linings.

Burnishing barrels are also made of cast steel without wood lining, or of iron with welded sheet steel lining. For burnishing iron or steel articles, these are more durable than wood and provide increased burnishing area, but are not recommended for brass, die castings or similar alloys. Brass-lined barrels have been used for ball burnishing brass with excellent results.

Ball Buffing. When small amounts of very fine abrasive, such as rouge or Vienna lime, are used in the burnishing barrel, the effect of buffing is obtained.

Small pellets of leather about the size of a marble are coated in glue, rolled in abrasive and, when dry, are used for dry barrel buffing of intricately shaped pieces that could not be finished on a wheel.

Deburring. It is sometimes necessary to remove burrs from machined pieces, castings and stampings, or to dull sharp edges without changing the other dimensions of the piece. This work is usually done manually with files or other tools. If it is possible to deburr such parts by a selective rolling or tumbling operation, the ratio of increase in output per operator may be as much as 100 to 1.

Some pieces are too large to be processed in a barrel; other pieces are too delicate or are made with tolerances too close. However, there are many pieces that can be deburred in barrels, once the suitable speeds, abrasives and especially the lubricants have been determined.

The rolling action utilized in this method of deburring, together with the protection against metal-to-metal contact provided by the addition of a suitable lubricant, limits the "cut" of the abrasive to projecting burrs. Some work has been deburred by rolling in a mixture of sand and water. However, deburring by this method is slow and there is danger of pitting the work.

Satisfactory results have been obtained, in some instances, by the use of oils and abrasives such as sand, alundum, emery or carborundum. This method can be applied to a considerable variety of relatively small burrs, particularly when, instead of a mineral oil, a suitable solvent soap lubricant is used, which gives better protection to the surfaces where dimensional changes are not desirable, and which also ensures easy, rapid and thorough removal of the lubricant and metal particles after deburring, without the use of special washing procedures. Recent applications of this solvent soap type of lubricant with stone chips as the abrasive material, have produced satisfactory results in the short-time deburring of both steel and aluminum parts of all sorts.

FERROUS METALS

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Composition Limits of Standard Steels

SOCIETY OF AUTOMOTIVE ENGINEERS AND AMERICAN IRON AND STEEL INSTITUTE

Carbon Steels (Revised April 16, 1947)

SAE Number	C	Mn	P Max	S Max	AISI Number
....	0.06 max	0.35 max	0.040	0.050	C1005
1006	0.08 max	0.25-0.40	0.040	0.050	C1006
1008	0.10 max	0.25-0.50	0.040	0.050	C1008
1010	0.08-0.13	0.30-0.60	0.040	0.050	C1010
....	0.10-0.15	0.30-0.60	0.040	0.050	C1012
....	0.11-0.16	0.50-0.80	0.040	0.050	C1013
1015	0.13-0.18	0.30-0.60	0.040	0.050	C1015
1016	0.13-0.18	0.60-0.90	0.040	0.050	C1016
1017	0.15-0.20	0.30-0.60	0.040	0.050	C1017
1018	0.15-0.20	0.60-0.90	0.040	0.050	C1018
1019	0.15-0.20	0.70-1.00	0.040	0.050	C1019
1020	0.18-0.23	0.30-0.60	0.040	0.050	C1020
....	0.18-0.23	0.60-0.90	0.040	0.050	C1021
1022	0.18-0.23	0.70-1.00	0.040	0.050	C1022
....	0.20-0.25	0.30-0.60	0.040	0.050	C1023
1024	0.19-0.25	1.35-1.65	0.040	0.050	C1024
1025	0.22-0.28	0.30-0.[illegible]	0.040	0.050	C1025
....	0.22-0.28	0.60-0.90	0.040	0.050	C1026
1027	0.22-0.29	1.20-1.50	0.040	0.050	C1027
....	0.25-0.31	0.60-0.90	0.040	0.050	C1029
1030	0.28-0.34	0.60-0.90	0.040	0.050	C1030
1033	0.30-0.36	0.70-1.00	0.040	0.050	C1033
1034	0.32-0.38	0.50-0.80	0.040	0.050	C1034
1035	0.32-0.38	0.60-0.90	0.040	0.050	C1035
1036	0.30-0.37	1.20-1.50	0.040	0.050	C1036
1038	0.35-0.42	0.60-0.90	0.040	0.050	C1038
....	0.37-0.44	0.70-1.00	0.040	0.050	C1039
1040	0.37-0.44	0.60-0.90	0.040	0.050	C1040
1041	0.36-0.44	1.35-1.65	0.040	0.050	C1041
1042	0.40-0.47	0.60-0.90	0.040	0.050	C1042
1043	0.40-0.47	0.70-1.00	0.040	0.050	C1043
1045	0.43-0.50	0.60-0.90	0.040	0.050	C1045
1046	0.43-0.50	0.70-1.00	0.040	0.050	C1046
1050	0.48-0.55	0.60-0.90	0.040	0.050	C1050
....	0.45-0.56	0.85-1.15	0.040	0.050	C1051
1052	0.47-0.55	1.20-1.50	0.040	0.050	C1052
....	0.50-0.60	0.50-0.80	0.040	0.050	C1054
1055	0.50-0.60	0.60-0.90	0.040	0.050	C1055
....	0.50-0.61	0.85-1.15	0.040	0.050	C1057
....	0.55-0.65	0.50-0.80	0.040	0.050	C1059
1060	0.55-0.65	0.60-0.90	0.040	0.050	C1060
....	0.54-0.65	0.75-1.05	0.040	0.050	C1061
1062	0.54-0.65	0.85-1.15	0.040	0.050	C1062
1064	0.60-0.70	0.50-0.80	0.040	0.050	C1064
1065	0.60-0.70	0.60-0.90	0.040	0.050	C1065
1066	0.60-0.71	0.85-1.15	0.040	0.050	C1066
....	0.65-0.75	0.40-0.70	0.040	0.050	C1069
1070	0.65-0.75	0.60-0.90	0.040	0.050	C1070
....	0.65-0.76	0.75-1.05	0.040	0.050	C1071
1074	0.70-0.80	0.50-0.80	0.040	0.050	C1074

Carbon Steels (continued)

SAE Number	C	Mn	P Max	S Max	AISI Number
....	0.70-0.80	0.40-0.70	0.040	0.050	C1075
1078	0.72-0.85	0.30-0.60	0.040	0.050	C1078
1080	0.75-0.88	0.60-0.90	0.040	0.050	C1080
....	0.80-0.93	0.60-0.90	0.040	0.050	C1084
1085	0.80-0.93	0.70-1.00	0.040	0.050	C1085
1090	0.85-1.00	0.60-0.90	0.040	0.050	C1090
1095	0.90-1.05	0.30-0.50	0.040	0.050	C1095
....	0.08 max	0.45 max	0.07-0.12	0.060	B1006
....	0.13 max	0.30-0.60	0.07-0.12	0.060	B1010
....	0.43-0.50	0.50-0.80	0.050	0.050	D1049
....	0.50-0.60	0.50-0.80	0.050	0.050	D1054
....	0.55-0.65	0.50-0.80	0.050	0.050	D1059
....	0.60-0.70	0.50-0.80	0.050	0.050	D1064
....	0.65-0.75	0.40-0.70	0.050	0.050	D1069
....	0.70-0.80	0.40-0.70	0.050	0.050	D1075

Resulfurized Carbon Steels (Free-Cutting Steels) (Revised April 16, 1947)

SAE Number	C	Mn	P Max	S	AISI Number
....	0.08 max	0.30-0.60	0.045	0.08-0.13	C1106
....	0.08-0.13	0.50-0.80	0.045	0.07-0.12	C1108
1109	0.08-0.13	0.60-0.90	0.045	0.08-0.13	C1109
....	0.08-0.13	0.30-0.60	0.045	0.08-0.13	C1110
....	0.08-0.13	0.60-0.90	0.045	0.16-0.23	C1111
....	0.10-0.16	1.00-1.30	0.045	0.24-0.33	C1113
1114	0.10-0.16	1.00-1.30	0.045	0.08-0.13	C1114
1115	0.13-0.18	0.60-0.90	0.045	0.08-0.13	C1115
1116	0.14-0.20	1.10-1.40	0.045	0.16-0.23	C1116
1117	0.14-0.20	1.00-1.30	0.045	0.08-0.13	C1117
1118	0.14-0.20	1.30-1.60	0.045	0.08-0.13	C1118
1119	0.14-0.20	1.00-1.30	0.045	0.24-0.33	C1119
....	0.18-0.23	0.70-1.00	0.045	0.08-0.13	C1120
....	0.22-0.28	0.60-0.90	0.045	0.08-0.13	C1125
1126	0.23-0.29	0.70-1.00	0.045	0.08-0.13	C1126
1137	0.32-0.39	1.35-1.65	0.045	0.08-0.13	C1137
1138	0.34-0.40	0.70-1.00	0.045	0.08-0.13	C1138
1140	0.37-0.44	0.70-1.00	0.045	0.08-0.13	C1140
1141	0.37-0.45	1.35-1.65	0.045	0.08-0.13	C1141
1144	0.40-0.48	1.35-1.65	0.045	0.24-0.33	C1144
1145	0.42-0.49	0.70-1.00	0.045	0.04-0.07	C1145
1146	0.42-0.49	0.70-1.00	0.045	0.08-0.13	C1146
1151	0.48-0.55	0.70-1.00	0.045	0.08-0.13	C1151
1111	0.13 max	0.60-0.90	0.07-0.12	0.08-0.15	B1111
1112	0.13 max	0.70-1.00	0.07-0.12	0.16-0.23	B1112
1113	0.13 max	0.70-1.00	0.07-0.12	0.24-0.33	B1113

Alloy Steels (Revised August 10, 1947)

AISI Number	C	Mn	P Max	S Max	Si	Ni	Cr	Other	SAE Number
1320	0.18–0.23	1.60–1.90	0.040	0.040	0.20–0.35	.....	.....	.....	1320
1321	0.17–0.22	1.80–2.10	0.050	0.050	0.20–0.35	.....	.....	.....	.....
1330	0.28–0.33	1.60–1.90	0.040	0.040	0.20–0.35	.....	.....	.....	1330
1335	0.33–0.38	1.60–1.90	0.040	0.040	0.20–0.35	.....	.....	.....	1335
1340	0.38–0.43	1.60–1.90	0.040	0.040	0.20–0.35	.....	.....	.....	1340
2317	0.15–0.20	0.40–0.60	0.040	0.040	0.20–0.35	3.25–3.75	.....	.....	2317
2330	0.28–0.33	0.60–0.80	0.040	0.040	0.20–0.35	3.25–3.75	.....	.....	2330
2335	0.33–0.38	0.60–0.80	0.040	0.040	0.20–0.35	3.25–3.75	.....	.....	.....
2340	0.38–0.43	0.70–0.90	0.040	0.040	0.20–0.35	3.25–3.75	.....	.....	2340
2345	0.43–0.48	0.70–0.90	0.040	0.040	0.20–0.35	3.25–3.75	.....	.....	2345
E 2512	0.09–0.14	0.45–0.60	0.025	0.025	0.20–0.35	4.75–5.25	.....	.....	2512
2515	0.12–0.17	0.40–0.60	0.040	0.040	0.20–0.35	4.75–5.25	.....	.....	2515
E 2517	0.15–0.20	0.45–0.60	0.025	0.025	0.20–0.35	4.75–5.25	.....	.....	2517
3115	0.13–0.18	0.40–0.60	0.040	0.040	0.20–0.35	1.10–1.40	0.55–0.75	.....	3115
3120	0.17–0.22	0.60–0.80	0.040	0.040	0.20–0.35	1.10–1.40	0.55–0.75	.....	3120
3130	0.28–0.33	0.60–0.80	0.040	0.040	0.20–0.35	1.10–1.40	0.55–0.75	.....	3130
3135	0.33–0.38	0.60–0.80	0.040	0.040	0.20–0.35	1.10–1.40	0.55–0.75	.....	3135
3140	0.38–0.43	0.70–0.90	0.040	0.040	0.20–0.35	1.10–1.40	0.55–0.75	.....	3140
3141	0.38–0.43	0.70–0.90	0.040	0.040	0.20–0.35	1.10–1.40	0.70–0.90	.....	3141
3145	0.43–0.48	0.70–0.90	0.040	0.040	0.20–0.35	1.10–1.40	0.70–0.90	.....	3145
3150	0.48–0.53	0.70–0.90	0.040	0.040	0.20–0.35	1.10–1.40	0.70–0.90	.....	3150
E 3310	0.08–0.13	0.45–0.60	0.025	0.025	0.20–0.35	3.25–3.75	1.40–1.75	.....	3310
E 3316	0.14–0.19	0.45–0.60	0.025	0.025	0.20–0.35	3.25–3.75	1.40–1.75	.....	3316
								Mo	
4017	0.15–0.20	0.70–0.90	0.040	0.040	0.20–0.35	.....	.....	0.20–0.30	4017
4023	0.20–0.25	0.70–0.90	0.040	0.040	0.20–0.35	.....	.....	0.20–0.30	4023
4024	0.20–0.25	0.70–0.90	0.040	0.035–0.050	0.20–0.35	.....	.....	0.20.0.30	4024
4027	0.25–0.30	0.70–0.90	0.040	0.040	0.20–0.35	.....	.....	0.20–0.30	4027
4028	0.25–0.30	0.70–0.90	0.040	0.035–0.050	0.20–0.35	.....	.....	0.20.0.30	4028
4032	0.30–0.35	0.70–0.90	0.040	0.040	0.20–0.35	.....	.....	0.20–0.30	4032
4037	0.35–0.40	0.70–0.90	0.040	0.040	0.20–0.35	.....	.....	0.20–0.30	4037
4042	0.40–0.45	0.70–0.90	0.040	0.040	0.20–0.35	.....	.....	0.20–0.30	4042
4047	0.45–0.50	0.70–0.90	0.040	0.040	0.20–0.35	.....	.....	0.20–0.30	4047
4053	0.50–0.56	0.75–1.00	0.040	0.040	0.20–0.35	.....	.....	0.20–0.30	4053
4063	0.60–0.67	0.75–1.00	0.040	0.040	0.20–0.35	.....	.....	0.20–0.30	4063
4068	0.63–0.70	0.75–1.00	0.040	0.040	0.20–0.35	.....	.....	0.20–0.30	4068
.....	0.17–0.22	0.70–0.90	0.040	0.040	0.20–0.35	.....	0.40–0.60	0.20–0.30	4119
.....	0.23–0.28	0.70–0.90	0.040	0.040	0.20–0.35	.....	0.40–0.60	0.20–0.30	4125
4130	0.28–0.33	0.40–0.60	0.040	0.040	0.20–0.35	.....	0.80–1.10	0.15–0.25	4130
E 4132	0.30–0.35	0.40–0.60	0.025	0.025	0.20–0.35	.....	0.80–1.10	0.18–0.25	.....
E 4135	0.33–0.38	0.70–0.90	0.025	0.025	0.20–0.35	.....	0.80–1.10	0.18–0.25	.....
4137	0.35–0.40	0.70–0.90	0.040	0.040	0.20–0.35	.....	0.80–1.10	0.15–0.25	4137
E 4137	0.35–0.40	0.70–0.90	0.025	0.025	0.20–0.35	.....	0.80–1.10	0.18–0.25	.....
4140	0.38–0.43	0.75–1.00	0.040	0.040	0.20–0.35	.....	0.80–1.10	0.15–0.25	4140
4142	0.40–0.45	0.75–1.00	0.040	0.040	0.20–0.35	.....	0.80–1.10	0.15–0.25	.....
4145	0.43–0.48	0.75–1.00	0.040	0.040	0.20–0.35	.....	0.80–1.10	0.15–0.25	4145
4147	0.45–0.50	0.75–1.00	0.040	0.040	0.20–0.35	.....	0.80–1.10	0.15–0.25	.....
4150	0.48–0.53	0.75–1.00	0.040	0.040	0.20–0.35	.....	0.80–1.10	0.15–0.25	4150
4317	0.15–0.20	0.45–0.65	0.040	0.040	0.20–0.35	1.65–2.00	0.40–0.60	0.20–0.30	4317
4320	0.17–0.22	0.45–0.65	0.040	0.040	0.20–0.35	1.65–2.00	0.40–0.60	0.20–0.30	4320
4337	0.35–0.40	0.60–0.80	0.040	0.040	0.20–0.35	1.65–2.00	0.70–0.90	0.20–0.30	.....
4340	0.38–0.43	0.60–0.80	0.040	0.040	0.20–0.35	1.65–2.00	0.70–0.90	0.20–0.30	4340
4608	0.06–0.11	0.25–0.45	0.040	0.040	0.25 Max	1.40–1.75	.....	0.15–0.25	4608
4615	0.13–0.18	0.45–0.65	0.040	0.040	0.20–0.35	1.65–2.00	.....	0.20–0.30	4615
.....	0.15–0.20	0.45–0.65	0.040	0.040	0.20–0.35	1.65–2.00	.....	0.20–0.30	4617
E 4617	0.15–0.20	0.45–0.65	0.025	0.025	0.20–0.35	1.65–2.00	.....	0.20–0.27	.....
4620	0.17–0.22	0.45–0.65	0.040	0.040	0.20–0.35	1.65–2.00	.....	0.20–0.30	4620
X 4620	0.18–0.23	0.50–0.70	0.040	0.040	0.20–0.35	1.65–2.00	.....	0.20–0.30	X 4620
E 4620	0.17–0.22	0.45–0.65	0.025	0.025	0.20–0.35	1.65–2.00	.....	0.20–0.27	.....
4621	0.18–0.23	0.70–0.90	0.040	0.040	0.20–0.35	1.65–2.00	.....	0.20–0.30	4621
4640	0.38–0.43	0.60–0.80	0.040	0.040	0.20–0.35	1.65–2.00	.....	0.20–0.30	4640
E 4640	0.38–0.43	0.60–0.80	0.025	0.025	0.20–0.35	1.65–2.00	.....	0.20–0.27	.....
4812	0.10–0.15	0.40–0.60	0.040	0.040	0.20–0.35	3.25–3.75	.....	0.20–0.30	4812
4815	0.13–0.18	0.40–0.60	0.040	0.040	0.20–0.35	3.25–3.75	.....	0.20–0.30	4815
4817	0.15–0.20	0.40–0.60	0.040	0.040	0.20–0.35	3.25–3.75	.....	0.20–0.30	4817
4820	0.18–0.23	0.50–0.70	0.040	0.040	0.20–0.35	3.25–3.75	.....	0.20–0.30	4820

AISI Number	C	Mn	P Max	S Max	Si	Ni	Cr	Other	SAE Number
5045	0.43–0.48	0.70–0.90	0.040	0.040	0.20–0.35	.....	0.55–0.75	.....	5045
5046	0.43–0.50	0.75–1.00	0.040	0.040	0.20–0.35	.....	0.20–0.35	.....	5046
.....	0.13–0.18	0.70–0.90	0.040	0.040	0.20–0.35	.....	0.70–0.90	.....	5115
5120	0.17–0.22	0.70–0.90	0.040	0.040	0.20–0.35	.....	0.70–0.90	.....	5120
5130	0.28–0.33	0.70–0.90	0.040	0.040	0.20–0.35	.....	0.80–1.10	.....	5130
5132	0.30–0.35	0.60–0.80	0.040	0.040	0.20–0.35	.....	0.80–1.05	.....	5132
5135	0.33–0.38	0.60–0.80	0.040	0.040	0.20–0.35	.....	0.80–1.05	.....	5135
5140	0.38–0.43	0.70–0.90	0.040	0.040	0.20–0.35	.....	0.70–0.90	.....	5140
5145	0.43–0.48	0.70–0.90	0.040	0.040	0.20–0.35	.....	0.70–0.90	.....	5145
5147	0.45–0.52	0.75–1.00	0.040	0.040	0.20–0.35	.....	0.90–1.20	.....	5147
5150	0.48–0.53	0.70–0.90	0.040	0.040	0.20–0.35	.....	0.70–0.90	.....	5150
5152	0.48–0.55	0.70–0.90	0.040	0.040	0.20–0.35	.....	0.90–1.20	.....	5152
E 50100	0.95–1.10	0.25–0.45	0.025	0.025	0.20–0.35	.....	0.40–0.60	.....	50100
E 51100	0.95–1.10	0.25–0.45	0.025	0.025	0.20–0.35	.....	0.90–1.15	.....	51100
E 52100	0.95–1.10	0.25–0.45	0.025	0.025	0.20–0.35	.....	1.30–1.60	.....	52100
								V	
6120	0.17–0.22	0.70–0.90	0.040	0.040	0.20–0.35	.....	0.70–0.90	0.10 Min	.....
6145	0.43–0.48	0.70–0.90	0.040	0.040	0.20–0.35	.....	0.80–1.10	0.15 Min	.....
6150	0.48–0.53	0.70–0.90	0.040	0.040	0.20–0.35	.....	0.80–1.10	0.15 Min	6150
6152	0.48–0.55	0.70–0.90	0.040	0.040	0.20–0.35	.....	0.80–1.10	0.10 Min	.....
								Mo	
8615	0.13–0.18	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.50–0.60	0.15–0.25	8615
8617	0.15–0.20	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8617
8620	0.18–0.23	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8620
8622	0.20–0.25	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8622
8625	0.23–0.28	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8625
8627	0.25–0.30	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8627
8630	0.28–0.33	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8630
8632	0.30–0.35	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8632
8635	0.33–0.38	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8635
8637	0.35–0.40	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8637
8640	0.38–0.43	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8640
8641	0.38–0.43	0.75–1.00	0.040	0.040–0.060	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8641
8642	0.40–0.45	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8642
8645	0.43–0.48	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8645
8647	0.45–0.50	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8647
8650	0.48–0.53	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8650
8653	0.50–0.56	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.50–0.80	0.15–0.25	8653
8655	0.50–0.60	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8655
8660	0.50–0.65	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25	8660
8720	0.18–0.23	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30	8720
8735	0.33–0.38	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30	8735
8740	0.38–0.43	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30	8740
8742	0.40–0.45	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30	.....
8745	0.43–0.48	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30	8745
8747	0.45–0.50	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30	.....
8750	0.48–0.53	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30	8750
.....	0.50–0.60	0.50–0.60	0.040	0.040	1.20–1.60	.....	0.50–0.80	.....	9254
9255	0.50–0.60	0.70–0.95	0.040	0.040	1.80–2.20	.....	.....	.....	9255
9260	0.55–0.65	0.70–1.00	0.040	0.040	1.80–2.20	.....	.....	.....	9260
9261	0.55–0.65	0.75–1.00	0.040	0.040	1.80–2.20	.....	0.10–0.25	.....	9261
9262	0.55–0.65	0.75–1.00	0.040	0.040	1.80–2.20	.....	0.25–0.40	.....	9262
E 9310	0.08–0.13	0.45–0.65	0.025	0.025	0.20–0.35	3.00–3.50	1.00–1.40	0.08–0.15	9310
E 9315	0.13–0.18	0.45–0.65	0.025	0.025	0.20–0.35	3.00–3.50	1.00–1.40	0.08–0.15	9315
E 9317	0.15–0.20	0.45–0.65	0.025	0.025	0.20–0.35	3.00–3.50	1.00–1.40	0.08–0.15	9317
9437	0.35–0.40	0.90–1.20	0.040	0.040	0.20–0.35	0.30–0.60	0.30–0.50	0.08–0.15	9437
9440	0.38–0.43	0.90–1.20	0.040	0.040	0.20–0.35	0.30–0.60	0.30–0.50	0.08–0.15	9440
9442	0.40–0.45	1.00–1.30	0.040	0.040	0.20–0.35	0.30–0.60	0.30–0.50	0.08–0.15	9442
9445	0.43–0.48	1.00–1.30	0.040	0.040	0.20–0.35	0.30–0.60	0.30–0.50	0.08–0.15	9445
9747	0.45–0.50	0.50–0.80	0.040	0.040	0.20–0.35	0.40–0.70	0.10–0.25	0.15–0.25	9747
9763	0.60–0.67	0.50–0.80	0.040	0.040	0.20–0.35	0.40–0.70	0.10–0.25	0.15–0.25	9763
9840	0.38–0.43	0.70–0.90	0.040	0.040	0.20–0.35	0.85–1.15	0.70–0.90	0.20–0.30	9840
9845	0.43–0.48	0.70–0.90	0.040	0.040	0.20–0.35	0.85–1.15	0.70–0.90	0.20–0.30	9845
9850	0.48–0.53	0.70–0.90	0.040	0.040	0.20–0.35	0.85–1.15	0.70–0.90	0.20–0.30	9850

Wrought Stainless Steels and Heat-Resisting Alloys (AISI), see pages 554, 555, 563; Corrosion-Resistant and Heat-Resistant Castings (ACI), see pages 550, 551, 571, 572, 576.

Coefficients of Linear Thermal Expansion of SAE Steels

By Peter Hidnert*

SAE Number[a]	Chemical Composition, Percentage									Treatment	Average Coefficients of Expansion per Degree Centigrade[c]											Observer[d][e]
	C	Mn	P	S	Si	Ni	Cr	Mo	V	Misc.[b]		15 to 75 C	20 to 100 C	20 to 200 C	20 to 300 C	20 to 400 C	20 to 500 C	20 to 600 C	20 to 700 C	20 to 800 C	20 to 900 C	20 to 1000 C	
												59 to 167 F	68 to 212 F	68 to 392 F	68 to 572 F	68 to 752 F	68 to 932 F	68 to 1112 F	68 to 1292 F	68 to 1472 F	68 to 1652 F	68 to 1832 F	
												×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	
Carbon Steels																							
1008[f]	0.06	0.38	0.017	0.035	0.01	0.55[g]	0.02	0.03[g]	....	Al 0.001 As 0.039 Cu 0.08	Annealed	....	12.6[h]	13.1[h]	13.5[h]	13.8[h]	14.2[h]	14.6[h]	15.0[h]	....	....	....	Sherratt & Challoner[1]
1008[f]	0.07	0.08[g]	0.01	0.02	0.01	....	....	....	....	Cu 0.02	Annealed	....	11.6	12.5	13.0	13.6	14.2	14.6	15.0	....	....	....	Driesen[2]
1010[f]	0.08	0.31	0.029	0.050	0.08	0.07[g]	0.04[g]	0.02[g]	....	Al 0.002 As 0.032 Cu tr Cu 0.10	Annealed	....	12.2[h]	13.0[h]	13.5[h]	13.9[h]	14.3[h]	14.7[h]	15.0[h]	....	....	....	Sherratt & Challoner[1]
1015[f]	0.14	0.39	0.015	0.030	0.31	....	....	....	....	....	Not known	11.9	....	....	....	....	....	....	....	....	....	....	Honda[3]
1015	0.17	0.42	0.012	0.035	....	....	....	....	....	....	Rolled	....	11.9[h]	12.5[h]	13.0[h]	13.6[h]	14.2[h]	....	....	....	....	....	Schad[4]
1015[f]	0.18	0.34	0.051[g]	0.044	0.10	....	....	....	....	Cu 0.10	Not known	12.1	....	....	....	....	....	....	....	....	....	....	Honda[3]
1020[f]	0.22	0.12[g]	0.01	0.03	0.01	....	....	....	....	Cu 0.04	Annealed	....	11.7	12.1	12.8	13.4	13.9	14.4	14.8	....	....	....	Driesen[2]
1022[f]	0.18 to 0.25[g]	0.67[g] to 0.92	0.019 to 0.023	0.015 to 0.022	0.24 to 0.28	....	....	....	....	....	Cast	....	12.5[h]	13.4[h]	14.2[h]	15.1[h]	....	....	....	....	....	....	Peters[5]
1022	0.22	0.90	0.01	0.017	0.25	....	....	....	....	....	Not known	....	12.5	12.7	....	....	....	....	....	....	....	....	Sieglerschmidt[6]
1022[f]	0.23	0.70	0.075[g]	0.100[g]	0.014	....	....	....	....	....	Rolled	....	(8.8,	−45 to +	100 C)	....	....	....	....	....	....	....	Andrews[7]
1022[f]	0.23	0.64[g]	0.034	0.034	0.11	0.07[g]	tr	....	....	Al 0.010 As 0.036 Cu 0.13	Annealed	....	12.2[h]	12.7[h]	13.1[h]	13.5[h]	13.9[h]	14.4[h]	14.9[h]	....	....	....	Sherratt & Challoner[1]
1025[f]	0.36[g]	0.32	....	....	0.20	....	....	....	....	....	Annealed	....	....	12.6	13.3	13.8	14.3	14.8	15.2	....	....	....	Jones & Heselwood[8]
1030[f]	0.31	0.65	0.013	0.028	0.23	....	....	....	....	Cu 0.13	Not known	11.7	....	....	....	....	....	....	....	....	....	....	Honda[3]
1035[f]	0.33	0.12[g]	0.01	0.03	0.03	....	....	....	....	Cu 0.03	Annealed	....	11.1	11.9	12.7	13.4	14.0	14.4	14.8	....	....	....	Driesen[2]
1040[f]	0.40	0.11[g]	0.01	0.03	0.07	....	....	....	....	Cu 0.03	Annealed	....	11.3	12.0	12.5	13.3	13.9	14.4	14.8	....	....	....	Driesen[2]
1040[f]	0.41	0.64	0.052[g]	0.061[g]	0.09	....	....	....	....	....	Annealed	....	11.1[i]	11.7[i]	12.7[i]	13.5[i]	14.0[i]	14.3[i]	14.7[i]	....	....	....	Souder & Hidnert[9]
1040[f]	0.42	0.64	0.031	0.029	0.11	0.06[g]	tr	....	....	Al 0.006 As 0.033 Cu 0.12	Annealed	....	11.2[h]	12.1[h]	13.0[h]	13.6[h]	14.0[h]	14.6[h]	14.8[h]	....	....	....	Sherratt & Challoner[1]
1040	0.42	0.68	0.012	0.025	0.23	....	....	....	....	....	Annealed	....	9.4[i]	10.9[i]	12.1[i]	13.0[i]	13.7[i]	14.3[i]	14.7[i]	....	....	....	Souder & Hidnert[9]
1045[f]	0.44	0.69	0.037	0.038	0.20	0.04[g]	0.03	....	....	Al 0.006 As 0.024 Cu 0.060	Annealed	....	11.6[h]	12.3[h]	13.1[h]	13.7[h]	14.2[h]	14.7[h]	15.1[h]	....	....	....	Sherratt & Challoner[1]
1045[f]	0.44	0.57[g]	0.013	0.033	0.16	....	....	....	0.14[g]	....	Annealed	....	11.2[i]	11.9[i]	12.7[i]	13.5[i]	14.1[i]	14.5[i]	14.8[i]	....	....	....	Souder & Hidnert[9]
1045[f]	0.44	0.67	0.043	0.043	0.34	....	....	....	....	Cu 0.09	Not known	11.6	....	....	....	....	....	....	....	....	....	....	Honda[3]
1052[f]	0.49	1.21	0.05[g]	0.050	0.12	....	....	....	....	....	Annealed	....	11.3[i]	11.8[i]	12.7[i]	13.7[i]	14.5[i]	14.7[i]	15.0[i]	....	....	....	Souder & Hidnert[9]
1055[f]	0.56	0.19[g]	tr	0.023	0.04	....	....	....	....	Cu 0.02	Annealed	....	11.0	11.8	12.6	13.4	14.0	14.5	14.8	....	....	....	Driesen[2]
1055[f]	0.56	0.30[g]	0.016	0.034	0.18	....	....	....	....	Cu 0.09	Not known	12.1	....	....	....	....	....	....	....	....	....	....	Honda[3]
1060	0.59	0.92	0.024	0.033	0.25	....	....	....	....	....	Annealed	....	11.1[i]	11.9[i]	12.9[i]	13.5[i]	14.1[i]	14.6[i]	14.9[i]	....	....	....	Souder & Hidnert[9]
1060[f]	0.64	0.27[g]	0.010	0.028	0.06	....	....	....	....	Cu 0.09	Not known	11.8	....	....	....	....	....	....	....	....	....	....	Honda[3]
1060[f]	0.65	0.12[g]	0.01	0.03	0.09	....	....	....	....	Cu 0.03	Annealed	....	11.0	11.6	12.3	13.2	13.8	14.2	14.6	....	....	....	Driesen[2]
1070	0.66	0.72	0.028	0.016	0.18	....	....	....	....	....	Annealed	....	11.3[h]	12.6[h]	13.3[h]	14.0[h]	....	....	....	....	....	....	Souder & Hidnert[10]
1080[f]	0.71[g]	0.62	0.014	0.032	0.36[g]	0.20[g]	0.04[g]	....	....	Co 0.03 Cu 0.18	Rolled	....	....	12.3[h]	....	....	....	....	....	....	....	....	Sieglerschmidt[11]
1080	0.75	0.69	0.026	0.024	0.21	....	....	....	....	....	Not known	....	11.5[h]	12.3[h]	13.0[h]	13.8[h]	....	....	....	....	....	....	Souder & Hidnert[10]
1080[f]	0.75	0.35[g]	0.010	0.018	0.10	....	....	....	....	Cu 0.07	Rolled	....	11.5[h]	12.3[h]	13.0[h]	13.8[h]	....	....	....	....	....	....	Honda[3]
1080[f]	0.80	0.30[g]	0.012	0.016	0.10	....	....	....	....	Cu 0.08	Not known	11.6	....	....	....	....	....	....	....	....	....	....	Honda[3]
1080[f]	0.81	0.10[g]	tr	0.025	0.06	....	....	....	....	Cu 0.02	Not known	11.7	....	....	....	....	....	....	....	....	....	....	Driesen[2]
1085[f]	0.82	1.65[g]	....	....	0.20	....	0.03	....	....	....	Annealed	....	11.0	11.6	12.4	13.2	13.8	14.2	14.7	....	....	....	Bain & Waring[12]
1095[f]	0.80[g]	0.32	0.008	0.009	0.13	0.13[g]	0.11[g]	....	....	Al 0.004 As 0.021 Cu 0.070	Not known	....	8.8[h]	9.8[h]	11.3[h]	12.3[h]	13.1[h]	13.6[h]	14.2[h]	....	....	....	Sherratt & Challoner[1]
1095[f]	0.94	0.35	0.016	0.018	0.13	....	....	....	....	Cu 0.08	Annealed	....	11.1[h]	11.7[h]	12.5[h]	13.2[h]	13.6[h]	14.2[h]	14.7[h]	....	....	....	Sherratt & Challoner[1]
1095[f]	1.02	0.36	0.013	0.014	0.08	....	....	....	....	Cu 0.05	Not known	11.5	....	....	....	....	....	....	....	....	....	....	Honda[3]
1095[f]	1.1[g]	0.3	0.025	0.025	0.2	....	....	....	....	....	Not known	11.5	....	....	....	....	....	....	....	....	....	....	Honda[3]
1095[f]	1.11[g]	0.27[g]	0.036	0.022	0.19	....	....	....	....	As 0.09 Cu 0.07	Annealed	9.7[j]	11.4[h]	....	....	....	....	....	....	....	....	....	Werner[13]
1095[f]	1.22[g]	0.35	0.009	0.015	0.16	0.13[g]	0.11[g]	0.01	....	Al 0.006 As 0.025 Cu 0.077	Hardened	10.8[j]	13.0[h]	....	....	....	....	....	....	....	....	....	Werner[13]
											Annealed	10.2[j]	12.6[h]	....	....	....	....	....	....	....	....	....	Sherratt & Challoner[1]
											Hardened	11.8[j]	14.4[h]	....	....	....	....	....	....	....	....	....	
											Annealed	....	10.6[h]	11.2[h]	12.1[h]	12.9[h]	13.5[h]	14.2[h]	14.7[h]	....	....	....	

* Physicist, National Bureau of Standards, Washington, D. C. and Chairman, Subcommittee on Linear Expansion of Steels. The following members of the committee assisted in the assembly of data: J. B. Austin (United States Steel Corporation) and R. B. Gordon (Westinghouse Electric Corporation). H. S. Krider (National Bureau of Standards) helped in the preparation of the table.

(Continued)

Coefficients of Linear Thermal Expansion of SAE Steels (continued)

SAE Number[a]	Chemical Composition, Percentage										Treatment	Average Coefficients of Expansion per Degree Centigrade[c]											Observer[d][e]
	C	Mn	P	S	Si	Ni	Cr	Mo	V	Misc.[b]		15 to 75 C 59 to 167 F	20 to 100 C 68 to 212 F	20 to 200 C 68 to 392 F	20 to 300 C 68 to 572 F	20 to 400 C 68 to 752 F	20 to 500 C 68 to 932 F	20 to 600 C 68 to 1112 F	20 to 700 C 68 to 1292 F	20 to 800 C 68 to 1472 F	20 to 900 C 68 to 1652 F	20 to 1000 C 68 to 1832 F	
												×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	
Free-Cutting Steels																							
1117[f]	0.22	1.00	0.022	0.021[g]	0.29	0.10[g]	0.08[g]	....	....	Co 0.04 Cu 0.17	Not known	....	....	12.8[h]	....	....	....	....	....	....	....	....	Sieglerschmidt[11]
1145[f]	0.42	0.64[g]	0.031	0.029[g]	0.11	0.06[g]	tr	....	....	Al 0.006 As 0.033 Cu 0.12	Annealed	....	11.2[h]	12.1[h]	13.0[h]	13.6[h]	14.0[h]	14.6[h]	14.8[h]	....	....	....	Sherratt & Challoner[1]
1145[f]	0.44	0.69	0.037	0.038	0.20	0.04[g]	0.03	....	....	Al 0.006 As 0.024 Cu 0.060	Annealed	....	11.6[h]	12.3[h]	13.1[h]	13.7[h]	14.2[h]	14.7[h]	15.1[h]	....	....	....	Sherratt & Challoner[1]
1145[f]	0.44	0.67[g]	0.043	0.043	0.34	....	....	....	....	Cu 0.09	Not known	11.6	....	....	....	....	....	....	....	....	....	....	Honda[3]
Manganese Steel																							
1340[f]	0.82[g]	1.65	....	....	0.20	....	0.03	....	....	....	Not known	....	8.8[h]	9.8[h]	11.3[h]	12.3[h]	13.1[h]	13.6[h]	14.2[h]	....	....	....	Bain & Waring[12]
Nickel Steel																							
2330[f]	0.33	0.78	0.014	0.035	0.09[g]	3.59	....	....	....	....	Annealed	....	10.9[i]	11.2[i]	12.1[i]	12.9[i]	13.4[i]	13.8[i]	....	....	....	....	Souder & Hidnert[9]
Nickel-Chromium Steels																							
3140[f]	0.40 to 0.50[g]	0.50[g] to 0.80	<0.04	<0.045	....	1.00 to 1.50[g]	0.45[g] to 0.75	....	....	....	Quenched and tempered	....	11.8[h]	12.3[h]	12.9[h]	13.4[h]	14.0[h]	....	....	....	....	....	Westinghouse Electric & Mfg. Co.[14]
3145[f]	0.43	0.78	0.015	0.027	....	1.87[g]	0.75	....	....	....	Quenched from 1550 F and tempered at 1050 F	....	12.0[i]	....	12.9[k]	....	....	....	....	....	....	....	Hidnert[15]
3240[f]	0.43	0.78[g]	0.015	0.027	....	1.87	0.75[g]	....	....	....	Quenched from 1550 F and tempered at 1050 F	....	12.0[i]	....	12.9[k]	....	....	....	....	....	....	....	Hidnert[15]
3240[f]	0.50[g]	0.64[g]	0.015	0.031	0.15[g]	1.90	0.88	....	....	....	Quenched from 1525 F and tempered at 1050 F	....	11.8[i]	....	12.8[k]	....	....	....	....	....	....	....	Hidnert[15]
[redacted]12[f]	0.32[g]	0.53	0.013	0.015	0.23	3.53	1.37	....	....	....	Rolled	....	11.2[h]	11.8[h]	12.4[h]	13.0[h]	13.6[h]	....	....	....	....	....	Schad[4]
4130[f]	0.39[g]	0.51	0.015	0.029	0.19	....	0.87	0.21	....	....	Not known	....	....	....	....	....	....	....	(13.7, 100 to 700 C)				Mochel[16]
4320[f]	0.27[g]	0.56	0.015	0.019	0.18	2.70[g]	0.10[g]	0.31	0.09[g]	....	**Chromium Steels**												
5140[f]	0.35[g]	0.31[g]	....	....	0.19	....	0.75	....	....	....	Annealed	....	....	12.6	13.4	13.9	14.3	14.6	15.0	....	....	....	Jones & Heselwood[8]
5140[f]	0.40	0.78	0.011	0.015	0.57[g]	....	0.78	....	....	....	Quenched from 1525 F and tempered at 1100 F	....	12.8[i]	....	13.8[k]	....	....	....	....	....	....	....	Hidnert[15]
5150[f]	0.6[g]	....	....	....	....	....	1.[g]	....	....	....	Not known	....	(11.3, 50 to 150 C; 14.8, 450 to 550 C)										Matsushita[17]
52100[f]	0.37[g]	0.33	....	....	0.21	....	1.57[g]	....	....	....	Annealed	....	....	12.8	13.4	13.8	14.2	14.4	14.6	....	....	....	Jones & Heselwood[8]
52100[f]	0.94	0.34	....	....	0.27	....	0.95[g]	....	....	....	Annealed Hardened	10.1[j] 10.6[j]	11.9[h] 12.6[h]	....	....	....	....	....	....	....	....	....	Werner[13]
Chromium-Vanadium Steels																							
6150[f]	0.22[g]	0.75	0.019	0.033	0.27	....	0.96	....	0.17	....	Annealed Quenched from 1475 F and tempered at 400 F	....	12.2 12.0	12.7 12.5	13.3 12.9	13.7 13.0	14.1 13.3	14.4 13.7	....	....	....	....	Hidnert[18]
6150[f]	0.35[g]	1.42[g]	0.013	0.057[g]	0.20	....	1.00	....	0.11[g]	....	Annealed	....	12.4[i]	12.6[i]	13.3[i]	13.8[i]	14.2[i]	14.5[i]	14.7[i]	....	....	....	Souder & Hidnert[9]
6150[f]	0.37[g]	0.74	0.008	0.011	0.16[g]	....	1.08	....	0.17	....	Quenched from 1700 F and tempered at 1175 F	....	11.7[i]	....	13.1[k]	....	....	....	....	....	....	....	Hidnert[15]
6150[f]	0.53	0.80	0.015	0.020	0.15[g]	....	1.02	....	0.17	....	Annealed Quenched from 1575 F and tempered at 800 F Quenched from 1575 F and tempered at 1200 F	....	12.4 11.8 12.3	12.8 12.4 12.7	13.4 13.1 13.4	13.9 13.6 13.9	14.2 13.9 14.3	14.5 14.1 14.7	....	....	....	....	Hidnert[18]

(Continued)

Coefficients of Linear Thermal Expansion of SAE Steels (continued)

SAE Number[a]	Chemical Composition, Percentage										Treatment	Average Coefficients of Expansion per Degree Centigrade[c]											Observer[d][e]
	C	Mn	P	S	Si	Ni	Cr	Mo	V	Misc.[b]		15 to 75 C 59 to 167 F	20 to 100 C 68 to 212 F	20 to 200 C 68 to 392 F	20 to 300 C 68 to 572 F	20 to 400 C 68 to 752 F	20 to 500 C 68 to 932 F	20 to 600 C 68 to 1112 F	20 to 700 C 68 to 1292 F	20 to 800 C 68 to 1472 F	20 to 900 C 68 to 1652 F	20 to 1000 C 68 to 1832 F	
												×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	×10⁻⁶	
Chromium-Nickel Austenitic Steels																							
30705	0.06	....	....	....	0.61	10.80	17.34	....	....	....	Quenched from 2000 F	....	16.7	17.1	17.6	17.9	....	18.4	18.8	19.0	19.2	19.5	Hidnert[19]
30705	0.06	0.36	0.016	0.012	0.28	9.6	17.7	....	....	....	Quenched from 1975 F	....	16.5	17.2	17.7	18.1	18.3	18.6	19.0	19.5	19.7	20.0	Hidnert[19]
30705	0.07	....	....	....	0.45	8.93	17.35	....	....	....	Quenched from 2000 F	....	17.2[h]	17.4[h]	17.8[h]	18.1[h]	18.4[h]	18.7[h]	18.9[h]	....	....	....	Austin & Pierce[20]
30705[f]	0.07	0.59	0.013	0.003	0.47	9.12	18.08	....	....	{Al 0.06 Ti 0.38}	Annealed	....	16.7[h]	17.2[h]	17.6[h]	18.1[h]	18.5[h]	18.8[h]	....	....	....	....	Austin & Pierce[20]
30705[f]	0.15[g]	1.92	0.012	0.011	0.49	13.25	23.50	....	....	....	Sheet bar	....	15.3[h]	16.2[h]	16.8[h]	17.3[h]	17.7[h]	18.0[h]	18.3[h]	....	....	....	Austin & Pierce[20]
30705[f]	0.18[g]	0.62	....	....	0.56	10.4	20.7	....	....	....	Forged and annealed	....	16.0	16.6	17.1	17.5	17.8	18.3	18.6	18.9	19.4	19.9	Hidnert[19]
30705[f]	0.18[g]	0.39	0.010	0.010	0.23	13.28	24.50	....	....	....	Hot forged	....	15.0[h]	15.8[h]	16.4[h]	16.8[h]	17.2[h]	17.6[h]	17.8[h]	....	....	....	Austin & Pierce[20]
30915[f]	0.06[g]	....	....	....	0.61	10.80[g]	17.34	....	....	....	Quenched from 2000 F	....	16.7	17.1	17.6	17.9	....	18.4	18.8	19.0	19.2	19.5	Hidnert[19]
30915[f]	0.06[g]	0.36	0.016	0.012	0.28	9.6	17.7	....	....	....	Quenched from 1975 F	....	16.5	17.2	17.7	18.1	18.3	18.6	19.0	19.5	19.7	20.0	Hidnert[19]
30915	0.10	....	....	....	....	8.0	18.0	....	....	....	Heated 336 days at 500 C	....	17.7[h]	18.0[h]	18.2[h]	18.6[h]	19.0[h]	19.2[h]	....	....	....	....	Austin & Pierce[20]
30915	0.12	0.41	0.017	0.016	0.37	8.9	17.5	....	....	....	Hot rolled and annealed	....	16.4	....	17.2	17.6	17.8	18.2	18.5	18.7	19.0	19.3	Hidnert[19]
30915[f]	0.14	0.45	....	....	0.28	7.80	17.28	....	....	{Al 0.18 Cu 0.14}	Hot rolled and annealed	....	16.4	17.0	17.7	18.2	18.6	19.0	....	....	....	....	Hidnert[19]
30915[f]	0.18[g]	0.62	....	....	0.56	10.4[g]	20.7[g]	....	....	....	Forged and annealed	....	16.0	16.6	17.1	17.5	17.8	18.3	18.6	18.9	19.4	19.9	Hidnert[19]
30915[f]	0.21[g]	0.24	....	....	0.89[g]	9.7	19.7	....	....	....	Forged and annealed	....	16.0	16.7	17.3	17.7	18.0	18.4	18.7	19.1	19.5	20.0	Hidnert[19]
Stainless Chromium Irons																							
51210[f]	0.09	0.43	0.009	0.016	0.33	0.06[g]	12.0	....	....	....	Annealed	....	....	10.2	....	11.2	....	12.0	....	....	....	....	Hidnert & Sweeney[21]
51210[f]	0.09	0.60	0.011	0.007	0.57[g]	0.19[g]	12.0	....	....	....	Annealed	....	10.2	10.5	10.9	11.3	11.6	11.9	....	12.3	....	....	Hidnert & Sweeney[21]
51210[f]	0.09	0.56	0.010	0.010	0.31	0.39[g]	12.3	....	....	....	Annealed	....	9.8	10.4	10.8	11.2	11.6	12.1	....	....	....	....	Hidnert & Sweeney[21]
51210	0.12	0.25	....	....	0.19	....	11.96	....	....	....	Annealed	....	....	11.2	11.4	11.7	12.0	12.3	12.6	....	....	....	Jones & Heselwood[8]
51210[f]	0.13	0.56	0.031	0.019	0.35	....	13.5[g]	....	....	....	Annealed	....	10.2	10.4	10.9	11.3	11.7	12.1	....	12.7	....	....	Hidnert & Sweeney[21]
51335	0.30	0.14	....	....	0.20	....	12.78	....	....	....	Not known	....	9.4[h]	10.3[h]	10.7[h]	11.1[h]	11.5[h]	11.9[h]	12.1[h]	12.1[h]	....	....	Bain & Waring[12]
51335	0.30	0.18	0.020	0.011	0.11	....	13.10	....	....	....	{Annealed Hardened	....	10.3 9.8	10.7 9.8	11.3	11.5 9.8	11.8 10.6	12.1 11.2	12.4	12.5} 11.8}	....	....	Souder & Hidnert[23]
51335	{0.30 to 0.40}	....	....	....	....	....	13.00	....	....	....	Annealed	....	10.0[i]	10.4[i]	11.0[i]	11.4[i]	11.8[i]	12.2[i]	12.4[i]	....	....	....	Souder & Hidnert[9]
X51410[f]	0.13	0.56	0.031	0.019[g]	0.35	....	13.5	....	....	....	Annealed	....	10.2	10.5	10.9	11.3	11.7	12.1	....	12.6	....	....	Hidnert & Sweeney[21]
51710[f]	0.04	0.28	....	....	0.62[g]	....	17.04	....	....	{Al 0.08 Cu 0.14}	Hot rolled	....	10.6	10.8	11.1	11.4	11.7	11.9	12.1	12.5	13.1	....	Hidnert[19]
51710[f]	0.04	0.29	0.021	0.021	0.28	0.08[g]	17.6	....	....	....	Annealed	....	10.1	10.4	10.7	11.1	....	11.6	11.8	12.2	12.8	....	Hidnert[19]
51710[f]	0.06	0.45	....	....	0.58[g]	0.01	17.08	....	....	....	Annealed	....	10.3	10.6	11.0	11.2	11.4	11.6	11.8	12.4	12.9	....	Hidnert[19]
51710	0.07	0.48	0.018	0.008	0.45	....	16.43	....	....	Al 0.08	Sheet bar	....	10.7[h]	11.2[h]	11.5[h]	11.8[h]	12.1[h]	12.3[h]	12.5[h]	....	....	....	Austin & Pierce[20]
51710[f]	0.12	0.39	0.016	0.013	....	0.09[g]	15.9[g]	....	....	....	Annealed	....	....	....	10.8	....	....	11.8	....	....	....	....	Hidnert & Sweeney[21]
51710	0.12	0.28	....	....	0.21	....	17.48	....	....	....	Annealed	....	....	10.7	11.0	11.3	11.6	11.8	12.0	....	....	....	Jones & Heselwood[8]
51710	0.13	0.16	0.01	0.01	0.25	....	16.4	....	....	....	{Quenched from 1850 F and tempered at 300 F	....	....	....	11.7	....	....	11.8	....	....	....	...}	Hidnert & Sweeney[21]
51710[f]	0.43[g]	0.35	....	....	0.28	....	18.88[g]	....	....	....	{Annealed Annealed	....	9.9	10.1 10.6	10.4 11.0	10.9 11.3	11.3 11.6	11.6 11.8	.... 12.1	12.4	....	...}	Jones & Heselwood[8]

(a) Some of the steels included in this table have compositions not strictly in accordance with SAE specifications. *See* footnotes (b), (f) and (g).

(b) Elements not included in SAE specification.

(c) To obtain corresponding coefficients of expansion per degree Fahrenheit, multiply the coefficients in this table by 5/9.

(d) Some of the cited publications give data on phase transformations. No coefficients of expansion are included in this table for temperature ranges within which transformations occurred.

(e) The superior numbers refer to the references at the end of the table.

(f) Chemical composition not strictly in accordance with SAE specification

(g) Lies outside the range of SAE specification

(h) From 0 C or 32 F instead of ■ C or 68 F

(i) From 25 C or 77 F instead of ■ C or 68 F

(j) From — 100 to 0 C (— 148 to + 32 F)

(k) From 25 to 270 C (77 to 518 F)

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Densities of Ferrous Metals

Metal and Condition	Density, g per cu cm	Density, lb per cu in.	Reference
Iron			
Electrolytic iron	7.874	0.2845	*
Ingot iron	7.866	0.2842	*
Carbonyl iron	7.860	0.2840	*
Wrought iron	7.7	0.28	*
Cast Iron			
Gray cast iron	6.95 to 7.35	0.251 to 0.265	*
White cast iron	7.7	0.28	(1)
Malleable iron (ASTM grade 35018)	7.20 to 7.45	0.260 to 0.269	*
Malleable iron (ASTM grade 32510)	7.25 to 7.34	0.262 to 0.265	*
Carbon Steel			
0.06 C, 0.01 Si, 0.38 Mn (ann 1700 F)	7.871	0.2844	(2)
0.23 C, 0.11 Si, 0.635 Mn (ann 1700 F)	7.859	0.2839	(2)
0.435 C, 0.20 Si, 0.69 Mn (ann 1580 F)	7.844	0.2834	(2)
1.22 C, 0.16 Si, 0.35 Mn (ann 1470 F)	7.830	0.2829	(2)
Low-Chromium Steel			
0.31 C, 1.00 Cr, 0.74 Mn (o-q 1650 F, tem 1350 F)	7.84	0.283	(3)
0.315 C, 1.09 Cr, 0.69 Mn (ann 1580 F)	7.84	0.283	(2)
0.35 C, 1.56 Cr, 0.24 Mn (ann)	7.83	0.283	(3)
1.73 C, 1.65 Cr, 0.30 Mn (ann)	7.80	0.282	(3)
0.80 C, 1.67 Cr, 0.28 Mn (ann)	7.82	0.282	(3)
0.62 C, 1.67 Cr, 0.22 Mn (ann)	7.82	0.282	(3)
0.98 C, 1.68 Cr, 0.28 Mn (ann)	7.81	0.282	(3)
0.20 C, 1.85 Cr, 0.14 Mn (o-q 1650 F, tem 1380 F)	7.84	0.283	(3)
0.22 C, 2.80 Cr, 0.10 Mn (o-q 1650 F, tem 1380 F)	7.82	0.282	(3)
0.21 C, 3.88 Cr, 0.19 Mn (o-q 1650 F, tem 1380 F)	7.81	0.282	(3)
0.30 C, 5.54 Cr, 0.08 Mn (o-q 1650 F, tem 1380 F)	7.79	0.281	(3)
0.35 C, 0.88 Cr, 0.20 Mo, 0.59 Mn (ann 1580 F, tem 1185 F)	7.845	0.2834	(2)
Low-Alloy Nickel-Chromium Steel			
0.33 C, 3.38 Ni, 0.80 Cr, 0.53 Mn (ann 1580 F, tem 1185 F)	7.85	0.283	(2)
0.325 C, 3.41 Ni, 0.71 Cr, 0.55 Mn (ann 1580 F, tem 1185 F)	7.85	0.283	(2)
1.28 C, 3.46 Ni, 1.80 Cr, 0.24 Mn			
(b-q 2190 F)	7.92	0.286	(3)
(ann 1435 F)	7.82	0.282	(3)
1.50 C, 3.46 Ni, 1.80 Cr, 0.25 Mn			
(b-q 2190 F in iced brine)	7.91	0.286	(3)
(ann 1435 F)	7.82	0.282	(3)
0.325 C, 3.47 Ni, 0.17 Cr, 0.55 Mn (ann 1580 F)	7.855	0.2838	(2)
0.51 C, 3.52 Ni, 1.72 Cr, 0.22 Mn			
(b-q 2190 F)	7.79	0.281	(3)
(b-q 2190 F, tem 375 F)	7.80	0.282	(3)
(b-q 2190 F, tem 690 F)	7.82	0.282	(3)
(b-q 2190 F, tem 1110 F)	7.835	0.2831	(3)
(ann 1435 F)	7.835	0.2831	(3)
0.34 C, 3.53 Ni, 0.78 Cr, 0.55 Mn, 0.39 Mo (ann 1580 F, tem 1185 F)	7.86	0.284	(2)
Wrought Stainless and Heat-Resisting Steel			
302 0.10 C, 18 Cr, 9 Ni	7.93	0.286	*
303 18 Cr, 9 Ni, 0.5 Mo, Zr	7.93	0.286	*
309 23 Cr, 13 Ni	7.98	0.288	*
310 25 Cr, 20.5 Ni	7.98	0.288	*
316 17 Cr, 12 Ni, 2.25 Mo	7.98	0.288	*
321 18 Cr, 10.5 Ni, Ti	8.02	0.290	*
410 12.5 Cr	7.75	0.280	*
416 13 Cr, 0.5 Mo, Zr	7.73	0.279	*
420 13 Cr	7.70	0.278	*
430 16 Cr	7.70	0.278	*
440 17 Cr, 0.6 Mo	7.68	0.277	*
446 25 Cr	7.60	0.273	*
0.07 C, 17.88 Cr, 8.26 Mn	7.77	0.281	(5)
0.07 C, 17.55 Cr, 10.48 Mn	7.76	0.280	(5)
0.09 C, 18.40 Cr, 5.33 Mn, 4.07 Ni, 0.78 Cu	7.91	0.286	(5)
0.06 C, 18.50 Cr, 6.79 Mn, 4.06 Ni	7.90	0.285	(5)
0.06 C, 18.04 Cr, 7.90 Mn, 2.06 Ni	7.78	0.281	(5)
0.07 C, 17.70 Cr, 9.40 Mn, 0.68 Cu	7.77	0.281	(5)

(Continued)

Densities of Ferrous Metals (continued)

Metal and Condition	Density, g per cu cm	Density, lb per cu in.	Reference
Corrosion-Resistant Castings			
CA 12 Cr	7.612	0.2750	*
CB 20 Cr	7.529	0.2720	*
CC 28 Cr	7.529	0.2720	*
CE 29 Cr, 9 Ni	7.667	0.2770	*
CF 19 Cr, 9 Ni	7.750	0.2800	*
CG 21 Cr, 11 Ni	7.778	0.2808	*
CH 24 Cr, 13 Ni	7.723	0.2790	*
CK 25 Cr, 20 Ni	7.750	0.2800	*
Tool Steel			
1.0 C, 0.71 Cr (ann)	7.84	0.283	(6)
(w-q 1470 F)	7.758	0.2803	(6)
(w-q 1470 F, tem 350 F)	7.765	0.2805	(6)
(w-q 1470 F, tem 600 F)	7.786	0.2813	(6)
(w-q 1470 F, tem 1000 F)	7.808	0.2821	(6)
18 W, 4 Cr, 1 V (ann)	8.67	0.313	(6)
18 W, 4 Cr, 2 V (ann)	8.67	0.313	(6)
8.24 Mo, 1.64 W, 3.68 Cr, 1.00 V, 0.80 C			
(q 2200 F)	7.925	0.2863	(7)
(q 2200 F, tem 1150 F)	7.87	0.284	(7)
4.11 Mo, 5.20 W, 4.60 Cr, 4.00 V, 1.32 C (hardened)	7.93	0.286	(8)
7.75 Mo, 4.39 Cr, 4.10 V, 1.20 C (hardened)	7.76	0.280	(8)
20 W, 4 Cr, 2 V, 12 Co (ann)	8.89	0.321	(6)
18 W, 4 Cr, 1 V, 5 Co (ann)	8.68	0.314	(6)
6 W, ▮ Mo, 2 V (ann)	8.16	0.295	(6)
8 Mo, 1.5 W, 1 V (ann)	7.88	0.285	(6)
Permanent Magnet Alloys			
Alnico 1 20 Ni, 12 Al, 5 Co	6.892	0.2490	*
Alnico 2 17 Ni, 10 Al, 12.5 Co, 6 Cu (cast)	7.086	0.2560	*
Alnico 3 25 Ni, 12 Al	6.892	0.2490	*
Alnico 4 28 Ni, 12 Al, 5 Co	7.003	0.2530	*
Alnico 5 24 Co, 14 Ni, 8 Al, 3 Cu	7.307	0.2640	*
Alnico 12 35 Co, 18 Ni, 6 Al, 8 Ti	7.197	0.2600	*
Miscellaneous Ferrous Alloys			
28.37 Ni, 0.28 C (q 1740 F)	8.16	0.295	(2)
Invar 36 Ni	8.00	0.289	*
Radiometal 45 Ni	8.3	0.30	*
Hipernik 50 Ni	8.25	0.298	*
Austenitic manganese steel: 1.2 C, 13 Mn (1920 F, a-c)	7.87	0.284	(2)

The following abbreviations have been used to indicate the condition of the metal:

ann	annealed	b-q	quenched in brine	o-q	quenched in oil	f-c	furnace cooled
q	quenched	w-q	quenched in water	a-c	air cooled	tem	tempered

All values of density measured at or near room temperature.

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Mean Apparent Specific Heats of Steels*

(in calories per gram per degree centigrade)

Composition	Temperature Ranges, deg Cent: 50 to 100	150 to 200	200 to 250	250 to 300	300 to 350	350 to 400	450 to 500	550 to 600	650 to 700	700 to 750	750 to 800	850 to 900
Pure iron	0.112	0.122	0.126	0.130	0.135	0.140	0.155	0.175	0.198	0.232	0.218	0.170
Carbon Steels												
0.06 C, 0.38 Mn	0.115	0.124	0.128	0.132	0.137	0.142	0.158	0.180	0.207	0.264	0.209	0.202
0.08 C, 0.31 Mn	0.115	0.125	0.130	0.133	0.136	0.142	0.158	0.177	0.205	0.272	0.229	0.195
0.23 C, 0.635 Mn	0.116	0.124	0.127	0.133	0.137	0.143	0.158	0.179	0.202	0.342	0.227	....
0.415 C, 0.643 Mn	0.116	0.123	0.126	0.131	0.136	0.140	0.155	0.169	0.184	0.378	0.149	0.131
0.80 C, 0.32 Mn	0.117	0.127	0.131	0.135	0.140	0.145	0.160	0.170	0.184	0.497	0.147	....
1.22 C, 0.35 Mn	0.116	0.129	0.130	0.133	0.138	0.143	0.152	0.167	0.195	0.499	0.155	....
Alloy Steels												
0.23 C, 1.51 Mn, 0.105 Cu	0.114	0.122	0.126	0.130	0.135	0.141	0.155	0.177	0.200	0.346	0.196	0.128
0.325 C, 0.55 Mn, 0.17 Cr, 3.47 Ni[a]	0.115	0.125	0.128	0.131	0.136	0.141	0.158	0.179	0.391	0.228	0.144	0.153
0.33 C, 0.53 Mn, 0.80 Cr, 3.38 Ni[a]	0.118	0.125	0.129	0.134	0.139	0.143	0.161	0.185	0.312	0.281	0.133	0.139
0.325 C, 0.55 Mn, 0.71 Cr, 3.41 Ni[a]	0.117	0.125	0.128	0.131	0.136	0.142	0.159	0.182	0.274	0.330	0.136	0.137
0.34 C, 0.55 Mn, 0.78 Cr, 3.53 Ni, 0.39 Mo[a]	0.116	0.125	0.129	0.133	0.139	0.145	0.160	0.184	0.251	0.397	0.152	0.152
0.315 C, 0.69 Mn, 1.09 Cr, 0.073 Ni	0.118	0.125	0.128	0.132	0.137	0.142	0.157	0.177	0.200	0.358	0.223	0.137
0.35 C, 0.59 Mn, 0.88 Cr, 0.26 Ni, 0.20 Mo	0.114	0.123	0.126	0.130	0.136	0.142	0.157	0.176	0.197	0.386	0.211	....
0.485 C, 0.90 Mn, 1.98 Si, 0.637 Cu	0.119	0.125	0.129	0.133	0.138	0.144	0.159	0.179	0.198	0.216	0.326	....
High-Alloy Steels												
1.22 C, 13.00 Mn, 0.22 Si[a]	0.124	0.133	0.136	0.139	0.141	0.143	0.138	....	....	....	....	....
0.28 C, 0.89 Mn, 28.37 Ni[a]	0.119	0.120	0.119	0.119	0.118	0.117	0.124	0.130	0.123	0.124	0.123	0.126
0.08 C, 0.37 Mn, 19.11 Cr, 8.14 Ni[a]	0.122	0.127	0.129	0.131	0.134	0.136	0.142	0.155	0.149	0.150	0.153	0.153
0.13 C, 0.25 Mn, 12.95 Cr[a]	0.113	0.123	0.127	0.132	0.138	0.145	0.163	0.186	0.209	0.216	0.165	0.160
0.27 C, 0.28 Mn, 13.69 Cr[a]	0.113	0.122	0.127	0.131	0.136	0.143	0.162	0.186	0.221	0.237	0.187	0.157
0.715 C, 0.25 Mn, 4.26 Cr, 18.45 W, 1.075 V[a]	0.098	0.104	0.108	0.111	0.116	0.120	0.132	0.143	0.152	0.171	0.171	0.176

(a) Steels heated discontinuously; all others heated at steady rate of about 3 °C per min.

* National Physical Laboratory, The Physical Properties of a Series of Steels, Part II, Iron and Steel Institute (London), 1946

Thermal Conductivities of Ferrous Metals

Metal	Thermal Conductivity, cal/sq cm/cm/°C/sec: 0 C 32 F	100 C 212 F	200 C 392 F	300 C 572 F	400 C 752 F	500 C 932 F	600 C 1112 F	700 C 1292 F	800 C 1472 F	1000 C 1832 F	1200 C 2192 F	Ref
Iron, Wrought Iron, Cast Iron												
Pure Iron	0.178	0.163	0.147	0.132	0.117	0.105	0.093	0.082	0.071	.....	.....	1
Wrought Iron 0.04 C, 0.265 Si, 0.136 P, 0.046 Mn, 0.025 S	.....	0.141	0.129	0.120	0.108	0.098	.....	.....	.....	.....	.....	2
Cast Iron 3.16 TC, 1.54 Si, 0.57 Mn, 0.22 P, 0.11 S	0.112	0.110	.....	.....	0.098	.....	.....	.....	.....	.....	.....	2
Cast Iron 3.93 TC, 3.34 GC, 0.59 CC, 1.40 Si, 0.63 Mn, 0.134 P, 0.077 S	.....	0.131	.....	0.117	.....	0.103	.....	.....	.....	.....	.....	2
Carbon Steels												
0.08 C, 0.31 Mn, 0.045 Cr, 0.07 Ni, 0.020 Mo, trace Cu	0.142	0.138	0.127	0.118	0.109	0.098	0.088	0.079	0.068	0.066	0.071	3
0.23 C, 0.635 Mn, trace Cr, 0.074 Ni, 0.13 Cu	0.124	0.122	0.117	0.110	0.102	0.094	0.085	0.076	0.062	0.065	0.071	3
0.415 C, 0.643 Mn, trace Cr, 0.063 Ni, 0.12 Cu	0.124	0.121	0.115	0.109	0.100	0.091	0.081	0.072	0.059	0.064	0.071	3
0.80 C, 0.32 Mn, 0.11 Cr, 0.13 Ni, 0.01 Mo, 0.07 Cu	0.119	0.115	0.108	0.099	0.091	0.084	0.078	0.072	0.058	0.064	0.072	3
1.22 C, 0.35 Mn, 0.11 Cr, 0.13 Ni, 0.01 Mo, 0.08 Cu	0.108	0.107	0.104	0.098	0.092	0.086	0.080	0.074	0.057	0.062	0.068	3
Alloy Steels												
0.325 C, 0.55 Mn, 0.17 Cr, 3.47 Ni, 0.04 Mo, 0.09 Cu	0.087	0.090	0.093	0.094	0.088	0.084	0.078	0.063	0.060	0.066	0.072	3
0.34 C, 0.55 Mn, 0.78 Cr, 3.53 Ni, 0.39 Mo, 0.05 Cu	0.079	0.081	0.084	0.085	0.085	0.080	0.073	0.067	0.064	0.068	0.072	3
0.315 C, 0.69 Mn, 1.09 Cr, 0.073 Ni, 0.012 Mo, 0.07 Cu	0.116	0.111	0.106	0.101	0.092	0.085	0.076	0.069	0.062	0.067	0.072	3
0.35 C, 0.59 Mn, 0.88 Cr, 0.26 Ni, 0.20 Mo, 0.12 Cu	0.102	0.102	0.100	0.097	0.093	0.087	0.081	0.074	0.063	0.067	0.072	3
Stainless and Heat-Resisting Steels (*See also* pages 555, 566 and 568 in this Handbook.)												
5 Cr, 0.50 Mo	.....	0.088	0.086	0.084	0.083	0.081	0.079	0.078	.....	.....	.....	4
410 12 Cr	.....	0.059	0.062	0.064	0.066	0.069	0.071	0.073	.....	.....	.....	4
430 17 Cr	.....	0.062	0.062	0.062	0.062	0.062	0.062	0.062	.....	.....	.....	4
446 27 Cr	.....	0.050	0.052	0.054	0.056	0.058	0.060	0.062	.....	.....	.....	4
304 18 Cr, 8 Ni	.....	0.039	0.042	0.045	0.048	0.051	0.054	0.057	.....	.....	.....	4
310 25 Cr, 20 Ni	.....	0.030	0.033	0.036	0.039	0.042	0.044	0.047	.....	.....	.....	4
High-Alloy Steels												
1.22 C, 0.22 Si, 13.00 Mn, 0.03 Cr, 0.07 Ni, 0.07 Cu	0.031	0.033	0.039	0.043	0.046	0.049	0.052	0.054	0.056	0.061	0.067	3
0.28 C, 0.15 Si, 0.89 Mn, trace Cr, 28.37 Ni, 0.03 Cu	0.030	0.035	0.039	0.042	0.047	0.052	0.055	0.058	0.060	0.066	0.071	3
0.08 C, 0.68 Si, 0.37 Mn, 19.11 Cr, 8.14 Ni, 0.60 W, 0.03 Cu	0.038	0.039	0.041	0.043	0.047	0.051	0.055	0.058	0.062	0.067	0.071	3
0.13 C, 0.17 Si, 0.25 Mn, 12.95 Cr, 0.14 Ni, 0.012 V, 0.06 Cu	0.064	0.066	0.066	0.067	0.066	0.065	0.063	0.061	0.060	0.066	0.073	3
0.27 C, 0.28 Mn, 13.69 Cr, 0.20 Ni, 0.25 W, 0.022 V	0.060	0.063	0.065	0.066	0.066	0.065	0.064	0.061	0.060	0.066	0.072	3
0.715 C, 0.25 Mn, 4.26 Cr, 0.067 Ni, 18.45 W, 1.075 V	0.058	0.062	0.065	0.067	0.068	0.067	0.065	0.064	0.062	0.066	0.070	3
0.83 C, 7.5 to 8.5 Mo, 4.0 Cr, 2.0 V	.....	.....	0.050	0.053	0.057	0.060	.....	.....	.....	.....	.....	2

NOTE. Some of the values given in the above table are experimental determinations and others have been taken from the extrapolated curves of thermal conductivity versus temperature.

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4 Wrought Stainless and Heat-Resisting Alloys, pages 553 and 562 in this Handbook.

Electrical Resistivities of Steels*

Composition	Electrical Resistivity, microhm-cm: 20 C 68 F	100 C 212 F	200 C 392 F	400 C 752 F	600 C 1112 F	700 C 1292 F	800 C 1472 F	900 C 1652 F	1000 C 1832 F	1100 C 2012 F	1200 C 2192 F	1300 C 2372 F
Carbon Steels												
0.06 C, 0.38 Mn	13.0	17.8	25.2	44.8	72.5	89.8	107.3	112.4	116.0	118.9	121.6	124.1
0.08 C, 0.31 Mn	14.2	19.0	26.3	45.8	73.4	90.5	108.1	113.0	116.5	119.3	122.0	124.4
0.23 C, 0.635 Mn	16.9	21.9	29.2	48.7	75.8	92.5	109.4	113.6	116.7	119.4	121.9	123.9
0.415 C, 0.643 Mn	17.1	22.1	29.6	49.3	76.6	93.2	111.1	114.9	117.9	120.7	123.0	....
0.80 C, 0.32 Mn	18.0	23.2	30.8	50.5	77.2	93.5	112.9	116.4	119.1	121.4	123.1	124.6
1.22 C, 0.35 Mn	19.6	25.2	33.3	54.0	80.2	96.4	115.2	119.6	122.6	124.9	127.1	128.7
Alloy Steels												
0.23 C, 1.51 Mn, 0.105 Cu	20.8	25.9	33.3	52.3	78.6	94.6	110.3	114.3	117.4	120.2	122.7	125.0
0.325 C, 0.55 Mn, 0.17 Cr, 3.47 Ni[a]	27.1	32.0	39.0	56.7	81.4	99.2	112.2	114.9	118.0	120.4	122.8	124.8
0.33 C, 0.53 Mn, 0.80 Cr, 3.38 Ni[a]	26.8	31.7	38.7	56.7	81.7	98.1	111.5	114.8	117.8	120.1	122.5	124.6
0.325 C, 0.55 Mn, 0.71 Cr, 3.41 Ni[a]	28.0	32.5	39.5	57.2	82.0	99.0	111.7	115.0	118.0	120.2	122.8	124.7
0.34 C, 0.55 Mn, 0.78 Cr, 3.53 Ni, 0.39 Mo[a]	28.9	33.7	40.6	58.2	82.5	99.4	111.4	114.6	117.6	119.9	122.2	124.2
0.315 C, 0.69 Mn, 1.09 Cr, 0.073 Ni	21.0	25.9	33.0	51.7	77.8	93.4	110.6	114.5	117.7	120.5	123.0	125.1
0.35 C, 0.59 Mn, 0.88 Cr, 0.26 Ni, 0.20 Mo	22.3	27.1	34.2	52.9	78.6	94.4	110.3	113.8	117.1	120.0	122.2	124.2
0.485 C, 0.90 Mn, 1.98 Si, 0.637 Cu	42.9	47.0	52.9	68.5	91.1	105.7	117.3	119.7	122.3	124.9	127.1	128.9
High-Alloy Steels												
1.22 C, 13.00 Mn, 0.22 Si[a]	68.3	75.6	84.7	99.4[b]	103.8[b]	114.7	120.0	123.8[c]	125.3	127.0	128.8	130.8
0.28 C, 0.89 Mn, 28.37 Ni[a]	84.2	89.1	94.7	103.9	111.2	114.1	116.5	118.4[c]	120.6	122.5	124.3	125.7
0.08 C, 0.37 Mn, 19.11 Cr, 8.14 Ni, 0.60 W[a]	71.0	77.6	85.0	97.6	107.2	111.1	114.1	117.1	119.6	122.0	124.1	125.7
0.13 C, 0.25 Mn, 12.95 Cr[a]	50.6	58.4	67.9	85.4	102.1	110.3	116.0	115.0	117.0[c]	119.8	121.6	125.3
0.27 C, 0.28 Mn, 13.69 Cr[a]	52.2	59.5	68.4	85.3	101.5	109.9	115.7	114.6	117.9	120.9	122.9	125.0
0.715 C, 0.25 Mn, 4.26 Cr, 18.45 W, 1.075 V[a]	41.9	47.2	54.4	71.8	92.2	103.7	115.2	117.3	120.9	123.6	126.6	128.1

(a) Steels heated discontinuously; all others heated at steady rate of about 3 °C per min.
(b) Value depends appreciably on time of heating in this temperature region.
(c) Value depends to lesser extent on time of heating in this temperature region.

* National Physical Laboratory, The Physical Properties of a Series of Steels, Part II, Iron and Steel Inst (London), 1946

MANUFACTURE OF IRON AND STEEL

Prepared by the

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The Iron Blast Furnace Process

BY CARL G. HOGBERG*

THE blast furnace process is unique among metallurgical processes, both because of its early origin and because its principles have undergone no change for several centuries. In iron smelting as practiced by the ancients, charcoal was used as a fuel to reduce the metal from relatively pure ores; then the resultant pasty mass was hammered to remove the impurities. The principle of this process is not unlike that governing a large number of low-temperature processes for direct reduction, on which time and effort have been spent in great amounts during the last several decades.

In about the fifteenth century someone conceived the idea of adding a stack over the early hearth-type furnace, in order to carry out the process of reduction prior to the entry of the materials into the hearth. This innovation resulted in an economy of heat enabling the generation of sufficient temperature in the hearth to separate the gangue in the ore from the molten iron and to permit the withdrawal of iron in essentially pure form.

In some of the ancient furnaces air for combustion of fuel was supplied by natural draft; later this was supplanted by hand-operated bellows. Still later, water power was used both in bellows and in blowers of the reciprocating-piston type. However, the real impetus to the development of the modern blast furnace came at the end of the eighteenth century with the use of the steam engine for blowing. Since the rate of iron production is limited largely by the rate at which the fuel can be burned within the furnace, and since the rate of burning is limited by the rate at which the air for combustion can be introduced, the application of the steam engine to blowing removed the greatest factor restraining increased productivity and left only the relatively minor limitations of physical size of the furnace and auxiliaries required to charge the raw materials and dispose of the products. These problems were solved by the combined efforts of enterprising engineers and daring and resourceful operators. The extent of their success is attested by the fact that in the relatively short span of 100 years the average maximum productivity of blast furnaces has increased from about 70 tons to more than 1500 tons per day for the large modern unit.

The Process. The process is essentially one in which iron ore, coke and flux are charged into the top of the furnace and air is introduced under pressure through openings called tuyeres, disposed peripherally around the bottom. Carbon in the coke is burned to carbon monoxide in front of the tuyeres and the resulting gases, rich in carbon monoxide, rise through the descending stock column; the ascending gases serve to preheat the stock and to reduce the iron oxide in the ore. Molten iron collects in the bottom of the hearth under a layer of molten slag and both are drawn off at regular intervals.

Carbon in the coke is burned by oxygen in the air blast in accordance with the following reaction:

$$2C + O_2 \rightarrow 2CO$$

This reaction takes place in front of the tuyeres and is completed before the air has penetrated approximately 40 in. into the interior of the furnace. The theoretical temperature in the zone of combustion in front of the tuyeres is approximately 3500 F when an air blast is used that is preheated to 1300 F in stoves provided for this purpose. The average temperature of molten iron in the hearth of a furnace producing basic iron approximates 2700 F; the average temperature of the molten slag is slightly higher.

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Prepared for the Subcommittee on Melting.

In its ascent through the furnace, the carbon monoxide in the gas reacts with the iron oxide in the ore in the approximate sequence of the following reactions; these reactions fall into the classification of "indirect reduction" and account for about 85 to 90% of the reduction in a normal blast furnace producing basic iron:

$$3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2$$
$$Fe_3O_4 + CO \rightarrow 3FeO + CO_2$$
$$FeO + CO \rightarrow Fe + CO_2$$

Iron oxide is also reduced directly by contact with solid carbon during the descent of these materials through the furnace, in accordance with the following reactions:

$$3Fe_2O_3 + C \rightarrow 2Fe_3O_4 + CO$$
$$Fe_3O_4 + C \rightarrow 3FeO + CO$$
$$FeO + C \rightarrow Fe + CO$$

These are the so-called "direct reduction" reactions which account for approximately 10 to 15% of the reduction process.

The rate and the extent to which reduction reactions are completed in the various sections of the furnace depend primarily on the temperature. In normal basic iron practice, using Mesabi ores, approximately 75% of the reduction takes place in the lowest third of the furnace. In its upward travel through the furnace, the gas is burdened with an increasing weight of oxygen and carbon dioxide from the ore and from the limestone or dolomite used as a fluxing agent. Because of the equilibrium relationship among the oxides of carbon and iron, the top gases leave the furnace with a considerable amount of carbon monoxide, as indicated in the following typical composition: 26.24% CO; 12.96% CO_2; 1.87% H_2; 0.22% CH_4; 58.71% N_2. These gases leave a normally operating furnace at a temperature of approximately 300 F.

The four principal slagmaking constituents in the burden are silica (SiO_2), alumina (Al_2O_3), lime (CaO), and magnesia (MgO). As noted in the section devoted to raw materials, the gangue in the ores used in the principal iron-producing districts of the United States is generally acid in character; that is, it contains silica and alumina predominantly, so lime in the form of limestone must be added as a flux in the charge to form a slag with proper characteristics of fusibility. The lime in the slag also serves the purpose of removing the sulfur in the process by the following reaction:

$$CaO + FeS \rightarrow CaS + FeO$$

Flux is added in a quantity depending on the amount of slagmaking constituents in the ore and coke and proportioned to achieve a ratio of approximately 1 to 1 between total bases and total acids in the slag. A lower ratio of basicity normally requires a lower temperature for melting the slag. An increase in flux raises the melting point of the slag and makes it more viscous at constant temperature, but enhances its desulfurizing power.

Someone once remarked, "You don't make iron in the blast furnace; you make slag." The implication is that if the furnace is burdened to make the proper slag, the operation of the furnace and the composition of the iron will be satisfactory. Considerable progress has been made during the last 25 years in taking the slagmaking phase of the operation out of the rule-of-thumb category. The development of ternary equilibrium diagrams for the mineralogical system SiO_2–Al_2O_3–CaO, and also research on the effect of slag composition on viscosity at various temperatures and on desulfurizing power have been applied by blast furnace operators to such an extent that this phase of the process has been reduced to a technological basis.

Contact of molten iron and coke in the lower region of the furnace results in carburization of the iron, with the result that the product contains from 3 to 5% C, depending on the silicon content of the iron. Of the manganese charged, about 75% appears in the pig iron while the remainder goes out with the slag in the form of oxides and sulfides. Phosphorus is not eliminated in the process. Sulfur, which is largely derived from the coke, is almost entirely eliminated by reactions forming calcium and manganese sulfides in the slag. Silicon will enter the pig iron in various percentages from 0.5 to 2% for ordinary grades of iron, depending on the slag basicity and temperature. For special grades of merchant iron, silicon may be as high as 4.5%, and in ferrosilicon a silicon content as high as 16% can be obtained. Calcium, magnesium and aluminum are not reduced in the process. Copper, nickel and vanadium, if present, are reduced and will appear in the pig iron. Chromium is reduced only under special conditions of high temperature. Zinc and lead volatilize and are difficult to contend with because they are absorbed by the refractories to the detriment of the life of the brick lining.

Since there is a tendency to oversimplify the theoretical principles of the blast furnace process, it should be emphasized that the countercurrent nature of both its thermal and chemical phases is such that it gives rise to a series of complex intermediate or side reactions not fully understood because of the practical difficulty of obtaining accurate data while the furnace is in operation. The impression is erroneous that the blast furnace can be divided theoretically into several vertical zones, each one performing a definite function, such as flux calcination, ore reduction, slag smelting and so on. Investigation has revealed not only that the transition of the mode of reactions in the furnace occurs gradually in a vertical plane, but that considerable differences exist radially in any one plane; for instance, calcination of limestone may be completed at a point 4 ft from the inwall lining in a plane 30 ft above the tuyeres, but may just have begun at a point 8 ft from the inwall lining in the same plane. Differences such as this are brought about primarily by radial differences in the temperature and composition of gases ascending through the furnace, and these differences contribute largely to the difficulty of obtaining accurate data concerning the process.

The Furnace Plant. The furnace plant is best described by referring to Fig. 1. Raw materials in stockhouse bins are drawn into a scale car in specified weighed amounts and are subsequently discharged into a cable-operated skip car, which travels on an incline to the top of the furnace. Material from the skip discharges over the small bell, which usually incorporates a device for periodic rotation of this compartment in order to compensate for inherent differences in the trajectory and angle of repose of various materials, thus enabling the achievement of the very important objective of uniform distribution of materials in the furnace. The small bell is then opened, allowing the materials to fall over the closed large bell. After a predetermined number of skips of material have been deposited on the large bell, the small bell is held closed to prevent the escape of gases to the atmosphere and the large bell is opened, dropping the charge into the furnace. The top of the stock in the furnace is normally maintained at a level 6 to 10 ft below the bottom of the closed large bell.

The furnace proper consists of a refractory brick shaft encased in a steel shell and provided with water-cooled bronze plates embedded in the brickwork in the inwardly sloping bottom part, or bosh, of the furnace. Large vertical water-cooled plates are arranged around the outer periphery of the hearth brickwork to maintain a submelting temperature of refractories in that area.

The dimensions and the proportioning of the dimensions of the brickwork in the furnace are very important factors in furnace performance, and the "lines" of a modern furnace represent an evolution—mostly by trial and error—over a period of many years. The following dimensions are those of a typical large blast furnace:

Hearth diameter	27 ft, 6 in.
Bosh diameter	30 ft, 6 in.
Stockline diameter	21 ft, 0 in.
Large bell diameter	15 ft, 5 in.
Total height	105 ft, 3 in.
Working height (centerline tuyeres to 6-ft stock level)	79 ft, $6\frac{7}{8}$ in.
Total volume, cu ft	51,654
Working volume, cu ft	44,849
Ratio of working volume to hearth area	75.5
Bosh angle	81.25 deg
Inwall batter, in. per ft	1.080
Number of tuyeres	18

An air blast is introduced into the furnace through tuyeres leading from a bustle pipe and disposed peripherally around the hearth. The accumulation of molten

iron in the hearth is "cast" at intervals of 5 or 6 hr by drilling through the clay plug of the tapping hole and subsequently lancing the remaining iron skull with oxygen. The slag notch is usually opened 3 hr after the casting of the iron is completed.

Gas, leaving the furnace through offtakes (usually four in number, arranged around the dome of the furnace) is subsequently passed through a brick-lined downcomer to the dustcatcher, which is essentially a large chamber where the reduction of gas velocity causes the larger dust particles to collect in the bottom, whence the dust is drawn at regular intervals. From a furnace operating on the relatively fine Mesabi ores, the dustcatcher will remove from 50 to 70% of the total dust content in the gas.

Gas is piped from the dustcatcher to the bottom of the gas-washer, the lower section of which is equipped with water sprays playing over banks of baffles consisting of wooden hurdles or ceramic tile. The upper section of the most modern unit consists of an electrical precipitator for further cleaning. The precipitator is made of nests of tubes with a heavily charged anode wire running through the central axis of each tube. By a charge imparted to the fine particles of dust, these particles are attracted to the cathode or tube wall, from which they are washed by a continuously flowing film of water. The dust-bearing sludge flowing from the bottom of the gas-washer is pumped to a thickener for dehydration and subsequent filtering. The filtered product, together with the dust recovered in the dustcatcher, is shipped to the sintering plant for agglomeration and re-use in the furnace.

Typical dust contents of gas at various points in a modern gas-cleaning system are as follows:

Location	Dust Content, grains per cu ft
At top of furnace	12.5
Dustcatcher outlet	4.4
After primary washing	0.075
After electric precipitation in tower	0.015

After cleaning, part of the gas produced is utilized in the stoves employed to preheat the air blast, and the remainder may be used for underfiring boilers, underfiring coke ovens or for miscellaneous heating applications in the steel plant. Normal blast furnace gas has a heating value ranging from 85 to 100 Btu per cu ft, depending on the carbon monoxide content.

Stoves perform the important function of preheating the air blast, thus contributing much to the fuel economy of the modern blast furnace. A typical modern stove consists of a steel cylinder approximately 25 ft in diam and 100 ft high, lined with brick in such a way as to provide a tall, vertical combustion chamber to insure combustion of the gas burned at the bottom of the stove; and a checker chamber filled with refractory shapes arranged to provide openings for the passage of gas and air. Three or four stoves are usually provided for each furnace; a portion of the air blast is being passed through one stove at all times while the remaining stoves are being heated with gas. The stoves are changed from gas to blast by the manipulation of valves, without necessity for interrupting the flow of blast to the furnace. Ordinarily, a stove is "on blast" from 2 to 4 hr and "on gas" from 5 to 8 hr. Blast temperature is controlled by using a butterfly type of valve in the cold-blast main. This valve is arranged to divert a portion of the blast through the stove, and is usually provided with a motor-operated, potentiometer-controlled device that automatically enables the attainment of a uniform blast temperature despite the gradual drain of heat from the stove during the blast cycle.

The blowing equipment for blast furnaces may consist of reciprocating engines operated by steam or gas, or the modern steam-driven turboblowers. At some plants the air is passed through special equipment for decreasing the water vapor in the blast to a low and uniform level.

Molten iron flows from the furnace into brick-lined hot metal ladles. In an integrated steel plant, hot metal is transported in ladles directly to the open hearth furnaces or the Bessemer converters. In isolated furnace plants or

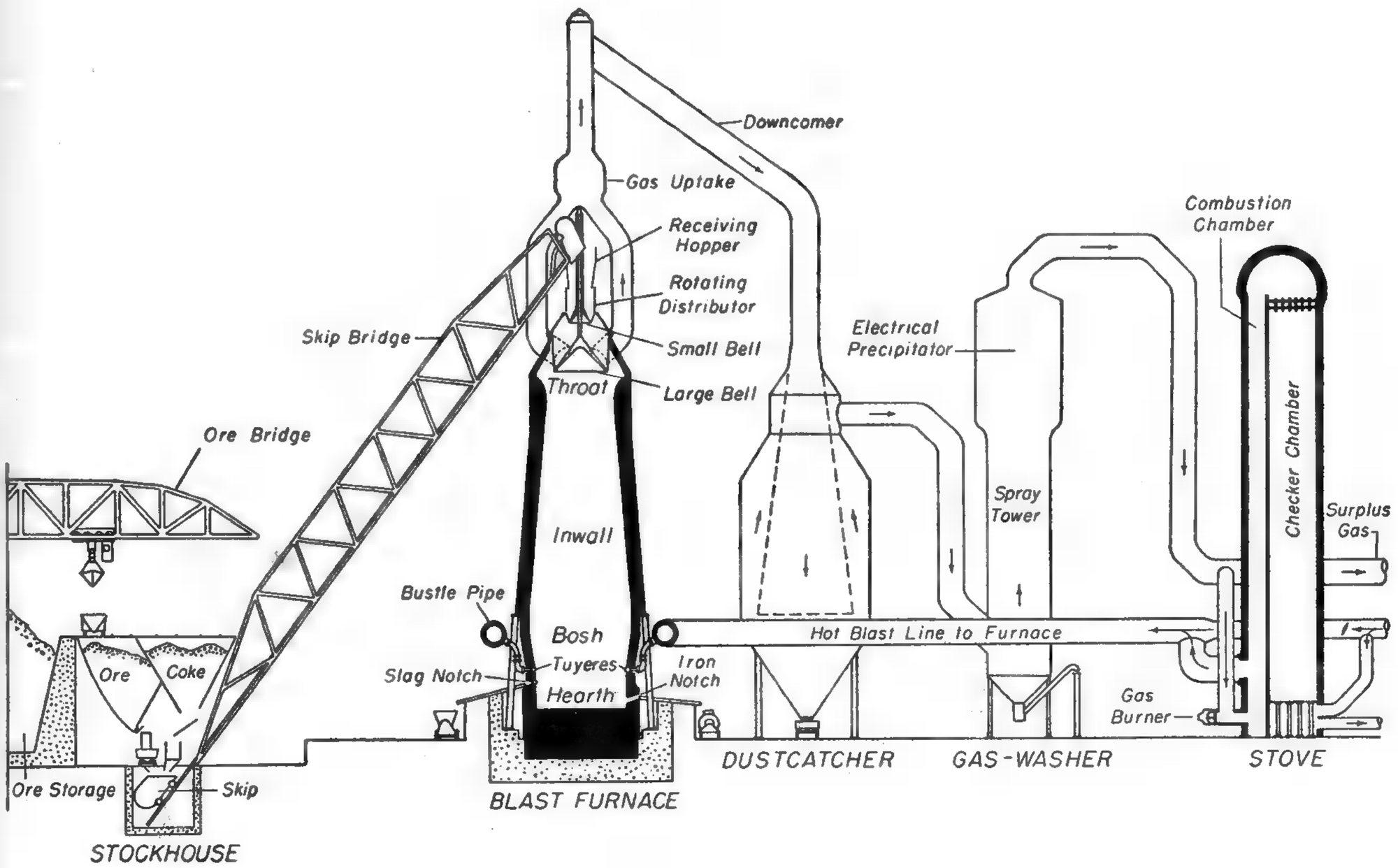

Fig. 1 Components of a modern blast furnace plant

Table I. Typical Compositions of Iron Ores

Ore	Source: State	Source: District	Chemical Composition—Natural Basis, per cent: Fe	P	Mn	SiO_2	Al_2O_3	CaO	MgO	H_2O	Approximate Screen Analysis: % Plus 3-mesh	% Minus 42-mesh
Group 2 (Bessemer)	Minn.	Mesabi Range	56.50	0.030	0.28	4.21	1.02	0.05	0.04	10.30	26.9	43.0
Group 3 (Non-Bessemer)	Minn.	Mesabi Range	50.81	0.055	0.64	5.97	1.89	0.32	0.18	13.34	37.3	30.2
Group 7 Conc (Non-Bessemer)	Minn.	Mesabi Range	49.45	0.048	0.13	15.56	0.58	0.27	0.14	7.65	65.2	7.0
Sintered Group 3 Fines.....	Minn.	Mesabi Range	65.53	0.057	0.30	4.09	2.80	0.20	0.05	1.50	65.0	4.3
Sintered Magnetic Conc.....	N.Y.	Port Henry	67.13	0.165	0.41	2.88	0.96	1.80	0.24	0.88	41.0	2.8
Sized Utah	Utah	Iron Mountain	54.20	0.166	0.10	10.32	2.30	2.86	2.16	Low	Various[a]	
Sized Red	Ala.	Birmingham	35.70	0.310	0.12	15.83	3.15	14.59	0.45	Low	Various[b]	

(a) Utah ore is screened and used raw in two sizes: 1½ in. by ¾ in.,and ¾ in. by ¼ in. The minus ¼ in. fines are sintered.
(b) Red ore is screened and used raw in two sizes: 1 1/16 in. by ⅜ in., and ⅜ in. by 1/16 in. The minus 1/16 in. fines are sintered.

where iron is being manufactured for shipment to the trade or for consumption in cold form by the steel plant, the product is sent to the pig machine. This unit consists of an endless chain of individual pig molds into which the metal is continuously poured and subsequently cooled by air or water. The pigs may weigh from 25 to 100 lb each, depending on the desires of the consumer.

Slag is disposed of by transportation in steel or cast-iron pots, by granulation with a stream of high-pressure water at the furnace site, or by pouring directly into a pit at the furnace site where the slag later solidifies and is removed by power shovels.

Flue dust and filter cake are disposed of by agglomeration in a sintering plant. Two types of sintering plants commonly used are the continuously traveling grate (Dwight-Lloyd) and the intermittent pan type (Greenawalt). The carbon in a mixture of flue dust and filter cake placed on the grates is subsequently ignited by a flame; suction applied to the bottom of the grate causes the zone of carbon combustion to travel downward gradually in a horizontal plane. The heat generated by burning the carbon, fuses the iron-bearing materials into a mass which, after cooling, has characteristics of strength and size that are beneficial in the blast furnace process. At some sintering plants only ore fines or ore concentrates are handled; at such plants carbon in the form of coke breeze or coal must be added to the mixture prior to sintering. This is in contrast with the sintering of flue dust, which carries its own carbon.

Raw Materials. The physical and chemical characteristics of raw materials are important factors in the performance of blast furnaces. The iron content of the ores is the chief factor in determining the heat requirement of the process. The physical character of the ores, as well as the physical character of the coke, largely determines the efficiency of transferring the heat required to reduce and smelt the ores.

Typical compositions of ores used in important iron-producing districts in the United States appear in Table I.

The principal source of iron ores in the United States is the Mesabi Range in the Lake Superior District. Ores from the Mesabi Range are generally high in iron content but are often objectionable in the blast furnace process because of their extremely high content of fines. Where these ores are screened for direct shipment of the oversize and agglomeration of the fines, the productivity and fuel economy of blast furnaces have improved considerably.

The effect of widely differing compositions of iron ore on burden requirements at blast furnaces may be illustrated by Table II, which shows typical burden requirements for production of basic iron at plants in the Pittsburgh and Birmingham Districts.

Coke used in blast furnaces is ordinarily produced in by-product ovens, with a relatively small proportion supplied by ovens of the beehive type. The composition of ash and sulfur in coke, which depends on the chemical composition of coals used in coking, is important because it affects the thermal requirements of the process in accordance with the quantity of ash impurities, and because sulfur thus introduced requires flux for its elimination by means of slag. The washing of coals for the reduction of ash and sulfur content prior to coking has been found extremely beneficial in subsequent blast furnace processing.

Table II. Representative Blast Furnace Burdens for Production of Basic Hot Metal

	Quantity, lb per ton hot metal: Pittsburgh District	Birmingham District
Metallics in ores, per cent	49.7	36.0
Total ores plus sinter.....	3510	5020
Scrap	29	160
Open hearth slag.....	376	....
Mill scale	60	....
Dolomite	138	832
Limestone	696	....
Coke	1794	2181
Slag produced	1116	2292

The physical character of coke is important because of its effect on the distribution of gases in the furnace stock column. Good coke is low and uniform in sulfur and ash content, has high strength and a size ranging from not more than 5 in. to not less than 1 in. The importance of quality of coke can hardly be overemphasized, and was summed up by a Russian blast furnace operator during a recent visit to a plant in the United States, when he remarked, "Good coke is best blast furnace superintendent!"

Limestone and dolomite when used as fluxes seldom present an operating problem, since good fluxing stone is available in large quantities in virtually all iron-producing districts.

Miscellaneous burden materials include: open hearth slag, which is used for its iron, manganese and lime content; rolling mill scale, which is nearly pure iron oxide; Bessemer converter slag, used for its manganese content; and scrap. Blast furnace smelting of scrap borings and turnings has been found to be more feasible than the disposition of these materials in the open hearth, because their light weight slows down the operation of charging them into an open hearth and their high ratio of surface area to weight increases oxidation.

Typical compositions of coke, fluxes and miscellaneous materials appear in Table III.

Table III. Representative Compositions of Coke, Fluxes and Miscellaneous Materials

	Fe	P	Mn	SiO_2	Al_2O_3	CaO	MgO	S	H_2O
Coke (raw coals) [a]	0.91	0.013	0.010	6.21	3.37	0.27	0.09	0.99	2.90
Coke (washed coals) [a]	0.75	0.011	0.010	5.37	3.04	0.22	0.08	0.89	2.86
Coke (raw coals) [b]	0.61	0.009	....	4.19	2.90	0.48	0.19	0.60	2.50
Limestone	0.14	0.004	....	0.46	0.25	52.90	0.93	0.06	...
Dolomite	0.25	0.004	0.010	0.93	0.53	30.51	20.65	0.05	...
Open hearth slag	27.00	0.040	6.08	10.47	2.20	27.25	6.85	0.17	...
Converter slag	21.90	....	10.75	54.10	3.79	1.85	0.13	0.03	...
Mill scale	70.00	0.015	0.56	0.89	0.42	0.30	0.10	0.03	...

(a) Coal Mixture: 100% Pittsburgh Seam (high volatile) coals
(b) Coal Mixture: 50% West Virginia (low volatile), and 50% Kentucky (high volatile) coals

Blast Furnace Practice and Performance. Because of the countercurrent nature of the process, slight variations in the physical and chemical character of raw materials have a marked effect on the smoothness of furnace operation and on the quality of the metal product. Because of the speed of the process and its continuous nature, the operator must be constantly on the alert to anticipate changes in furnace conditions before they materialize detrimentally. Improper furnace operation reveals itself in increased pressure of the blast; increased temperature of top gas; fluctuating pressure of top gas, or hanging and slipping of the stock column; and visual appearance of the slag, indicating the presence of abnormal amounts of unreduced oxides. A trend toward higher sulfur and lower silicon in the metal is indicated by a visual examination of a chilled sample of the iron and by subsequent chemical analysis. All of these indications manifest a disturbance in the delicate thermal and chemical balance within the furnace, which can be corrected to a greater or lesser extent by immediate application of one or more of the following means which the operator has at his control: a change in the temperature and quantity of the air blast; a change in the ratio of the ore to the coke charged; a change in the quantity of flux in the burden; and a change in the filling sequence used in charging the furnace. These routine measures are applied as a matter of course in daily operations.

Data for a month's performance of a typical blast furnace in the Pittsburgh district, operating on 100% raw Mesabi ores and producing basic iron, are shown in Table IV.

Table IV. Typical Blast Furnace Practice and Performance Data for Production of Basic Hot Metal

Production:	
Iron, net tons per day	1,400
Flue dust and sludge, lb per ton iron	237
Consumption:	
Coke, lb per ton iron	1,766
Flux, lb per ton iron	790
Unrecovered metallics, per cent	1.9
Iron composition, per cent:	
Silicon	0.96
Sulfur	0.028
Phosphorus	0.274
Manganese	2.38
Carbon	4.65
Casts over 0.050% S, per cent	6.3
Slag analysis, per cent:	
Silica	35.05
Alumina	12.40
Lime	45.28
Magnesia	3.80
Sulfur	1.80
Ratio: bases to acids	1.03
Calculated volume, lb per ton iron	1,100
Practice:	
Air blown, std cu ft per min	86,976
Blast pressure, psi	21.0
Blast temperature, deg Fahr	983
Top gas data:	
Composition (dry basis) per cent by vol	
Carbon monoxide	26.24
Carbon dioxide	12.96
Hydrogen	1.87
Methane	0.22
Nitrogen	58.71
Total	100.00
Cu ft dry top gases produced per net ton iron	118,900
Calorific value, Btu per cu ft	92.7
Top gas temperature, deg Fahr	320

Products of the Blast Furnace. Products of the blast furnace in the United States, in the approximate order of their production and importance, are as follows: (1) basic iron, (2) Bessemer iron, (3) merchant pig irons (malleable and foundry), (4) blowing iron, (5) ingot mold iron and (6) ferro-alloys (ferromanganese, ferrosilicon or "silvery" pig iron, spiegeleisen and silicomanganese).*

* For further information concerning ferro-alloys, see the article on page 337 of this Handbook.

As the names imply, basic iron and Bessemer iron are used in the production of steel by the basic open hearth and the Bessemer converter processes, respectively. Blowing iron is a special grade made for the purpose of blowing in Bessemer converters, for conversion into so-called "synthetic scrap" or blown metal used in the duplex process. Ingot mold iron is produced for the casting of ingot molds used in steelmaking, and is usually applied directly for this purpose.

Merchant grades are made in numerous compositions, depending on the specified phosphorus, silicon and manganese content. They are used for a large variety of applications in the castings industry.

Ferromanganese is used as a deoxidizer and desulfurizer in the production of steel, and as an alloying element. Ferrosilicon made in the blast furnace is of the type commonly known to the trade as "silvery iron", and is used as a deoxidizer and alloying element both in steelmaking and in the castings industry. Spiegeleisen, which might be termed a low-grade ferromanganese, is also used as a deoxidizer in steelmaking. Silicomanganese, another deoxidizer and alloying agent, is rarely produced in the blast furnace.

The amount of manganese in the product is dictated both by the manganese content of the ores and by the heat generated within the hearth, which is in turn governed by the quantity of coke consumed in relation to the quantity of product. Phosphorus content of the product is determined solely by the phosphorus content of the charge. The silicon content of the product is established largely by the heat generated within the furnace (higher temperature is required for increased silicon), and to a lesser extent by the chemical compositions of the ores and slag. The quantity of coke and slag associated with production of various grades has an important bearing on the rate of production and the manufacturing cost of iron.

Typical compositions of various grades of blast furnace products and representative coke rates in pounds per ton of product are shown in Table V.

Table V. Compositions and Required Coke Consumption Rates for Various Grades of Blast Furnace Products

Grade	Representative Composition, % Si		P	Mn	Typical Coke Rate, lb per ton iron
Basic—Northern	0.96	0.028	0.274	2.38	1766
Bessemer	1.40	0.024	0.077	0.54	1830
Blowing Iron	1.43	0.027	0.120	0.57	1820
Ingot Mold	1.51	0.041	0.144	1.22	1840
Intermediate Low-Phos	1.96	0.021	0.048	0.72	1947
Malleable	1.06	0.032	0.206	0.79	1855
Malleable	3.04	0.024	0.218	0.84	1961
Northern Foundry, Low-Phos.	2.07	0.025	0.396	0.91	1952
Northern Foundry, High-Phos.	3.92	0.018	0.580	1.14	2028
Southern Foundry	1.89	0.041	0.780	0.48	2352
Ferrosilicon (Silvery Iron)	10.21	0.032	0.221	0.88	2760
Spiegeleisen	1.12	0.025	0.202	19.49	2880
Ferromanganese	0.52	0.016	0.240	80.20	4275

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The Acid Bessemer Process of Steelmaking

By G. B. Waterhouse*

THE invention of the Bessemer process of steelmaking was a great event in the world's economic history. Previously steel had been scarce and expensive, made chiefly by the crucible process. It was reserved for special purposes, while wrought iron, cast iron, and bronze were used for structures, engines, and ordnance. Henry Bessemer developed the process during his search for an improved material for guns. He started his experiments in Dec 1854, shortly before his forty-second birthday. The first public description of the process was in Aug 1856 before it had been perfected. Many difficulties were encountered, later, principally because of phosphorus in the pig iron which was used as the raw material.

Application for a patent disclosed that William Kelley had worked on a similar method since 1847 and a patent was granted to Kelley in 1857. As soon as the patent controversy was ended in 1865, developments were rapid, mainly because of the energy and genius of the great engineer, Alexander Lyman Holley.

The American steel industry grew up on Bessemer steel. More than three-fourths of the steel made in the United States between 1885 and 1900 was made by this process. Even in 1900, 65.7% of all the steel made in the United States was Bessemer grade.

The application of this process to pig iron high in phosphorus was developed in 1877 by Sidney Gilchrist Thomas, who discovered the proper basic refractories and the importance of a basic slag. His method, the basic Bessemer or Thomas process, is of great importance in Europe.

The Bessemer Converter. Molten blast furnace iron (pig iron) of the proper composition is poured into the Bessemer converter, a pear-shaped steel vessel mounted on trunnions. The converter is tilted to receive the metal. The charge varies from 5 to 30 tons. The lining of the converter is of acid refractory material and the slags produced consist of more than 50% silica, so the process is known in this country as the "acid Bessemer". When the vessel is charged, air is admitted from the blowing engines or turboblowers through one of the two trunnions supporting the vessel, to a blast box at the bottom of the converter. From this box the air passes through numerous holes or tuyeres, ½ to ⅞ in. in diam, to the interior of the converter. The blast pressure is about 20 psi, but often ranges from 25 to 32 psi. Several plants use automatic controls to deliver the necessary volume of air at a uniform rate per minute, so as to avoid peaks and valleys in volume delivery, caused by a number of variables such as blanked tuyeres and variations in depth of bath. These converters are known as "bottom blown". This article will not describe the process carried out in side-blown converters used in foundries that make steel castings. These vessels, often called "baby Bessemers" (Tropenas converters), usually vary from ½ to 3 tons capacity.

Operation of Acid Bessemer Converter. After the blast is turned on, the vessel is slowly turned upright. The air blows through the charge and oxidizes the silicon, manganese, and carbon, in the order given. The combustion of these materials, especially of silicon and some of the iron, furnishes the heat to carry on the process. The progress of the operation is shown by the flame issuing from the mouth of the converter. At first this flame is short and dry with very little visibility; then a reddish-brown flame of low luminosity occurs during the period when silicon and manganese are oxidized. As the carbon burns, the flame changes in character and increases in size, becoming yellowish white and reaching about 30 ft in height (Fig. 1). When the flame drops in a characteristic way at the end of the blow, the vessel is again turned down on its side and the blast is shut off. The photocell is now being used in some plants to control the blow, to determine when to turn down the vessel, and also to aid in better control of temperature.

This whole operation or "blow" usually takes from 12 to 18 min. The material now known as "blown metal" contains traces of silicon and manganese and 0.06% C or less. Substantially all the phosphorus and sulfur of the original pig iron are present in the blown metal, which also contains about 0.2% FeO (iron oxide). This last constituent makes the metal "red short", incapable of being successfully forged or rolled; consequently a deoxidizing agent is added to the blown metal. In making soft or low-carbon steel, ferromanganese, crushed to egg size, is usually added to the blown metal while it is being poured from the converter into the ladle. Then the ladle is swung or carried over the ingot molds and the ingots are poured.

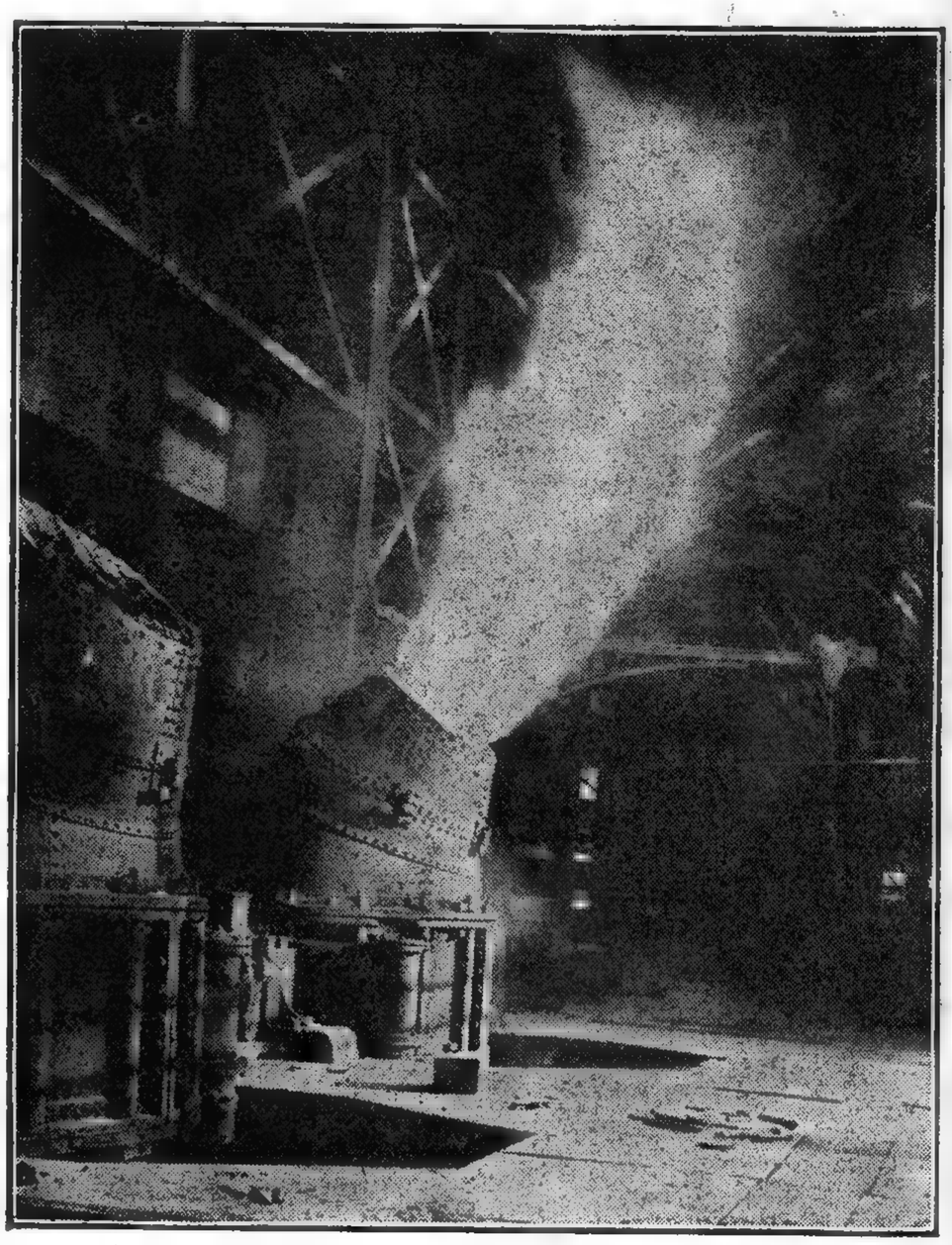

Fig. 1 A Bessemer blow

The work of the physical chemists during the last 20 years has shown that the chemical processes during Bessemer steelmaking are very similar to those taking place in the open hearth furnace. Thermodynamic studies of the effect and intensity of different deoxidizing agents have shown that fully blown Bessemer metal, treated with selected quantities of molten pig iron in the converter, can be deoxidized readily, much as open hearth steels are "blocked" during the refining operations. Such deoxidized blown metal can then be poured into the teeming ladle and manganese, silicon, aluminum, titanium, and other elements can be added in proper amounts to produce killed steel (as contrasted with open, effervescing, or rimmed steel, mentioned in the previous paragraph). In recent years about a million tons of killed Bessemer steel made by this procedure has been used satisfactorily for all sizes of seamless pipe, for carburizing steels and for forging steels.

Raw Material. The main raw material is liquid pig iron. This is usually brought from the blast furnace or furnaces in ladles and poured for storage into containers known as "mixers", because various casts are mixed or averaged. These mixers hold from 200 to as much as 1200 tons. They are constructed of steel lined with firebrick or other re-

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Prepared for the Subcommittee on Melting.

fractory material and can be rotated electrically or by hydraulic power. When needed, metal is poured from the mixer through a spout into a ladle standing on a scale. Mixers are equipped for heating by gas, oil or tar so that heat may be added to the bath when necessary, to offset losses from radiation. Care is taken to prevent blast furnace slag from entering the mixers with the iron, since it would cause slopping and bad working in the Bessemer converter.

The composition and amount of iron entering the mixer is very important to the operation of the converter. For good practice the pig iron is held within fairly close limits.

Silicon, the most important element, varies from about 1.00 to 1.80%. It should be held as nearly constant as possible and at the particular amount found to work best for the individual shop.

The total carbon content does not vary much in a given plant combination of blast furnaces and Bessemer converters. The carbon content of each cast of iron is not usually determined, and may vary from about 3.80 to 4.50%, depending on individual blast furnace operations.

The manganese content is usually less than 0.60%. The percentage should not be much higher, for high manganese makes a thin slag in the converter, which slops out of the vessel onto the floor of the shop, causing a loss of steel and handicapping the operator in producing steel of a specified composition.

All the phosphorus entering the blast furnace with the charge is reduced and ultimately enters the liquid iron. Phosphorus in the iron varies from about 0.080 to 0.100% and almost all of this remains in the blown metal and in the finished steel. Thus the phosphorus content of the iron governs the phosphorus content of the finished steel to a certain extent, and it is important that this content be kept sufficiently low to prevent exceeding the maximum allowed in the final product. In general this is 0.110%, although some specifications for Bessemer steel allow a maximum content of 0.13%. The reason why iron ores are classed as Bessemer and non-Bessemer now becomes obvious. The Bessemer ores are so low in phosphorus that the blast furnace iron made from them is low enough in phosphorus to be used in making Bessemer steel.

The sulfur content, usually about 0.04%, varies from 0.03 to 0.08%. Both phosphorus and sulfur are about 8% higher in the finished steel than in the blast furnace iron, because of loss of iron and other elements and the resulting concentration of phosphorus and sulfur.

Temperature Control. After the liquid iron has been poured into the vessel, the blast turned on and the vessel turned upright, the scrap chute is swung into the nose of the vessel and the correct amount of scrap is added. This scrap addition affords the operator a means for adjusting temperature, the control of which is his most important duty.

The finished steel in the ladle must be at the proper temperature for the grade of steel being made. It must pour cleanly from the ladle into the ingot molds so that the ingots will set properly. If the metal is too cold, a large skull* will be left in the ladle and there may be trouble in pouring the ingots. If the metal is too hot, the internal structure of the ingots will not be correct and surface as well as interior defects may develop during rolling.

In general, the operator tries to control the temperature so that a small skull is left in the ladle after pouring the finished steel. There are two possible methods for reducing temperature. One is by the addition of scrap; the other is by using steam admitted with the air. In the first method, bloom butts or crop ends of steel weighing about 100 lb are ordinarily added, but sometimes cold pig iron is employed. Only about 15% by weight of the liquid iron can be used, so the Bessemer is not a scrap-using process.

The chemical composition of the liquid iron, particularly the silicon content, is generally maintained to give a reserve of temperature during the blow; consequently scrap or steam is usually needed. Occasionally cold heats are encountered. If these are recognized in time, ferrosilicon can be added with the liquid pig iron, or added down the scrap chute, or the vessel can be blown on its side so that part of the air rushes over the surface of the metal. This causes excessive loss of iron, but does raise the temperature.

Additions. In the production of most of the steels listed in Table I, ferromanganese is added while the blown metal is being poured into the ladle. This brings about deoxidation and adds the amounts of carbon and manganese required to give good rolling and working properties and to meet the specifications. During this operation there is a loss of about 35% Mn, which is allowed for, and experience soon shows the correct weight of ferromanganese to be added. The sulfur needed for the free-cutting steels is added to the converter in the form of pyrites, or to the converter or ladle as stick sulfur in a strong paper bag. About 45% of the sulfur addition is lost.

For the higher-carbon steels, the proper weight of liquid iron is brought from the mixer and added to the blown metal in the converter. It is often the practice, in making such steels, to turn on the blast and then turn the vessel up and down to give a "puff" and mix the materials thoroughly. Ferromanganese is added, as usual, while the steel is being poured into the ladle. Sometimes the required carbon content is obtained by adding bags of dry crushed anthracite coal or coke to the blown metal while it is being poured from the converter.

Rail steel and other high-carbon steels were formerly made by adding a molten mixture of spiegeleisen and pig iron to the blown metal in the converter. This mixture was first melted in cupolas and carefully calculated to take care of losses. The requisite amounts of carbon, manganese and silicon were added, by means of the correct weight tapped from the cupolas. Additions of molten pig iron have been found to be entirely satisfactory for steels containing between 0.20 and 0.50% C, avoiding the use of spiegeleisen and the expense of separate melting equipment for handling molten spiegel. Almost any grade of carbon steel can be made by the Bessemer process, if the use of steel high in phosphorus can be allowed.

Dephosphorized and Low-Phosphorus Acid Bessemer Steel. Several steel companies are making or planning to make Bessemer steel from low-phosphorus pig iron, with the final percentage of phosphorus in the steel ranging from 0.050 to 0.070%.

A process has now been developed for the dephosphorization of blown Bessemer metal while it is in the ladle. More than a million tons has already been made with final phosphorus content less than 0.050%. The iron is of controlled silicon and manganese content, so that a thick viscous vessel slag is produced when the metal is blown with proper control of temperature. This slag is easily prevented from entering the ladle with the blown metal. Additions to the ladle of readily fusible slag-producing materials then cause a reaction that brings about the dephosphorization. The steel is used in many ways: as cold reduced sheet for corrugated roofing, as galvanized sheet, black plate, blue iron, building materials, conduit pipe and other welded pipe, oil-well and water-well tubing. The steel is soft and ductile, can be cold rolled, formed and drawn, and is said to produce a finished product of better final stiffness and rigidity than soft open hearth steel.

Composition of Acid Bessemer Steel. During the first part of the blow, silicon and manganese are rapidly oxidized and enter the slag. This is characterized by a short dry flame. The flame then turns to a yellowish white as the carbon is oxidized, and begins to increase in size until it is 25 to 30 ft in height. At the end of the blow there is a well-marked drop of the flame, and the vessel is turned down. The heat may be turned down "green" or it may be "full blown", depending on the type of steel being made.

The blown metal contains from about 0.04 to 0.10% C, traces of Mn and Si, from about 0.085 to 0.110% P, and about 0.03 to 0.07% S, except when sulfur has been added in the vessel. The additions required to make the finished steel are added usually in the ladle or else both in the vessel and in the ladle.

Typical compositions of finished Bessemer steel are shown in Table I.

Table I does not include bars, small structural shapes, and materials for railroad purposes, such as spikes, bolts, and nuts, for which considerable Bessemer steel is used.

* The term "skull" refers to the frozen shell of metal sometimes remaining in the bottom of the ladle.

Table I. Chemical Composition of Acid Bessemer Steel

Material	Carbon, %	Manganese, %	Phosphorus, %	Sulfur, %
Soft Bessemer Steel Grades				
Skelp	0.10 max	0.30 to 0.60	0.11 max	0.06 max
Sheet and tin bar	0.10 max	0.30 to 0.50	0.11 max	0.07 max
Soft wire	0.08 max	0.45 max	0.11 max	0.06 max
Medium wire	0.08 to 0.13	0.30 to 0.70	0.11 max	0.06 max
Hard wire	0.12 to 0.17	0.70 to 1.00	0.11 max	0.08 max
Screw Stock				
AISI B 1111 SAE 1111	0.08 to 0.13	0.70 to 1.00	0.07 to 0.12	0.10 to 0.15
B 1112 1112	0.08 to 0.13	0.70 to 1.00	0.07 to 0.12	0.16 to 0.23
B 1113 1113	0.08 to 0.13	0.70 to 1.00	0.07 to 0.12	0.24 to 0.33
Reinforcing Bar[a]				
Reinforcing bar	0.15 to 0.35	0.70 max	0.12 max	0.08 max
	0.08 to 0.15	1.00 max	0.12 max	Normal or added

Deoxidized or Killed Steels					
			Phosphorus, %	Sulfur, %	Silicon, %
Seamless pipe	0.15 to 0.50	0.30 to 1.25	0.11 max	0.06 max	0.15 to 0.30
Forging steel	0.25 to 0.40	0.60 to 0.90	0.11 max	0.06 max	0.15 to 0.30
Carburizing steel	0.15 to 0.25	0.60 to 0.90	0.11 max	0.06 max	0.15 to 0.30

[a] Specifications governing reinforcing bars prescribe mechanical test requirements rather than chemical composition. The compositions shown above are an approximative equivalent expression for the tensile test requirements of the several grades.

The composition of steels for these purposes does not vary greatly from that shown for skelp and sheet bar, except that as a rule only the phosphorus is specified and tensile test requirements are imposed. In many of these steels, especially those exposed to atmospheric corrosion, from 0.20 to 0.30% Cu is present and has been found very helpful.

Application. The main uses of Bessemer steel, as indicated in Table I, include skelp for making lap-welded and butt-welded pipe, especially the smaller sizes; sheet bar for rolling into sheet for tin plate and galvanized material; bars and special shapes for free-machining purposes, especially automatic screw-machine products; and wire products of many different kinds. The Bessemer process is the third steelmaking method of the country in regard to tonnage. Its capacity is about 5.60% of the total steelmaking capacity.

Also considerable steel is made by the duplex process, a combination of the acid Bessemer and the basic open hearth processes. The steel produced in this way is known and shipped as open hearth steel. One other application of the Bessemer process is the Aston process for making wrought iron. Various combinations of the Bessemer and electric furnace processes are listed on page 329 of this Handbook.

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The Open Hearth Process of Steelmaking

By C. H. Herty, Jr.*

SINCE pig iron is unsuited to the purposes for which steel is used, it must be refined. The refining consists of removing carbon, manganese, and silicon by oxidation; sulfur by reaction with the slag; and suspended oxide material and gases by scrubbing. In the basic process it is necessary to supply a strong base that will form stable compounds with the oxides of phosphorus and silicon, and with sulfur, in order to hold these permanently in the slag—which is the molten magma formed when the lime and various oxides unite with or dissolve in one another.

The Basic Open Hearth Process

The Open Hearth Furnace. Figures 1, 2 and 3 show sections through an open hearth furnace having a capacity of 175 tons. The basic furnace consists mainly of a shallow, elliptical vessel lined with some suitable basic refractory. This hearth, on which the steel is made, is covered with a silica roof to form a combustion chamber. On one side of the furnace suitable spaces are left for doors through which the operations can be controlled.

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Prepared for the Subcommittee on Melting

The hearth is usually lined with magnesite brick and covered with a mixture of burned magnesite or dolomite and open hearth slag. The bottom is kept in repair with raw or clinkered dolomite, or both, or in certain instances with ground magnesite and open hearth slag. The banks, particularly above the slag line, are protected with dolomite or chrome ore.

In many modern furnaces the backwall slopes at an angle instead of being straight. This sloping backwall prolongs the life of the furnace because the flame cannot cut the brick so readily as it can when a straight backwall is being used. A sloping backwall also facilitates repairs.

In the rear of the furnace, at the center and bottom of the hearth, is the tap hole, which is between 4 and 8 in. in diam, depending on the size of the furnace and the type of practice. During the steelmaking period, this hole is filled with a suitable refractory material that can be removed easily when the heat of steel is to be tapped. In a tilting furnace, the tap hole is put in above the level of slag and metal and the metal flows out through this hole when the furnace is tilted.

Open hearth furnaces are of the regenerative type, in which the hot gases are passed through checker chambers and transfer heat to the brickwork. Approximately every 15 or 20 min, the flow of gases through the furnace is re-

versed and cold air enters the hot chambers, where it is heated to about 1800 F, a system promoting economy of fuel and control of temperature.

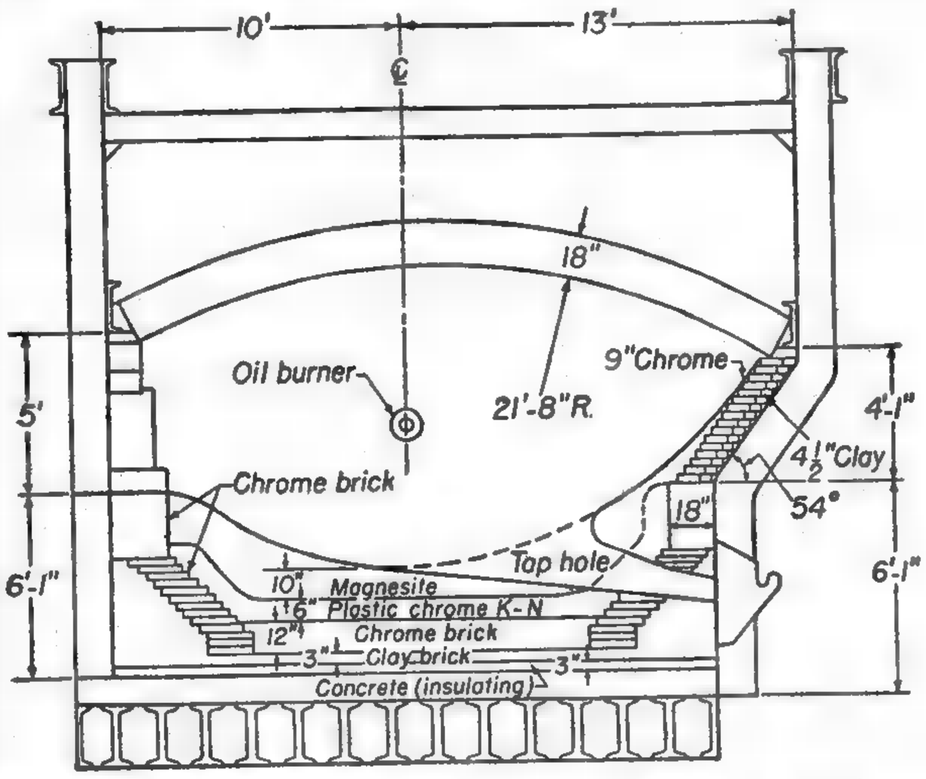

Fig. 1 Cross section of a 175-ton stationary open hearth furnace showing bottom construction and the principal dimensions (Ref 1)

Producer gas, and sometimes mixtures of blast furnace and coke-oven gas are fuels that are preheated in the checkers before they enter the furnace. Tar and oil are brought directly to the port and atomized with high-pressure steam or air, after preheating to about 300 F in order to increase their fluidity. Natural gas and coke-oven gas are delivered directly to the port. The design of the port depends on the type of fuel used.

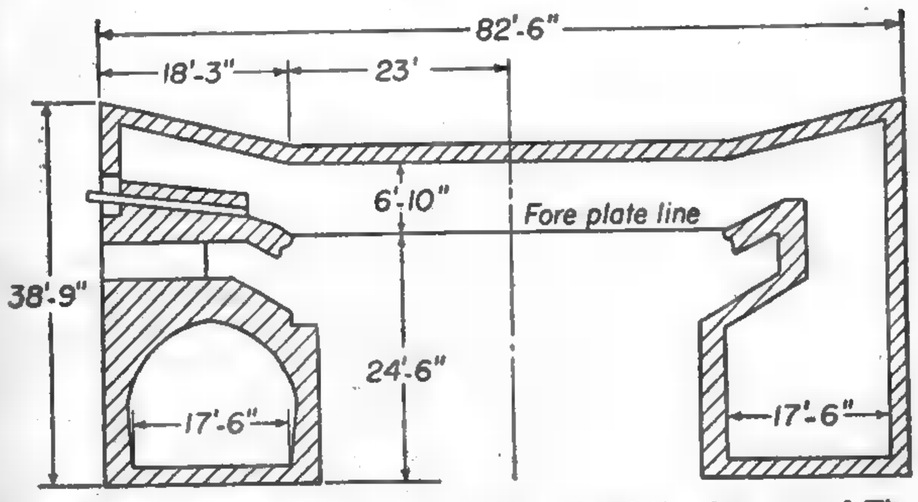

Fig. 2 Vertical section through the length of the furnace of Fig. 1. Centerline of burner at left, center of air uptake at right (Ref 1)

Oil is the fuel most commonly used today in American open hearth furnaces.

Most of the open hearth furnaces that have been built during the last few years, have capacities between 150 and 200 tons per heat.

Charging the Furnace. The scrap, cold pig iron, limestone and ore are loaded into charging boxes. A charging machine picks up the individual boxes and places the contents on the hearth of the furnace. When a charge consists of limestone and scrap, the limestone is placed on the hearth first, followed by the scrap, until the charging is completed or the furnace is full. If large amounts of light scrap are being charged, it is often necessary to fill the furnace and then melt down the scrap somewhat, before charging the rest of the scrap. It is sometimes advisable to charge a layer of scrap on the hearth of the furnace before adding the limestone, particularly if the limestone shows a great tendency to stick to the hearth. If ore is charged, it is usually added prior to or immediately after the limestone addition, depending on the condition of the bottom. When cold pig iron is used, it is ordinarily charged after the scrap. If hot metal (molten pig iron) is used—and the largest tonnage of steel is made by this method—it is brought to the furnace in a ladle and poured through a spout inserted in one of the charging doors. The hot metal is added after the scrap has melted down somewhat and after the furnace is well heated.

Since large amounts of alloy steel scrap were produced during World War II, it was necessary, in almost all steel plants, to segregate the scrap in order to recover the alloying elements. It has now become general practice to inspect and segregate incoming scrap much more carefully than before the war.

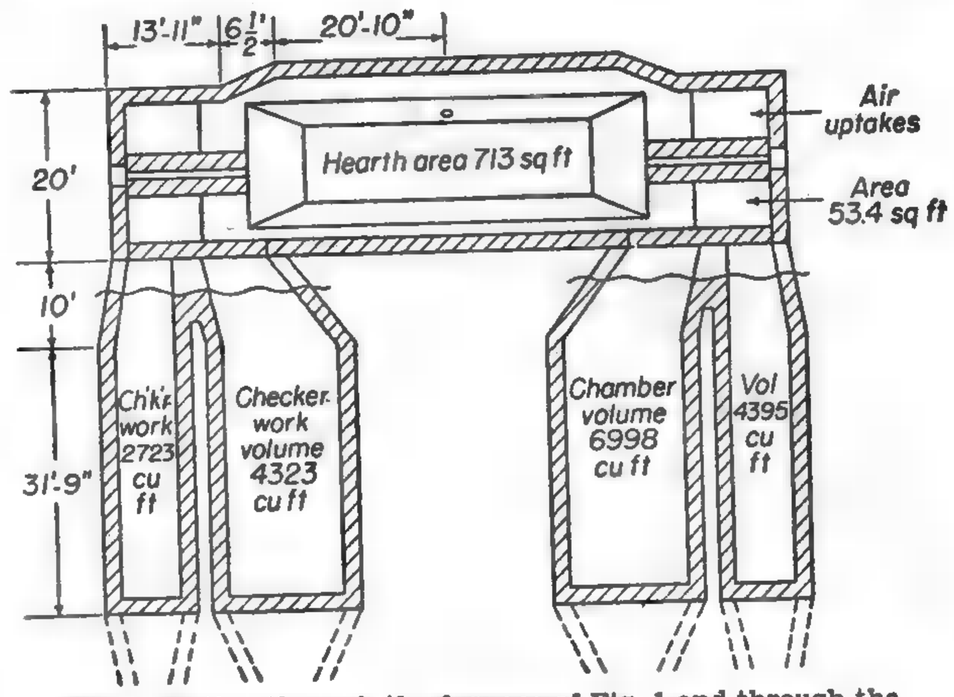

Fig. 3 Section through the furnace of Fig. 1 and through the checker chambers (Ref 1)

Melting the Charge. During the period between the charging of the scrap and the addition of hot metal, two chemical reactions take place in the bath: oxidation of the scrap while it is melting, and calcination of part of the limestone. As soon as the hot metal is added, much of the scrap and all of the limestone are submerged in liquid metal. The oxidation of the exposed scrap proceeds until sufficient scrap has melted to raise the level of the liquid metal enough to cover all solid material. During this melting period large amounts of carbon dioxide are being evolved from the calcination of the limestone by the reaction:

$$CaCO_3 = CaO + CO_2$$

A heavy boiling action results from the evolution of CO_2, and simultaneously this gas reacts with the liquid iron to form iron oxide.

$$CO_2 + Fe = FeO + CO$$

As the scrap continues to melt, pieces of limestone, which have been held on the bottom by the scrap, begin to rise through the metal bath and float in the slag. The period during which the lime rises is known as the "lime boil", and the agitation caused by the evolution of gas assists greatly in the transfer of heat from the fuel to the bath, because the hot upper layer of metal is mixed thoroughly with the colder lower layers.

Function of Slag in the Steelmaking Process. In order to remove carbon, manganese, phosphorus and silicon as oxides, and to prevent phosphorus from reverting from the slag to the metal during the later stages of refining, it is necessary to have a large percentage of lime in the slag, to form a stable calcium phosphate. The iron oxide in the slag removes a large amount of the manganese, carbon, phosphorus and silicon from the steel, by oxidation. Thus the slag acts as a regulator of oxidation and as a carrier of undesirable impurities. If the slag is weakly basic, considerable erosion of the furnace lining will take place. If the slag is too basic, it is usually very viscous and the reactions that occur will be retarded. According to the best data available at the present time, the slag is evidently calcium silicate, which changes in composition as the heat progresses, and contains dissolved CaO, $3CaO \cdot P_2O_5$, MnO, FeO and CaS. The magnesia in open hearth slags is generally assumed to be suspended as periclase (MgO), in which some iron oxide may be dissolved.

It is very desirable that the slag have a certain definite consistency during the working period, because the oxidation of the bath is controlled not only by the amount of iron oxide in the slag, but also by the rate at which iron oxide diffuses from the slag into the metal, and this rate of diffusion depends on the viscosity of the slag. If the slag is too viscous it may be thinned out by addition of fluorspar; if the slag is too thin (too fluid) it may be thickened (made more viscous) by additions of burnt lime.

The Formation of the First Slag. During the initial melting period a large amount of iron oxide is formed by the oxidation of the scrap. This oxide combines with some of the calcined limestone on the hearth of the furnace and with some of the dolomite on the banks to form a slag high in iron oxide and lime. As soon as the hot metal is added, the slag formed during melting reacts with silicon and manganese, eliminating them rapidly. This decreases the iron oxide content of the slag and increases the SiO_2 and MnO content. These slags are weakly basic and cause severe erosion of the furnace banks; if high-silicon pig is used, this corrosive action is intensified. For high-iron charges in stationary furnaces, about 5 to 10% (metallic) of iron ore is charged with the scrap and, when this ore reacts with the hot metal, a large amount of the early slag is flushed out through a suitable hole in the back of the furnace.

The composition of the slag at the time the heat is melted, has a pronounced effect on its oxidizing power during the finishing period of the heat. The reason for this is that a great deal of oxidation takes place through the action of the furnace gases on the FeO in the slag, and the higher the FeO content of the liquid slag, the greater the oxidation throughout the heat.

Working the Heat. After the heat is melted, a sample of metal is taken from the furnace and the carbon content is estimated. In this way the furnace operator judges the quantity of ore that should be added in order to lower the carbon content of the metal to a desired figure. The ore is introduced either by shovel or charging box, and a lively reaction starts at once because of the oxidation of the carbon. While the carbon is being eliminated, samples are taken to determine the carbon content. This determination is usually accomplished by means of a "carbometer" or other magnetic device instead of by methods of chemical analysis or estimation of the carbon content by fracture. While the carbon is being eliminated, the operator attempts to "shape up" the slag so that, at the finishing period, the slag is of a creamy consistency and the metal is at the proper temperature. The temperature of the bath may be judged by stirring a rod through the heat and noting the appearance of the end of the rod when it is withdrawn from the furnace; by pouring a test specimen and noting the tendency of the skull (solidified crust) formed in the spoon; and also by noting the fluidity and nature of the steel during pouring. The temperature of the bath is regulated by the amount of fuel used, and this is ordinarily under the control of the operator. If the amount of fuel is kept constant, the temperature of the bath will be influenced by: (1) the amount and viscosity of the slag; (2) the amount of agitation; and (3) the chemical reactions in the bath, which may or may not influence the agitation. All these factors are controlled to some degree by the operator and must be considered in securing the desired temperature in the bath. A great deal of work is in progress on the methods of determining bath temperature. In many shops the fuel rate is determined by measurements of roof temperature, and the fuel is automatically cut off when the roof becomes too hot.

Finishing the Heat. Unfortunately, during the process of eliminating unwanted elements from the metal by oxidation, a considerable amount of iron oxide dissolves in the steel bath. Before the steel can be poured into the molds, it must be deoxidized, partially or fully, either in the furnace, the ladle or the molds. For so-called "quality steel", as much deoxidation as possible is done in the furnace, because the elimination of nonmetallic matter resulting from deoxidation depends, to a considerable extent, on the distance the inclusions must rise before leaving the metal. Since the average depth of the steel bath is about 30 in. and the average height of a ladle about 12 ft, it is obvious that less time will be required for the elimination of nonmetallic matter if the steel is deoxidized in the furnace instead of in the ladle. On the other hand, when the steel is deoxidized in the furnace, if the heat is held in the furnace to allow nonmetallic matter to rise out of the metal, iron oxide will diffuse from the slag into the steel.

Since the area of the slag-metal interface in the furnace is much greater than in the ladle, it is evident that more iron oxide will diffuse back from the slag in the furnace than from the slag in the ladle. There is therefore a balance between the factors favoring deoxidation in the furnace and those favoring deoxidation in the ladle. However, when the viscosity and iron oxide content of the slag are regulated properly, deoxidation in the furnace is found more satisfactory than in the ladle. Some deoxidizing additions must be made in the ladle because of the oxidizing conditions in the furnace. Thus, if a heat is being deoxidized with ferromanganese and ferrosilicon, it is customary to add ferromanganese in the furnace and ferrosilicon in the ladle. The selection of deoxidizers and the manner of deoxidation are extremely important in making the best steel from a given open hearth heat. In some instances the steel is deoxidized in the mold and for many applications this practice is very satisfactory. Ordinarily aluminum is the only deoxidizer used in the molds. Ferrosilicon is used for some grades of steel, but this is the exception rather than the rule.

The time required to make a 200-ton heat of open hearth steel is about 11 hr divided as shown in Table I.

Table I

Division of Time for Making a 200-Ton Open Hearth Heat

Total Time, 11 hr

Operation	Percentage of Total Time
Start of charge to end of charging	19
Actual time spent in charging	6
Start of charge to hot metal addition	35
Final charging of scrap to hot metal addition	15
Duration of lime boil	27
Working the heat	23
Deoxidation to tap	1 to 5
Tapping	1
Finish of tap to start of repairs on banks	1
Repairs on banks and bottoms	2
Finish of tap to start of charging	4

Killed, Semikilled, and Rimmed Steels. There are three classes of plain carbon steels: killed, semikilled, and rimmed. All forging steels and, in general, all steels containing more than about 0.25% C are killed. Structural steels containing from 0.15 to 0.25% C are generally semikilled, and many steels with less than 0.15% C are rimmed.

Killed Steel. In forging steels and other high-carbon steels, the essential quality is soundness (freedom from blowholes and segregation), because this material usually goes into a product where soundness is desired. The term "killed" indicates that the steel has been deoxidized sufficiently (by proper additions of ferrosilicon, aluminum and other strong deoxidizers) for the metal to lie perfectly quiet when poured into an ingot mold. In killed steel there is no evolution of gas, and the top surface of the ingot solidifies almost immediately.

In making killed steels, the general practice is to "catch the heat coming down", that is, to bring the carbon content to the desired percentage and then to tap the heat. The heat is usually left in the furnace from 6 to 30 min after the addition of the deoxidizer, depending on the type of deoxidation employed.

Semikilled Steel. In making semikilled steels, the heat is caught coming down at the desired carbon content, and manganese is added either in the furnace or in the ladle. If silicon is used, it is added in the ladle as 50% ferrosilicon. When aluminum is used, it is sometimes added in the molds, although in most plants additions of aluminum are made both in the ladle and in the molds.

Rimmed Steel. For many applications, particularly in soft steels where the surface of the product is important, the process called rimming is preferred, in which the steel is partially deoxidized with manganese, used alone or with some other deoxidizer. When the metal begins to solidify,

a brisk evolution of gas cleanses the surface of the growing crystals. The result is a skin of very clean metal. The thickness of this skin depends on the skill of the steelmaker. When the metal has cooled to the point where solidification proceeds throughout the liquid, a great deal of gas is trapped and a porous interior results. In making rimmed steel, the steelmaker attempts to obtain the proper rimming action in the molds, because this action determines to a large extent the solidity of the surface of the ingot. The rimming action is controlled by the iron oxide content of the slag, the slag viscosity, the temperature at which the metal is poured, and the deoxidizers used.

In rimmed steel the outside surface of the ingot is quite clean and low in carbon; this gives an excellent surface to the finished product. A wide variety of steels for deep drawing, where ease of forming is the major consideration, are made by the rimming process.

The Acid Open Hearth Process

In the acid open hearth process, the lining of the furnace is made of silica sand, an acid material. Since any basic material in the slag would tend to attack the lining rapidly, the acid process is confined to materials low in sulfur and phosphorus content, because these two elements require lime for their elimination.

In an acid slag, a large part of the iron oxide is combined with silica as silicate of iron and manganese. This combined iron oxide will not diffuse into the metal, nor will it be oxidized readily by the furnace gases. Therefore, for a given amount of iron oxide in the slag, the metal will be much less oxidized in the acid open hearth furnace than in the basic open furnace, and consequently there will be fewer products of deoxidation to be removed.

One of the most important advantages of the acid process over the basic is that the composition and nature of the slag can be controlled almost at will.

A typical percentage composition of an acid slag is: FeO, 15; MnO, 21; SiO_2, 53; CaO, 4; and small amounts of Al_2O_3, Cr_2O_3, and other oxides. The amount of FeO plus MnO is automatically regulated by the fact that iron-manganese silicates will dissolve as much as 60% of the SiO_2 from the furnace banks. By regulating the amount of MnO in the slag, the FeO can be closely controlled.

The acid open hearth process is used almost entirely for the manufacture of killed steel. A very small tonnage of rimmed steel is made by this process.

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The Basic Electric-Arc Process of Steel Melting

By Gilbert Soler* and James P. Gill*

THE first attempt on record to melt steel electrically dates back to 1878 when Siemens conducted his initial experiments with arc melting in a small crucible, although the discovery of the carbon arc was made by Sir Humphrey Davy in 1800. The development of electrometallurgy was rather slow during the next 20 years, because the availability of electric power was limited and the cost was comparatively high. In about 1890 Heroult developed a furnace for the production of ferro-alloys. In 1899 Heroult placed in operation the first successful commercial direct-arc furnace for melting steel. During and following Heroult's work there was great activity in developing direct-arc furnaces abroad. Among these furnaces may be mentioned the Girod, Harmet, Keller, Nathusius, Electrometal, Gronwall, Stobie and Greaves-Etchells designs.

No arc furnaces were developed in the United States until the first Heroult furnace was installed at Syracuse, N. Y. in 1906. It was a single-phase, two-electrode furnace of four-ton capacity. The first three-phase direct series arc furnace was installed at South Chicago in 1909. This 15-ton furnace was the counterpart of the modern Heroult type of electric-arc furnace used today. American designs or modifications include the Ludlum, Vom Baur, Booth-Hall, Moore, Greene, Swindell and Volta furnaces.

The Furnace. Of the many arc furnaces designed to melt steel electrically, it appears that only the system employed first by Heroult has stood the test of time. In this system, the steel in the furnace forms the common conductor for the current flowing between the electrodes, which enter the furnace through the roof. The mechanical details of this general type of furnace vary. For example, some furnaces tilt on rockers, others on trunnions; work material is charged into some through the doors, into others through the top by removing the roof. Figure 1, showing a trunnion-type of six-ton furnace, will serve to illustrate the essential parts of a typical arc furnace.

The tilting mechanism, the electrode control motor, and the switchboard control apparatus are often installed in separate rooms, a practice which affords protection from dirt and from the danger of heats burning through the bottom into the pit.

Current is supplied from a suitable source, through the bus bars *F* and electrode holders *G* to the electrodes (three in number) arranged in the form of a triangle. Electrodes may be either graphite or amorphous carbon. Arcs are sprung from the electrodes to the bath *K*, thus heating the metal both by direct conduction from the arc, and by radiation from the roof and walls. The height of the electrodes above the bath, and consequently the heat input, are controlled automatically by the winch motors *H*, which raise and lower the electrodes.

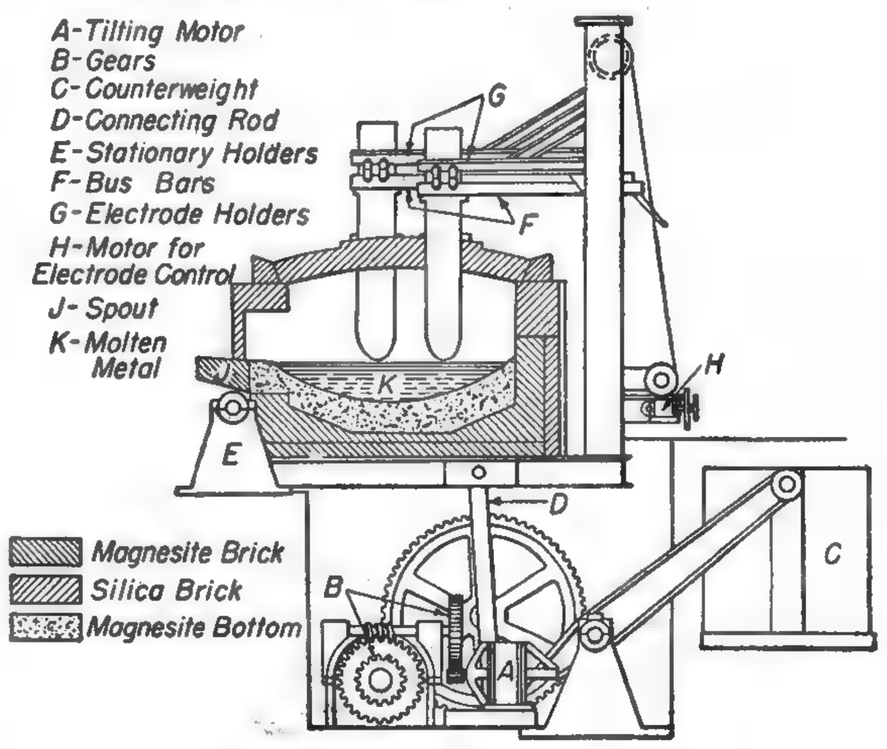

Fig. 1 Basic electric-arc melting furnace

The furnace proper consists of a cylindrical steel shell, lined with refractories as indicated in the legend. The detachable roof may be removed for top charging. The furnace is tilted about the stationary axis or trunnion *E*, placed directly under the spout *J*. The tilting mechanism consists of a motor *A*, which raises the furnace by means of the connecting rod *D*, operated through a series of gears *B*. The weight of the furnace is balanced by the counterweight *C*.

The refractories for the basic electric furnace should be carefully chosen. The hearth itself must be a basic material, such as magnesite or burned dolomite, to withstand

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Prepared for the Subcommittee on Melting.

the lime slags used in the basic process. The walls and roof, on the other hand, need not be of basic material but must be capable of withstanding extremely high temperatures. Silica brick and magnesite encased in metal are used for sidewalls, and silica brick is used almost exclusively for roofs.

The hearth is either rammed in by layers, using a grain material with a suitable binder, and then burned in as a whole, or the bottom material, often mixed with a suitable flux such as open hearth slag, is shoveled into the hot furnace and burned in, layer by layer. This is done by the heat of electric arcs formed between the furnace electrodes and other electrodes placed across the hearth.

Electric furnace refractories are subjected to severe service. The arches, jambs, and door brick have an especially short life, which can be lengthened by the use of water-cooled doors and frames. Protection of refractories by water cooling is an advantage of the larger furnaces.

The tonnage capacities in which commercial units of this type of electric furnace are built, together with the transformer capacities, are as follows:

Nominal Furnace Capacity, tons	Shell Diameter, feet (approximate)	Transformer Capacity, kva
1	6 ft, 0 in.	1,000 to 1,200
3	8 ft, 0 in.	2,000 to 3,000
6	10 ft, 0 in.	3,000 to 4,000
10	12 ft, 0 in.	4,000 to 7,500
15	13 ft, 0 in.	4,000 to 7,500
25	14 ft, 6 in.	7,500 to 10,000
40	16 ft, 6 in.	10,000 to 13,500
50	18 ft, 0 in.	10,000 to 13,500
60	19 ft, 0 in.	10,000 to 15,000
70	20 ft, 0 in.	10,000 to 15,000
100	29 ft, 0 in. by 20 ft, 0 in. (elliptical)	15,000 to 20,000 (2 transformers)

All sizes except the 100-ton size have three electrodes on the one three-phase circuit, while the 100-ton furnace has 6 electrodes with the two three-phase circuits.

The tendency is toward higher voltages during the melting-down period—voltages as high as 250 for some furnaces. During the refining period, the voltages may be as low as 85 to 100. Switches are usually provided, so that two to five voltages are available and numerous variations of power input are thus possible.

Capacity and Production. In the early period of development of the electric-arc furnace in the United States, furnace sizes ranged from 1-ton to 35-ton capacity. In 1927 a 100-ton unit was installed at Canton, Ohio, followed by a 50-ton unit installed at Detroit in 1935. During the period from 1925 to 1938, continued developments were made in mechanical and electrical improvements for the electric-arc furnace. These developments were followed by extensive expansion in electric furnace capacity during the period from 1939 to 1943. Steel capacity of electric furnaces was placed at 5,455,890 tons annual capacity in 1945 as compared with 1,490,858 tons annual capacity in 1938. This increase in electric furnace capacity was comprised, to a great extent, of large arc furnaces of 50-ton to 70-ton nominal rating.

The electric-arc furnace is used both for the production of steel ingots and for the production of steel castings. The greater tonnage of steel ingots is made in the basic furnace, but the greater tonnage of steel castings is made in the acid furnace. In the United States during 1945 there were 185 electric-arc furnaces actively engaged in making steel ingots. The size distribution was as follows:

Furnace capacity, tons	1 to 5	6 to 10	11 to 50	51 to 100
Number of furnaces	37	64	64	20

In the casting industry, which employs small furnaces of 1-ton to 5-ton capacity almost exclusively, mostly of the acid type, the total number of electric-arc furnaces is estimated at 508 units.

The electric-arc furnace is used primarily for melting alloy, stainless, and tool steels. Stainless grades and tool steels are made almost exclusively by this process. In the alloy grades, the electric furnace produces bearing steels, valve steels, steels that resist corrosion and heat, ordnance steels, aircraft steels, automotive steels, and alloy constructional steels for a variety of purposes. Compared with other melting processes, the basic electric furnace process has certain inherent characteristics that can be readily translated into quality. These characteristics include: (1) almost unlimited, yet completely controlled, heat input during melting and refining; (2) furnace atmospheres and slags that are under close control, and quickly reach equilibrium with the bath; (3) almost complete sulfur elimination; (4) a degree of deoxidation that makes it possible to add alloying metals directly to the bath with little loss; (5) a relatively complete and rapid control of oxygen in slag and bath, as well as control of the amount and character of the deoxidation products in the metal.

General Description of Process. In brief, the process consists of charging into the hearth of the furnace a known weight of scrap of suitable physical and chemical character, and melting down the material as quickly as possible. When the charge is melted, the usual practice is to add a quantity of burned lime with some fluorspar or sand to act as fluxes which, together with the oxides resulting from the melting of the scrap, form a highly oxidized basic slag. This same end is sometimes accomplished by adding limestone or burned lime to the charge. Iron ore or mill scale is added as required in order to oxidize carbon, phosphorus, chromium, and manganese from the bath.

The procedure from this point depends on the practice best suited to the type of steel being made. The customary practice in alloy steelmaking is to tilt the furnace slightly and rake off the black oxidizing slag. A new reducing slag to finish the heat is made of burned lime, fluorspar and sand, with coke or crushed ferrosilicon as a reducing agent. In making tool steels or other grades in which a high recovery of alloying elements from the charged scrap is desired, the first or oxidizing slag is not removed, but is deoxidized by additions of coke or crushed ferrosilicon until it becomes "white" or reducing. At intervals during the melting process, samples of the bath are taken for quick chemical analysis, so that chemical composition is known at all stages of the process. The melter is thus enabled to make accurate adjustments in composition with carbon or ferro-alloys.

Since the electric-arc furnace is quite flexible in its operation, many variations in practice are possible. Any combination of oxidizing, reducing, or neutral slags can be utilized to attain the objectives sought. These may be applied to the so-called "cold melt process", or to the hot metal process used in the production of tonnage steels. There are wide differences among the practices employed in various electric melting plants, and it would be beyond the scope of this article to discuss all of them. Typical, however, is the so-called "cold charge two-slag process", and since this is the process most commonly used, it will be described in some detail.

Cold Charge Process. The operation of the electric furnace on cold scrap charges may be divided into two periods—the oxidation period and the deoxidation period. The former may be subdivided into four operations, namely: charging, melting, oxidizing, and slagging off. This last operation takes place in several steps—making the reducing slag, adding ferro-alloys, and recarburizing, finishing the heat, tapping and pouring.

Charging. Electric furnaces are either of the top-charge or door-charge type. In the first type, the charge is assembled in a large orange-peel bucket, lifted over the open furnace shell and lowered into place. In the latter type, either machine or hand charging is employed. Furnaces of medium and large size use charging machines; hand or chute charging is confined to small furnaces.

The bulk of the charge consists usually of selected steel scrap of such composition that when the material melts, the bath will contain a lower percentage of the various elements than is required for the final composition. This obviously allows for proper final adjustment with ferro-alloys and carbon additions. Of equal importance is the physical condition of the charge, the thermal and electrical conductivity, and the distribution in the furnace. All these factors influence the economy of furnace operation. Consequently, considerable care is taken in obtaining the proper balance between heavy and light scrap, in distrib-

uting these properly, and in distributing any other materials used, such as ore, scale and certain ferro-alloys.

Melting. The proper handling of the electrodes and regulation of power input during the melt-down are of extreme importance. If the heat has been charged properly, little difficulty is encountered. The melting down of the charge is conducted at a voltage as high as possible in order to hasten the process, thus increasing furnace economy and decreasing melting losses.

For the first few minutes after the arcs have been struck and the furnace is operating under automatic control, the electrodes "search" their way through the scrap, rising and falling, until each electrode melts a hole through the scrap. The current fluctuates widely but is steadied by the reactors. As soon as a pool of molten metal is formed beneath each electrode on the bottom of the furnace, the general movement of the electrodes is upward while the scrap in the vicinity melts and augments the pool. When the charge is partially melted, a single pool of appreciable size is formed, and the furnace man starts pushing the unmelted scrap toward the center of the furnace, cleaning off the banks, and gradually working all loose scrap into the bath. As soon as this is accomplished, a test can be taken for early carbon, and ore or slagmaking additions can be made.

Oxidizing. The oxidation period actually starts with the melting of the charge and ends only when the heat is slagged off. The electric furnace is a flexible unit allowing the melter considerable leeway in handling lime, fluxes, and oxidizers. These additions can be made to the charge, to the heat when partially melted, to the bath when melting is complete, or at any time before the oxidizing slag is removed. In the oxidizing period, the hot metal is refined by oxygen introduced in solid form as iron ore, roll scale, or rust on scrap. By oxidation, silicon can be removed almost entirely; and the other easily oxidizable elements—carbon, phosphorous, manganese, and chromium—are removed either wholly or in part, according to the conditions present, and the preference of the operator. Also during the oxidizing period the bath is cleansed of hydrogen and solid nonmetallic matter by means of the "boil", which results from the reaction: $2C + O_2 = 2\,CO$.

Limestone or burned lime is added for slagmaking purposes during the oxidizing period. The amount of limestone or burned lime added, regardless of whether the addition is made with the charge or after the heat is melted, depends on the nature of the scrap and its silicon content, the amount of phosphorus removal required, the amount of silica introduced with the iron ore, and the slag basicity desired. The slag must be sufficiently basic to prevent bottom erosion, which would result from a slag that was too acid, and must provide a suitable covering to protect the molten metal from the arc. Greater basicity may be required for phosphorus removal or partial elimination of sulfur during the oxidizing period. The control of manganese and chromium is related to basicity; greater elimination is obtained under semibasic slags and greater recovery is obtained under basic slags.

The first slag is formed during the melt-down from the addition of lime or limestone and oxidizers to the charge, or to the partially molten bath. The lime (CaO) combines with the oxides formed during melting, from the reaction of the oxidizing agents with silicon, phosphorus, manganese, and chromium to form a slag on top of the molten metal bath. After the scrap is all melted clear of the bottom and the heat is completely molten, refining can proceed. A preliminary sample is taken and an analysis is quickly made by the laboratory. On the basis of the preliminary test, additional iron ore may be added for further oxidation of carbon and phosphorus as required. Sufficient lime must be added to produce a satisfactory basic slag. Fluorspar may be added from time to time to thin the slag, or burned lime may be added to thicken the slag. When the oxidizable elements—carbon, phosphorus, manganese, and chromium—are low enough for the final specification to be met when the alloying additions are made during the reducing period, the heat is ready for slagging off. Another chemical analysis is usually made before slagging off. If temperature is under control and the melter is sure of the composition, slagging is started.

Slagging Off. In slagging off, the furnace is tilted backward very slightly. Then the furnace man introduces a rabble or skimmer into the furnace door and, by a raking motion, scrapes or pulls the slag off the metal and out the door into the pit. In this way the black or oxidizing slag is completely removed from the metal.

Making the Reducing Slag. After removal of the oxidizing slag, a new slag is made up by additions of burned lime, fluorspar, and silica sand, with sufficient crushed coke or fine ferrosilicon to make it reducing. This reducing or finishing slag has several functions. It serves as an insulating blanket over the molten steel, protecting the hot metal from oxidation. It also protects the bath from the direct heat of the arc and avoids excessive pickup of carbon from the electrodes. The reducing slag also acts as a medium by which any excess oxygen in the bath is reduced to the equilibrium value, as regulated by the carbon or silicon content of the steel. A major function of the reducing slag is to remove sulfur from the steel, and to reduce the content of this impurity to a low value. The removal of sulfur to low values is unique with the basic electric process. In no other steelmaking process can sulfur be removed so easily.

Two varieties of finishing or reducing slags are common in electric furnace practice. The carbide slag employs powdered coke or crushed electrode as a reducing agent, while in the white silicon-type slag the medium for slag deoxidation is fine ferrosilicon (50 to 75% grade) or calcium-silicon. Both types are made up with lime as a base and fluorspar as a flux. Some silicon may be used as a flux in either type of slag. When white silicon-type slags are used, the silica content builds up as a result of oxidation of the silicon employed as a slag deoxidizer. The carbide slag is normally used for steels over 0.10% C, and the white silicon-type slag for steels of 0.10% C or lower. Other types of finishing slags are used for special purposes; for instance, the cement clinker slags for finishing stainless steels. During the finishing period of the heat, which will vary from 1½ to 2½ hr, alloying elements and recarburizers are added.

Additions of Ferro-Alloys and Recarburizers. On the basis of the chemical test taken before slagging off, the bulk of the ferro-alloys and recarburizers may be added to the bare bath immediately after slagging off and before the reducing slag is made up. This practice allows ample time for the ferro-alloys to melt and dissolve in the steel. Elements that may be added at this time are chromium, manganese, nickel and molybdenum. However, certain elements cannot be added until late in the heat. Vanadium, silicon, aluminum, titanium, and columbium, all readily oxidizable elements, are added late in the heat, usually 20 to 30 min before tapping. In the making of stainless steels, the large amount of ferrochromium required would chill the bath excessively, if added all at once. For this reason, ferrochromium is preheated and added in several batches when stainless grades are being made. The nonoxidizable elements—nickel, molybdenum and copper—may be added with the charge. Alloy scrap containing these elements can be charged, and such practice has considerable economic justification.

At slag-off the carbon content of the bath should be 4 to 10 points (0.04 to 0.10%) below the desired aim, depending on the probable increase to be expected from later ferro-alloy additions and pickup from the reducing slag and electrodes. In some baths, the carbon will be considerably lower and recarburization will be required. It is possible to recarburize after slag-off, since the bare metal quickly absorbs any carbonaceous material added to it. For this purpose, either coke, anthracite coal, or broken pieces of electrodes can be used. Recarburization can be accomplished by dipping the furnace electrodes into the bath, but this is an expensive and hazardous procedure. For adjustment of carbon late in the heat when only a few points are required, the addition of wash metal, low-phosphorus pig iron, or carbon briquettes is satisfactory.

Finishing the Heat. After the additions have been made at slag-off, and the finishing slag has been deoxidized and is strongly reducing, the slag must be maintained in this condition until the heat is tapped. Final preliminary tests are then taken, alloying elements are added to ad-

just the composition of the steel, and the temperature is adjusted according to the grade of steel being made. Deoxidizers are then added to finish the heat, including any that may be required for grain-size control.

At least one, and sometimes two samples are taken during the deoxidation period to determine the progress of the heat and to provide an accurate analysis of the bath, so that the melter can make proper final additions. Knowing the composition of the metal before slagging off, the melter makes his additions after slag-off accordingly, builds up the deoxidizing slag, and then takes out the final samples. The time from slag-off to the final preliminary test will be from 45 min to 1 hr. It is essential that the slag be completely deoxidized to insure that the bath will remain constant in composition throughout the rest of this period (except for the carbon, which increases slightly). The results of the final preliminary test are reported and the alloy additions necessary to meet the final specification are added to the bath. The additions of easily oxidizable alloying elements and of deoxidizers are also made late in the heat, or in some steels may be used as ladle additions.

Possibly some deoxidation of the metal bath is accomplished by the reducing slag; however, for complete deoxidation, silicon, aluminum or both must be added to the metal. Preliminary deoxidation may start as early as slag-off, but final deoxidizing additions cannot be made earlier than 20 to 40 min before tapping. Deoxidation consists in converting those oxides that are soluble in the steel (FeO and CO) into insoluble ones (such as SiO_2 and Al_2O_3), and in their separation from the metal by gravity. These insoluble oxides may be highly infusible, or certain combinations of insoluble oxides may readily flux one another to form fusible slags. For this reason the order and timing of deoxidizing additions is extremely important. In addition to aluminum and silicon, other deoxidizers, such as calcium silicide and aluminum-silicon alloys, may be used for final deoxidation. For grain-size control, definite amounts of aluminum must be added carefully late in the heat.

During the finishing period, temperature must be carefully controlled by regulating the power input from slag-off until the furnace is tapped. Temperature may be judged visually by the color and brightness of the molten metal when it is poured from a well-slagged spoon and viewed through dark glasses. Other indications of temperature level are shown when a spoonful of metal is poured slowly onto the floor. Various means of determining temperature include the set test, sighting the optical pyrometer on a spoonful of molten metal, the recently developed immersion-type platinum thermocouple and the immersion-tube photocell method.

Tapping and Pouring. The heat of steel, now of proper composition and temperature and properly deoxidized or "killed", is ready to tap into the ladle. This operation, as well as the final pouring, is performed with the greatest care. The ladle (of the bottom-pour type) has been properly dried and is now brought up to the furnace and placed under the spout. The furnace is slowly tilted into the tapping position, and the metal is allowed to flow in a steady stream into the ladle. The exact practice employed in tapping varies in different plants. Some operators tap through a runner-brick walled into the spout, thus holding back the slag until the tap is finished; others prefer to tap slag and metal together. During tapping, temperatures are often taken with the optical pyrometer for record, and for the guidance of the melter.

In pouring the ingots, the ladle is usually suspended directly from the ladle crane, which travels over the line of molds. The molds may be placed on ingot buggies adjacent to a pouring platform or may be placed in a pouring trench below ground level. The principal precautions in pouring are to regulate the pouring rate properly and the character of the stream, so as to pour with a minimum of splashing in the molds, thus insuring a good ingot surface. Soundness of ingots and freedom from shrinkage cavities are insured by proper mold design of the big-end-up type and by application of the so-called "hot top". The latter consists of a refractory form placed on top of the mold or partially inserted into it, and acts as a reservoir of molten metal, from which the ingot is continuously fed until completely solidified.

Variations in Practice. The flexibility of the electric furnace provides for many possible variations in practice. The most common variation in cold charge processes is the single-slag practice. Hot metal processes have been developed in an effort to lower the cost of intermediate grades of electric-furnace steel or to increase unit production during periods of peak demand for electric-furnace steel.

Single-Slag Practices. Single-slag practices are employed for two distinctly different methods of electric steelmaking. In the first method, conditions similar to those of open hearth practice are maintained. The heats are made as rapidly as possible under an oxidizing or black slag. By this method, rimmed, semikilled, and fully killed steel of a quality comparable with open hearth steel can be produced in the electric furnace.

The second method involves a practice of melting down and turning the slag with crushed silicon, coke, or exothermic silicon compounds, in sufficient quantity to form a reducing slag. This method is used generally for the maximum recovery of oxidizable elements—such as chromium, vanadium, and tungsten—that may be contained in the scrap charge. The practice is widely used in the making of high speed tool steels and other high-alloy grades.

Modified Two-Slag Process. Heats of stainless steel, in which considerable stainless scrap may be charged, are made by a modified two-slag practice. Stainless steels are usually made to ■ low-carbon specification; consequently, under the highly oxidizing conditions necessary during melting, large amounts of chromium are oxidized to the slag. In order to return this chromium from the slag to the bath, a considerable quantity of silicon or of silicon-containing alloys must be used as a slag deoxidizer. Coke cannot be used because the bath would pick up carbon. Thus, the slag is made quite acid and the slag volume is large. If sufficient lime is added to make the slag basic so that a satisfactory reducing slag can be obtained, slag volumes will be excessive. For this reason it is simpler to remove the first slag, after the chromium has been reduced from the slag to the steel, and to finish the heat under a second reducing slag. Finishing slags may be either of the white silicon type, cement clinker type, or various lime-alumina combinations that will avoid carbon pickup and gasiness.

Variations in oxidizing practice may be utilized in making alloy steels of the various carbon grades. The heat can be melted under conditions of complete or partial oxidation. A complete or partial slag-off of the oxidizing slag early in the heat, followed by a second oxidizing slag and a final reducing slag, is not an uncommon practice when excessive phosphorus, chromium or manganese must be removed from the metal.

In some practices, two finishing slags are employed in making the electric-furnace heat. The first is the conventional reducing slag which removes oxygen and sulfur from the metal; the second finishing slag is used merely as a cover to protect the surface of the bath from oxidation while adding a high-melting-point oxidizable alloy late in the finishing period of the heat. A typical practice employing such a protective slag is that used in making stainless steels with additions of titanium or columbium.

Hot Metal Processes. Interest in hot metal processes, in which the raw materials for electric-furnace steel are delivered to the electric furnace in premelted form, was heightened by the tremendous need for electric-furnace capacity during World War II. Various hot metal processes have been considered and tried on a large scale. If iron ore is used as the basic raw material, then the suitable premelting unit is the blast furnace; if steel scrap is used as a raw material, then the cupola or open hearth furnace is chosen as a premelting unit. In either the blast furnace or the cupola, it is desirable to refine the premelted metallics further before finishing in the electric furnace. This refining is done in the Bessemer converter, in the open hearth furnace, even in the electric furnace, or in various combinations of these steelmaking units. The open hearth combines the melting and refining functions if it is used as a premelting unit. The various combinations that have been used are listed here:

1 Blast furnace—open hearth—electric furnace process.
2 Blast furnace—Bessemer—electric furnace process.
3 Blast furnace—Bessemer—open hearth—electric furnace (triplex) process.
4 Cupola—Bessemer—electric furnace process.
5 Cupola—electric furnace process.
6 Open hearth—electric furnace process.

Various slag combinations are used in the electric furnace in conjunction with hot metal practice, depending on the degree of refining required. In the most simple practice, the hot metal is transferred to the electric furnace and finished under a reducing slag. Usually, however, an oxidizing slag is made up so the metal can be brought to the proper temperature, the oxidizing slag removed, and the heat finished under a reducing slag. If considerable refining must be done in the electric furnace, then the time under the oxidizing slag must be increased proportionately. For instance, in the cupola–electric furnace process, the electric-furnace bottom is first bedded down with hematite ore before the hot cupola metal is added. Considerable boiling is required to oxidize the silicon and carbon from the hot metal, and large additions of burned lime are required to keep the slag basic.

In practice, two main problems are encountered in hot metal processes: (1) to co-ordinate all units by size, rate of production, and tapping time so that down-time and delays are held to a minimum; (2) to avoid excessive yield and transfer losses, by proper selection of melting and refining processes. Proper co-ordination cannot be obtained in a small shop, so by necessity a hot metal electric-furnace process requires a large, fully integrated shop, especially planned and engineered for this purpose. Furthermore the type of product must be of such a nature that finishing times in the electric furnace are nearly equal and can be predicted well in advance of the tapping of other units.

Tool Steel Practice. The practices used in the melting of tool steels are quite varied, depending on the grade; in general, however, they are covered in the preceding sections. The melting of high-quality carbon and low-alloy tool steels, in which the recovery of alloying elements is a minor consideration, is usually conducted by the normal two-slag practice. For high-alloy steels in which large amounts of tungsten, vanadium, and chromium (oxidizable elements) must be recovered from the scrap to make operation economical, single-slag practice is employed. This single-slag practice, though capable of removing some impurities from the charge, places a heavy responsibility on the selection of high-grade scrap; since phosphorus may be readily reverted to the metal from the oxidized slag, along with chromium, tungsten and vanadium, when the slag is made reducing with silicon, coke or exothermic silicon compounds. This practice is employed widely in the making of tungsten tool steels, in which the tungsten exceeds 3 to 4%; such steels include the tungsten hot work steels and high speed steels. Methods of refining, deoxidation, temperature control and pouring practice do not differ greatly from those described previously, with the possible exception that deoxidizers used in the tool steel industry may include those elements, such as titanium, zirconium, and calcium, which have an especially strong affinity for oxygen. These are used in conjunction with preliminary silicon deoxidation and may or may not be accompanied by aluminum.

The Acid Electric-Arc Process of Steel Melting

By John W. Juppenlatz*

IN the acid electric practice, the term "acid" refers to the silica-base refractory lining used to withstand the silica-base slags common to the process.

In the United States the acid electric furnace is now one of the major sources of molten steel for castings. Over two million tons of acid electric steel was poured into steel castings during 1943. An abundant supply of low-phosphorus, low-sulfur steel scrap for remelting has contributed largely to the popularity of the acid electric process. In addition, the process is particularly suited to the production of high-grade carbon and alloy steel castings. Some of the reasons why steel foundrymen prefer this process may be briefly stated as follows:

1 Rapid production of carbon and alloy steels for castings.
2 Favorable power and refractory costs when compared with other processes.
3 Very high temperatures obtainable for fluidity.
4 A viscous slag that is readily controlled when the metal is poured from top-pour ladles.

The methods for producing acid electric steel have not become standardized, so it is impossible in this review to cover the minor variations of practice. Only the major principles and practices will be outlined.

General Melting Procedure. The procedure for making a heat of steel consists briefly of placing on the bottom of the furnace a known weight of steel scrap of suitable composition, referred to as the "charge". Power is introduced through the electrodes. An electric arc is produced between electrode and charge, and melting begins. The metal is usually melted as rapidly as possible, while a molten pool forms and grows on the bottom of the furnace. The "melting-down period" is accompanied by oxidation of the bath, resulting in partial elimination of carbon, manganese and silicon. As the molten pool of metal forms, the products of oxidation combine into a complex silica-base slag. Since it is lighter than the steel, this slag rises and covers the metal bath. Oxidation may be increased by the addition of iron ore or mill scale. As the temperature increases under oxidizing conditions, a boiling action starts. This indicates the removal of carbon from the bath by oxidation with the evolution of carbon monoxide gas. As the temperature increases toward the end of the oxidizing period, the boiling action will slow down because the oxidizing power of the bath and slag has been substantially decreased. The input of power to the furnace is usually reduced at this time, since the metal is quite hot, and the "refining and deoxidation" period begins. Preliminary tests are conducted to ascertain conditions of bath and slag, and the composition is adjusted by additions in order to meet requirements. Temperature tests are taken and the heat is ready to be deoxidized with the final addition of ferro-alloys, such as ferromanganese and ferrosilicon. Steel for casting purposes must be thoroughly deoxidized or "killed", so that gas pockets do not form during solidification. When a thoroughly killed heat of steel is assured, with the proper temperature and composition, the molten bath is then tapped by tilting the entire furnace and pouring the metal into suitable ladles. A further deoxidizing treatment consists of adding about 2 lb Al per ton of steel, in the ladle. While tapping, it is desirable to trap the slag in the furnace until most of the metal has drained into the ladle. The slag then drains from the furnace and covers the metal protectively.

Now that the practice has been briefly outlined, the various phases will be discussed in greater detail.

Furnace. Modern acid electric furnaces are of strong construction with mechanical features for charging. The steel shell is usually circular and lined with silica brick or siliceous material of "acid" type with a saucer-shaped bottom and removable silica brick roof. (See Fig. 1 for diagrammatic sketch.) In the roof three openings are provided for the electrodes. Heavily powered for rapid melting, the electrodes produce an arc when contact is made with the scrap charge. Many furnaces are provided

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Prepared for the Subcommittee on Melting.

with mechanized removable roofs that permit mechanical charging.

Water cooling is often desirable for refractories and furnace parts subject to severe temperatures and operations. Figure 1 shows water coolers around every electrode, the roof ring, the door arch and the door. These features vary with the design and the rated capacity of the furnace.

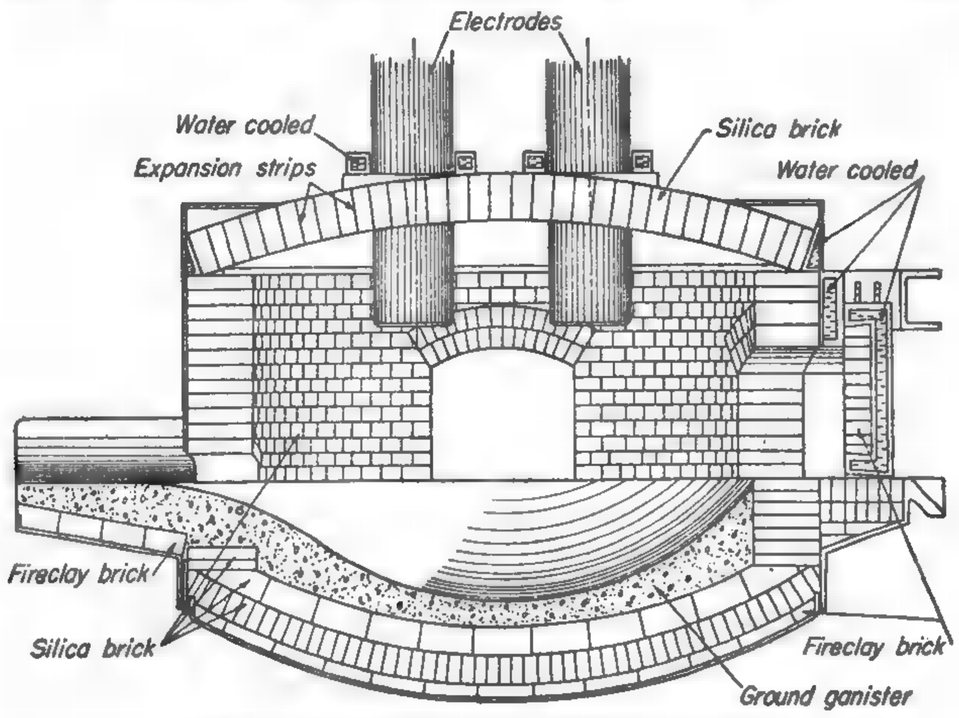

Fig. 1 Acid electric-arc melting furnace

Furnace capacities vary from about 500 lb to 30,000 lb of charged weight. The majority of furnaces are capable of melting from 3 to 5 tons of charged material. The time of making a heat will vary according to the input of power and the grade of metal being produced. The average time for a 4-ton heat of carbon steel is usually less than 2 hr, increasing with increase in furnace capacity. Because of variation in the size of furnace, power input, plant facilities and plant requirements, furnace operation is not uniform and must be compensated for accordingly.

Lining. Silica bricks, which are "acid" refractories, are commonly used for construction of sidewall and roof with very satisfactory results and low cost for continuous operation. Intermittent operating schedules often cause considerable deterioration of the lining—chiefly spalling as a result of the heating and cooling cycles. To compensate for thermal expansion and contraction with physical changes of the silica refractories, ample allowance for expansion—about ¼ in. per ft—is commonly needed when silica bricks are laid in roofs and side walls. Rammed siliceous linings and even rammed roofs on small units are used with good results. Mullite, sillimanite and other "super-refractories" may be used around electrode openings in the roof and in other locations where spalling conditions are unduly severe.

A new bottom is usually made from a ganister or silica sand mixture that is firmly rammed on a base lining of silica brick, as shown by Fig. 1. These materials of the proper grain size are mixed with small amounts of refractory clay, possibly some organic binder, and sufficient water so that the green and dry strengths are adequate for retaining the proper shape of the bottom and for bearing the burden of the charge. To aid in the preservation of a newly prepared bottom before surface sintering has been effected, steel plates are often placed over the bottom so that the impact of the charge will not impair its rammed form.

It is always good practice to dry free moisture from the lining before attempting to produce a heat of steel. The top surface of the rammed bottom is sintered by the heat from the electrodes as the scrap is melted. Acid slag from a previous heat is usually added to form a slag that has better chemical balance for aiding in the sintering operation. This method of making a new bottom is being successfully practiced but must be performed with skill and care.

Completely sintered bottoms are made by building up successive layers on the base made of silica brick. Heat is obtained from the electrodes which arc on triangularly placed pieces of other electrodes on the bottom. Thin layers of ganister or a fine grade of silica sand are placed on the bottom bricks and sintered by heat radiated from the arc. This operation is repeated until the bottom and side walls above the slag line are properly shaped and uniformly sintered.

Lining and bottom repairs are often required between heats, particularly around the slag line. Such repairs are made by placing ganister or silica sand in a slightly moistened condition, in proper position to maintain the desired shape of the banks. Often some admixtures are added to the patching material to promote a low-temperature frit so as to prevent sliding of the patch.

The taphole shown in Fig. 1 is quite large. Some operators prefer a smaller hole, which aids in the retention of slag in the furnace while the metal is being tapped. This is accomplished by lining the taphole with silica brick or tile to the desired size. However, the hole should be large enough to permit full drainage of both metal and slag.

Electrical Equipment. The power per square foot of bath area and per ton of capacity of the acid furnace is usually somewhat higher than that of the basic furnace of equal capacity. The kilovolt-ampere capacity per square foot of bath area is often as high as 100, which contributes toward the speed of melting considered essential in the industry.

Many of the more modern installations are powered with overcapacity air-cooled or water-cooled transformers. Tap changes provide the operator a choice of several voltages, varying from about 90 to 250. Current conductors, bus bars, and other electrical fixtures are also extra heavy, to avoid the necessity for water-cooling these parts. Designers have given considerable attention to the transformer and electrical parts, in an effort to minimize resistance, reactance and hysteresis losses.

Electrodes may be either graphite or amorphous carbon. For the smaller furnaces, graphite seems to be preferred because of its increased strength and the smaller electrode opening required in the roof. Electrode controls, drives and the features of mechanical alignment should be properly constructed and maintained for maximum efficiency. The smooth operation of the furnace depends on sensitive, quick-acting regulators for positioning and maintaining the correct arc length. Electrode clamps should provide a positive electrical contact. The joints of electrode assemblies should be close-fitting and snug for best operation.

When the proper electrical and mechanical equipment is used, coupled with good operation, maximum efficiency and speed may be expected. Energy consumptions of 500 kwhr per ton are not uncommon with continuous operation and high tapping temperatures. Electrical capacities capable of overload are desirable, as mentioned; however, there are optimum values of current (arc) input. Excessive input of power can actually result in slower melting, with increased maintenance costs of electrode clamps, bus bars, and refractories. These conditions are controllable by the operator.

Charging. Phosphorus and sulfur contents are not reduced by the acid process. Therefore it is necessary to select scrap with these elements below the maximum specified for the final composition. Copper, nickel and molybdenum as constituents of the charge are recovered.

The scrap for the charge should be free from excessive rust or oil. Fine scrap and turnings, if not long and curly, are desirable for a small percentage of the charge. Larger and more bulky scrap—foundry scrap, plate, forgings, and the like—usually constitutes the remainder of the charge. Unwieldy, protruding shapes that cause bridging are not desirable and should be avoided. If compact scrap is available, the entire charge can be made at one time; if not, it will be necessary to charge additional scrap during the melting of the heat.

Most modern furnaces are mechanically charged by removing the roof and placing the charge on the bottom with a drop-bottom bucket. By this method of charging from the top, the entire charge is quickly put in with a minimum of labor.

Scrap should be placed in the charging bucket or furnace in such a way that melting can proceed without interruption. Heavy scrap that would cause delays or breaking of electrodes, should therefore be placed on the bottom with lighter scrap on the top.

Consideration should be given to the carbon and manganese contents of the over-all charge. Some scrap may be deficient in these elements for normal slag requirements and for the carbon boil. It is also true that reverse conditions result in an excessive volume of slag or a prolonged period of boiling. Proper balance of these elements aids greatly in the efficient processing of a heat.

Melting and Oxidation. When the charge has been placed properly on the bottom of the furnace, the electrodes are mechanically lowered until more than one electrode has made contact to produce an electric arc, and melting begins. Melting is usually started with an intermediate voltage (about 175) until the electrodes have worked into the scrap. Melting is then continued at higher voltages (about 235), producing long flaring arcs that cause melting over a greater area, thereby forming a larger pool of molten metal beneath the electrodes. The electrodes arc on this molten pool and the melting process continues from the bottom upward. When the bulk of the charge has melted, a lower voltage (about 140) is employed with a shorter arc that does not excessively attack the refractory lining. When molten metal is formed, a complex metal oxide slag, lighter than steel, rises and covers the bath. Oxidizing, slag-forming materials, such as iron ore and lime, are often intentionally added to promote reactions, so that the slag and its volume become significant factors in the process.

In the absence of a uniform or standardized melting procedure, oxidation may be partial or complete. Partial oxidation requires the addition of limited quantities of oxdizing materials, such as iron ore or mill scale. This practice results in rapid production with low refractory, power and electrode consumption. Partial oxidation has the disadvantage of producing a somewhat inferior metal that often has lower ductility, lower fluidity and a higher gas content.

The complete oxidation method, more widely employed, requires the judicious use of ample quantities of iron ore or mill scale. The final product from this practice has the advantage of good fluidity, good mechanical properties and low gas content. The time required for making such a heat is somewhat greater, and refractory and other production costs are higher. The iron oxide content of the bath will be high and the slag will be fluid and very black in color. Composition of a typical oxidizing slag would be 42% SiO_2, 40% FeO, 12%MnO and 6% CaO. If lime is not used, the iron and manganese oxides will be proportionately higher. Limestone is occasionally used for the purpose of fluxing and increasing the total basic oxides of the slag. A large portion of the silica of the slag is obtained from the silica lining as a result of the fluxing action of the basic or oxidizing materials.

According to best practice, oxidation of the melt is highly desirable for quality steels. This process is based on the following fundamental reactions:

$$Mn + FeO \rightarrow MnO + Fe \quad (1)$$
$$Si + 2FeO \rightarrow SiO_2 + 2Fe \quad (2)$$

With sufficient ore present to produce free FeO in the bath and the slag, reactions (1) and (2) proceed after melting, and are independent of heat input, since the reactions are exothermic. This oxidation should continue until the silicon is well below 0.10% and manganese below 0.15%. As the temperature of the bath increases and free FeO is available, the carbon boil will start.

$$C + FeO \rightarrow CO + Fe \quad (3)$$

Since the carbon boil, reaction (3), is endothermic, considerable heat input is required for an active boil and the reduction of the carbon content of the bath to the desired level. With continued heat input, this carbon boil will continue until the FeO content is reduced to a point where little or no available FeO in bath or slag is free for reaction.

Some operators prefer to add the amount of iron ore required for oxidation and permit the carbon boil to continue until it slows down as the bath becomes deficient in oxidizing power. This practice may result in the carbon content of the bath dropping to lower levels than desired, so that recarburization becomes necessary. Some operators prefer to check or stop the carbon boil by adding ferrosilicon or other deoxidizers when the carbon content of the bath has reached the desired level.

Refining and Deoxidation. When the carbon boil subsides or is checked, the refining period begins, the purposes of which are composition adjustment and the "shaping up" for final deoxidation. At this time the temperature of the metal is usually above 3000 F, and the power input is reduced. Preliminary tests are made in order to determine the composition of the bath and the amount of oxidizing power remaining, which is often indicated by the slag. Before final deoxidation, the slag will have a lower iron oxide content, approximately 18%, with a silica content above 50%, and will be fairly viscous and green in color. Recarburization of the bath is ordinarily required, and is effected by using low-silicon pig iron, by dipping the electrodes, or by adding carbonaceous materials. Pig iron is preferred, reducing any excessive oxidation, according to reaction (3), and thus permitting the bath and slag to approach equilibrium. Adjustments of the slag are often necessary also, and additions to the slag for this purpose vary considerably, depending on the degree of deoxidation; such additions consist of silica sand, limestone, powdered ferrosilicon or ferromanganese, coke and the like. When the bath and slag have been adjusted and the desired temperature has been reached, ferro-alloy additions, such as chromium and vanadium, are made prior to the final deoxidation, which will be discussed later.

When the iron oxide content of the bath and slag has been drastically reduced as a result of high temperatures and heavy power input, silicon and manganese can be reduced from the slag by the following reactions:

$$SiO_2 + 2C \rightarrow Si + 2CO \quad (4)$$
$$MnO + C \rightarrow Mn + CO \quad (5)$$
$$2Mn + SiO_2 \rightarrow Si + 2MnO \quad (6)$$

Reactions (4), (5) and (6) take place easily in the acid electric furnace because of the high temperatures commonly obtained. When bath temperatures exceed 3000 F, these reducing reactions are more difficult to prevent as time goes on, since the free oxygen content of both the bath and the slag decreases continuously at high temperatures. These reactions can be retarded by the judicious use of basic materials, such as ore and lime, but as the temperature increases, the reactions continue in rapid cycle.

The normal deoxidation procedure at the end of the refining period is usually accomplished by adding ferrosilicon and ferromanganese, or other deoxidizers, to the furnace. When steel is to be made into castings thorough deoxidation is essential, since the metal must solidify without the formation of gas inclusions. For this reason it is common practice to make "solidity" tests at the furnace to determine whether the metal has been properly "killed".

Temperature tests are then made, and with the previous adjustments assuring the proper composition and adequate deoxidation, the heat is ready to be tapped. Further and final deoxidation in the ladle is commonly conducted with additions of aluminum ranging from 2 to 3 lb per ton. Other deoxidizers, such as calcium and titanium alloys, may also be used. Final deoxidation in the ladle should always be performed with care to avoid reaction with the slag rather than with the metal. For this reason tap holes are usually constructed to permit the steel to enter the ladle before the slag when the furnace is quickly tilted. The metal is then ready to be cast into molds.

Slag Control. The control of slag during the various stages of the heat is effective in assuring consistent results.[1] Fluidity of the slag appears to be the most practical measure of the degree of oxidation during all stages of the process.[2] A modified Herty viscosimeter for the quantitative measure of fluidity has been successfully applied to many production furnaces.[3] A very fluid slag, common at the melt-down period and before the boil, may show a viscosity of 11 in. with a silica content of about 40% and an iron oxide content of about 41%. This may be considered an active oxidizing slag.

As the carbon boil continues, the fluidity decreases and

the acidity of the slag increases. A viscosimeter reading of about 4½ in. indicates a slag containing about 50% each of acids and bases. There is very little oxidizing or reducing power in such a slag from an operational viewpoint.

As the temperature increases and the metal is ready for final deoxidizing additions, the fluidity is further reduced. Slag viscosity readings of about 2 in. indicate a silica content of about 56%; the remainder is the basic constituents FeO, MnO and CaO.

Recovery of Alloying Elements. The recovery of alloying elements usually increases with increasing carbon content. A variable recovery is anticipated on account of the different degrees of initial oxidation and deoxidation normally occurring under actual operating conditions. With a complete oxidation process and a charge of 50% alloy-bearing scrap of the same type, average values for the recovery of manganese, silicon, and chromium at different carbon levels may be expected as shown below.

Carbon Content	% Recovery of Final Alloying Additions				
	Manganese		Silicon	Chromium	
	0.60%	1.35%	0.40%	0.50%	1.50%
0.15	72	65	87	90	88
0.30	75	70	98	92	90
0.45	80	74	110	93	92

Temperature Control. Many methods are used to indicate temperature and fluidity. Immersion pyrometers may be used but they are too costly for general control work. Optical pyrometers are reasonably satisfactory for control purposes when sighted on molten metal without interference of oxide film or smoke.

The spoon or set test is commonly used for estimating the temperature at the furnace. Test spoons are immersed in the molten bath and a representative sample is withdrawn. After the slag has been removed the sample is poured into a mold of standard size. A record is kept of the time in seconds required for the oxide film to cover the test sample completely and this information, correlated with other temperature readings, indicates the temperature. The immersion of low-carbon steel rods in the bath for a given period of time is also used to indicate temperature. As the metal temperature increases, an increasing amount of steel rod dissolves.

Fluidity is probably the best method of indicating temperature and is significantly important to the foundryman. This test requires that about 8 lb of metal be withdrawn from the furnace and cast into a standard mold for the fluidity test. The mold, developed at the Bureau of Standards, is of the spiral type and indicates the casting fluidity in inches. Further details of testing the fluidity of metals are covered in the article on page 199 of this Handbook.

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The Induction Furnace Process of Steel Melting

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THE coreless induction furnace, commonly known as the high-frequency furnace, was invented in 1916 by the late Edwin F. Northrup. Until about 1925, the furnace was confined to small sizes, used mostly in laboratories and for melting precious metal, for melting in small-scale production and for miscellaneous heat treatment of metals. However, in 1925 commercially large and efficient generators became available for production-size units, and in 1926 the first production steel-melting furnace was installed, utilizing 150 kw of 2000-c power. Since that time the use of these furnaces has increased rapidly.

Most of the furnaces installed by the steel industry have been used for melting tool steel, stainless steel and various special alloys. These installations have been supplied with power principally by 960 or 1000-c single-phase generators. Heating installations utilizing up to 7000 kw in a single plant, and melting furnaces ranging to ten tons in melting capacity have been built. To date (1946), some 250,000 kw of high-frequency melting furnace capacity has been installed throughout the world.

Application. Though the coreless induction principle of heating is being applied successfully to various fields, such as melting of both ferrous and nonferrous alloys, heating for hot forming, heating for surface hardening, and brazing, the present article is concerned primarily with the application of the induction heating principle to steel melting. In this field the high-frequency furnace is used both in the making of ingots and in the steel foundry. In ingot practice this furnace is well adapted to the melting of special tool steels such as high speed, and the high-grade nickel-chromium alloys used for electric-resistance and high-temperature applications. Because of the absence of carbon pickup and low melting losses, this furnace provides a good tool for the production of low-carbon stainless steel, since it makes possible the use of a high percentage of stainless steel scrap in the charge.

In the foundry the high-frequency furnace is valuable because of its flexibility in operation, particularly in the production of small alloy castings. Virtually all the magnet steels of the aluminum-nickel-iron type are made in the coreless induction furnace. Although it is not the only melting method adapted to centrifugal casting, it lends itself well to this practice, and it is interesting to note that probably all the centrifugally cast guns for World War II were made from steel melted by this method.

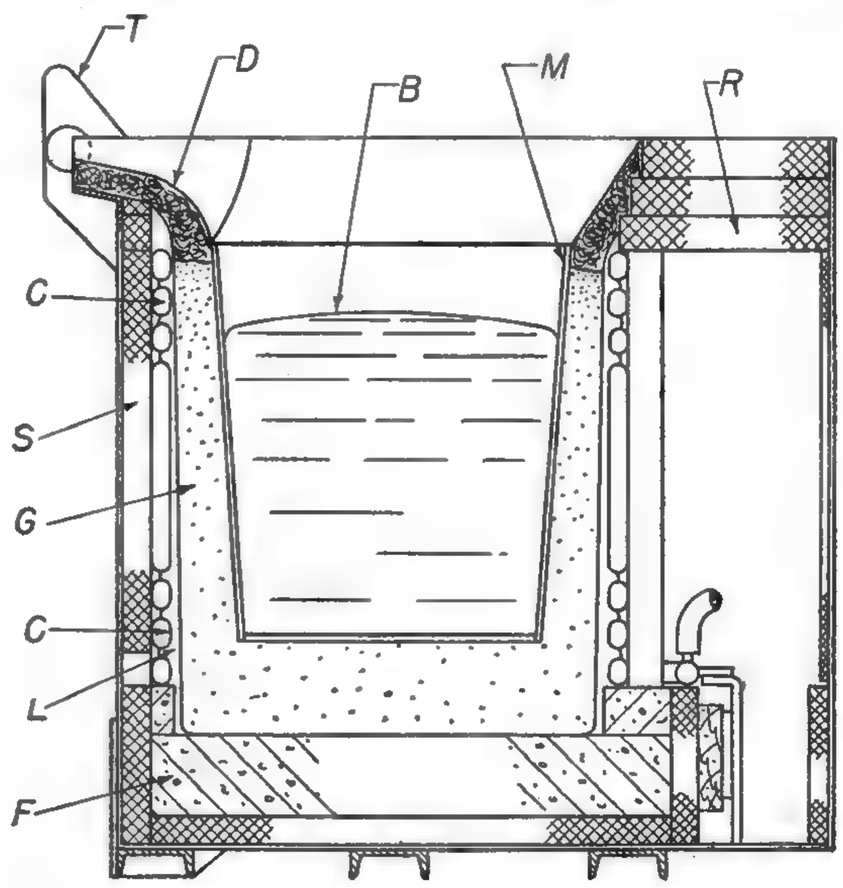

Fig. 1 Cross section drawing of induction furnace,
B metal bath
C water-cooled copper coil
D pouring spout
F firebrick base
G refractory packing
L protective coil liner
M crucible or liner
R asbestos lumber
S asbestos lumber
T trunnions

Construction of the Furnace. The coreless induction furnace is really an air-cored transformer, having the furnace coil as primary and the melt, or other conducting body to be heated, as secondary.

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The primary is a helical coil of copper tubing, insulated between turns, through which water is passed for cooling the copper. When high-frequency current is applied to the terminals of the helix, all the space inside the coil is subjected to a rapidly alternating electromagnetic field. Any electrical conductor inside the coil (in practice, the furnace charge) has currents induced in it, causing rapid and efficient heating. The essential parts of a commercial furnace are shown in Fig. 1, which represents a longitudinal center section. The outer shell *S* is made of asbestos lumber and carries the trunnions *T* on which the furnace pivots in tapping or pouring. The coil *C*, consisting of a helix of water-cooled copper tubing, is lined with a thin layer *L*, of refractory material—usually an air-setting cement, such as sillimanite, that acts to keep the dry refractory from leaking out between the turns and to protect the coil in the event of a metal leak. Some prefer to omit this thin lining and use asbestos cloth against the coil. This layer is continued above and below the coil against the asbestos support *R*, and the firebrick base *F*. The coil lining and the firebrick bottom provide a cavity into which the refractory lining of the furnace is built. This lining may take the form of a thin-wall crucible or supporting shell *M*, packed into the cavity with grain refractory *G*, or it may be in the form of a sintered lining. This lining holds the charge or bath of metal *B*, and is grooved out at the top on one side to form the pouring spout *D*.

Furnace Refractories. Small furnaces, usually up to 500 lb in capacity, are lined with preformed crucibles, either acid or basic, as required. After the coil has been protected with either the sillimanite cement or asbestos cloth, dry granular refractory, acid or basic, is poured into the bottom of the furnace and tamped to eliminate voids, to a level about even with the bottom of the coil. The prefired crucible is then placed in the furnace, centered, and the granular backing material is hard rammed into place. About 1 in. or so from the top of the crucible, the lining is finished off with an air-setting cement.

In the larger furnaces, the crucible is formed in the furnace. A thin composition-asbestos liner is commonly used as a form and the granular refractory material is rammed between it and the coil as before. During the first heating, the liner slags off and helps sinter the granular material, thus forming a crucible for the molten metal.

For acid linings in small furnaces, the crucibles are preformed of silica with a binder, and the backing between the crucible and coil is a high-grade silica sand. In large furnaces, the acid lining is formed around the composition asbestos liner and consists of 98% pure SiO_2 or ganister. Where a binder is used, this may be either silicate of soda or clay.

For basic linings in small furnaces, the crucible is preformed of electrically fused MgO and backed with electrically fused MgO of assorted grain size. For basic linings in large furnaces, where the crucible is formed in the furnace, a very popular mixture is 60% electrically fused magnesia and 40% electrically fused alumina.

The life of either basic or acid linings varies greatly. In general, acid linings have a shorter life and require more patching but are less costly.

Principle of Operation. In the operation of the furnace, high-frequency current is passed through the primary coil or helix *C* (Fig. 1), inducing a much heavier secondary current in the charge and thus heating it by resistance to the desired temperature. The charge may consist either of a single lump of metal or a quantity of loose pieces such as ordinary steel scrap. Even comparatively fine turnings can be melted successfully if a sufficient amount of heavier scrap is used to provide some conductivity through the charge. The current in the charge circulates in a path about its periphery in a direction parallel to and opposite to that of the coil. The higher the resistivity of the charge and the lower the frequency of the current applied, the greater will be the radial thickness of the current path. Though high-frequency heating is effective over a wide range, the most practical frequency in production steel melting is about 1000 cycles per second.

The heat is developed in the outer part of the charge and is quickly carried to the center by conduction, which is rapid through solid metals. After the charge has started to melt and a pool has formed in the bottom of the furnace, a stirring motion occurs. This not only carries heat to the center of the charge by convection, but accelerates melting by washing molten metal against solid metal. It also mixes thoroughly the elements in the charge, thus assuring uniformity. The vigor of the stirring can be controlled by varying the power input or location of the charge in relation to the coil.

Since the amount of heat generated in the charge is directly proportional to the power input, it follows that the speed of melting depends on the power input per ton of charge. Using an average scrap charge, a 350-kw generator is capable of producing 1000 lb of finished steel per hour. A 1000-lb furnace using 350-kw power will thus tap a heat every hour, while a 2000-lb furnace will tap about every two hours. On the other hand a 2000-lb furnace using 700-kw power will tap in about one hour. The choice of furnace size in relation to power input is governed by specific operating conditions in each individual plant.

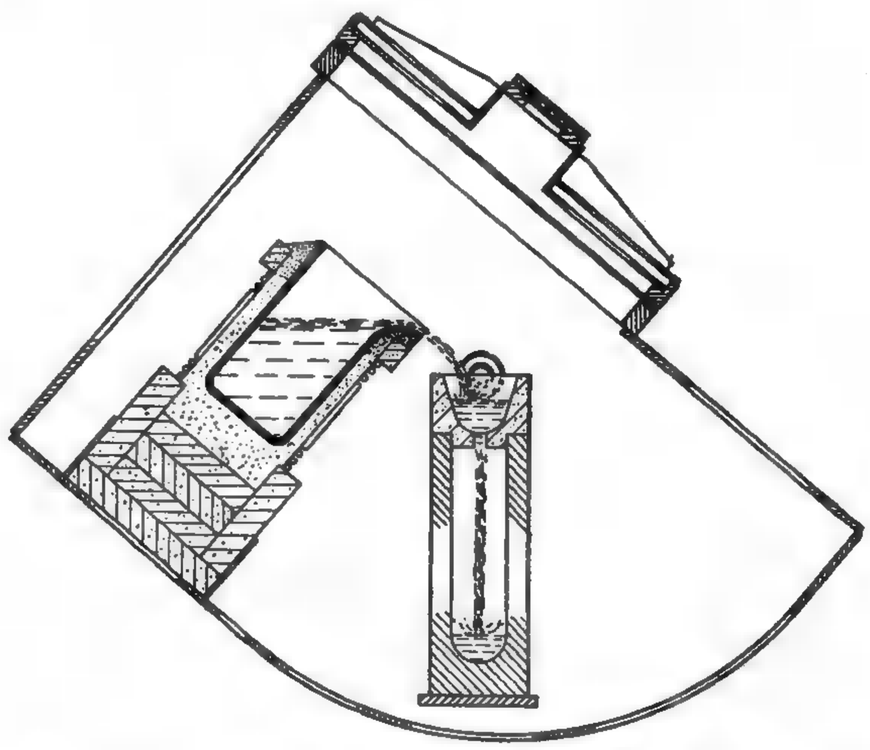

Fig. 2 Arrangement for melting and pouring in a vacuum or under pressure

Melting Procedure. In most steel plants using induction furnaces, the melting procedure is essentially a crucible process. Since the heat is generated entirely in the charge itself, melting is rapid and there is only a slight loss of the oxidizable elements. Furthermore, on account of rapidity of operation, preliminary bath analyses are seldom made. Consequently, the charge is usually made of carefully selected scrap and alloys which together will produce the composition desired in the finished steel without further additions, except possibly small amounts of ferromanganese, ferrosilicon or other final deoxidizers.

The heavy scrap is charged first and as much of the charge as possible is packed into the crucible. The current is turned on and, as a pool of molten metal forms on the bottom, the charge sinks and additional scrap is then introduced progressively until the entire charge has been added. In a 1000-lb furnace with an input of 350 kw, the charge will melt down in 45 min to 1 hr, depending on the character of the scrap. The additional time required to finish the heat depends on the amount of superheating and refining necessary.

Ordinarily no attempt is made in induction furnaces to melt under a slag cover, since it is difficult to keep a slag blanket on the metal because of the convexity of the bath, resulting from the stirring action. Fortunately, oxidation from the atmosphere is so slight that a slag is not considered necessary for protection alone. However, slags are being used successfully both during the melting-down operation and for refining. The degree of convexity of the bath is governed largely by the rate of power input to the melt and by the relative position of the charge with respect to the coil. A slag blanket on a one-ton furnace powered with 350 kw will be easier to maintain than on a one-half ton furnace with the same power input. The character and

effectiveness of such slags are, of course, governed by whether the furnace is acid lined or basic lined.

While it is common practice to operate the furnace with the top open, some melters prefer to cover the furnace with a refractory cap or roof as soon as the bath is melted down. This is said to reduce heat losses and to assist in controlling temperature and slag reactions.

As soon as the charge has been melted clear and refining has been completed, any further necessary additions of alloys or deoxidizers are made and the bath is superheated to the proper pouring temperature. The current is then turned off and the furnace is tilted to pour the metal over the lip, directly into the mold, into a funnel or pouring box placed over the mold, or into a ladle from which it is later poured into molds. In foundries making small castings it is sometimes the practice to pour into shank ladles. As soon as the heat has been poured, the furnace is scraped clean of adhering slag and immediately recharged for the next heat.

A variation of the usual melting procedure, adapted to the melting of certain special alloys, consists in melting either in a vacuum, or under pressure in the presence of inert gases. In these processes the entire furnace and mold are encased in an airtight container, which can be evacuated or put under pressure at will. Figure 2 shows a section of such an arrangement with the furnace in the pouring position.

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Ingot and Pouring Practice

BY THE SUBCOMMITTEE ON MELTING

AFTER the furnace operations are complete, the next step in producing a heat of steel is to make a solid homogeneous casting. In foundry practice the casting will be of approximately finished size and shape; in ingot practice the casting will take the form of a chilled ingot to be rolled or forged into the final form. Regardless of the steelmaking process used, the procedure after the metal leaves the furnace consists of two distinct steps: (1) tapping the heat into a container called a *ladle*, and (2), pouring from the ladle into molds that have the size and shape of the ingot desired.*

* There are two possible exceptions, namely, in the crucible process, where it was sometimes customary to pour directly from the pot into the mold, by what is known as "single practice"; and in the high-frequency induction furnace, where it is sometimes the practice to pour from the furnace directly into the mold.

Ladle Practice. The function of the ladle is to serve as a container or reservoir for the molten steel after it leaves the furnace. From the ladle the molten steel is poured into the mold. Since steel practices and furnace capacities differ greatly, the character and size of ladles differ also to fit various operating conditions. Steel ladles vary in size from approximately 100 lb, typified by the small hand-shank ladles used in foundries, to 100 tons or more, employed in large open hearth plants. In type, they fall into two general classes: *lip-pour,* and *bottom-pour*.

Lip-Pour Ladle. This ladle, used in steel foundries and in some Bessemer plants, is constructed so that the metal is poured over the lip by tilting the ladle. It usually consists of a bucket-shaped shell of steel plate having trunnions on the sides for engagement with a crane bail. Small hand-shank lip-pour ladles are simply steel pots carried in suitable shank handles and must usually be tilted for pouring. The shell may be lined with a layer of special refractory firebrick, or a mortar of ganister and clay or other siliceous ramming mixture, or sometimes a magnesia-type base material.

In practice when the metal is tapped from the furnace, the slag is allowed to run on top to act as a cover. While pouring molten metal into molds, the ladle is tilted on the trunnions, usually by means of a worm and gear, and the metal runs over the lip, but the slag is held back. A modification of the lip-pour ladle is the so-called "teapot ladle", in which an independent spout or tube is built down through the lining so as to connect at the bottom. This allows lip-pouring in such a way as to draw the metal from the bottom of the ladle, thus avoiding contamination by the slag. This type of ladle is particularly adapted to high-manganese steel, which is notably corrosive on stoppers and nozzles, and in this instance is often used for transferring the metal to smaller shank ladles.

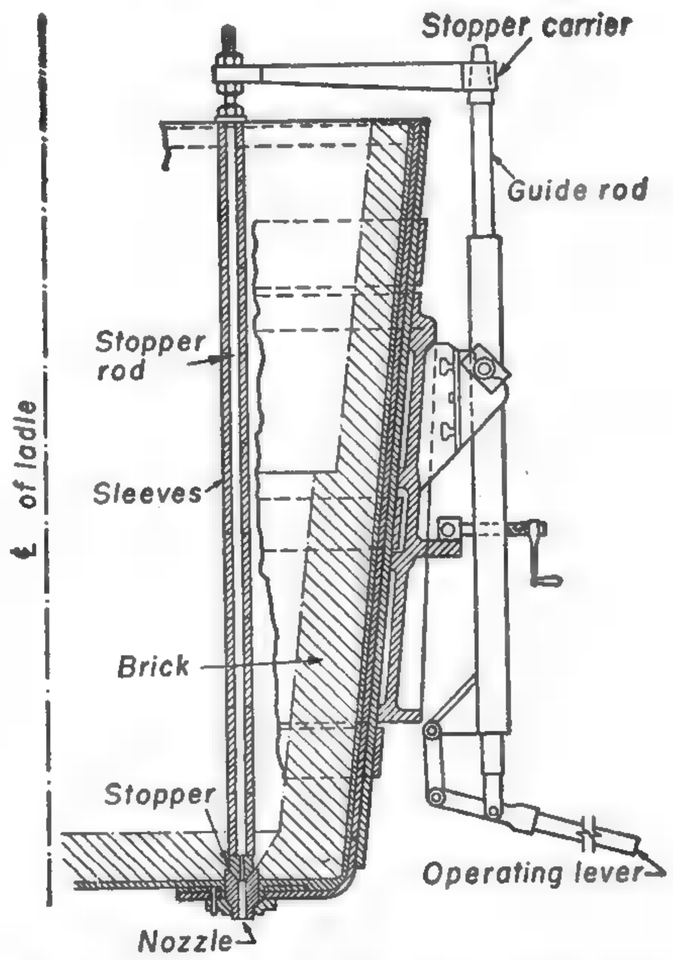

Fig. 1 Section of a bottom-pour ladle (Boylston)

Bottom-Pour Ladle. This has a steel shell of much the same shape as the lip-pour ladle. It has trunnions for either hanging on a crane by means of a bail or holding in a carriage or a buggy. Bottom-pour ladles are usually lined with brick, sometimes with an additional plaster of fire clay over the surface. In foundries, monolithic rammed linings are often made for the smaller ladles. Near the rim at the bottom, the shell has a hole in which is inserted a refractory *nozzle* made of clay, graphite-clay or magnesia. Into this nozzle fits a *stopper head* or *plug* made of a graphite-clay mixture. This stopper head is held on a steel stopper rod that is protected by clay sleeves and extends vertically through the metal in the ladle. The top end of the rod, protruding above the top of the ladle, is fastened to a gooseneck extending over the side of the ladle, which is raised and lowered by a lever. The flow of metal through the nozzle can be controlled by this arrangement. The sizes and types of nozzles and stoppers vary to suit specific purposes. The primary purpose is to deliver a smooth stream at the proper rate and temperature with the minimum amount of erosion of the stopper parts. Figure 1 shows the section of a bottom-pour ladle.

Operation. All ladles must be carefully dried before tapping the metal and in some instances, particularly with the smaller ladles, not only dried, but heated to a good red heat. In the bottom-pour ladle, the stopper is set when the ladle is cold, then unlocked from the rigging, and the ladle and stopper may be heated separately. When the steel is ready to tap, the stopper is keyed into the ladle, pulled tight into the nozzle, and held there with a set screw on the saddle of the stopper rigging. A handful of sand is then thrown around the stopper head to test the stopper for tightness. In open hearth and electric-arc practice, the ladle is carried by crane, and usually set on a steel and concrete stand under the spout of the furnace for tapping. Additions of deoxidizers or recarburizers are often made in the ladle during the tapping. Occasionally deoxidizers or alloying elements (such as lead, in making the leaded free-machining steels) may be added to the molds during pouring. In Bessemer practice, the ladle is brought to the converter by crane or buggy and the converter is tilted to tap into the ladle. The necessary recarburizing additions are made during the transfer.

When large heats of steel are to be poured into small molds, the ladle is often rigged with two nozzles and two stopper rods so that a double row of ingots can be poured simultaneously. In such an arrangement the ingot molds have to be placed very accurately, so that any given position of the ladle will find the two nozzles centered over the molds.

When the entire heat of steel has been tapped or transferred into the ladle, the metal is assumed to be at the proper temperature for pouring, or at a somewhat higher temperature, uniform throughout, and covered with a slag blanket as protection against oxidation and chilling by the air. If the temperature is too high, the ladle may be held for a length of time calculated to cool it to the proper temperature; then the steel is poured into the molds.

After pouring, the ladle is immediately dumped to clean out slag and residual metal, and is permitted to cool. When cold, the ladle is chipped free of slag and metal preparatory to repatching the lining. Sometimes when the heat of steel is tapped too cold, a shell of steel, known as a *skull,* is left in the ladle. This must be removed, and often requires extensive repairs because it tends to pull with it much of the refractory lining with which it is in contact. The amount of skull left in the ladle is often taken as an indication of the temperature of the metal.

When the ladle has been cleaned of slag and metal, it is patched with mortar and sometimes with brick, and a new nozzle and stopper are set. The ladle is then ready for drying for the next heat. With minor repairs after each heat, brick-lined ladles run a limited number of heats per lining, after which the inner course of brick must be entirely torn out and replaced.

Ingot Practice. Assuming that the heat of steel in the ladle is at the proper pouring temperature, the process of pouring into the molds to form a sound ingot may appear at first glance to be ■ very simple matter. On the contrary, the operation involves a great many complex reactions, the control of which is extremely important, since in pouring the ingot the steelmaker is virtually laying the foundation for every step that comes after. To comprehend this clearly, it is necessary to look briefly into the mechanism of the freezing of steel.

Freezing of Steel. In the molten condition, steel is virtually a uniform liquid with every part like every other part. The various elements in addition to iron, such as carbon, manganese, silicon, phosphorus, sulfur, chromium, nickel and vanadium, are all in uniform solution in the iron, or nearly so. However, after freezing, the steel no longer has this complete uniformity. The reason is that, like all other metals, steel crystallizes during freezing and, in so doing, solidifies selectively. Solidification begins with

the formation of crystals rich in the element that raises the freezing point of the alloy. The liquid left between the crystals is rich in the elements that lower the melting point of the alloy. If cooling is fast, they are quickly trapped between the original crystals, which are called *dendrites* because of their treelike form. In this condition the dendrites are not harmful, since they are well distributed and in a condition that can be broken up readily in hot working. However, if cooling is quite slow, the low-melting constituents will remain liquid for a length of time sufficient to allow them to gather in certain parts of the ingot, particularly the axis. The gathering of these low-melting constituents is called *segregation*. The extent and location of such segregations depend on the speed of freezing, which in turn depends on the sectional size of the ingot, pouring temperature, rate of pouring, and the design of the mold.

During freezing, steel contracts or shrinks, so if the mold is poured full of molten steel, it will no longer be full after the steel has solidified. It will be found that the steel has not simply settled down, leaving an air space above it, but that the location and shape of this air space or *shrinkage cavity* depend largely on the shape and design of the mold.

Mechanism of Freezing. The first metal that freezes against the mold wall shrinks slowly and this shrinkage is

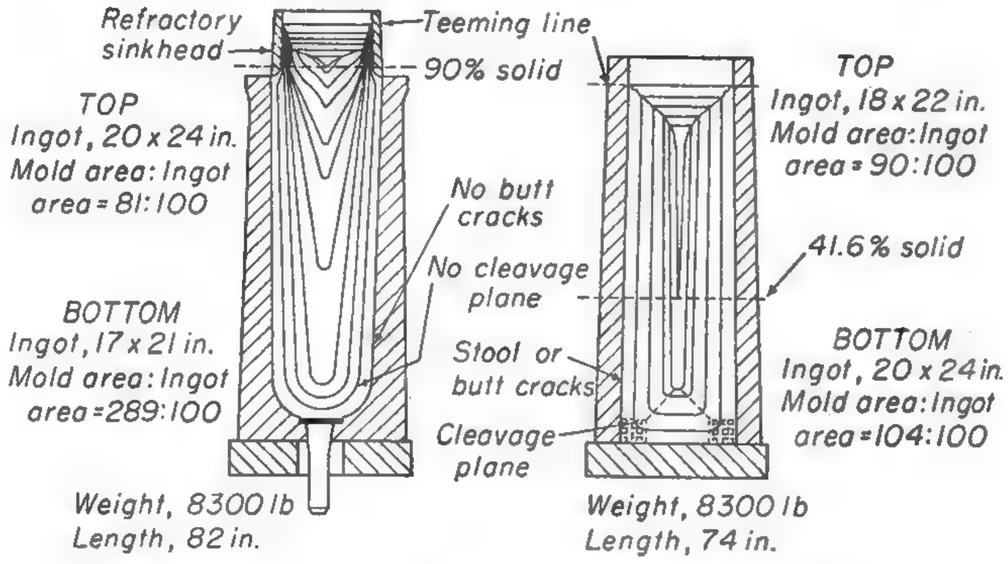

Fig. 2 Section of big-end-up and big-end-down molds

immediately filled by the molten metal in contact with it. Each succeeding layer freezing parallel to the mold surface shrinks similarly and robs molten metal from the center. In a cylindrical or prismatic mold, the steel freezes progressively from the walls. The molten pool in the center gradually sinks downward as it feeds these shrinking walls. This continues as long as the chilling effect of the mold wall is felt in the molten pool. When this effect is no longer felt, the molten metal freezes slowly throughout and shrinks downward. The net result is an ingot with sound walls, and with an axial cavity, or pipe, extending a considerable distance downward. This pipe can be made to extend deeper into the ingot by designing the mold large at the bottom and small at the top (big-end-down), and it can be made much shallower by reversing the procedure and designing the mold big-end-up. Figure ■ shows sections of big-end-up and big-end-down molds and the difference in freezing behavior.

Another result of the shrinkage of steel during freezing is the behavior of the surface metal. The first molten metal coming in contact with the mold wall freezes instantly. As it does so, it also shrinks and the surface metal pulls away from the mold wall, leaving an air gap. Therefore, the shell of metal is now supporting the molten metal inside and is no longer in direct contact with the mold wall. This has two disadvantages: (1) it greatly reduces the chilling effect of the mold, and (2) it introduces the danger of the molten metal rupturing the shell, with consequent bleeding and a rough or cracked ingot as a result. The round-sectioned mold introduces the greatest hazard in this respect. The square mold is a considerable improvement over the round; and the fluted or corrugated mold is an additional improvement over the square.

Therefore, the design of the mold is a very important factor in the production of sound ingots. It should be mentioned, however, that the conditions described can be modified by adjustments in the pouring temperature and pouring rate, factors that must not be overlooked when shrinkage and segregation are being discussed.

Another characteristic of steel is that it liberates absorbed gas during freezing; the amount depends on the method of manufacture. Killed steel liberates a comparatively small amount but open or rimming steel evolves large quantities of gas. The evolution of this gas must be controlled by proper deoxidation methods and a suitable amount of chill to keep the resulting blowholes deep under the surface where they will be comparatively harmless.

Thus far the conditions considered affect the internal structure of the ingot. The surface condition is of equal importance, since this determines the amount of expensive chipping or grinding that must be done on the resulting billet to insure a finished bar or forging free from surface defects. To produce a good ingot surface requires a good mold surface and a minimum of splashing during the pouring of the ingot, controlled largely by proper nozzle size and pouring rate. The production of good ingot surface is sometimes accomplished by pouring the ingots from the bottom by means of a gate or runner, often in groups. This practice, called "bottom-pouring", is used principally in the production of forging ingots. The use of mold washes also improves ingot surface.

Mold Design. Ingot molds are ordinarily made of cast iron, although a few steel molds have been used with indifferent success. Water-cooled molds have also been used to a limited extent, although these are still in the experimental stage. The small molds ranging from 3 to 6 in. sq are often of the split or two-piece type to facilitate stripping. Molds larger than 6 in. are usually of the one-piece type, although some larger split molds are used. Molds fall into two general classes: big-end-up and big-end-down. Big-end-down molds have the advantages of lower first cost and easier stripping; big-end-up molds have the advantage of higher yields and sounder steel. Molds may be of various shapes—square, rectangular, corrugated round, 8 sides fluted, or 12 sides. Big-end-down molds are open at both ends and are set upon a cast-iron or copper stool, which forms the bottom of the mold. Big-end-up molds usually have a round hole in the bottom which is closed with a tapered plug, as in the Gathmann type. Such plugs are usually cast iron but other materials, such as copper, refractory or graphite, are being used successfully.

Setting the Molds. The method of setting the mold preparatory to pouring varies in different plants. In most open hearth plants, molds are set on buggies—three to each car—and are spotted along a pouring platform from which the ladleman operates. In some plants the molds are placed on the floor; in others they are set in pits so that the ladleman needs no platform.

Before they are set up, molds are carefully cleaned and if they do not retain some heat from the previous cast, they should be preheated. The mold coating is then applied. Coatings include tar, whitewash and aluminum. Sometimes the molds are coated with rosin smoke. In open hearth practice, molds may be either coated with tar by dipping, or sprayed with powdered pitch or graphite.

In many plants making killed steel, a *hot top* is placed on the top of the mold to control the depth of the pipe. In small ingot practice these hot tops usually take the form of fire clay shells, which are heated as much as possible before being placed on the molds. In large ingot practice, hot tops may be sectional pieces of fire clay, brick, or even lined steel castings; and the preheating is not so important because of the volume of hot metal they will contain. These hot tops are smaller in section than the mold and are shimmed up above the mold top so that they can float on the metal in the filled mold, thus giving ample space for shrinkage to take place without binding the hot top to the top of the mold. If such binding should occur on various types of high-carbon, alloy and high speed steel, ruptured ingots might result. The space thus exposed between the mold and the hot top may be sealed with wet sand to prevent leakage as the metal rises in the hot top, or leakage may be prevented by delaying the pouring

for a short time at the joint. Hot-top volume, depending on the type of steel, will vary from 10 to 18%; but this does not mean that an equivalent weight of metal remains after the ingot solidifies, because the steel in the hot top will feed into the ingot pipe as it develops, and will thus reduce in volume during the process of solidification.

The metal in the hot top may be kept molten by several methods: by replenishment at a stated interval after the first pouring, or by the use of "pipe eliminators" which are placed on the top of the hot-top metal and either burn to generate heat or enter into exothermic chemical reactions to keep the metal liquid. Some of these reagents are carburizers, so they must be selected according to the type of steel being made. Lastly, single-arc electrodes or even induction coils are sometimes used to keep the hot-top metal fluid.

In pouring "rimmed" steel or "effervescing" steel, hot tops are not used; but at the proper time, the ingot top is "capped" to cut off the flow of escaping gases and allow the metal to solidify with the gases trapped in the steel. Such ingots do not have pipe or shrinkage cavities in the usual sense.

In bottom-pouring, the stools are especially designed with a hole in the center into which a brick cup is inserted. This cup is connected to a built-up tube of brick, known as a "runner", which is elbowed in turn to a vertical brick runner into which the metal is poured.

Pouring Operation. The ladle is spotted over the properly set mold, or over the "runner" or "fountain" in bottom-pouring. The steel is carefully poured at the proper rate, which is controlled chiefly by nozzle size and often timed by watch. Sometimes instead of being poured directly into the mold, the steel is poured into a pouring box which has one or more nozzles in the bottom. This pouring box is used to reduce pressure and thus eliminate splashing.

When the ingots are entirely frozen or *set*, they are removed from the mold or *stripped*. For car-type molds, special stripping cranes are in use, adapted either to big-end-up or big-end-down practice. In small mold practice, stripping is done by hand with the assistance of the crane.

The cooling of the ingot after stripping, particularly in the higher alloy steels, is of considerable importance and must be done carefully to prevent cracks. Usually when the hot ingots are not taken directly to a soaking pit, they are buried in ashes or other insulating material to insure slow cooling.

Metals and Ferro-Alloys Used in the Manufacture of Steel

By G. K. Herzog*

Howe's classical definition of a ferro-alloy as "iron so rich in some element other than carbon that it is used as a vehicle for introducing that element in the manufacture of iron or steel" is still about the best short definition that has been devised. Common usage, however, has made the term "ferro-alloy" mean somewhat more than this; it now includes a number of alloys so low in iron that they cannot properly be called "iron". For example, calcium-silicon, generally containing a maximum of 6% Fe, is usually classified as a ferro-alloy.

A number of ferro-alloys and metals are in common use in the manufacture of steel. Some are used for the special properties they impart to steel when in solid solution with the iron or when they combine, either wholly or partially, to form carbides; others are used for the beneficial effect they have on the impurities in the steel; and still others are employed to counteract harmful oxides or gases, and do not remain in the steel to any great extent after solidification, but merely act as fluxes or scavengers of objectionable impurities.

The melting points of the ferro-alloys used are generally of only minor importance in the manufacture of steel. The solubility of ferro-alloys in molten steel is of much greater significance. Throughout this chapter, the melting "ranges" of the various alloys are given. In general, the lower figure indicates when the alloy begins to melt, while the higher figure shows when it is completely molten. In a few instances, the lower figure gives the temperature at which the alloy having the highest carbon content of a series begins to melt, and the higher figure gives the temperature at which the alloy having the lowest carbon content is completely molten.

Standard Ferromanganese. Manganese is generally added to the molten steel in the form of ferromanganese. The standard or high-carbon grade has approximately the following composition:

Manganese	78 to 82%
Iron	12 to 16%
Carbon	6 to 8%
Silicon	1.00% max
Phosphorus	0.30% max
Sulfur	0.05% max

This alloy is furnished in various crushed and ground sizes. A common form ranges in size from lumps weighing 75 lb each to pieces about ½ in. in diam. When made under favorable and closely controlled conditions, standard ferromanganese will not disintegrate or crumble. It is used in all grades of steel, including Bessemer, open hearth and electric, for forgings, rolled products and castings.

The melting range of standard ferromanganese is between approximately 1960 and 2310 F.

Low-Carbon Ferromanganese. This alloy is used for adding manganese to steels so low in carbon content that the required manganese cannot be added either as standard ferromanganese or as medium-carbon ferromanganese. Low-carbon ferromanganese is particularly suitable for adding manganese to the austenitic chromium-nickel steels of the 18% Cr, 8% Ni type in which the carbon content must frequently be kept below 0.10%.

Low-carbon ferromanganese is available in several grades with maximum carbon content ranging in steps from approximately 0.06 to 0.75% and phosphorus content as low as 0.06%, as follows:

	(1)	*(2)*	*(3)*
Manganese	90.00%	80 to 85%	80 to 85%
Carbon	0.07% max	0.10% max	0.15% max
Silicon	1.00% max	1.00% max	1.00% max
Phosphorus	0.06% max	0.20% max	0.20% max

	(4)	*(5)*	*(6)*
Manganese	80 to 85%	80 to 85%	80 to 85%
Carbon	0.30% max	0.50% max	0.75% max
Silicon	1.00% max	1.00% max	7.00% max
Phosphorus	0.20% max	0.20% max	0.25% max

This ferro-alloy is furnished in several sizes ranging from 50-lb lumps to a ground size of 80-mesh and smaller.

The melting range of low-carbon ferromanganese is 2190 to 2220 F.

Medium-Carbon Ferromanganese. This alloy is generally used for making low-carbon steels. It is sometimes used in the manufacture of Hadfield (13% Mn) austenitic steel when large quantities of returned scrap are being melted.

Medium-carbon ferromanganese is available in one grade, as follows:

	(1)
Manganese	80 to 85%
Carbon	1.50% max
Silicon	1.50% max

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This ferro-alloy is available in a number of crushed and ground sizes. For furnace additions, the preferred material ranges in size from 50-lb lumps to pieces 2 in. in diam, while for ladle additions, material crushed to 2 in. or 1 in. and smaller is found most satisfactory. The melting range of medium-carbon ferromanganese is about 2220 to 2230 F.

Spiegeleisen or Spiegel. Spiegeleisen is virtually a high-manganese pig iron used in both Bessemer and basic open hearth practices. It is made in either the blast furnace or the electric furnace; the more important grades include the following:

	(1)	(2)	(3)
Manganese	16 to 19%	19 to 21%	26 to 28%
Carbon	6.50% max	6.50% max	6.50% max
Silicon	3.00% max	3.00% max	1.00% max

Since spiegeleisen is generally used as a furnace addition, it is furnished either in pigs weighing as much as 100 lb or in large lumps. The melting range is from 1950 to 2265 F.

Silicospiegel. Silicospiegel is used in much the same manner and for much the same general purposes as spiegeleisen. When made in the electric furnace silicospiegel usually contains 25 to 28% Mn, 5 to 6% Si, and approximately 4% C.

Silicomanganese. Because of the low ratio of carbon to manganese, this alloy is particularly suitable for introducing manganese into low-carbon steels in which the added silicon is not objectionable. Many producers of high-grade steels prefer silicomanganese to other alloys for the blocking of heats, because of the saving of time from block to tap and the improved cleanliness of the steel produced.

Silicomanganese can be made in various grades, but the grade that satisfies almost any requirement contains 65 to 70% Mn, 17 to 20% Si, 1.50% C (max). This alloy is available in various sizes. For furnace addition, lump material is preferred, having a maximum size of 75 lb and a minimum size of 2 in.; for ladle additions, material crushed to ½ in. and smaller gives best results.

The melting range of silicomanganese is from 1960 to 2400 F.

Ferrosilicon. Ferrosilicon is furnished in a number of grades, depending on the purpose for which it is to be used.

Fifteen Per Cent Ferrosilicon. Fifteen per cent ferrosilicon is available as a product both of blast furnaces and of electric furnaces. A number of grades range in silicon content by steps from 14 to 18%.

The electric-furnace grade will usually meet the following specification: 14 to 18% Si, 1.00% C (max), 0.05% P (max), 0.04% S (max). Because of its low phosphorus and sulfur contents, the electric furnace product is generally preferred for the production of quality steels. It is used for blocking heats, and as a deoxidizer and cleanser prior to the addition of more expensive alloys. Since this grade of ferrosilicon is used only as a furnace addition, it is ordinarily supplied in the form of pigs or half-pigs, ranging in weight from about 50 to 100 lb.

The melting range of 15% ferrosilicon is from 2220 to 2280 F.

Twenty-Five Per Cent Ferrosilicon. This grade is used for the same general purposes and in about the same manner as the 15% grade. It contains 25 to 30% Si and is available in lump and crushed form.

The melting range of this alloy is from 2200 to 2400 F.

Fifty Per Cent Ferrosilicon. This is the grade of ferrosilicon most widely used in the steel industry as a deoxidizer in the production of most grades of killed or semi-killed steel. It is also used for adding silicon to the high-silicon steels, such as those used for the production of springs, electrical sheets and various other products.

Fifty per cent ferrosilicon contains approximately 46 to 52% Si and is available in lump form as well as in various crushed sizes suitable for different purposes. If it is made under the correct manufacturing conditions, 50% ferrosilicon will not disintegrate or crumble when exposed to the air. The melting range is from 2210 to 2230 F.

Seventy-Five Per Cent Ferrosilicon. Some melters prefer this grade for the production of high-silicon spring and electrical sheet steels because it contains a higher percentage of silicon and, consequently, smaller additions of alloy to the ladle obtain the desired final silicon content. Furthermore, when ferrosilicon containing more than approximately 75% Si is added to molten steel, heat is generated, so instead of chilling the bath, the addition actually heats it somewhat. This is a great advantage in producing steels that contain more than 2% Si.

This grade of ferrosilicon, containing about 74 to 79% Si, is furnished in lump form as well as in various crushed sizes. The melting range is from 2200 to 2400 F.

Eighty-Five Per Cent Ferrosilicon. This grade is used for the same general purposes and in much the same manner as the 75% grade. Because of its still higher silicon content, even smaller amounts of cold alloy are added to the ladle in order to introduce the desired amount of silicon. Also this grade generates more heat when added to molten steel and thus enables the melter to add higher percentages of silicon without chilling the steel.

This alloy may contain from 80 to 90% Si and is frequently furnished in two ranges of silicon content, 80 to 85% and 85 to 95%, available in lump form and various crushed sizes. The melting range is from 2200 to 2460 F.

Ninety to Ninety-Five Per Cent Ferrosilicon. The remarks about the 75% and 85% grades of ferrosilicon apply with greater emphasis to the 90 to 95% grade. It is available in lump size as well as in various crushed sizes. The melting range is from 2200 to 2520 F.

Ferrochromium. Chromium is added to steel as ferrochromium, and because the types of chromium-bearing steels differ widely in carbon and chromium contents, a number of grades of ferrochromium are required to fill industrial needs properly. The ferrochromiums are divided into two broad classes—low-carbon ferrochromium and high-carbon ferrochromium.

Low-Carbon Ferrochromium. This is used in producing chromium steels of low carbon and frequently high chromium contents, such as the various types of steels resistant to corrosion and heat and commonly known as "stainless". Low-carbon ferrochromium is available in a number of grades having different carbon contents, but all contain from 67 to 72% Cr. The maximum carbon contents of the various grades are 0.03%, 0.04%, 0.05%, 0.06%, 0.10%, 0.15%, 0.20%, 0.50%, 1.00% and 2.00%.

This alloy is available in various crushed sizes and in lump form. The largest lumps weigh about 50 lb. The melting range of low-carbon ferrochromium varies inversely as the carbon content, being from 2500 to 3110 F for the 0.03% C grade, and from 2340 to 2460 F for the 2.00% C grade.

High-Carbon Ferrochromium. For making medium- or high-carbon steels of relatively low chromium content, high-carbon ferrochromium is commonly used. This alloy is available in several grades, ranging from 65 to 70% Cr, and from 4 to 9% C.

This ferro-alloy is furnished in various crushed sizes and in lumps weighing as much as 75 lb. The melting range is from approximately 2230 to 2790 F.

High-Nitrogen Ferrochromium. Ferrochromium with a nitrogen content equal to approximately 1% of the chromium content is available in both the high-carbon and low-carbon grades.

Special Ferrochromiums. Ferrochromiums especially designed for ladle additions are also available. Among these are SM low-carbon ferrochromium and SM high-carbon ferrochromium, with the following chemical compositions:

	Low-Carbon	*High-Carbon*
Chromium	62 to 66%	60 to 65%
Silicon	4 to 6%	4 to 6%
Manganese	4 to 6%	4 to 6%
Carbon	1.25% max	4 to 6%

Both the low-carbon and the high-carbon grades, furnished in lump form and in various crushed sizes, are distinguished by the readiness with which they dissolve in liquid steel.

Foundry Grade Ferrochromium. This grade is especially

designed for the ladle addition of chromium to cast iron, but may be used for steel as well. The chemical composition ranges from 62 to 66% Cr, 6 to 9% Si and 4 to 7% C. This ferro-alloy is furnished in lump size and in a number of crushed and ground sizes suitable for furnace and ladle additions.

Alsifer. This alloy is used for final deoxidation and for control of grain size. In open hearth practice it is ordinarily added to the ladle; in electric furnace practice it is added preferably in the furnace. The approximate composition is 20% Al, 40% Si and 40% Fe. Alsifer is furnished in lump form as well as in various crushed sizes.

Simanal. This combined deoxidizer and grain refiner has the following approximate composition: 20% Si, 20% Mn, 20% Al and 40% Fe. It is available in lump form as well as in various crushed sizes.

Calcium-Silicon. Calcium-silicon is used as a deoxidizer and degasifier in the production of steel. Both calcium and silicon are active deoxidizers and their reaction products form a low-melting-point slag that frees itself readily from the metal. Calcium-silicon also improves the fluidity of liquid steel. In open hearth practice this alloy is added in the ladle; in electric furnace practice it is added preferably in the furnace.

The composition ranges from 28 to 35% Ca, 60 to 65% Si and 6.0% Fe (max).

The melting range of calcium-silicon is from 1800 to 2030 F. This ferro-alloy is furnished in lump form and in various crushed sizes suitable for ladle additions.

Calcium-Manganese-Silicon. This alloy is used for the same purposes and in the same manner as calcium-silicon. The range of composition is as follows: 16 to 20% Ca, 14 to 18% Mn, and 53 to 59% Si. The melting range of calcium-manganese-silicon is from 1800 to 2020 F. This alloy is furnished in lump form and in various crushed sizes suitable for ladle additions.

Ferromolybdenum. The molybdenum added to engineering steels rarely exceeds 1%. In tool steels the amount may be as high as 10%, while in stainless steels of the austenitic chromium-nickel variety, as much as approximately 3% Mo is frequently added. Ferromolybdenum is available in several grades, containing from 55 to 75% Mo and either 0.10, 0.60 or 2.50% C (max). This ferro-alloy is generally crushed to 1 in. and smaller, and is usually added in the furnace, since molybdenum does not oxidize under steelmaking conditions. The approximate melting point is 2965 F.

Molybdenum Silicide. This ferro-alloy, containing about 60% Mo, 30% Si and about 1% Fe, is produced for those who wish to add molybdenum and silicon simultaneously. It is furnished crushed to a size suitable for either furnace or ladle addition.

Calcium Molybdate. Calcium molybdate contains 40 to 48% Mo, 10 to 25% calcium oxide and is virtually free from carbon. It is usually packed in containers holding an exact amount of molybdenum. This material is added in the furnace at any time during the progress of the heat, preferably after the charge is melted. As much molybdenum is recovered from additions of calcium molybdate as from additions of ferromolybdenum.

Molybdic Oxide. Molybdic oxide can be used in much the same manner as calcium molybdate. It can be obtained packed in cans containing definite and exact weights of molybdenum or in briquets weighing approximately 5 lb each and containing 2½ lb Mo.

Ferrovanadium. The amount of vanadium added to engineering steels is generally 0.10 to 0.25%. In high speed steel, the amount ranges from approximately 1.00 to 2.50%, although some steels are made with a still higher vanadium content. Ferrovanadium is available in several grades that have the following approximate composition: 35 to 55% V, 1.50 to 12% Si and 0.20 to 3.50% C. This ferro-alloy is produced in lump, crushed and ground sizes. Because vanadium oxidizes readily it is usually added to the ladle in open hearth practice. In basic electric practice it is ordinarily added to the furnace. The melting range of ferrovanadium is from 2700 to 2770 F.

Ferrotitanium. Several grades of ferrotitanium are used in steelmaking. The low-carbon variety is available in a number of grades having the compositions given below. These are used largely in the production of the so-called "stabilized" austenitic chromium-nickel steels.

	(1)	*(2)*	*(3)*	*(4)*	*(5)*
Titanium	20 to 25%	24 to 26%	38 to 42%	38 to 42%	40 to 45%
Aluminum	3.00% max	5 to 6%	6 to 9%	2 to 5%	7.00% max
Silicon	4.00% max	3 to 4%	3 to 5%	9 to 13%	4.00% max
Carbon	0.10% max	0.10% max	0.10% max	0.10% max	0.10% max

The high-carbon variety of ferrotitanium, frequently known as ferrocarbon titanium, is available in two grades —high-carbon and medium-carbon—having the following approximate compositions:

	High-Carbon	*Medium-Carbon*
Titanium	15 to 16%	17 to 20%
Aluminum	1 to 2%	1 to 2%
Silicon	2 to 3%	2 to 3%
Carbon	6 to 8%	3 to 5%

These grades are used as deoxidizers and scavengers in steel in such amounts that only a barely appreciable percentage remains in the solid steel. In medium- or high-carbon killed steels, ferrocarbon titanium is used as a final deoxidizer to prevent segregation and the occurrence of objectionable inclusions, and occasionally to control grain size.

One grade of ferrotitanium contains 25 to 27% Ti, 20 to 24% Si, 1.00% Al (max) and 1.00% C (max). All the titanium alloys are available in various lump, crushed and ground sizes suitable for different purposes.

Tungsten. The principal use of tungsten is for the manufacture of high speed tool steel, in which tungsten may range from about 2% to 22%. It is used also in the production of steels for hot working dies for certain high-temperature alloys and is used to a limited extent in permanent magnet steels. The various tungsten steels are ordinarily made in the electric furnace.

Ferrotungsten is the alloy commonly used for adding tungsten to steel, although tungsten metal powder is sometimes used, as well as some tungsten compounds such as calcium tungstate. The range of tungsten contents of standard ferrotungsten is from 70 to 80% with a maximum of 0.60% C. A number of grades falling outside these limits are, however, commercially available as follows:

	Special	*Grade B*	*Grade C*
Tungsten	65 to 72%	78 to 82%	78 to 82%
Carbon	2.50% max	0.25% max	1 to 2%

Ferrotungsten is furnished in various crushed and ground sizes; the largest is about 1 in. The melting range of standard ferrotungsten is relatively high, from approximately 3000 to 5000 F. However, this alloy dissolves quite readily in molten steel, so that an addition of as much as 20% W involves no particular difficulty.

Tungsten metal powder, like ferrotungsten, is available in a number of grades suitable for the production of tungsten steels, as well as in grades of very high purity with closely controlled, extremely fine particle sizes suitable for the production of tungsten carbide tools and similar applications.

Zirconium. Zirconium is added to steel in amounts ranging from less than 0.05 to approximately 0.20%. This element acts as a deoxidizer and scavenger, combining readily with oxygen, nitrogen and sulfur, which are thus either eliminated from the bath or rendered harmless. The reaction with nitrogen, resulting in the formation of zirconium nitride, reduces age hardening in the deep-drawing steels. In high-sulfur steels formation of zirconium sulfide diminishes the hot shortness. Additions of more than 0.10% Zr will usually give a fine-grained steel, but smaller additions, such as approximately 0.05% Zr, will give thorough deoxidation without grain refinement.

Two zirconium alloys are used for the majority of the

zirconium additions made to steel. The approximate compositions of these alloys are as follows:

	(1)	(2)
Zirconium	12 to 15%	35 to 40%
Silicon	39 to 43%	47 to 52%
Iron	40 to 45%	8 to 12%

Zirconium alloys, available in a number of lump, crushed and ground sizes, begin to melt at about 2300 to 2450 F.

Nickel. Nickel is used in a wide range of percentages in many types of steel. In engineering steels the percentage of nickel may vary from about 0.40 to 6.00% and is occasionally somewhat higher. When it is used in combination with chromium in steels resisting corrosion and heat, nickel may be present from about 1% to about 40% or even higher. Some of the alloys still higher in nickel contain so little iron that they cannot be listed properly as steels. The same remark would apply to some of the special nickel alloys used for magnetic and other purposes.

Because nickel is not oxidized in a molten steel bath, it may be added to the furnace charge at any time during the progress of the heat. Nickel is supplied in the form of electrolytic cathodes sheared to a convenient size. It is also available in the form of shot and ingots made of remelted cathodes. The approximate composition and melting point of these grades is as follows:

	Electrolytic Cathode	Remelted Cathode
Composition, percentage nickel plus cobalt	99.95	99.60
Melting point, deg Fahr	2650	2600

Columbium. Columbium is used mainly in the production of "stabilized" austenitic chromium-nickel steels. It is used also to reduce the air-hardening characteristics in the plain chromium steels of the corrosion-resistant type. For these applications the columbium seldom exceeds 1%; the amount added is from 5 to 10 times the carbon content. Columbium (as much as several per cent) is also a constituent of some of the alloys developed for use at high temperatures, since it increases their creep strength.

Columbium is available as ferrocolumbium containing 50 to 60% Cb and having 5% Mn (max), 8% Si and 0.40% C. When this ferro-alloy is added to a deoxidized steel bath 12 to 15 min before tapping, 80% may be recovered. Ferrocolumbium is available in a number of crushed and ground sizes. The melting range is from 2550 to 2750 F.

Cobalt. Cobalt resembles nickel in appearance and chemical properties; however, its effects on steels and other ferrous alloys are quite different from those of nickel. Cobalt is the only metal that is known to reduce the hardenability of the steel in which it is present. It is added to high speed steels in amounts from 5 to 12%, to permanent magnet steels in amounts from 5 to 40%, and in various percentages to steels and alloys for high-speed cutting tools and for use at high temperatures. Cobalt is ordinarily added to steel as cobalt metal, in the form of rondelles and shot containing 97 to 99% Co. The melting point of pure cobalt is about 2720 F.

Aluminum. Because it is an extremely active deoxidizer and degasifier, aluminum is used in virtually all steelmaking processes, either as a mold addition for quieting turbulent steel, or as a ladle addition for obtaining a fine grain size and preventing porosity in steel castings. Aluminum is a constituent of a majority of the nitriding steels. It is available in several forms, such as shot, sticks and small ingots. The amount used—ordinarily only a few hundredths of a per cent—depends on the steelmaking practice and the intended application for the steel. The nitriding steels may contain as much as 1.50% Al. The melting point of aluminum is 1220 F.

Copper. Copper is added to steel in various amounts ranging from a few tenths of a per cent to several per cent. The greatest tonnage of copper steels consists of those containing 0.20 to 0.50% Cu, in which copper increases corrosion resistance without greatly affecting the mechanical properties. Low-alloy high-strength structural steels may contain as much as 1% Cu. Some of the high-chromium, corrosion-resistant steels contain as much as 1 to 4% Cu, and many cast steels as much as 2.50% Cu.

Copper for addition to steel is available in several forms. Virgin copper is best used in the form of pigs. However, scrap material of almost any kind may be used. Because copper does not oxidize in the steel bath, it may be added at any time during the production of the heat. The melting point of copper is 1981 F.

Boron. Boron is used in steel for one purpose only—to increase the hardenability; that is, to increase the depth to which the steel will harden when quenched. Only a few thousandths of a per cent is ordinarily added. Several alloys available for adding boron to steel, range in boron content from about 0.20 to as much as 24.00%. At least four grades of ferroboron can be obtained, having the following approximate compositions:

	(1)	(2)	(3)	(4)
Boron	10 to 14%	14 to 19%	19 to 24%	17.50% min
Carbon	3% max	3% max	3% max	0.50% max
Silicon	4% max	4% max	4% max	1.50% max

Also available are manganese-boron, containing 15 to 20% B, the remainder mainly manganese; and nickel-boron, containing 15 to 18% B, the remainder mainly nickel. Because of the extremely small percentages of boron that are added, and because boron itself is readily oxidized at steelmaking temperatures, some operators prefer an alloy relatively low in boron but containing substantial percentages of other elements that serve to protect the boron from oxidation in the steel bath. Some of these special boron alloys, occasionally referred to as "intensifiers", contain elements that impart desired properties to the steel in addition to protecting the boron. The more important of these alloys, all sold under trade names, have the following approximate compositions. The various boron alloys are available in a number of crushed and ground sizes.

Boron	0.20%	0.20%	0.50%	0.70%	0.70%	1.00%	1.75%	3.50%
Aluminum	10.00%	12.00%	13.00%	6.00%	7.00%	1.50%	14.00%	....
Titanium	15.00%	20.00%	20.00%	10.00%	10.00%	16.00%	17.00%	....
Vanadium	25.00%	13.00%	....	10.00%	....	....	....	....
Zirconium	....	....	4.00%	6.00%	4.00%	....	....	....
Manganese	....	....	8.00%	....	....	....	23.00%	....
Silicon	....	....	5.00%	38.00%	38.00%	3.00%	21.00%	43.00%
Calcium	....	....	....	....	10.00%	....	....	....
Carbon	....	....	....	....	....	7.00%	1.00% max	....
Remainder—mainly iron								

The Use of Aluminum for Deoxidation and Control of Grain Size in Steel

By H. W. McQuaid* and John Chipman*

THE importance of the control of grain size in commercial steels has become so widely recognized that the method used in obtaining this control is of interest to everyone responsible for the treating and application of commercial steel. "Grain size" refers here to the austenite grain as indicated by the McQuaid-Ehn carburizing test[1] (*see* page 407) or by other suitable measures of austenitic grain size (*see* page 399) and is rated usually according to the chart of the ASTM. Virtually every heat of carbon and alloy steel specified in this country for heat treated parts is made according to a certain melting practice designed to provide properties in the steel that will make it most suitable for the part in which it is to be used. The grain size serves as an indicator of the characteristics of the particular steel in its response to heat treatment, machining and other processing. Grain size is now recognized to be as important, in many instances, as the chemical specification, in the results obtained from the commercial heat treatment of steels.

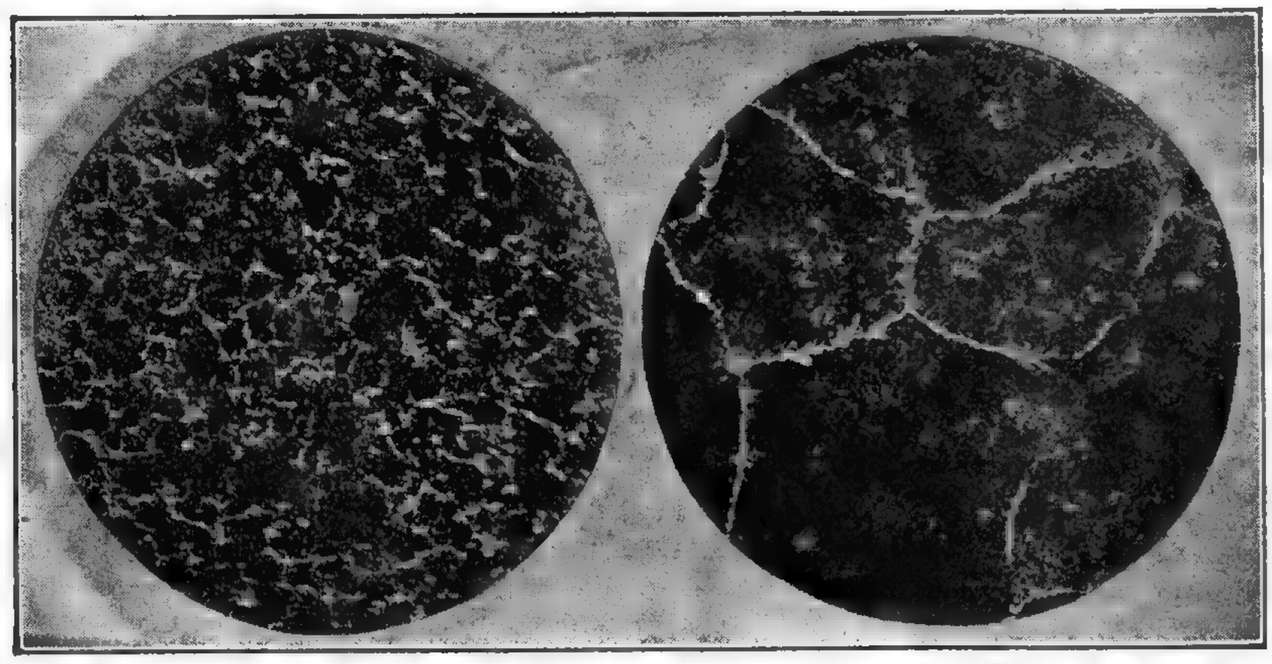

Fig. 1 The fine grain obtained by aluminum deoxidation as contrasted with the coarse grain obtained by deoxidation with manganese. (× 200)

The most important single factor in the control of grain size today is aluminum. Experience has shown that the amount of aluminum required to produce the properties characteristic of the fine-grained steels varies from a few ounces to as much as 4 lb per ton, depending on the condition of the steel to which it is added.

The production of steel within a definite range of grain size is commercially possible only when the specifications cover either a coarse-grained type or a fine-grained type. Although steel can be made that will show an intermediate grain-size range and specifications call for it at times, steel of this type requires very careful control of every factor and is not ordinarily considered "commercial".

One of the earliest published evidences of the effect of aluminum on grain size is reproduced in Fig. 1.[1] The first active work in connecting the aluminum addition with grain size was done hardly more than 20 years ago. As soon as the first chart appeared in 1924 and some steel users insisted on obtaining steel of a definite grain size, it was found necessary to develop a melting technique that would make it possible to meet these specifications commercially.

In a recent paper, J. H. Whiteley[3] has pointed out that at least eight factors influence grain size. These are the temperature, time and rate of heating, the initial grain size, hot work, the rate of cooling after solidification, the aluminum content of the steel, and the state of the carbide.

In the coarse-grained type of steel, a relatively gradual grain coarsening occurs when the steel is heated above the transformation range. In steels that have been made fine-grained by proper addition of aluminum, there is little evidence of grain coarsening until a temperature has been reached several hundred degrees above the transformation temperature. Further heating causes pronounced grain growth and the rate increases with rising temperature. A steel that is cooled during this period of growth invariably shows a duplex structure of fine and coarse grains, rather than an intermediate grain size. The final state of the fine-grained steel, after heating above the coarsening range, may be even coarser-grained than a similarly treated coarse-grained type of steel. Figure 2, taken from the work of Bain,[4] illustrates the effect of heating temperature on the ASTM grain size of typical steels of the two types.

Aluminum as a Deoxidizer. Of the elements commonly used as deoxidizers, aluminum is the most potent and affords the most nearly complete removal of dissolved ferrous oxide. The reaction in its simplest form is written as follows:

$$FeO \text{ (dissolved)} + Al \text{ (dissolved)} = Fe \text{ (liquid)} + Al_2O_3$$

When an excess of aluminum is employed, the inclusions formed in the reaction consist of Al_2O_3 more or less contaminated by other oxides. When a deficiency of aluminum is used, the resultant inclusions are mainly ferrous aluminate with exact composition unknown and probably variable.

The completeness with which aluminum removes dissolved FeO from the steel bath is shown in Fig. 3, obtained from the calculated equilibrium constant of the reaction. This diagram shows, for example, that in a bath at 2910 F, if enough aluminum is added to react with the other oxides present, and to leave a residual of 0.01% metallic aluminum dissolved in the steel, the content of dissolved FeO will be reduced to 0.002%. Similarly, if the bath temperature is 3090 F, and the residual metallic aluminum 0.02%, the dissolved FeO will be less than 0.005%. It should be emphasized that these figures are based on calculated

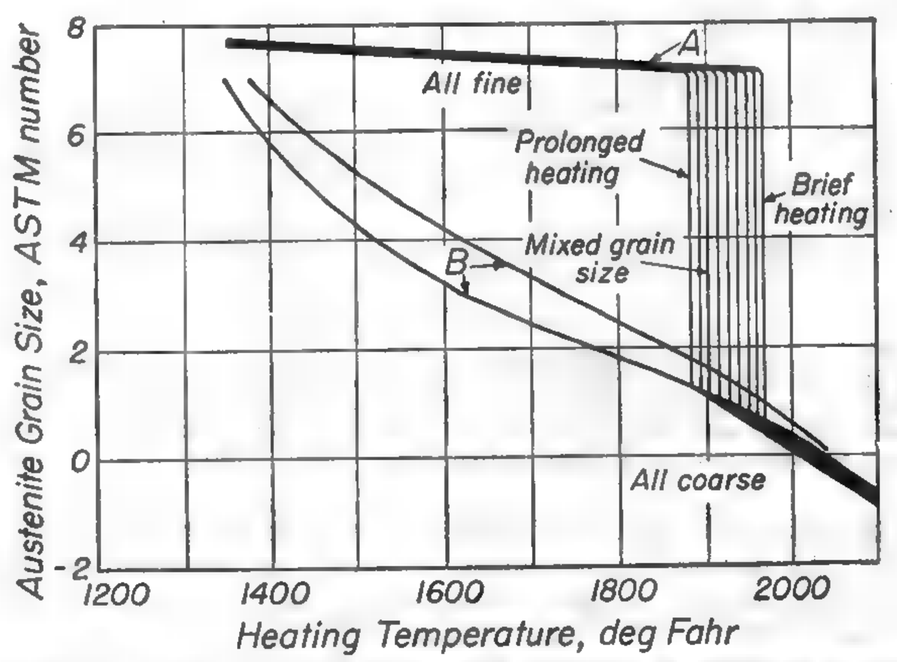

Fig. 2 Comparison of the coarsening behavior of steels of the fine-grained type (Curves A) with those of the gradually coarsening type (Curves B). Note that in general 1700 F is a satisfactory temperature for distinguishing between types. (Schematic, after Bain[4])

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rather than experimental values of the equilibrium constant. However, in view of the limitations of present experimental methods when applied to small amounts of aluminum and oxygen at high temperatures, these calculations are probably more dependable than direct determinations.

Aluminum Requirements. The amount of aluminum that must be added to produce a fine-grained heat depends on the amount of (1) aluminum losses by reaction with air, slag, refractories and the like, (2) aluminum consumed in the deoxidation reaction, and (3) residual aluminum desired in the steel.

The first of these factors depends largely on the individual steelmaking practice and therefore no quantitative

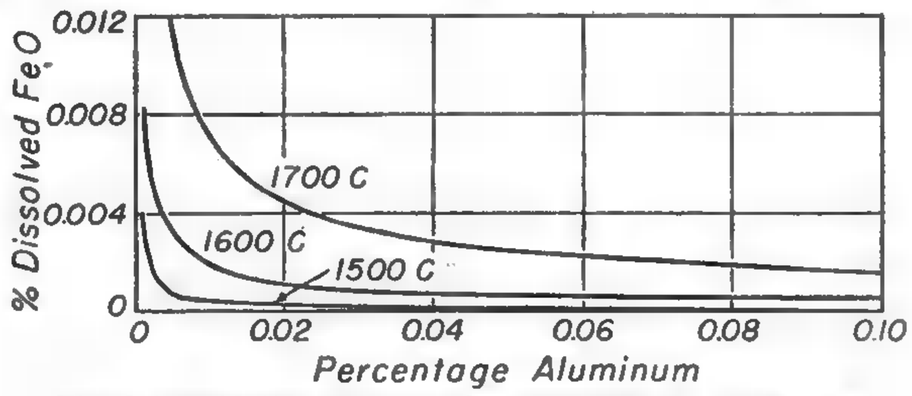

Fig. 3 Deoxidation diagram for aluminum in liquid steel

statement can be made that will be widely applicable. The efficiency of the addition is greatest when added to the molds and least when added to the furnace. Furnace additions are not ordinarily used for control of grain size, except in certain electric furnace practices.

The amount of aluminum required for actual deoxidation of the bath depends on the oxygen content of the metal. In the open hearth this oxygen content is determined principally by carbon content and other deoxidizer additions and, to a smaller extent, by slag composition. The calculated requirement, based on the highest oxygen content normally found in the open hearth bath at any given carbon level, is shown in Curve A of Fig. 4. The addition of silicon reduces the aluminum requirement, especially in low-carbon steels. When substantial quantities of silicon are present, the aluminum requirement in low-carbon steels may differ little from that of the higher carbon grades.

The minimum amount of residual aluminum required to produce a fine-grained steel has not yet been determined

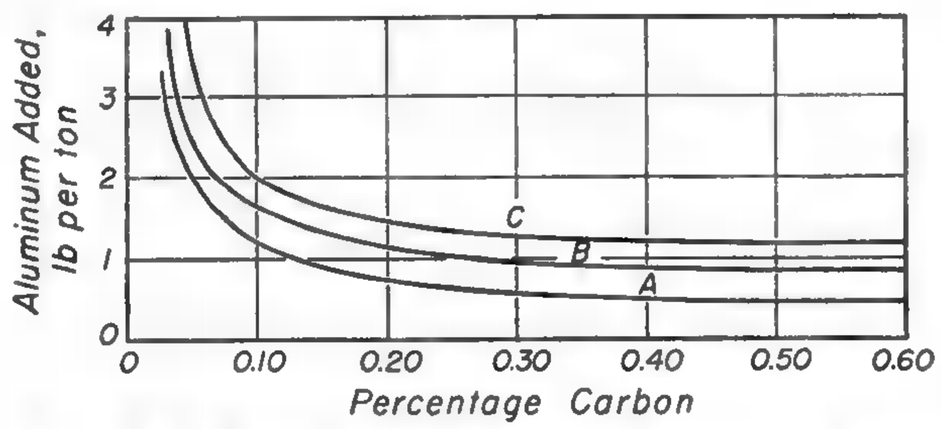

Fig. 4 Effect of carbon content on the normal aluminum requirement for fine-grained open hearth steel (calculated). Curve A shows amount required for deoxidation only. Curve B provides for an excess of 0.02% above the amount required for deoxidation. The normal commercial range of additions is generally between Curves B and C.

with accuracy. Fine-grained steels containing as little as 0.01% Al have been reported. The grain-coarsening temperature reaches a maximum at 0.02 to 0.03% Al,[5] decreasing somewhat with larger percentages, as shown in Fig. 5.

For purposes of comparison, Curve B of Fig. 4 shows the aluminum addition to yield a residual of 0.02%, neglecting losses. Since the efficiency of the addition is never perfect, a somewhat greater amount is required in practice, and the band between B and C represents approximately the addition required in open hearth steel containing little or no silicon.

Additions of Aluminum to Molten Steel. Aluminum must be carefully added to liquid steel, if the losses caused by oxidation are to be within reasonable limits and also if the aluminum is to be effective in its role as agent for control of grain size.

Because of the great affinity of aluminum for oxygen, the addition of stick aluminum to the ladle will result in high losses from oxidation at the surface of the steel. A special effort must be made to keep the aluminum completely submerged in order to prevent both the high loss of aluminum in the slag and the formation of large masses of aluminum oxide in the steel itself.

The common practice in this country is to add aluminum in the ladle whereas, according to Ohman,[6] the Swedish practice is to add it in the mold. Epstein and co-workers[7] show that the mold addition is apparently more effective than the ladle addition in producing fine grain, and theoretically the mold addition should be the more economical. Experience has shown that in large basic open hearth heats more uniform results are obtained by a ladle addition.

In the basic electric furnace, the FeO in the finishing slag and in the bath itself is relatively low. Thus less

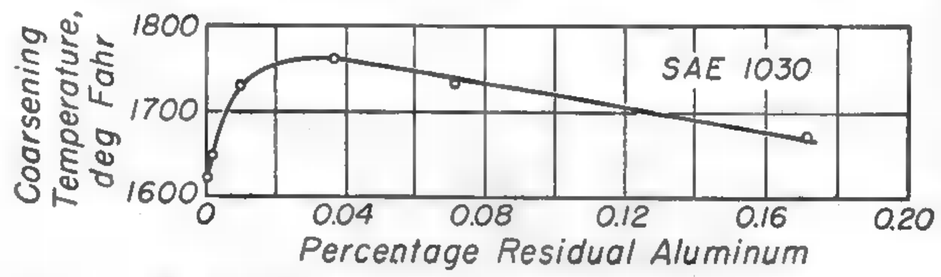

Fig. 5 Effect of residual aluminum on the grain-coarsening temperature of SAE 1030 steel. (Washburn[5])

aluminum is required than when steel is made under a basic open hearth slag, and frequently the aluminum addition is made in the furnace. The additions of aluminum required for obtaining a fine-grained steel are usually smaller than in the open hearth, depending on the character of the charge and the type of slag used. It is difficult to give any hard and fast rule as to the exact amount of aluminum that must be added to produce a fine-grained heat in basic electric furnace practice, but usually from 1 to 1½ lb per ton is sufficient.

Aluminum is commonly added in the furnace by the use of cast aluminum blocks or rods, which should be carefully handled to insure lower losses from oxidation. Aluminum alloys, such as silicon-aluminum-manganese, iron-aluminum-silicon, and iron-aluminum have all been used for better control of the aluminum addition. However, the common practice is still to use metallic aluminum, which is thrown by hand into the ladle while it is being filled.

Aluminum is added to rimming and semikilled steels to diminish the content of active FeO and to control the action in the molds. The amount used in rimming steels ranges from 0 to 0.4 lb per ton in the ladle; for semikilled, 0 to 0.7 lb per ton, and as much as half this amount in the molds. The amount will vary with the carbon and manganese content of the steel, the composition of the slag, the size of the heat and the size of the mold. In general, the rimming action contributes to the removal of the products of deoxidation, and the use of aluminum in the molds does not necessarily lead to the presence of nonmetallic inclusions. The amount of aluminum added is never sufficient to react with more than a small fraction of the ferrous oxide present. Reference to the deoxidation diagram shows that the residual metallic aluminum is virtually nil, in rimming and semikilled steels.

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SHAPING AND FABRICATION

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Hot Mechanical Working of Steel

BY THE SUBCOMMITTEE ON HOT MECHANICAL WORKING OF STEEL*

STEEL cast from the melting furnace into ingot molds must be reduced from the ingot by mechanical force through the intermediate stages of bloom and billet to bar, structural shape, plate, sheet, strip, coil or forging, which are the common hot finished forms of steel. For several essential reasons this mechanical force is applied to the steel while hot.

The ingots into which the steel is cast from the melting furnace usually represent a considerable mass of metal that is slow to solidify and cool to room temperature; hence its structure, by virtue of the natural laws that govern the solidification of liquid metal, is a disorderly arrangement of very coarse crystals and incidental impurities with varying chemical composition. Ingot metal in this condition is deficient in ductility and is highly stressed. The stresses can be of sufficient magnitude to cause rupture if the mass is subjected to unequal or sudden temperature changes; hence such ingot metal is unsuited for safe use as an engineering material. Consequently, one of the primary reasons for the hot mechanical working of steel is to bring about as complete a reconstruction and refinement of this crystalline structure as possible. When steel is heated to its plastic state and mechanically worked, the coarse crystallinity of the steel ingot is progressively fragmented and rearranged, and the metal is made to flow in the desired directions. This results in a reduced section of a more homogeneous character and finer crystalline structure. By proper selection of temperature and by mechanical working through rolls, dies and the like, the physical properties of the steel may be improved both statically and dynamically, as compared with those of the original cast ingot.

Hot Working Range and Effects. Heating steel above the so-called "blue-heat range" near 700 F constantly decreases the strength and increases the plasticity until, at a temperature where the lowest melting constituent of the steel starts to melt, the strength is greatly decreased and the mass also loses plasticity and tends to crumble under applied stress. When this point is reached, mechanical work cannot be performed, since the steel will crumble rather than flow.

The optimum hot working temperature is therefore a balance or average between decreasing strength and increasing plasticity. This temperature, varying with different compositions of steel, is covered by a range called the hot working range. The top of the range is limited by a margin of safety below the melting point of the lowest melting constituent; the lower end is limited by the temperature at which strength increases and plasticity decreases to such an extent that excessive pressures are required to cause flow, thus limiting the efficiency of the process and possibly causing ruptures in the metal.

Finishing Temperatures. Although the final properties of the finished steel are often determined by heat treatments applied subsequent to the hot mechanical working, the temperature at which the mechanical work is finished (known as the "finishing temperature") is important in governing the final treatments necessary and the properties obtained. It is generally conceded that the lower the finishing temperature, the finer the structure of the piece when mechanically worked and the more amenable it will be to simple heat treatments. However, the actual temperature is limited by mass, shape, process and other considerations. A special application of this principle is illustrated by the austenitic steels, wherein certain desirable physical properties can be obtained only by closely controlled finishing temperatures. Large forgings and intricate shapes to be flowed into dies require relatively high finishing temperatures, and the required refinements of structure must be taken care of by subsequent heat treatment. For small and simple pieces, the finishing temperatures can be at or near the lower transformation point, which produces refined structures that respond readily to simple heat treatment. A good example of the latter is the Damascene swords, which received repeated light workings at critical and subcritical temperatures. The extremely refined structure thus produced responded to subsequent hardening, and a blade of remarkable properties was obtained.

Cooling Practice. Certain grades of carbon and alloy steel must be slowly cooled immediately after the mechanical working has ceased and while the metal is still hot, to avoid internal as well as external ruptures. Some alloy steels are so sensitive that they require program annealing before they can be removed from the furnace; refer to articles on "Heating Steel for Forging" and "Hot Working of Large Sections", pages 348 and 350.

Ingot Structure. The ingot of cast steel is composed of a mass of grains of various sizes. The central portions of these grains are comparatively pure iron or ferrite, whereas the portions near the grain boundaries are higher in the alloying elements and impurities. The resultant chemical heterogeneity is not entirely destroyed by diffusion or by mechanical hot working. Mechanical hot working causes these nonhomogeneous grains to be elongated in the direction of the working. The macro-etching of a section parallel to the direction of working shows laminations or lines resulting from the chemical heterogeneity. Such

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lines are known as "flow lines" because they indicate the direction in which the metal "flowed" or was worked.

Steel may differ markedly in mechanical properties, especially in ductility and resistance to shock, in a direction parallel to the flow lines and perpendicular to them, particularly if the metal is not clean. In forging practice, consideration must be given to the service for which the forging is intended. As an example, if rings are forged from a slab produced by elongating the ingot into a long block of rectangular section and subsequently trimming it to shape, certain sections of the rings will show radial flow lines and will probably have less ductility than the portions 90 deg away, which have tangential flow lines. For this reason, rings and forgings subject to tangential stresses during service are best upset or expanded in such a direction as to increase the physical properties in the desired way.

In general, the amount of mechanical hot working, or of reduction from the ingot, is regulated by the ultimate use of the steel product and the type of stress involved.

The conditioning of ingots, as well as blooms, billets and slabs, is vitally important in the production of high-quality steel products and should be given careful consideration at all times. Conditioning may be accomplished by chipping, scarfing, swing-grinding, blasting and pickling. (*See* page 346.)

Mechanism of Hot Mechanical Working. The mechanism of the hot mechanical working of steel may be either rolling or forging. Rolling, as the term implies, works the metal by rolls; forging works the metal by hammers, presses and forging machines.

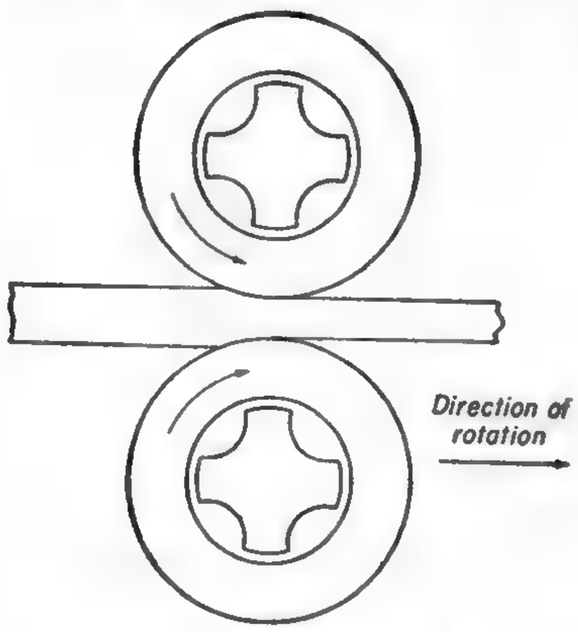

Fig. 1 Action of rolling

Hot Rolling. In this method of hot working, the hot metal is fed between two rolls rotating in opposite directions. Hot rolling accomplishes three main purposes: (1) reduction of cross-sectional area, (2) refinement of structure, and (3) shaping of the metal into desired forms, such as bars, sheets, plates, rails, angles and I-beams. The flow of metal in the rolling operation is continuous and almost entirely in a longitudinal direction (Fig. 1).

Blooming Mill. Except for some flat rolled products, the rolling mill in which the first hot mechanical working of the cast ingot is done is known as the "bloomer" or "blooming mill". The function of the bloomer is to take the hot ingot as received from the soaking pit and break it down or reduce it to a smaller size called a bloom or billet. This bloom is a semifinished product to be rolled subsequently on a billet mill or finishing mill, or used for forgings. The sizes of the majority of blooming mills range from 28 to 54 in. The size is based on the distance from center to center of the pinions. Most bloomers are of the two-high reversing type, which consists of two rolls mounted one above the other and reversible in the direction of rotation to allow for the passage of the metal back and forth through the rolls. Grooves or passes cut in the rolls are of a size and shape to accommodate the ingot and the various reductions desired. The most frequent procedure is a flat center pass called a "bull head", used for breaking down the ingot to the size of the first pass, which is usually 13 to 14 in. wide. In addition, the blooming rolls contain several small passes, usually 8, 6, or 4 in. wide, depending on the finished bloom sizes required.

Operations on Blooming Mill. For example, in rolling a 24-in. corrugated ingot to a 4 by 4 in. bloom on a reversing bloomer, the following method, requiring about 27 passes, is used for alloy steels: The ingot is broken down to 18 by 13 in. under the bull head, by giving light drafts and turning the ingot each pass for the first four passes; then two passes each way are given while the metal is being slabbed to 18 by 13 in. Then it is turned and entered into the 14-in. pass, given two passes and turned; then two passes to 14 by 8 in.; turned and entered into the 8-in. pass, given one pass and turned; then one pass to 5 by 8 in.; turned and entered into the 6-in. pass to achieve 6 by 6 in.; turned and given one pass to 6 by 4 in.; then turned and entered into the 4-in. pass, and finished to 4 by 4 in.

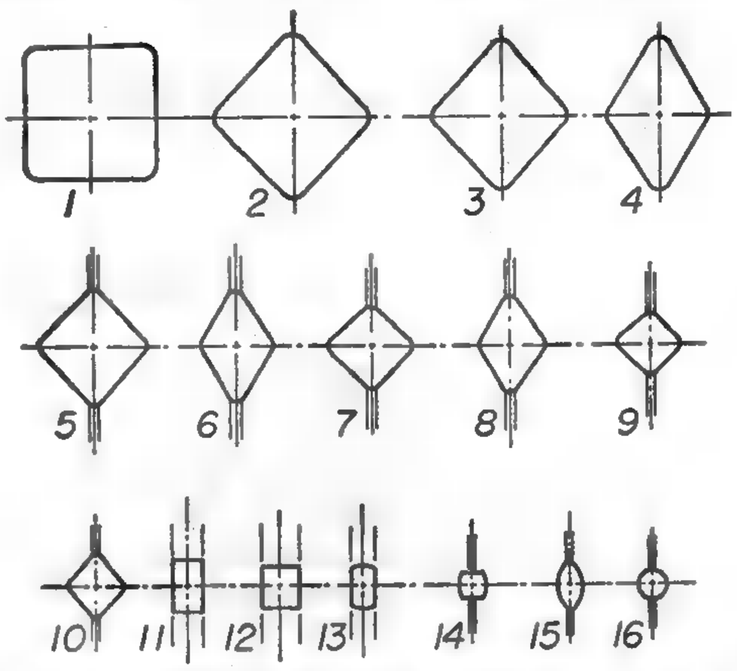

Fig. 2 Passes and reductions of a 4 by 4-in. billet to a ¾-in. round bar

Billet Mill. In order to produce the size of billet necessary for use in the smaller finishing mills, it is customary to reroll the blooms, either with or without reheating, in some type of billet mill. The billet mill may be of the 3-high type, or may be continuous.

Finishing Mill. The billets or blooms, if not used for forging purposes, are rolled on smaller mills into bars of varying shapes and sizes. They may be rounds, hexagons, flats or special shapes. Round bars are generally rolled in open-pass rolls. Figure 2 shows the passes and reduction of a 4 by 4 in. billet to a ¾-in. round. For special steels more passes may be required and the shape of the passes may not be the same as shown.

Flat bars are sometimes rolled in open-pass rolls and many times are rolled in tongue-and-groove rolls.

Sheets. The practice covering the rolling of sheet and strip is given on page 352.

Plates. Plates are produced either from slabs or directly from ingots by hot rolling. They are termed "sheared plates" or "sheared mill plates" when rolled between straight horizontal rolls only and trimmed on all edges. They are termed "Universal plates" or "Universal Mill plates" (abbreviated "U M" plates) when rolled between straight horizontal and vertical rolls and trimmed on the ends only. Universal plates are sometimes rolled in grooved rolls.

There are various types of mills for producing sheared plate, such as two-high, three-high, four-high and tandem. The two-high mill has two horizontal rolls propelled in opposite directions. In one type of mill the material is passed one way and then returned overshot for repeating operations until finished. In another type, the direction of the rolls is reversed after each draft, so the material passes back and forth through the mill as in a blooming mill.

The three-high mill has one top and one bottom power-driven roll of the same diameter, and one middle or floating roll of smaller diameter. The middle roll rotates by friction and is lowered or raised as the material passes back and forth through the rolls. This type of mill is fitted with tilting tables both in front of the rolls and behind them, and these tables are raised or lowered in order to re-

ceive and return the material through the top and bottom passes. The direction of rotation of the rolls is constant.

The four-high mill consists of one or more stands of rolls in which the top and bottom, or backing-up rolls, are larger in diameter than the two work rolls in the center. The material being rolled passes between the two center rolls, and the top and bottom rolls act as "stiffeners" to back up the center rolls. In one-stand mills, the direction of the rolls is reversed between passes so that working takes place as the material is passed back and forth through the mill. In the case of mills having several stands in tandem, the rolling is the same as that for hot rolled strip described on page 352.

Tandem mills have two or more stands of rolls so arranged on a straight line as to permit the product to be run continuously from one to the other. The first stand in this arrangement is called a "roughing mill" and may be either a two-high, three-high or four-high mill. The other stand or stands may be either three-high or four-high and are usually called "finishing mills".

It is customary to cross-roll in producing sheared mill plates; that is, to roll the ingots or slabs in both directions so that tension and bend tests taken both parallel and transverse to the greatest dimension give quite similar results.

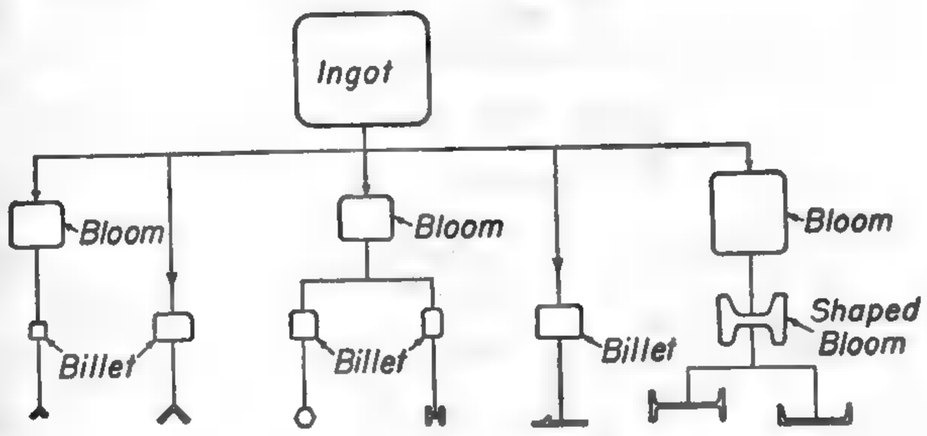

Fig. 3 Bar and structural shapes

The Universal Mill is usually a reversible mill consisting of two horizontal and four vertical rolls, the latter being so placed that they can be manipulated for side rolling, one in front and one behind at each end of the horizontal rolls. This arrangement produces a straight, almost parallel "mill" edge. By this method of rolling, the slab or ingot does not receive cross-rolling, but is merely elongated in one direction. Therefore, this product cannot be expected to have ductility as great as that of sheared mill plates when tested in tension transversely to the direction of rolling, or when bent parallel to the direction of rolling.

Shapes. Steel can be rolled into many different shapes, and special passes are made in rolls, depending on the specified shape of the finished product. In the majority of cases, these shapes are rolled from a square or rectangular bloom or billet; all the shaping is done in the intermediate passes of the mill.

Forging. The term "forging" may be used to describe all mechanical hot working of metal, but it is usually applied more specifically to the mechanical working of metals by the application of an intermittent force rather than of a continuous one, as in rolling. Thus a forging hammer works the metal by successive blows, while a forging press applies a kneading or squeezing action. These typify the simplest tools for forging. There are numerous other forging devices in addition to these, including drawbenches, which form objects by forcing them through dies; forging machines that can be made to perform a series of varied operations by the mechanical action of a series of dies; forging rolls that apply intermittent action by the cam principle; extrusion presses and the like. Many of these are described in other articles in this Handbook, pages 33 to 43.

Hammering. The simplest and oldest of forging operations is performed by the blacksmith in forming metal objects by hammering the hot metal on his anvil.

Early mechanical hammers consisted of means for raising a heavy upper die and then allowing it to fall on the object to be forged. In the so-called "helve" hammer, the falling weight was attached to a long beam or lever, having the fulcrum in the central portion. A cam or similar device on the farther end forced the weight to be raised, and then released it.

Early steam hammers utilized a steam cylinder for raising the ram, which was then allowed to fall by its own weight on the object to be forged. Modern board drop hammers still use this principle. The upper die or falling weight is attached to a board or boards, and is raised by the action of rollers on this board. At the top of the stroke, the rollers release the boards, and the upper die assembly falls by its own weight.

Most modern steam hammers are "double acting"; that is, steam is applied on both sides of the piston, and the upper die is driven down upon the work metal by power, in addition to the force exerted by the falling weight.

The steam hammers used for "open-die work", as described in this section, usually have anvils mounted on foundations separate from the one supporting the hammer frame, with consequent reduction of vibration in the working parts. The hammers used for "closed-die work", variously called "hot die forging" or "drop forging", must be more rigidly constructed to insure alignment of the dies during the striking. In hammers of this type the ram that supports the upper die, slides in a series of parallel grooves in the hammer frame. The anvil must be part of the same rigid structure; one block supports both the anvil and the columns of the hammer. This type of structure requires massive parts for rigidity and strength.

Drop forging is discussed on page 36.

Pressing. Hot mechanical working may also be applied to metal objects by presses, which differ from hammers in that they subject the metal to a series of squeezing actions, rather than to a series of blows.

Forging presses may be mechanical, hydraulic or steam-hydraulic.

Mechanical presses* are most widely used for nonferrous metals. They find special application, however, in the production of quantities of identical forgings, such as artillery shells. Presses of both toggle and screw types are used. They have somewhat different action; the toggle press gives more of a squeezing and the screw press gives a sudden pressure or bump approaching that of a hammer. The screw press consists essentially of an enclosed frame similar to a drop hammer with lower die mounted on the anvil. The upper die is carried on a double- or triple-thread screw, which is turned through a large wheel by two friction disks rotating on opposite sides of the wheel. When in contact with one disk, the screw is rotated rapidly in a direction to drive the die down onto the anvil; then the other disk is thrown into contact, reversing the screw and raising the die. The operation of the toggle presses is similar to that of forging machines, as described in another article in this Handbook (page 38).

Hydraulic or steam-hydraulic forging presses are used principally for the production of steel forgings, usually of the larger sizes. The purely hydraulic type is driven by pumps, usually acting through an accumulator. The steam-hydraulic type uses a steam-hydraulic intensifier to supply the water at high pressure for the press cylinders. Such presses consist essentially of one or more cylinders, usually mounted on the top of the press, to which water at high pressure is admitted. The admission of water into the cylinder pushes down a ram to which is attached the crosshead, which is guided by the press columns. The upper die is attached to the lower face of the crosshead. The lower die is supported on a base plate to which the columns are also attached. Thus the whole unit is self-contained, and only a simple foundation is required. For lifting the crosshead, auxiliary cylinders supplied with either steam or water are usually attached to the main cylinder or its entablature.

The largest forgings ever produced have been made in forging presses of the hydraulic or steam-hydraulic type.

Tools for Hammers and Presses. The tools used in connection with forging hammers and forging presses find their counterparts in the blacksmith's hand tools.

Auxiliary equipment on the forging hammer must with-

* *See* "Mechanical Press Forging", page 41 in this Handbook.

stand the vibration or impact of the forging blows. Because of this, manipulators have not been developed and used on hammers as extensively as they have been applied on presses. Smaller forgings are held in tongs, sometimes supported by chains from overhead. Occasionally the shape and dimensions of a forging are such that it need not be held in tongs or similar equipment, but is kept in place on the die by lever bars. Larger forgings are held by porter bars that have an enlarged end or chuck for holding the piece to be forged, and a counterweight on the opposite end. Manipulators or charging machines may be used to charge and remove pieces from the heating furnace and to place them on the die where they may be grasped by tongs, porter bars or similar holders.

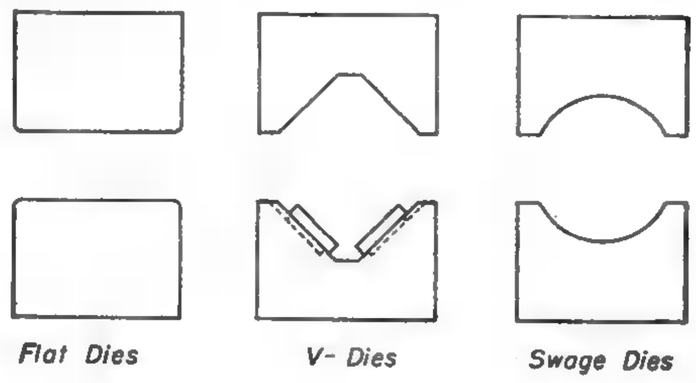

Fig. 4 Simple forms of forging dies

Manipulators for forging presses have been so far developed that now virtually all but the larger forging presses have such equipment. Because of the absence of shock, manipulators are used to hold the piece on the die, to feed it between the dies between squeezes, to rotate it and so on. The selection of the proper manipulators for a press plant is important because it has a vital effect on the efficiency and production of the shop. Manipulators may be suspended from an overhead crane, but are more frequently operated on the shop floor, often on rails. They utilize power-operated grip jaws to hold the forgings.

The largest forgings are held on presses by means of chains actuated by power-operated sprockets for turning.

Auxiliary tools for hammers and presses include slicing bars for cutting forgings to length, pegs for gages or spacing blocks used in bringing forgings down to size, V-tools to initiate setdowns or changes in section on forgings, and swages for finishing rounds.

Forgings are frequently cut to length at the hammer or press with a gas torch. Burning equipment is also frequently employed for hot scarfing or the removal of surface defects. Availability of such equipment at the forging tool makes it possible to remove defects with a minimum delay, without need for controlled cooling and removal by machining, chipping or grinding.

Dies. Dies may be considered the most important tools used on hammers and presses. The dies for closed-die or drop forging must be most carefully designed, made and treated. These dies are described in another article in this Handbook (page 36). Dies for open work are of three basic types, as shown in Fig. 4.

Flat dies are most commonly used for hammer work. Even round forgings, such as those used for the manufacture of round bars or shafts, may be forged down in flat dies as hexagons or octagons, and the corners may or may not be knocked off subsequently, or the forgings may be rounded in swage dies.

The use of V-dies, either for both upper and lower dies or for the lower die alone with a flat upper die, is most common for press operations. The greater the power that can be exerted by the press, the larger the die surface that can be used, and therefore the more effective the press can be in working the central portions of large masses.

Mandrels, both supported and unsupported at the ends, are used for hollow forgings. Punches are used for opening holes in or through forgings. Coring tools are also used for the same purpose.

Hammer and Press Operations. The principal forging operations, performed either by the hammer or the press, are as follows:

1 *Rounding up, cogging or roughing.* These first operations on the ingot are meant to refine and rearrange the surface crystals and to consolidate the central portion of the ingot.

2 *Cutting or slicing.* This operation cuts blocks, billets or forgings to length.

3. *Forging down or drawing.* This operation increases the length and decreases the diameter of the piece.

4 *Upsetting or forging* so as to change the major axis of the forging through an angle of 90 deg. Thus bars are upset to form disks.

5 *Setting down.* This reduces the cross-sectional area of a portion of the forging, as the journals of a shaft are forged down. Large "setdowns" are accomplished under the press, using a V-tool to start the reduction. Large fillets should always be allowed.

6 *Punching or coring.* Punches are used to pierce or open a hole through a forging. The hole is usually carried almost all the way through; then the forging is turned over, and the punch is started from the opposite side. Only a very small portion of the metal is removed. Coring utilizes a hollow punch to cut out the central portion.

7 *Hollow forging on mandrels.* After holes have been punched or cored, mandrels may be inserted, and the forging is then continued on the mandrels to produce hollow cylinders or rings. Mandrels are supported at the ends for expanding the piece by forging between the upper die and the mandrel. The forging down or drawing of hollow forgings is carried out on the unsupported mandrel.

Conditioning of Semifinished Steel

BY THE SUBCOMMITTEE ON CONDITIONING OF SEMIFINISHED STEEL*

IN the fabrication of steel, rejections of product are occasionally caused by steel imperfections, such as pipe, segregation, porosity, seams, laps, scabs, slivers, and the like, that are developed in the casting, heating and rolling of ingots into blooms, billets and slabs. Semifinished steel is inspected and conditioned to remove defects that are considered injurious for the intended application, in order to avoid the shipment of steel of unsatisfactory quality.

Inspection Prior to Conditioning. As a preliminary to conditioning for surface imperfections, steel is inspected for internal defects. Methods of inspection consist of:

1 *Examination of Sheared Ends for Piped Steel.* Pipe will usually show as a fairly distinct lip on the sheared end.

2 *Fracture Testing.* (*a*) To fracture, only shallow nicking or cutting is required, so most of the fractured cross section may be examined for pipes, cooling cracks, and injurious porosity or segregation. (*b*) Hardened disks are fractured in the inspection of certain steels to evaluate the results of deep etching. A hardened disk of full cross section is broken under a hammer or special fixture and longitudinal surface or surfaces are exposed. In some instances the piece is nicked in order to localize the break.

3 *Etch Testing.* A cross section is sawed from the billet and etched in hot acid, a test that will reveal any pipe condition present, and also segregation, blowholes, and general unsoundness of the interior, if present to an injurious extent. (*See* the article on page 389.)

Because internal defects cannot be removed after the steel is made, unfit material must be rejected. Accordingly, any internal inspection or testing is usually completed and rejections are disposed of before surface conditioning.

Extent of Conditioning. The extent of conditioning work performed depends on the final application of the steel.

*The members of this subcommittee are J. H. Flaherty, *Chairman* (Jones & Laughlin Steel Corporation), J. B. R. Anderson (Carnegie-Illinois Steel Corporation), E. V. Bennett (Bethlehem Steel Company), L. Fogg (Youngstown Sheet and Tube Company) and H. J. Weigel (Republic Steel Corporation).

When the surface requirements of the finished product are nominal, the conditioning is merely sufficient to remove scabs, tears, or heavy slivers, in order to permit passage of the billets through the rolling stands without damage to guides or rolls.

The majority of commercial products, including bars for cold finishing, bending, machining, welding, or common forging purposes, require somewhat better conditioning. This involves the removal of open and deep seams, cracks and slivers, but not the removal of light surface seams.

The most severe trade requirements, where a minimum of seams is essential in the finished part, necessitate extra processing and conditioning and make mandatory the removal of all visible defects. In order to reveal small defects, mill scale may be removed by high-pressure water jets, pickling, shot blasting or torch descaling.

Although surface conditioning is largely confined to semifinished steel, frequently forging ingots, castings, forgings and finished bars are conditioned for removal of similar defects.

Methods of Surface Conditioning. In early practice, surface conditioning was performed rather roughly with hand hammers and chisels. When that method was found inadequate, special beds were provided where the steel could be inspected closely and defects could be removed with pneumatic chipping hammers. Chipping involves a great deal of manpower and has led to the successful development of other methods. Some of these new methods employ machine tools, variously referred to as billeteers, deseamers, or gougers (which, in principle, are flexible-head planers or millers). Such tools are capable of cutting larger and deeper chips of metal more quickly than the pneumatic hammer. They are useful where the entire surface is to be removed or where deep defects are involved, and are particularly applicable to billets and blooms more than 4 in. sq.

Currently, torch scarfing is perhaps the most widely used conditioning method. The oxyacetylene torch has been progressively developed until today, in the hands of a competent operator, it will remove a great deal more metal per hour than a chipping hammer. Since the cost of fuel is a major factor, natural gas and other substitute fuels are often used. One of the main disadvantages of torch conditioning lies in the reaction of hardening grades of steel to the high temperature of the torch, and the quenching action of the adjacent cold steel. Steel of such grades is preheated before scarfing or torch cutting operations, to avoid the quenching action and residual stresses.

Turning or peeling steel on special lathes is another means of conditioning. This method is used for the most part on round billets for piercing into seamless tubes. It is necessary to inspect turned rounds to detect seams not removed by the arbitrary cut, and their removal by chipping or scarfing is a supplementary operation. The advantages of the method are that less prior conditioning is required and complete removal of the surface metal is effected rapidly.

Grinding is still another conditioning method, used on extremely hard alloy steels where other methods are not applicable. It is usually employed where seams or defects are fairly shallow. The billets are placed in position under a grinder track, which relieves the operator of the load of the wheel, and makes it necessary for him to apply his weight only at the spots to be conditioned.

Methods of Quality Control.* One of the duties of the steel works metallurgist is to minimize steel defects through quality controls in the melting, pouring, heating and rolling operations. Such controls are exerted through designation of the chemical limits, deoxidation, pouring, mold preparation, ingot handling schedules, heating and rolling practices.

To hold down conditioning costs, rejections and losses, many methods are employed, including hot topping, improved mold design, mold preparation, reheating, rerolling, hot scarfing in the mill, and slow cooling.

For certain grades or qualities, the use of a refractory top on the ingot mold is primarily to concentrate all the contraction cavities, porosity, slag enclosures and excessive chemical segregation within the hot top portion, and to eliminate such defects from the main body of the ingot.

Mold preparation involves proper mold surfaces, temperature, cleaning and coating, to avoid defects caused by splash, spray, hanger cracks, bleeding or pits.

"Saddening" is the taking of two to eight light passes on a heated ingot and then recharging into the soaking pits in order to toughen the skin. Reheating at some intermediate stage in the rolling also permits scaling and makes possible higher temperatures and greater plasticity in the finishing passes. This is known as "double conversion" and tends to minimize surface defects. Conditioning may be resorted to at the intermediate stage in conjunction with the double conversion.

In recent years, scarfing torches have been set in some mills for the removal of the original surface of the bloom or slab during the rolling operation. These torches remove from $\frac{1}{32}$ to $\frac{3}{16}$ in. of surface metal and have the advantage of working on hot steel. However, they are not selective in their operation; they remove the entire surface under the torches and not merely localized defects. Deep defects that will not be removed in this way require further conditioning.

Some grades of steel are air hardening; that is, they will harden during cooling in still air. When that occurs, enough stress may be developed to crack the billet or to emphasize cracks or seams already present. In order to avoid this, the semifinished steel is piled hot in pits, buried in ashes or set in covered cars and cooled slowly. More recently, furnaces for controlled cooling (gas- or oil-heated) have been installed in some mills, to enable suitable control of temperature for each grade of steel. Such a procedure has the advantage of increasing cooling capacity, because of better control of cooling cycles, and gives greater assurance of freedom from flakes.

Internal Defects. The more common types of internal defects found in semifinished steel are the following:

1 *Pipe.* A cavity formed in metal (especially ingots) by contraction during solidification.

2 *Porosity or Blowholes.* These terms describe unsoundness produced, during the solidification of the metal, by evolved gas failing to escape and being held in pockets which elongate in rolling.

3 *Segregation.* This is the variation of chemical composition throughout the ingot, caused by selective freezing of the various soluble constituents of steel. Segregation may be negative as well as positive, as expressed in variation from the average composition of the heat.

4 *Inclusions and Stringers.* Nonmetallic particles caused by deoxidation products or slag, which become entrapped during solidification. They are present in greater size and number in sulfurized steel.

5 *Flakes or Cooling Cracks.* Two theories exist as to the cause of these internal cracks or discontinuities which may occur in steel that has been improperly cooled: (*a*) Cooling stresses are occasioned by difference in temperature between the inside and outside of an ingot, bloom or billet, and hydrogen content. (*b*) Hydrogen is assumed to come out of solution at subcritical temperatures and to build up pressures that cause ruptures.

Factors promoting flakes or cooling cracks are: rapid rates of cooling, large sections, high carbon content, high alloy content, and cold weather.

Cooling cracks present in large sections can sometimes be welded completely by a reheating and rerolling operation, assuming that there is a sufficiently large reduction in cross section.

Surface Defects. The principal types follow:

1 *Seam.* A crack in the metal surface, which has been closed but not welded. These are caused by cracks in ingots, which have been elongated during rolling.

2 *Scab.* A flat bead of metal caused by a rolled-in splash on the ingot surface.

3 *Sliver.* An elongated layer of metal loosely adhering to the billet and usually caused by elongation of surface tears in rolling.

4 *Spongy, Burnt or Feathery Surface.* A condition attributed to insufficient deoxidation, chemical composition, excessive flame impingement in blooming-mill heating, or improper rolling temperatures.

* For information concerning the application of statistical methods to quality control, see the article on page 187.

5 *Corner Cracks.* A crack in bloom or billet, resulting from planes of weakness developed at mold corners or corrugations during solidification of the ingot.

6 *Lap.* A surface defect that has the appearance of a seam, caused by folded-over hot metal, fins or sharp corners, rolled or forged but not welded into the surface.

7 *Overfill.* Excessive metal on the corner of rolled steel, resulting from improper rolling temperature or incorrect setting of rolls. *Underfill,* or incomplete filling of corners, is a defect of an opposite nature.

8 *Double Skin.* A lamination type of defect, showing a surface layer separated from the main body of the bloom by a thin film of oxide. Double skin is usually at a maximum in the bottom part of an ingot, and is frequently caused by solidification of original metal splash followed by partial remelting and incomplete welding in rolling.

9 *Guide Scratches.* Scoring caused on the surface of the billet, in the direction of rolling, by improper setting or poor condition of guides.

The imperfections described above are the main surface defects, although occasional instances of rolled-in scale, embedded refractory or other foreign matter, may occur.

Heating Steel for Forging

BY THE SUBCOMMITTEE ON HEATING STEEL FOR FORGING*

THE details to be observed in the practice of heating and forging steel depend to some extent on the type and size of forging, the method of forging, the composition of the steel and the subsequent disposition of the forging. The following suggestions for heating prior to forging are based on normal good practice for the production of carbon and low-alloy steel forgings from bars and billets as large as 9 in. square. The heating of stainless steels, tool steels and the other highly alloyed ferrous materials is not discussed specifically in this article; however, many of the general considerations mentioned here apply also to the more highly alloyed steels.

Eight major factors should be considered in the heating and forging of steel: scaling, decarburization, overheating, burning, equipment used for heating, rate of heating to forging temperature, forging temperature, and cooling after forging.

Scaling. The surface layer of iron oxide resulting from exposure of steel to oxidizing atmospheres at high temperatures is called scale. Scaling causes loss of metal and loss of time in removing the scale, and is responsible for other forging difficulties. Scale may react with the refractory of the furnace lining or hearths to form a slaglike material, with consequent deterioration of the refractory. Scale is often hammered into the surface of the forging, causing a pitted surface and sometimes sticking of the piece in the forging dies. Since it is desirable to have as little scale as possible, a minimum time of heating should be employed. The presence of free oxygen in the furnace atmosphere causes a decided increase in scaling. However, when the presence of free oxygen is avoided, little is gained in reduction of scale if more than a moderate excess of carbon monoxide is present. It has been found that in a gas-heated furnace, using ordinary city gas, nearly the same amount of scale is formed when the atmosphere contains 8.0% CO as when 0.5% CO is present, and it is necessary to exceed 12% CO before a marked reduction in scaling is produced. This applies also to furnaces heated with oil or butane, provided no free oxygen is present. The rate of scaling increases rapidly with increased temperature.

Decarburization. Little is known about the rate of decarburization in different atmospheres at forging temperatures higher than 2000 F. It is probably safe to assume that increasing the heating time or temperature will increase the depth of decarburization. Since decarburization causes great loss of strength at the surface, all precautions should be taken to avoid decarburization or to be certain that the decarburized layer is machined off. Because forging bars and billets are nearly always decarburized as received from the mill, and under ordinary conditions of heating for forging, some additional decarburization will occur, it is essential to machine off the decarburized layer if resistance to high stress is required.

When the hardness of unmachined forgings is measured, it is necessary to remove the decarburized layer in the area to be tested, in order to get accurate readings.

Overheating. Overheating may be produced in the forgings by heating to such a high forging temperature that the austenite grains become excessively large. This grain size results in impaired physical properties of the metal, unless the grain is refined by proper mechanical or thermal treatment. It has been found that the overheating of alloy steels can be so severe that normalizing, quenching and tempering does not refine the grain or refines it incompletely. This may be most easily observed by fracturing perpendicular to the grain flow, after normalizing, quenching and tempering to about 300 Brinell. Sufficient further mechanical working of the steel, as by forging or other means, will eliminate this coarse grain condition, provided it is done at temperatures below those causing the overheating.

Burning. If parts are heated to a temperature above that causing severe overheating, the phenomenon known as burning occurs. Burning is an extremely overheated condition that causes the more fusible constituents of the steel to melt. This melting usually occurs at austenite grain boundaries and results in hot shortness of the material. The term burning, as applied to steel, is somewhat misleading, because the chemical reaction of the steel with oxygen is not necessary to produce the so-called burning. This is evident since steel that is burned entirely on the inside, may appear quite satisfactory on the surface. In general, however, the surface of a burnt forging shows evidence of the burning. The burning of steel entirely on the inside is usually caused either by decarburization on the surface or by an inside temperature much hotter than the surface at the time of forging. However, the presence of turbulent free oxygen in the atmosphere surrounding the steel will usually cause the steel to burn at a much lower furnace temperature than with no free oxygen.

Burning may occur in the heating furnace before the steel has been forged at all. Especially when the flame is of an oxidizing nature, direct impingement of it against the steel is likely to produce spot burning or overheating, and should therefore be avoided. Likewise, impingement of a jet of air against the steel is to be avoided in the heating furnace. Above about 2400 F, air oxidizes steel so rapidly that the temperature of the metal will increase because of this reaction. However, air may be used to blow the scale off the steel during the forging operation, provided the proper forging temperature is not exceeded.

Equipment. Several types of forge furnaces are prominent in the heating of billets for forgings; of these the slot type, gas or oil-heated, is the most common, although it is the most difficult in which to attain good automatic temperature control. For better control, closed furnaces are more desirable, such as the stationary-door type, rotary-hearth or continuous-pusher type, all usually heated by gas or oil. (*See* "Fuels and Fuel-Heated Industrial Furnaces", page 267, and "Electrically Heated Industrial Furnaces", page 273.) Because of the greater ease of temperature control and better control of the heating cycle, continuous furnaces should be employed whenever possible. The use of the continuous furnace has advantages, in that the stock can be uniformly preheated at any rate of heat input desired, and the cycle or time in the furnace can be standardized under mechanical control, thus removing the danger of leaving the stock in the furnace too long or not long enough. Electrical induction heating has been used

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for some special applications. (*See* the article on "Induction Heating", page 280.)

All the furnaces mentioned above should have equipment for control of temperature, such as a platinum-rhodium thermocouple or a controlling radiation-pyrometer sighted on the inside of a refractory tube. Extreme care must be taken to protect these couples from contaminating influences, such as iron, silicon and carburizing gases; and frequent checks are necessary in order to be certain of the accuracy of the thermocouples. It is important that the thermocouple should record the temperature of the steel and not that of a cool part of the furnace or flame temperature. By far the most frequent cause of difficulty with temperature-controlled equipment is inequality of temperature in the furnace so that the thermocouple does not indicate the temperature of the steel.

If optical or radiation pyrometers are used, it should be remembered that smoke, the reflection of incandescent flames on furnace walls, the distance from the hot object, the presence of scale and lack of blackbody conditions appreciably affect the accuracy of the reading. It is possible to correct for lack of blackbody conditions and the presence of scale, but much smoke or reflection from flames may make the readings valueless. On the other hand, if conditions can be made ideal, accurate readings are obtainable with the optical pyrometer. (*See* "Pyrometry", page 174.)

In heating with oil, the selection of the proper burner is essential; good atomization and proper combustion are not only economical but lead to safe heating practice. The burner selected should be as simple in design as possible for easy maintenance and for good atomization, and should be constructed to avoid the formation of carbon deposits ("nigger heads") in the burner or furnace. The design of the port and installation of the burner should be given much thought if the burner is to be efficient and economical to operate and repair. When heavy oil is used, provision for preheating the oil must be made in order to obtain proper combustion. Heavy fuel oil is satisfactory for use as a forging fuel when proper precautions are taken to insure satisfactory uniformity of temperature and pressure. The viscosity of oil varies with temperature. Unless special precautions are taken, constancy in rate of flow may be interrupted by alterations in line pressure caused by variations in oil temperature, pump pressure, discharge pressure at the end of the tail pipe, fluctuating use of oil throughout the circulating system, and other conditions subject to change. The temperature-viscosity index of different fuel oils varies. Precautions should be taken also to prevent stratification of various shipments of oil in storage tanks and undue accumulation of sludge. Sludge accumulation may be hastened by overheating. Oil should be free from water, solids and other foreign matter when it reaches control equipment or burners.

Rate of Heating to Forging Temperature. The time of heating should be just sufficient to bring the center of the bar or billet to the forging temperature. Longer heating than this results in greater scale formation, greater decarburization and larger grain size.

Plain carbon steels of 0.50% C and less, in sizes up to and including 3 in. in diam or thickness, may be heated at the maximum rate of 5 min per in. of diam or thickness; alloy steel bars 3 in. in diam or thickness may be heated at the maximum rate of 6 min per in. of diam or thickness. From 3 in. to 9 in., the heating time per inch of diameter or thickness should not be less than 15 min. Although this is common practice, some metallurgists consider a slower rate more desirable. For steel that contains more than 0.50% C somewhat slower rates of heating should be used in order to avoid rupturing from too rapid heating. The rate of heating to be used will depend on the size of the bar and its composition. In general, bars that contain 1% C or more and have a diameter of 1 in. or more, should be preheated between 1300 and 1400 F before being placed in the forging furnace.

Forging Temperatures. The safe forging temperature for steels depends on the composition of the steel, the furnace atmosphere, the temperature-measuring equipment, furnace equipment and type of operation.

In general, for either carbon or alloy steels the forging temperature is lowered as the carbon content of the steel is increased. The effect of the various alloying elements on the forging temperature must be considered in relation to the quantity used and the other elements that are combined with them.

The flow of steel or its plasticity at the forging temperature depends on the composition of the steel and the forging temperature. The higher the forging temperature, the greater the plasticity, with resultant low operating costs; but the finishing temperature is then generally higher, producing coarser grains. With higher forging temperatures the steel is heated nearer to the overheating and burning range; consequently good furnace equipment and accurate devices for measuring temperature are necessary to avoid the danger of burning.

Table I gives the maximum temperatures recommended for forging carbon and alloy steels.

Table I. Maximum Forging Temperatures

Carbon, per cent	Maximum forging temperatures for carbon steels, deg Fahr	Maximum forging temperatures for alloy steels, deg Fahr
0.10	2400	2350
0.20	2375	2300
0.30	2350	2250
0.40	2350	2250
0.50	2300	2200
0.60	2250	2200
0.70	2225	2175
0.90	2150	
1.10	2075	
1.50	1900	

The term "alloy steels" means the usual structural, oil-hardening steels, such as the 4300, 4600, 5100 series and the like. Certain types of stainless steel, steels for use at high temperatures, and tool steels require special time-temperature cycles and, in some instances, special furnace atmospheres.

Finish Forging Temperature. The temperature at which to stop forging depends on several factors, all of which must be considered. It should be well above the transformation range to prevent rupturing of the steel and excessive wear on the forging and trimmer dies. It should be low enough to prevent excessive grain growth. Except for high-carbon steels, a finishing temperature of 2000 F should prove satisfactory.

Cooling after Forging. The rate of cooling after forging is an important factor in the production of sound forgings. Too rapid cooling results in internal ruptures. The material used and the size of the finished forging are controlling factors in determining the rate of cooling.

Alloy steels are much more susceptible to cooling bursts than plain carbon steels. Small forgings with sections less than 3 in. are usually permitted to cool in air. Large forgings weighing more than 100 lb frequently require slow cooling, even though their section is less than 2 in. When slow cooling is required, it is usually accomplished either by furnace cooling or by burying in a medium such as crushed blast-furnace slag. If blast-furnace slag is used, the rate of cooling can be controlled to some degree by the size of the slag particles. It is desirable to bring the temperature down to 350 F before removing the steel from the slow cooling pits.

Precautions to be Observed in Forging.

1 Cold steel should not be loaded into a hot furnace when larger sizes are used. Sizes up to 4 in. in diam are commonly put into a hot furnace, unless made of high-carbon or special alloy steel.

2 The steel should be heated slowly until the transformation temperature range has been passed, then rapidly to the desired forging temperature.

3 The desired forging temperature should be determined and controlled.

4 Stock should not be held at the forging temperature for a long time. (For alloy steels, 30 min at 2200 F should be the limit.)

5 The initial forging operation should be performed in such a way as to prevent rupturing.

6 Material susceptible to cooling bursts should be cooled slowly after forging.

The Hot Working of Large Sections

BY THE SUBCOMMITTEE ON LARGE FORGINGS*

VARIOUS PRECAUTIONS must be observed in hot forming large sections. No definite over-all rules can be set down. Size, chemical composition, working facilities and the like are the governing factors. As the carbon or alloy contents and size increase, careful control becomes increasingly important.

Further, methods of production will vary, depending on a number of conditions, such as whether or not the melt and forge shops are integrated, whether hammers or presses are available, the capacity of the equipment, and other contributing factors. The capacity of the forging tool must be adequate to work the entire section.

In general, trouble may be avoided by observation of the following precautions:

1 Heat the metal slowly and as uniformly as possible.
2 Preheat cold steel when size and composition require this treatment.
3 Control the furnace atmosphere properly.
4 Soak the steel fully at forging temperature, but do not burn or overheat. Avoid direct impingement of the flame on the metal.
5 Charge the entire piece into the furnace whenever practicable.
6 When the composition is susceptible to thermal ruptures, protect heated parts extending from the furnace by covering with heated hoods.
7 Use equipment of sufficient capacity.
8 Completely remove surface defects that open during hot forming, during the same operation, or before the next hot operation.
9 When size or composition requires it, control the cooling to prevent thermal ruptures.

Proper forging technique will avoid internal bursts and lack of consolidation of the central metal, and will ensure best direction of flow lines. Forging operations should be conducted so that the axis of the ingot is maintained in the most favorable relation to finished forging contours.

Where the melt and forge shops are integrated, it is the usual practice, in handling ingots, to transfer them hot from the melt shop to the forge furnace in order to prevent cracks. Where the melt and forge shops are not integral, the size and composition of the steel dictate the method of handling. Under these conditions, it is usually necessary with large ingots, and always with alloy steel ingots, to apply a treatment cycle before they cool to room temperature. Cold ingots, or cold billets of large section or of high alloy content, if not charged into a cold furnace, should be warmed by using a preheater, by heating in water, by placing the metal pieces adjacent to a hot furnace or by some similar method, before charging into the hotter furnace. After this preheating, the ingot or semi-finished steel should be heated very slowly and uniformly, particularly in the lower temperature range, when heating for forging. Ingots that have been stripped hot and charged into heated furnaces, should be equalized at a safe temperature before the reheating cycle is started.

In heating for forging, when the differential between the forging and the furnace is more than 500 °F, the steel should be equalized at furnace temperature, after which the temperature should be raised gradually to approximately 1200 F. At this temperature, the metal should be equalized again for uniformity throughout the mass. From about 1200 F to the forging temperature, the heating may be accelerated, but precautions must be taken not to overheat locally. It must be emphasized that the heated ingot or billet should be as uniform in temperature as possible, before forging.

During the forging operation, the hot work should be stopped when the forging has cooled to about 1500 F, and the partially forged part should be reheated uniformly to forging temperature. On the other hand, as much reduction as is consistent with good practice should be carried out between the heating operations, since extra reheating means loss in weight by scaling. Ample forging reduction should be left for the last forging operation, if control of the finishing temperature is important.

The maximum temperature to which the part should be heated depends primarily on the composition of the steel being used. In general practice, the maximum forging temperature varies between 2100 and 2400 F, depending on the carbon content of the steel. As the carbon content of the steel decreases, the higher forging temperatures in this range may be used.

Control of furnace atmosphere is necessary in good forging practice. Neutral or slightly reducing atmospheres are recommended. Oxidizing atmospheres cause excessive scaling.

When forging large parts, it is a general practice to forge all over the surface first with fairly light reduction. This first reduction can then be followed by heavier reduction consistent with good forging practice. In many instances, the ultimate purpose for which the part is intended may dictate the method of hot forming. As an example, a long shaft forging, subject to torsional stresses, should be drawn out longitudinally; whereas for parts subject to radial stresses, the hot working operation should include some upsetting.

Top and bottom discards vary with the plant practice and the type of product. Sufficient top discard should be cut to remove all central ingot shrinkage that would be injurious in the finished product and as much more as the specification may require. Sufficient bottom discard should be cut to remove any defects that would be injurious in the finished product.

During the hot forming operations, it is quite common for surface defects to open. These tears or cracks should be removed before the operation is continued. The method of doing this varies in different shops, but is ordinarily along the following lines:

1 Hot chipping under the press with special gouges
2 Hot scarfing with special lances
3 Hot grinding
4 Annealing the partially forged part where necessary and removing defects by chipping or grinding; then reheating and further forging

After forging, the best practice is to employ controlled cooling, especially when handling types of steel susceptible to flaking (thermal cooling cracks). A number of different methods and cycles are used before allowing the forging to become cold. Typical cycles include prompt transformation and holding at a temperature that will provide most rapid diffusion of hydrogen and relief of transformation stresses. This temperature varies with different grades of steel but the desired results can usually be accomplished at 1100 to 1200 F. Another cycle includes charging the part into a hot furnace as soon as the forging operation is completed, then equalizing at some temperature approximating the Ac_1 transformation point and cooling slowly until all sections are below the lowest transformation temperature. The controlled cooling may also be co-ordinated with the heat treating cycle. Repeatedly heating and cooling the steel through the transformation range tends to prevent the formation of flakes. Another method employed for large, highly alloyed parts is to forge the ingot partially to a block and then to cycle anneal, reheat, finish the forging operation, and finally to cool under controlled conditions. A widely used method is to cool the forgings very slowly in ashes, pits, silocel, or other insulating material.

Large, hollow cylindrical forgings are made from bored or cored ingots or blocks and are hot worked on a mandrel.

There are no set rules concerning the capacity of press or hammer to be used for individual parts. However it is necessary that the press or hammer should have sufficient capacity to work the steel thoroughly throughout its section.

The amount of hot reduction, though sometimes limited by specifications, varies considerably and is often governed by the ingot sizes that are available.

The steel must be sufficiently worked throughout the mass to refine the ingot structure. The best general practice is to use the smallest ingot that will give the desired amount of hot reduction. Where tangential tests are required, excessive drawing out is objectionable; however, results of longitudinal tests benefit by this practice.

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The Piercing of Steel

By Stevenson Findlater*

THE forging operation in the production of seamless steel tubes is classified under four general headings: rotary piercing, hydraulic piercing, cupping, and extrusion. Of these four methods, rotary piercing is ordinarily employed for quantity production.

Rotary Piercing. In the rotary piercing of steel (Fig. 1), the principle of helical rolling is employed. The two steel rolls that bring into play the forces used to produce the cavity in the work piece are located side by side and have their axes inclined at angles (6 to 12 deg) opposite the horizontal center line of the mill. The shafts of these rolls are mounted in bearings, which can be adjusted laterally in the housing to permit the space between the rolls to be properly set for the size of work piece being rolled. The roll surfaces are contoured so that in a horizontal plane through the center line of the pass, the space between the rolls converges toward the delivery side for a length of about 10 in. to a minimum, called the "gorge", and then diverges for approximately 12 in. to form the pass outlet. The elevation of the center line of the pass is determined by two guides, one of which is mounted above and the other below the center of the mill.

Between these guides in the pass outlet, a tapered piercing mandrel is held in position on the end of a water-cooled mandrel support bar located on the delivery side of the mill. The pointed end of the piercing mandrel extends just beyond the gorge toward the entering side of the rolls. The opposite end of this bar is mounted in a thrust bearing, which is carried in a reciprocating carriage that is latched in a stationary position during the piercing.

A solid round bar or billet of the proper length and diameter (2 to 14-in. diam by various lengths to 18 ft) to make the size and weight of tube desired, is heated uniformly to the usual temperature for rolling light sections. With the rolls revolving at a constant speed (800 to 1000 surface fpm) the heated billet is transferred to a horizontal trough that keeps the axis of the billet coincident with the center line of the pass.

The heated billet is pushed forward into the space between the rolls, which have been adjusted so that the gorge is approximately ¾ in. smaller than the diameter of the billet. As soon as the billet has come in contact with the rolls, the force of the pusher is removed. Because of the obliquity of the roll axes, the motion imparted to the billet by the rolls is one of rotation and axial advance. When the leading end of the billet has advanced to the gorge, it encounters the nose of the piercing mandrel. The grip of the rolls is sufficient to continue the advance of the work piece against the retarding effect imposed by the piercing mandrel. Once the end of the piercing mandrel has penetrated the axial center of the billet, the mandrel serves as a third roll so that, with a properly designed pass, the metal of the work piece is helically rolled over the piercing mandrel (rather than extruded) to produce the hollow shell. These shells—as long as 40 ft—are produced in 10 to 30 sec. It should be especially noted that the amount of metal displaced increases considerably as the size is increased. Resulting difficulties have been overcome by further reduction of the wall thickness of the hollow shell through additional rolling in a second piercing mill. This practice has permitted the total displacement to be divided between two operations when large tubes are made. Additional rolling operations are performed on the pierced shells to produce finished tubes.

Hydraulic Piercing. In hydraulic piercing, a heated solid blank, usually of square section, is dropped into a cylindrical container located directly in line with the plunger of a hydraulic ram. The descending plunger causes the piece to assume the shape of the cylindrical container as it is displaced up and around in the space between the plunger and container. When the down stroke has been completed, the plunger is withdrawn by reversing the direction of the ram, after which the pierced blank or cup is ejected by a kicker pin. When this process is augmented by hot drawing, wherein a powerful plunger forces the cup through a push bench in which a series of annular dies or grooved rolls are installed, the length of the piece may be extended to form a tube.

Hydraulic piercing (Fig. 2) is used in the production of large and small cylinders, such as water bottles, gas, and air bottles, and as the primary operation in manufacturing tubes by the "push bench" method.

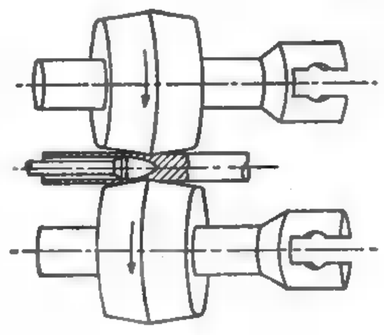

Fig. 1

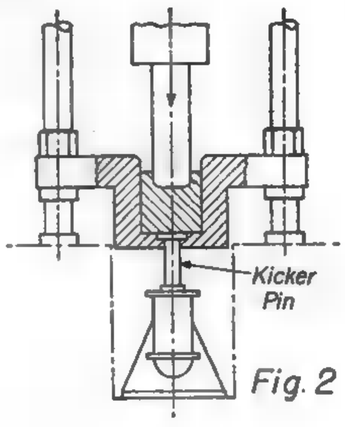

Fig. 2

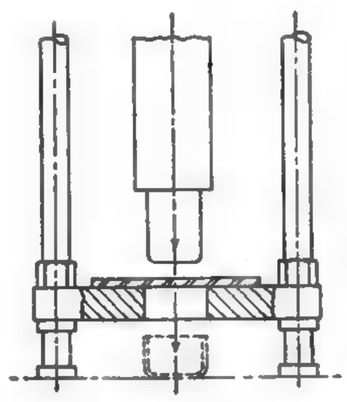

Fig. 3

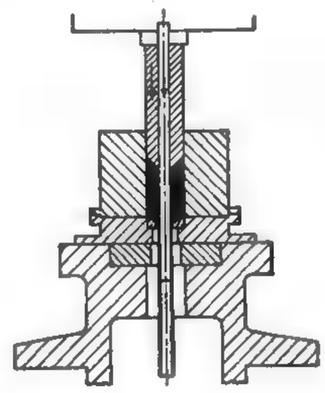

Fig. 4

Fig. 1 Mannesmann pierces, piercing solid billet
Fig. 2 Hydraulic piercing, solid blank
Fig. 3 Cupping operation, plate
Fig. 4 Extruding solid billet

Cupping. In the cupping process (Fig. 3), steel plate of required thickness is sheared, machined or gas cut to circular shape. The heated plate is accurately placed over a die centrally located beneath the plunger of a hydraulic ram. The descending plunger forces the plate through the die to form a cup, which is removed when the plunger has been withdrawn. To avoid buckling when cupping, the annular opening between the plunger and the die is proportioned to exceed the initial thickness of the plate. Requisite alterations in the length, wall thickness, and diameter of the heated cup are subsequently made in a push bench. This process is in common use in manufacturing containers for oxygen and acetylene and for other cylinders which require a closed end.

Extrusion. The extrusion process (Fig. 4) has not been used for the production of steel tubes in the United States, although several European plants employ it. The elevated temperatures which provide the necessary plasticity of a steel work piece require that the operation be rapid to avoid excessive transfer of heat and severe wear of tools during the working stroke of the press. This requisite has resulted in the development of the practice known as "impact extrusion" in which the work stroke, in extruding tubes 30 ft long, is completed in less than 3 sec. In this process, either bored or solid rounds are heated and placed within a cylindrical container, in the bottom of which a die is mounted in alignment with a crank or hydraulically operated plunger. When solid rounds are used, a differentially actuated piercing punch is enclosed within the extrusion plunger. In operation, the weight of the extrusion plunger is allowed to rest on the surface of the work piece while the piercing punch is forced through the work piece and die. When the end of the piercing punch has passed through the die, the piercing and extrusion plungers are locked together, permitting the piercing punch to act as a moving mandrel, while the rapidly

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moving extrusion plunger forces the work metal through the annular opening between the die and piercing punch. Pressures greater than 90,000 psi obtain within the container in producing the 20 to 1 section reduction usually employed. When the plungers have been withdrawn, a flash that remains in the bottom of the container is sheared off, thereby releasing the extruded tube from the die.

When bored rounds are used, the piercing punch is ordinarily attached directly to the working end of the extrusion plunger. The operation is the same as when solid rounds are used, except that piercing is omitted.

Because of the great pressure required, the application of the extrusion process to the manufacture of steel tubes has been limited to tubes less than 5 in. in diam.

Steels for Piercing. The piercing processes described above have enabled seamless tubes to be made from most types of steels and many nonferrous alloys. Usually, killed open hearth and electric furnace steels are preferred, but satisfactory seamless tubes have been made from capped open hearth steels that had been melted under certain prescribed conditions.

Most commercial steels are available as seamless tubes. The SAE steels, high-sulfur free-machining steels, ball- and roller-bearing race steels, and many stainless and heat-resistant alloys are now satisfactorily pierced. In general, steels that have two phases (austenite plus ferrite) at forging temperatures (2000 to 2300 F) are difficult to pierce by the rotary process, but can be formed in the cupping or extrusion processes. Nonferrous alloys that contain more than one phase are also more readily pierced by extrusion methods. Steel is seldom extruded because the high forging temperatures and high pressures are severe on extrusion tools, but the process has been highly successful on nonferrous alloys.

The steels used for seamless tubes must be sound both externally and internally because of the severe forging operations involved in piercing. Steel shown by deep-etching tests on cross sections to be sound and dense, free from porosity and ingot pattern, is most satisfactory for seamless tubes. Tube steels must also be free from surface defects, so it is common practice, before piercing, to peel round or plane square sections in addition to treating them by conventional chipping methods.

The Manufacture of Hot and Cold Rolled Steel Sheet and Strip

BY THE SUBCOMMITTEE ON STEEL SHEET AND STRIP*

HOT and cold rolled sheet and strip, unlike other steel commodities, are used primarily in consumers' goods. This type of market requires materials that are serviceable under a wide variety of conditions, and also adaptable to low-cost techniques of mass production and to considerations of sales appeal in the finished product.

Hot and cold rolled sheets and strip must therefore incorporate, in various degrees and combinations, ease of fabrication, predetermined strength after fabrication, adequate resistance to corrosion, ductility, attractive appearance before and after fabrication, as well as compatibility with various coating processes and materials. In special compositions, such as the alloy and stainless grades, some or all of these qualities are procurable, as well as the properties commonly associated with flat rolled materials. To attain these characteristics under the most economical conditions for production, the bulk of the tonnage of flat rolled steel (which in peace time amounts to about one-fifth of the total steel output) is of low carbon content.

Until the advent of the wide continuous strip mills, all hot rolled sheets were produced from sheet bars on the old-style hand sheet mills. As the wide strip mills continued to develop, more and more hot rolled sheets were produced on these newer mills, until at the present time only a small percentage of the hot rolled sheets are produced on the old hand mills.

Most continuous hot strip mills are capable of producing hot rolled sheets in thicknesses down to and including 18-gage, so that currently those producers who have both continuous and hand-operated mills, produce the 18-gage and heavier sheets on the continuous mills and the lighter sheets on the old hand mills.

Classification of Sheet and Strip. The classification in Table I shows the ranges of thickness and width for sheets and strip. Because of overlapping in the width range of manufacturing facilities there is no sharp dividing line between sheet and strip from a manufacturing standpoint. The selection of facilities will be governed by requirements and by the equipment available.

Hot Rolled Sheet or Strip. Sheets and strip can either be hot rolled directly to the desired thickness, or hot rolled to an intermediate thickness and then cold rolled to the desired thickness. The latter process is used if improved surface finish or special temper and properties are desired. Hot rolling is classified here as including rolling operations in which the material is heated before it is passed between the rolls. Sheets are hot rolled by a number of methods—on broad hot strip mills from slabs, on hand mills from sheet bar, and on hand mills from broad strip sheared breakdowns.

Broad Hot Strip or Continuous Mill Practice. The rolling of broad hot strip, or "sheets in coils", has been a continuous development since 1926, when the first mill was built capable of rolling a strip more than 24 in. wide. The strip process differs from the sheet process since in the strip process, the reduction is performed in long lengths subsequently cut up or coiled, while in the sheet process, the reductions are performed in unit lengths or a small multiple of a unit length.

In strip practice the rolling is generally done parallel to the axis of the ingot, while in sheet or hand mill practice, the rolling may be done either parallel to the ingot axis (breakdown practice), or partially transverse to the ingot axis (sheet bar practice).

In strip rolling, a slab ingot is cast and rolled to a slab 3 to 6 in. thick and of a width and length suitable for charging into the slab-reheating furnace, where it is brought up to a temperature of 2200 to 2300 F for rolling.

The broad strip mills consist of a roughing train and finishing train set in tandem, with the finishing train set on close centers, so that the strip is in all the finishing stands at the same time. The number of roll stands can be varied to suit the variety of products manufactured in any given mill, but usually varies from 4 to 7 roughing stands and from 4 to 8 finishing stands. The roughing train usually consists of a two-high scale-breaker to break up the scale on the surface of the slab, and a spreading mill to spread the slab, when necessary, to the desired width of strip, after which it is turned 90 deg and squeezed to straighten the edges. The slab is then rolled to the desired thickness of the rough bar, in the rest of the roughing mills, which are usually of the four-high type and equipped with vertical edging rolls to hold an accurate width in the bar. In the roughing reductions, the slabs, as they progress through the mills, are usually sprayed with water under high pressure to descale the surface. As a modification in practice, the slab can be rolled to a rough-down bar on a reversing universal mill. After roughing, the bar goes through another scale-breaker and high-pressure spray and into the four-high hot strip stands, where it is reduced to the desired thickness. The speed of these mills is synchronized so that each successive mill takes the strip at a speed exactly the same as the

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The section on Flattening was prepared by R. S. Burns (American Rolling Mill Company).

Table I. Standard Classification by Size of Flat Rolled Carbon Steel

Width, inches	Thickness, inch							
	0.2500 and thicker	0.2499 to 0.2031	0.2030 to 0.1875	0.1874 to 0.0568	0.0567 to 0.0344	0.0343 to 0.0255	0.0254 to 0.0142	0.0141 and thinner
To 3½ incl	Bar	Bar	Strip	Strip	Strip	Strip	Sheet	Sheet
More than 3½ to 6 incl	Bar	Bar	Strip	Strip	Strip	Sheet	Sheet	Sheet
More than 6 to 12 incl	Plate	Strip	Strip	Strip	Sheet	Sheet	Sheet	Sheet
More than 12 to 32 incl	Plate	Sheet	Sheet	Sheet	Sheet	Sheet	Sheet	Blk Plate
More than 32 to 48 incl	Plate	Sheet	Sheet	Sheet	Sheet	Sheet	Sheet	Sheet
More than 48	Plate	Plate	Plate	Sheet	Sheet	Sheet	Sheet	....

Cold Rolled

Width, inches	Thickness, inch		
	0.2500 and thicker	0.2499 to 0.0142	0.0141 and thinner
To 12 incl	Bar	Strip[c]	Strip[c]
More than 12 to 24 incl	Strip[a]	Strip[a]	Strip[a]
More than 12 to 24 incl	Sheet[b]	Sheet[b]	Black Plate[b]
More than 24 to 32 incl	Sheet	Sheet	Black Plate
More than 32	Sheet	Sheet	Sheet

(a) When a particular temper, as defined in ASTM Specification A 109, or a special edge or special finish is specified.
(b) When no special temper, edge or finish is specified.
(c) When the width is greater than the thickness, with a maximum width of ½ in. and a cross-sectional area not exceeding 0.05 sq. in, and the material has rolled or prepared edges, it is classified as flat wire.

delivery speed of the preceding mill. The delivery speed varies from 1000 to 2100 fpm. The finishing temperature can be varied over a considerable range by varying the slab-heating temperature and the time of holding the slab before it enters the strip mill. In general, the finishing temperature varies from 1300 to 1600 F and must be closely controlled in order to keep the thickness uniform throughout the length, and to provide desired grain size and mechanical properties.

After the strip has been delivered from the last stand, it can be either coiled, or cut to length, flattened by leveling and piled. It must be coiled or piled at a temperature low enough to avoid appreciable grain growth.[1]

The product of the hot strip mill has a wide variety of uses. It may be cut as breakdowns for a hot sheet or hand mill, if a lighter gage is desired than can be produced on the hot strip mill. It may be shipped directly, or after heat treating and pickling, if better properties or surface are necessary for the particular requirements under consideration. After being pickled in coils, the strip may be further processed by continuous cold reduction for the production of lighter gages than can be rolled directly on the hot strip mill. It may be used also for applications where closer control of thickness is required, as well as a better and smoother surface than can be obtained on a hot strip mill.

The process for narrow strip is similar to that for broad strip, except that lighter equipment can be used and less power is needed. The wider the strip desired, the more massive the equipment must be and the greater the power requirements, which are approximately 400 to 500 connected hp per in. of width capacity.

In producing 18-gage and heavier hot rolled sheets on continuous strip mills, rimmed steel is ordinarily used. Typical ladle analyses will show approximately 0.05 to 0.10% C, 0.25 to 0.50% Mn, 0.03% P max, and 0.045% S max. Where only mild forming is involved, a certain latitude is permissible, especially for phosphorus and sulfur. In sheets for deep drawing, the phosphorus in particular, and the sulfur are held as low as possible. Further variations in mechanical properties necessary to fit the requirements are usually secured by subsequent treatments, such as normalizing, open annealing, box annealing, cold rolling, or pickling.

Sheet Bar Practice. The sheet bar practice for the production of hot rolled sheets involves the rolling of an ingot to a rectangular sheet bar. The bar is usually 8 or 12 in. wide and ½ to ¾ in. thick, in order to allow cross rolling on a hot hand mill to the desired thickness and length. The sheet bar is cut so that the length is slightly greater than the width of the sheet to be made from it. The hot mill consists of two stands of rolls, known as the "roughing" and "finishing" stands, and two furnaces. One of these furnaces is known as the "pair furnace" because the bars are withdrawn in pairs for rolling; the other furnace is called the "sheet furnace" because in it the partially rolled sheets are reheated for finishing. The sheet bars are heated in the pair furnace to a temperature of 1300 to 1600 F, depending on the grade of steel and the surface finish required. After the pair of bars has been withdrawn from the furnace, they are rolled to the breakdown gage in single thickness until partially reduced; then the two pieces are matched and rolled in pairs (double thickness) until the breakdown gage is reached. At this point the breakdown sheets are matched, reheated in the sheet furnace, and then rolled to the desired sheet thickness.

After hot rolling to the desired thickness, the sheets in packs are trimmed to the desired dimensions and separated. They are then ready for further processing.

Sheared Breakdown Practice. This process is somewhat like the sheet bar practice, except that the breakdowns are sheared from broad hot rolled strip of a width slightly greater than that of the desired sheet, and of a length sufficient to make a sheet of the desired gage and length. The breakdown operation is eliminated and consequently only one stand of finishing rolls is necessary. This practice lends itself readily to the utilization of continuous pack-heating furnaces and mechanized feeding and catching tables.

In the pack rolling of sheets in the lighter gages (20-gage and lighter), the pressure of the rolls tends to weld the sheets together. This effect can be counteracted by adding phosphorus to the steel, or phosphorus in combination with silicon, a practice sometimes followed, particularly for 26-gage and lighter sheet. However, both phosphorus and silicon harden the steel, and where ease of forming or deep drawing is required, these elements are often a hindrance.

Cold Rolled Sheet or Strip. Sheet and strip are cold reduced to the desired thickness for several reasons: to obtain the desired surface finish, to impart desired mechanical properties, to make gages lighter than the hot strip mill can produce economically, and to produce sheet and strip of more uniform thickness.

The cold reduction can be accomplished either in unit

lengths or in coils, but it is more economical from the standpoint of yield to perform the reduction in coils.

The harder grades of steel, such as alloy, electrical and higher-carbon compositions, are carefully cold reduced to finished gage by introduction of a softening anneal between the first and second stages of cold reduction.

There are numerous types of equipment for performing the cold reduction, but as in hot strip mills, the wider the material to be cold reduced, and the thinner the desired gage, the more rigid the mill, and the more power required. For narrow widths (less than 20 in.) the reductions can be performed conveniently on two-high mills, but for the greater widths, the four-high mill is used almost entirely. As the width is increased or the thickness is decreased, the diameter of the backing-up rolls is increased. The diameter of the working roll is kept as large as is compatible with the maximum screw pressure allowable.

The amount of cold reduction performed is governed largely by the application that is being considered. For example, sheet and strip for drawing are cold reduced from 30 to 70% in thickness. Increasing amounts of cold reduction will tend to make the resulting sheet and strip finer grained and harder after annealing.

For cold reducing steel sheet and strip, equipment is available that makes use of the following applications of power to effect the desired reduction: all power applied to the working rolls; all power applied as forward and back tension; power applied partly to the working rolls and partly as forward tension; and power applied to the working rolls, also as forward and back tension.

All Power Applied to the Working Rolls. The cold tandem sheet mill, or single-stand mill for reduction of strip breakdowns in units, is an example of this method of application of power, which involves the production of more scrap because of the multiplicity of ends sheared from the sheets when heavy reductions are performed. This method is also used extensively in skin rolling sheets after annealing, in order to remove the tendency to form stretcher strains when drawn. Skin rolling involves little reduction in thickness of the section.

All Power Applied as Forward and Back Tension. This method of application of power is employed by the "Steckel Mill", a four-high mill with small working rolls for rolling coiled material. This type of mill is limited in the amount of cold reduction that can be taken in a given pass but, built to reverse, it can reduce steel any number of passes and to any practical thickness desired. The small-diameter working rolls present a small surface area and hence wear rapidly and must be replaced frequently or whenever the surface of the strip being rolled is unsatisfactory. This mill is popular for extremely hard or thin materials and high-priced specialties with extremely close tolerance in variation of thickness.

Power Applied Partly to the Working Rolls and Partly as Forward Tension. This method of reduction is followed in a great majority of tandem cold reduction mills where coil stock is used. In general, the reduction mill is made of three, four or five tandem stands of four-high mills, with a reel that produces forward tension. The capacity of this type of mill is governed largely by the thickness and width being rolled, and by the delivery speed of the mill. Cold mills making tin-plate gages, deliver up to approximately 4000 fpm, whereas the heavier sheet gages are usually delivered up to 1000 fpm. This type of mill has the advantage of high capacity and low cost for labor and for rolls, although the investment is high. Disadvantages are a lack of flexibility for rapid changes in section, and the limited number of passes received by the metal.

Power Applied to Working Rolls, also as Forward and Back Tension. This application of power is exemplified by the single-stand reversing mill. This type of mill, radically different from the Steckel mill, is not limited in the amount of reduction per pass or in the possible number of passes. Besides, such a mill requires a lower investment cost and less floor space than a tandem mill. The energy expended in back tension is regenerated by driving the back reel as a generator against the line load. The back tension also serves to reduce the screw pressure and the net energy required for the deformation. On the other hand, the investment per ton capacity, the cost of labor, and the cost of rolls, is higher than for a tandem mill.

Annealing of Sheet and Strip. It is necessary to perform some annealing operation on hot reduced and cold reduced sheet and strip unless a hard temper is desired. This may not be necessary on some hot rolled strip finished at 1500 to 1600 F or more, and coiled hot so that an annealing is accomplished in the coil. If the sheets are reduced to gage below the recrystallization temperature, as they are on the sheet bar finishing mill, or in cold reduction practice, the grain structure is fragmented, resulting in preferred orientation.

There are a number of softening operations used in the production of sheet and strip. The most important of these are the following: cold strain, low-temperature recrystallization annealing; normalizing; and stress-relief annealing.

The Cold Strain, Low-Temperature Recrystallization Anneal. This process may be used on material cold reduced more than 30% and on hot rolled material finished at a temperature low enough to give strain equivalent to that of material rolled cold. This type of annealing, also known as "processing annealing" and "box annealing", is carried out by placing coils or stacks of sheets on a bottom plate and then covering. The charge may vary from 5 to 200 tons, depending on the size of the sheet or strip and the height of the stack. After heating to the predetermined temperature, variable from 1100 to 1400 F, the charge is allowed to soak until the temperature is uniform throughout, after which it is allowed to cool before being uncovered.

This annealing may be carried out in stationary furnaces into which the charge, including plate and cover, is inserted for the necessary heating and soaking, and then removed for cooling; or in the radiant-tube type of furnace, in which the plate is stationary and the furnace is lifted from charge to charge for the necessary heating and soaking. The source of heat may be gas, coal, oil or electricity.

Material that has been cold reduced or descaled before annealing is usually "bright annealed" in a protective atmosphere, in order to prevent the formation of oxide on the sheet during the heating, soaking and cooling cycle. This protective atmosphere is ordinarily produced by partially burning natural, coke-oven or butane gas to a gas composition that is slightly reducing to iron oxide, but will not break down further and deposit carbon at the annealing temperature. Most of the water vapor produced from the partial burning is removed from the protective gas by refrigeration. Material that is intended to have an oxide finish is either annealed without the protective atmosphere, or "steam blued" by adding steam under the cover, after the charge has been removed from the furnace and when the temperature has decreased to below 1100 F.

Normalizing. The normalizing operation consists of heating the sheet or strip to a temperature above the Ac_3 point (approx 1650 F for a steel that contains 0.10% C max) and cooling to room temperature. This recrystallizes and refines the grain structure through the medium of a phase transformation. The normalizing operation is utilized to the greatest extent on hot reduced material to produce improved drawing properties, since often a low-temperature box anneal would result in critical grain growth resulting from a low residual strain in the hot reduced product.

Furnaces for normalizing sheets are usually of the chain type, roller type or walking-beam type. Fuels may be gas, oil or electricity. With electric furnaces or muffle types, it is possible to "bright normalize" by using an inert or a reducing atmosphere to protect the surface of the strip from oxidation.

The grain size and hardness of normalized material can be controlled within limits by varying the soaking time above the Ac_3 point, and also by varying the cooling rate from the Ar_3 to the Ar_1 point.[2]

Stress-Relief Annealing. This operation is a low-temperature pack or box anneal performed in order to improve the drawing properties by removing the residual stresses that have resulted from the rapid cooling during the normalizing operation, and during leveling or light rolling operations after normalizing. This operation, commonly

known as a "second anneal" or "white anneal", is carried out in the same manner and with the same equipment as the cold strain box anneal, except that the temperature of annealing is in the range between 950 and 1200 F. A protective atmosphere can be used under the cover to prevent oxidation, or the charge may be steam-blued.

Typical values for mechanical properties of mild steel sheet and strip, after the annealing operations referred to, are given in Table II.

Table II. Mechanical Properties of Steel Sheet and Strip

Condition	Yield Point, psi	Tensile Strength, psi	% Elong in 2 in.	Rockwell Hardness Number	Olsen Cup, inch
0.035-in. Sheets					
Hand Mill	50,000	65,000	10	B 70	0.200
Hand Mill Annealed	22,000	38,000	30	B 40	0.390
Hand Mill Normalized	28,000	45,000	35	B 48	0.400
Cold Reduced	85,000	85,000	2	B 90	0.100
Cold Reduced Annealed	28,000	44,000	40	B 45	0.410
0.048-in. Sheets					
Hot Strip	40,000	60,000	30	B 65	0.380
Hot Strip Annealed	33,000	52,000	35	B 55	0.400
Hot Strip Normalized	30,000	48,000	40	B 50	0.420
Hot Strip Normalized and Annealed	25,000	43,000	45	B 45	0.420

Temper Rolling. The processing of cold rolled sheet and strip is varied to control the mechanical properties within the ranges found most suitable. This is done by controlling the hot strip practice, the amount of reduction, the annealing, and the final amount of cold rolling after the anneal. These influencing factors are worked out according to the equipment and conditions in each plant, so that the finished material will have certain desired physical characteristics. The amount of cold work can vary from a pass through the roller leveler, which does not affect the thickness to any appreciable extent, or a pass on the skin mill with reductions up to a maximum of several per cent, to heavy cold rolling that reduces the thickness as much as 50% or more. The increase in hardness compared with the annealed condition depends on the amount of cold work done after annealing. The ductility decreases rapidly as the amount of cold work increases.

Surface Characteristics. The surface texture of sheets and strip can be varied between rather wide limits. For chromium plating and similar finishes, a smooth bright surface is necessary, but for porcelain enameling and many drawing operations, a certain dullness or roughness of surface is more suitable. In porcelain enameling, roughness tends to improve the uniformity of coating and the adherence of the enamel; and in certain drawing operations where heavy pressures are developed, the duller type of surface retains more lubricant, helping the sheet to draw better. This type of surface also seems to aid in the distribution of the draw. Minor surface imperfections and slight strains are not so noticeable on a dull surface as on a bright one. However, the surface should not be so dull that subsequent paint finishes will not cover. The smooth surface may be obtained by grinding and polishing the rolls, and the dull surface may be obtained by either etching or shot-blasting.

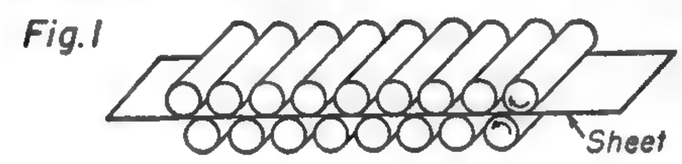
Flattening. Sheets are ordinarily sold in two grades of flatness: commercial flatness, in which the sheets are to be severely drawn, so that the original flatness does not have much effect on the shape of the drawn article; and the stretcher-level standard of flatness, in which the sheets are used for panel work, where little forming is done on the sheet and the finished product is desired flat and free from buckles. Simply because sheets are flat before moderate forming does not necessarily mean that they will be flat after fabrication, unless the fabricator takes care that no buckling occurs in the sheets during forming. Commercial flatness can ordinarily be produced on a roller leveler or on temper rolls, but where very flat sheets are required, producers may resort to stretcher leveling or other processes producing a similar standard of flatness.

The permissible variations for commercial standards of flatness in hot and cold rolled sheets and stretcher-leveled standards of flatness are set up by the Technical Committees of the American Iron and Steel Institute, and are stated in their Steel Products Manual, Section 11.

Roller Leveling. A roller-leveling machine consists of two sets of several horizontal rolls of small diameter, held in a housing and arranged so that the top and bottom rows are offset, permitting the rollers to mesh. Consequently the sheet passing through the leveler is flexed alternately up and down (Fig. 1). The amount of flexing is decreased in proceeding from the entrance to the exit end of the leveler. Near the exit end the action is chiefly that of straightening.

Stretcher Leveling. Stretcher leveling is a positive means of producing flatness by stretching the sheet lengthwise between jaws (Fig. 2). The stretching may vary from about 1 to 3% elongation, which exceeds the elastic limit of the steel and hence results in some permanent elongation. It is necessary that the sheet be processed before stretching, so that it will spring back uniformly across its full width and remain flat.

Other types of equipment suitable for producing the stretcher-level standard of flatness are also being used by some manufacturers.



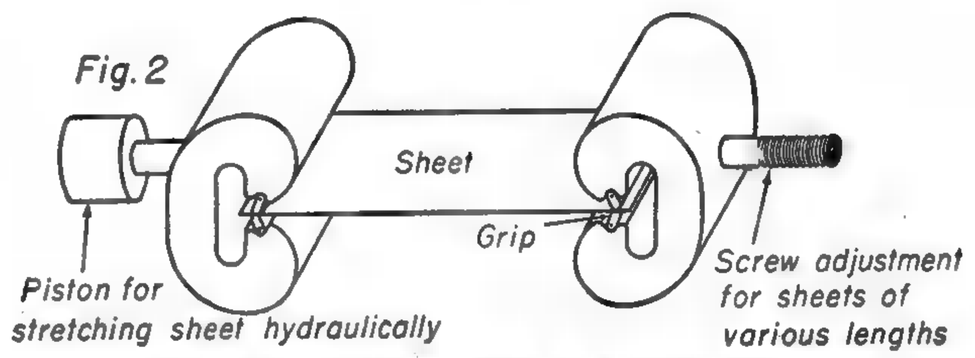


Fig. 1 Diagrammatic sketch of a roller leveler
Fig. 2 Diagrammatic sketch of a stretcher leveler

Mechanical Testing. Tests for hardness, ductility and tensile properties are widely used for sheet metal products. For detailed information concerning these tests, the reader may refer to the articles on pages 93, 105 and 128.

For testing the drawing qualities of the material during processing at the mill and at the time of shipment, tension tests are too time-consuming. Consequently the simpler and more rapid tests, such as Rockwell hardness and the Olsen or Erichsen cup-draw or ductility tests, are used as a guide in controlling the quality of the product. In the Olsen and Erichsen cup tests, the surface near the break gives an indication of the grain size, the position of the break gives an indication of the amount of cold work the material has received after annealing, and the shape of the break gives some indication of the character of the anneal. It is usually possible to establish some correlation between Rockwell hardness, ductility tests and actual performance in the drawing dies; it is ordinarily considered that hardness tests and cup tests, properly evaluated, are indicative of drawing quality, but are not a guarantee of satisfactory performance. For determining the drawability of sheets for deep drawing, Boulger and Dahle[3] have described a new test that does not require a compensation for differences in thickness.

Microscopic Examination. The microstructure of the metal is most important in the deep drawing and extra deep drawing grades. Usually samples are taken parallel to the direction of rolling, but it is often desirable to examine the structure in both the longitudinal and transverse directions. Individual samples may be mounted in bakelite or a number of samples may be bolted together, so that the cross section may be polished and examined.

All steels contain nonmetallic inclusions. Whether or not these are harmful depends on the number, size, type and distribution of them in the steel. The same is true of the carbides that are found even in the very low-carbon steels or irons.

Various types of drawing require different grain structures, varying from rather large to very fine grains. The grain structure may be controlled within reasonably close limits through control of the composition of the steel and

close control of processing. Usually the grain size will vary somewhat from the surface to the central plane of the material as a result of segregation. On a straight rolled material there will be some difference in grain size from edge to center, and some difference from end to midlength of sheets cross rolled from sheet bars.

Any irregularity in normalizing, and the usual differences in temperature within the annealing box, are reflected as slight differences in grain size. These are normal and expected differences that cannot be entirely eliminated. These differences affect the drawing quality only when they are abnormally large.

At present there are many variables in testing practice, and it would be almost impossible to devise "standard" tests that would meet all contingencies to the satisfaction of both producer and consumer.

Inspection. Certain defects are more likely to occur on strip and sheet made by the continuous process, while certain other defects found in sheet-mill sheets are absent from the strip product. The following is a partial list of the imperfections that may be found during inspection—some warrant immediate rejection, others cause the material to be degraded into a lower class, or rejected, depending on the severity of the defect.

Annealing border
Annealing sticker
Blisters
Camber
Chatter
Coil break
Corrugations
Dimples
Dirt pits
Enter and end marks
Fluting
Grease pits
Hickey
Hot mill scale
Laminations
Loose oxide
Normalizer break
Normalizer scale
Not flat
Pinchers
Pipe
Reel kink
Roll mark
Roll stop (for mill adjustment)
Scale pattern
Scratches
Slivers
Stains
Strains
Stringers

Fabrication. Breakage in drawing operations often is not the fault of the material. The die practice may be poor, as a result of poor design, improper clearance, too much deformation between anneals, improper hold-down or drawing adjustments, or poor lubrication. In some instances the sheet is too thin for the amount of deformation it is expected to withstand.

When multiple draws are involved, there is always a possibility of allowing too much time to elapse between successive drawing operations, with the result that the sheet may age and undergo consequent changes in properties, and breakage. In many instances this hazard can be overcome by expediting the various operations, or by using nonaging steel.

Winlock and Kelley[4] have stated: "The manner in which the draw is accomplished is, within limits, of equal if not greater importance to the success of the operation, than the physical properties of the steel itself." Montgomery[5] points out that, next to design of the dies, lubrication is the greatest factor in producing good stampings. "Efficient lubrication in production operations will effect a greater net saving to the average stamping plant than any other single factor except die design and construction."

The actual strength of the sheet or strip for most forming and drawing jobs is comparatively low. Except in the harder tempers, where the carbon content may be as high as 0.25%, the steel used for drawing contains a maximum of 0.10% C, determined by ladle analysis. Winlock and Kelley state[6] in regard to the strength of the material: "Strength and rigidity are usually imparted to a stamping by designing it so that it will most effectively resist the forces imposed upon it in use by virtue of a high section modulus."

Aging.* Aging of rimmed and capped steels is another factor influencing the drawing quality of sheet and strip. A material at the time of shipment may be perfectly suited for the job, but if it is not used within a reasonable time and aging takes place, probably increased breakage will result and surface disturbances will be present in the finished part. The amount of aging depends on the composition, method of manufacture of the steel, amount of skin rolling, time and temperature of storage and the original hardness range of the material.[7, 12]

After a material has aged to a certain extent, it loses in ductility, and if it is then worked or formed, stretcher strains occur. Winlock and Lavergne,[8] along with many others, have studied "stretcher strains", "worms", or "Lüder's lines", and have found that this disturbance may occur in parts deformed 1.5 to 10% during forming. In tension, the lines are low spots; in compression, they are elevations. These investigators attribute the stretcher strains to fluctuations at the yield point. Cold working, by roller leveling or skin rolling, generally eliminates the sharp yield point and the tendency to stretcher strain.

Composition Suitable for the Various Grades. The whole field of low-carbon steel (less than 0.15% C), as it relates to the manufacture of sheet and strip, has received much less attention in educational and research institutions than its economic importance deserves. Since the difference between success and failure in any given job may amount to only a small number of defective parts in each hundred fabricated, it is imperative that both the application and the processing of the steel be carefully controlled.

Except for special compositions, or special requirements, rimming steel is used for the majority of sheet and strip applications. The softness and ductility of rimming steel are particularly well suited to certain work, such as deep drawing and forming. In some applications the type of steel makes no particular difference, but in some fabricating requirements killed steel is preferred.

In a rimmed steel the dissolved gases are allowed to separate as the liquid metal freezes. The rimming action progresses until the ingot is capped or freezes over the top. When properly carried out, rimming produces a thick-skinned ingot with a heavy "rim", which may be hot rolled with a minimum of surface defects. The rimming action also reduces the carbon content and, to a lesser extent, the manganese content, in the outer or rim portion of the ingot, and increases the content of these elements at the "core" or segregate. This segregation of metalloids accounts for variations in composition found in different parts of a sheet or order.[9, 10]

Killed steels are made by adding a sufficient quantity of a strong deoxidizer to the furnace, ladle, or ingot molds. The deoxidizing materials have a greater affinity for oxygen than carbon, iron or manganese have, and form largely stable insoluble compounds that may be eliminated during subsequent solidification, processing and cropping. Since little gas is formed, either by reactions or by gases coming out of solution, the top of the ingot freezes rapidly and the ingot solidifies as a comparatively homogeneous mass with little segregation taking place. The compositions of the various parts of the ingot are more uniform than in a rimmed steel.

These characteristic differences in the two types of steel have definite effects on the sheet and strip produced from them. The rimmed steel has a thicker skin, which results in a sheet comparatively free from surface defects. A killed steel generally has a more sensitive skin, which may or may not be ruptured in the mills during hot reduction from the ingot to the bar or slab. If a rupture occurs, it may result in either surface laminations or seams. For this reason, when surface is important, rimmed steels are generally used.

A modification of rimmed steel that is finding increasing application is the so-called "capped" grade. This differs from rimmed steel in that the top of the liquid metal in the ingot mold is artificially chilled either by the introduction of a steel cap or by the addition of shot aluminum to provide a solid top, while the bulk of the ingot metal is still fluid. This greatly reduces the effervescing action in the metal and serves to trap most of the dissolved gases, thus providing less over-all segregation while maintaining the surface benefits of the low-metalloid skin. Largely because of the entrapped gases, such a steel is inherently finer grained, harder and less ductile than rimmed steel, but is proving satisfactory for applications requiring a uniformly fine grain throughout the section.

There are certain advantages in favor of the killed steels, such as uniform composition and properties.

In recent years extremely deep draws have led to the development of a fully aluminum-killed steel of high uniformity and excellent ductility. This grade, subject to the natural surface disadvantages of killed steels, and requiring extremely careful control of all processing steps,

* *See also* the article entitled "Aging of Iron and Steel", page 438.

has provided fabricators with a material eminently suited to economical production techniques.

In the heavier gages, such as those rolled on the hot strip mill, many specifications require special mechanical properties or check analyses. Here killed steels are often specified or required, because the composition of the sheet will usually correspond closely to the ladle analysis.

The characteristics of rimmed steel leave much to be desired, especially in the deep drawing of cold reduced sheets. Although, with present methods of control, greater uniformity from heat to heat is now possible, there still remains the variation within the ingot (top to bottom as well as rim to core) and the variation from ingot to ingot within a heat. Differences between top and bottom may be somewhat lessened, if desired, by diverting the top portion and, on occasion, even the bottom portion of the ingot to other work. However, such diversion is not economical. In straightaway rolling, the rimmed area is usually in the hold-down of the die where it is not detrimental.

Perhaps the most objectionable characteristic of rimmed steel in cold reduced sheets is the aging that occurs after the final temper rolling. This is manifested by the return of the tendency to stretcher strain, by an appreciable increase in hardness and yield strength, and by a decided decrease in ductility, as measured by cup tests, by elongation in tension testing and by performance in the press shop. Aging begins immediately after the final cold working, but it is usually not serious until after three or four weeks. The extent to which it affects performance depends largely on the properties of the steel at the time of temper rolling. For example, a 20-gage sheet with a hardness of 45 Rockwell B and Olsen value of 0.420 in., may age harden to Rockwell B 50 and 0.400-in. Olsen value and still draw satisfactorily. However, if the initial Rockwell B hardness had been 50 and the Olsen value 0.400 in., and the same amount of aging had occurred, it is possible that breakage would result in certain difficult fabrication.

The theory of aging of cold reduced sheet and strip has been fairly well established, and material is now being marketed in which the aging characteristics have been virtually eliminated.

Sheets for Specialized Application. *Sheets for Porcelain Enameling.* Sheets for porcelain enameling are subjected to high temperatures during the fusion of the enamel, and may warp and sag considerably unless the composition and processing are closely controlled. A typical composition for a sheet of suitable quality for vitreous enameling, is 0.03% C, 0.05% Mn, 0.010% P and 0.025% S. Some improvement in drawing quality may be obtained by increasing the manganese content to approximately 0.15%.

Low-Alloy High-Strength Sheets. The low-alloy high-strength steels are used when higher strength and improved resistance to atmospheric corrosion are required. These steels are used primarily for transportation equipment where greater strength of the steel allows appreciable saving in weight.[11] These steels have a minimum yield strength of 50,000 to 60,000 psi and a minimum tensile strength of 65,000 to 75,000 psi. The minimum elongation is generally around 20%. Various elements and combinations of elements are used as strengtheners in this type of steel, in order to obtain the best combination of strength, ductility and resistance to corrosion. The ranges are approximately as follows: 0.12% C max, 0.20 to 2.00% Mn, residual up to 0.200% P, 0.045% S max, residual up to 1.00% Si, 0 to 1.5% Cr, 0.30 to 1.75% Cu, 0 to 2.25% Ni, 0 to 0.12% Mo, 0 to 0.20% Al.

Electrical Sheets. Sheets with guaranteed magnetic properties are furnished to several subdivisions of the composition range 0.03 to 0.08% C, 0.15 to 0.45% Mn, and 0.20 to 4.50% Si, with other elements as low as possible. These grades may be manufactured by either the hot rolling or the cold reducing processes, or by both.

Metallic Coatings. In recent years there has been considerable development in coatings for sheet and strip.

Tin coatings may now be applied by either the hot dip method or by electrodeposition. The same is true of galvanized or zinc coatings. Coatings of terne (an alloy containing approximately 85 to 90% Pb and 10 to 15% Sn) are applied by the hot dip method. More recently sheets with a much higher lead content in the coating have appeared on the market. A number of producers of sheet are now able to supply sheets with a coating of zinc phosphate to promote adherence of paint.

For information concerning metallic coatings, the reader may refer to pages 703 to 724 in this Handbook.

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Cold Drawing Steel Wire

By A. E. Hibschman*

WIRE is a term that may be applied to any thread or filament, or to any slender rod or bar of metal that has a uniform cross section. A great many products shaped by pulling metal through a die are called wire. The most common shapes are round, square, hexagonal, octagonal, oval, half oval, half round, and flat or rectangular. Numerous other regular and irregular shapes are produced. As many as 785 different shapes of wire have been made by one manufacturer.

Wire is of ancient origin. Evidence has been found that the Assyrians and Babylonians used wire as long ago as 1700 B.C. Almost nothing is known about the methods of manufacture used by these ancients, although the specimens of ancient wire that have been found are flat and were probably made by hammering. It is not known when, how, or of what material round wire was first made. Many believe that drawn wire was used for making the chain armor worn by the knights in the Middle Ages.

Available records indicate that wire was drawn on a commercial scale in France as early as 1270. The first wire mill in this country was built in 1775 by Nathaniel Miles at Norwich, Connecticut.

General Description of Process. The limits for drawn wire range from 0.001 in. to approximately 1 in. in diam. The process of drawing steel wire begins with the rod hot rolled in coils that weigh from 100 to 600 lb, depending on the type of rod mill and quality of rod desired. The fabrication of the wire and requirements of service determine whether Bessemer, acid or basic open hearth, or electric-furnace steel should be used. Alloy steels are used mostly for the coarser sizes of wire, which are subjected to heat treatment to develop special mechanical properties. Com-

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binations of composition, heat treating of rods and process wire, and cold working, may produce a wide range of properties for a varied range of applications.

The range of composition of plain carbon steel is 0.05 to 1.30% C, 0.15 to 1.65% Mn, with the other elements standard for the type of steel.

Most common wires are drawn from a No. 5 size (0.218 in.) rod, which is the smallest usually hot rolled. The largest percentage of the wire is drawn dry; however, fine sizes and some special finishes are drawn by the so-called wet process.

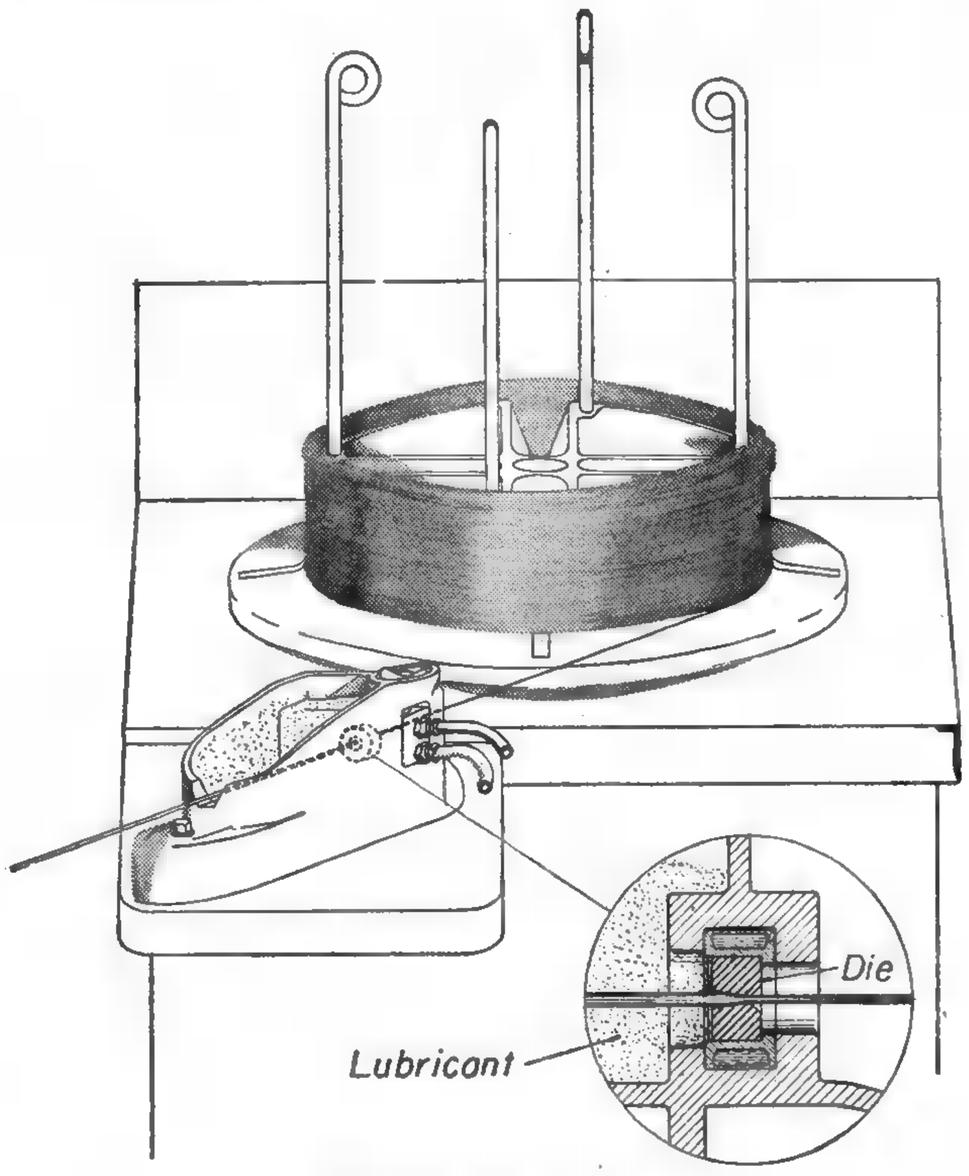


Fig. 1 Wire-drawing block

Usually the rod is cleaned in hot acid, coated with lime or some other alkaline solution, baked, and drawn through a die with a dry soap lubricant in the die box. The rod is swaged to a point, then pulled through the die and the end is anchored to the wire-drawing block, which then revolves, drawing the wire continuously and coiling it on the block. (*See* Fig. 1.)

In wet drawing, the wire, after having been cleaned, is usually metallic coated by dipping in a solution of copper and tin sulfates, and is then drawn with a solution of soap or soluble oil as lubricant.

Cleaning and Baking. The production of good wire depends on the proper cleaning of the rods before wire drawing. Insufficient cleaning leaves residual scale on the rods, produces scratched wire and reduces die life, while overcleaning causes a pitted, rough and mottled surface with possible acid brittleness of the wire. The rods are usually cleaned by immersion for 15 to 30 min in a vat of hot sulfuric acid, the concentration of which is governed by the composition and type of material being cleaned (pickled). Inhibitors in the acid bath prevent excessive use of acid, which would cause a loss of steel, pitting of the steel surface, and excessive fuming of acid.

After they have been cleaned in acid, the wire rods are rinsed in cold water and are washed with a high-pressure hose to remove impurities that may cling to the surface. Usually the rods are dipped in a lime or emulsion-like whitewash. A sull or rust coat, or copper-dip coat may be applied previously, depending on the wire finish desired. According to the number of drafts to be used, the lime coating may be controlled by the following concentrations of lime in the vat: light lime, 3 to 5%; medium, 6 to 9%; heavy, 10 to 12%; and extra heavy, 12 to 15%. The larger the number of drafts, the heavier the lime coating.

The limed rods are baked at the proper temperature and for the length of time necessary to dry the lime and release occluded hydrogen, which would cause brittleness if not eliminated. The rods are usually baked at about 300 F for 5 to 10 hr. Modern fast bakers perform this process in 5 to 30 min at approximately 550 F.

Drawing. *Dies.* In general, the wire-drawing die can be defined as a small plate or nib of suitable material, containing one or more tapering holes called "die holes". The die is an important element in wire-drawing equipment. For the production of a satisfactory product the die must be made of strong material highly resistant to wear, and the hole must be smooth and properly shaped. Chilled iron, several of the alloy steels, tungsten carbide, and diamond possess the required qualities and are used for particular applications, although the tungsten carbide single-hole die is becoming more widely used. Diamond dies are still preferred for finishing drafts on very fine sizes of wire; and because of the limited production of "shape" wire, hardened, punched chromium steel dies are employed. However, tungsten carbide dies are being used increasingly for drawing shapes.

Lubricants. In dry drawing, some form of lubricant is required, in addition to the coatings previously described, in order to prevent excessive heating and wearing of the die, and to produce a uniform smooth surface on the wire. A suitable lubricant is usually placed in the box of the die holder so that the rod or wire passing through will draw a sufficient amount into the die hole. Various substances are used for this purpose, including specially prepared greases or drawing compounds, tallow, pulverized soap, or a mixture of oil and flour or meal. The choice of lubricant depends on the number of drafts a wire is to be drawn, as well as the coating or freedom from coating desired on the finished wire. In wet drawing, a thin solution of liquid soap or soluble oil may be used.

Drawing Equipment. Cold drawn wire may be produced on what is known as a wire-drawing frame. Each frame is composed of a bench with several wire-drawing blocks or cylinders, revolving and drawing the wire through the die. Such a block mechanism and die box is shown in Fig. 1. In such an arrangement of several blocks to a bench or frame, the wire is drawn on the first block, then transferred to a reel and drawn a second draft onto a second block, and so on. In this respect, the method differs from multiple drafting.

"Bull blocks" are used for drawing large sizes of wire. A bull block is a large cylindrical block or capstan, 30 to 36 in. in diam, which revolves at a slow speed about a central spindle or shaft, usually horizontal, drawing the wire through a die and winding it around the bull block. When several hundred pounds of wire has been coiled and stored on the block, it is stopped and the wire coil removed. Bull blocks are used mainly for drawing wire that is from ½ to about ⅞ in. in diam.

Double-deck and triple-deck wire-drawing blocks are designed in tiers, one above another, with the same central spindle or shaft having a special arrangement of die holders in relation to the various levels of the blocks and permitting the wire to be drawn continuously for two or three drafts.

Continuous wire drawing has been made possible by modern improvements in wire-drawing equipment. The wire is drawn through a succession of dies simultaneously in a machine of the type illustrated in Fig. 2. The amount of reduction per draft and the number of drafts are limited by work hardening. After a certain amount of work hardening, the steel becomes so brittle that it must be softened by heat treatment before further drawing can be accomplished.

Since the pull required for drawing the wire through a die, may be more than half the strength of the wire, it is necessary to supply the power individually by placing a block after each die, and winding the wire at least two or three times around each block or drum in succession.

Since the wire is reduced in diameter at each draft and lengthens accordingly, the speed of wire travel increases at a corresponding rate. This increase may be compen-

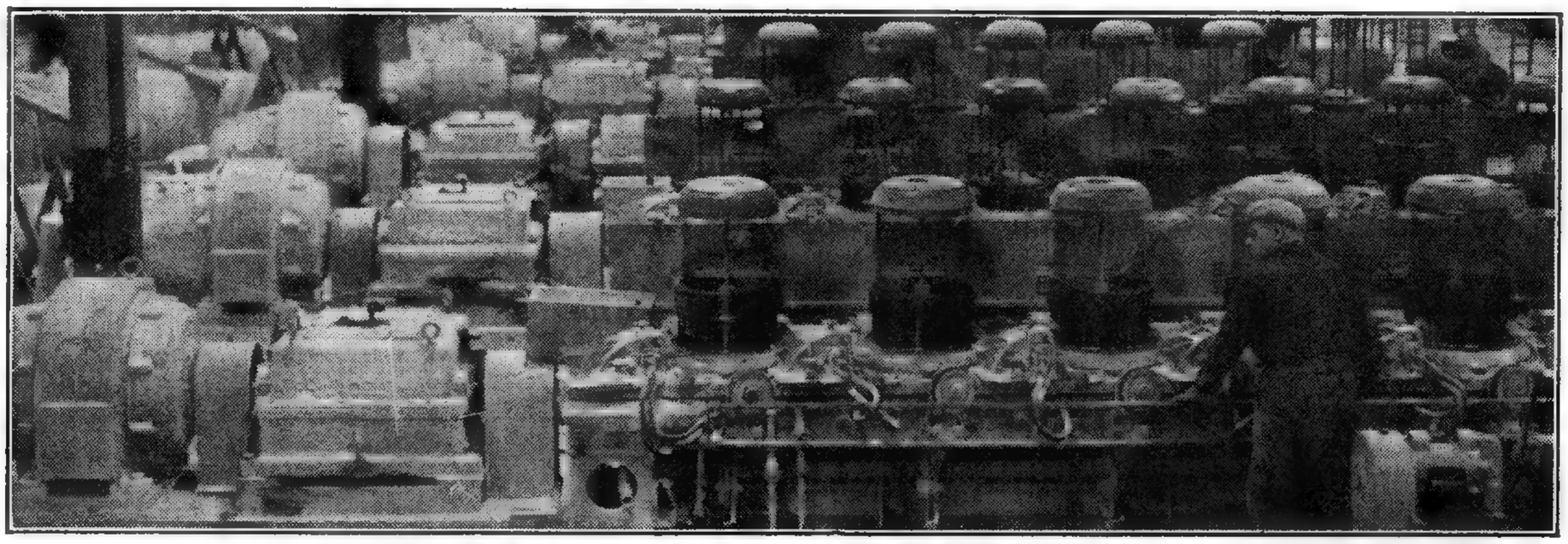


Fig. 2 A machine for the continuous drawing of wire

sated for by increasing the successive block diameters or block speeds in direct proportion to the increase in wire length. The blocks are usually 26, 22, or 16 in. in diam for wire sizes down to 20 gage.

Because plastic deformation of the wire, during travel through the die, produces both frictional and internal heat in the wire at each draft, the accumulated heat resulting from dry drawing may become great enough to affect adversely the quality of both lubricant and wire. This injurious effect is more pronounced in drawing the harder high-carbon steels than in drawing low-carbon wire, and provision is usually made, therefore, to restrict this heat in the wire by the use of water-cooled die holders and either air-cooled or water-cooled drawing blocks.

Continuous machines for wet drawing fine wire may be used for four or more successive drafts. These machines generally consist of the cone type of wire-drawing sheaves. In order to minimize slippage and wear, these sheaves of variable diameter on the same shaft are designed in steps for various surface speeds in relation to the increase in length of wire at each draft. In some types of equipment the sheaves are arranged in a tub of soap solution, which serves as a lubricant for the wires that pass through it. In other types the dies are lubricated by streams of solution forced through jets.

Dry drawing may reduce the area about 40% or less per draft for low-carbon steel and 35% or less for high-carbon steel. In wet drawing, the reduction of area may amount to only 20% or less.

Process Heat Treatments. To improve drawing quality and to meet special requirements of mechanical properties, many sizes and grades of wire are heat treated in rod, process, or finished sizes. Low-carbon wires are usually annealed for softening or recrystallization in preparation for further drafting (Fig. 3*a*, 3*b*, 3*c*); some high-carbon wires may also be process annealed or spheroidized (Fig. 3*d*) for fabrication purposes. The high-carbon steels are usually patented (Fig. 3*e* and 3*f*) in process to improve drawing quality as well as to fulfill predetermined requirements for mechanical properties. The high-carbon wires of very high tensile strength are made from "lead patented" process wires.

Annealing. Annealing may be of several different types, depending on the structures or mechanical properties desired, although much of the annealing of hard drawn low-carbon process wire may be largely to remove the hardness induced by wire drawing and to soften the wire for further drawing. The annealing processes are: (1) normalizing—either batch or continuous, (2) continuous lead annealing, (3) salt pot or "batch" annealing, and (4) pot or bell-type annealing or spheroidizing. Except for normalizing and full annealing, which are performed at temperatures above the transformation range, common annealing is usually accomplished by heating the wire to temperatures in the vicinity of, or below the critical point. The common or subcritical annealing practices may differ widely in the time of annealing; the continuous lead annealing is finished in several minutes, while the others require increasing time, in the order listed above. Spheroidizing, done mostly on higher-carbon steels, may require 24 to 48 hours for completion.

The effect of time and temperature of annealing cold drawn wire of various carbon contents is indicated in the lower curves of Fig. 6. Subcritical short-time-cycle annealing results in incomplete recrystallization, and wire so treated has tensile properties higher than the same material full annealed above the transformation range and slowly cooled for complete recrystallization. Subcritical annealing with a longer heating and cooling cycle similar

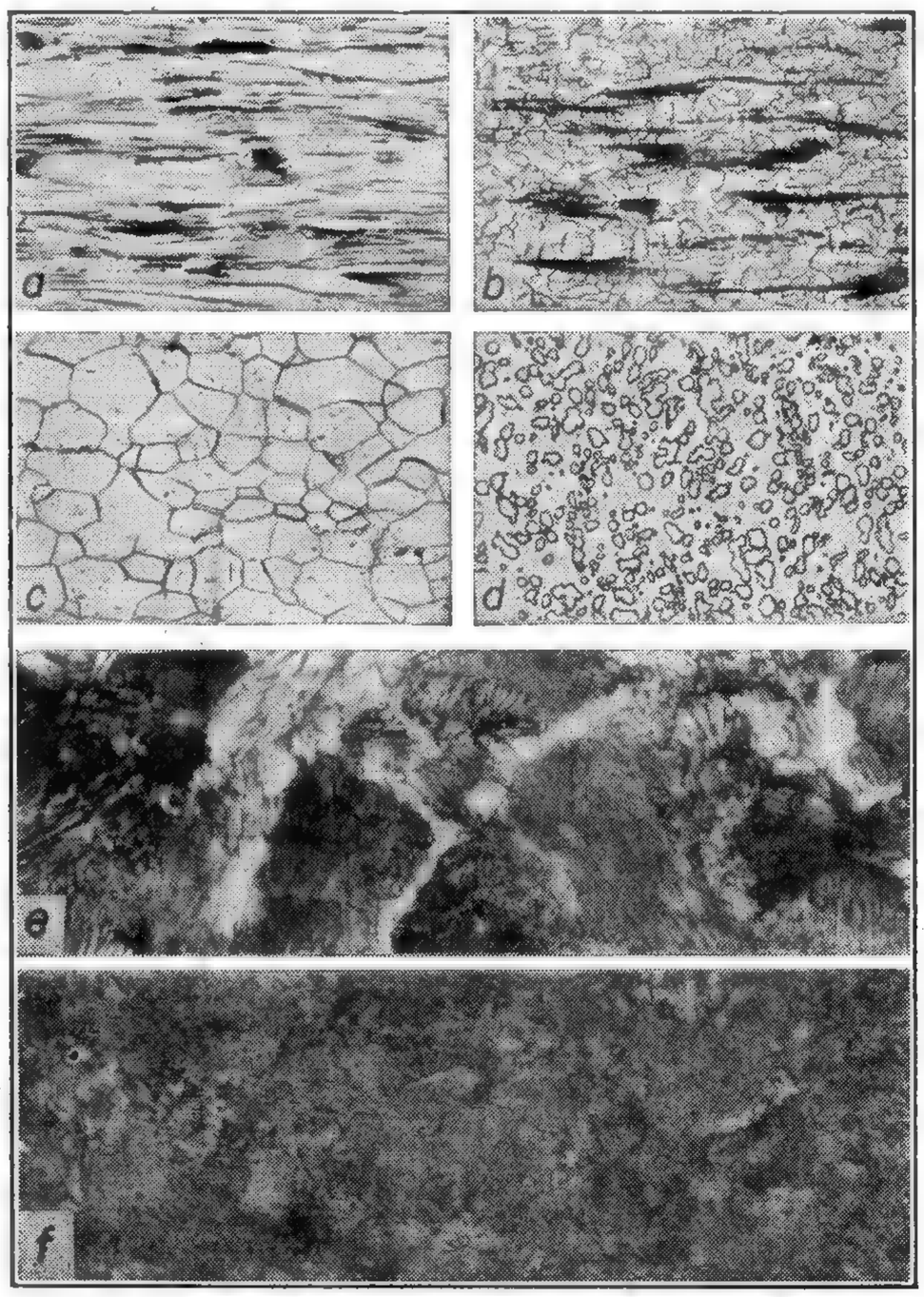


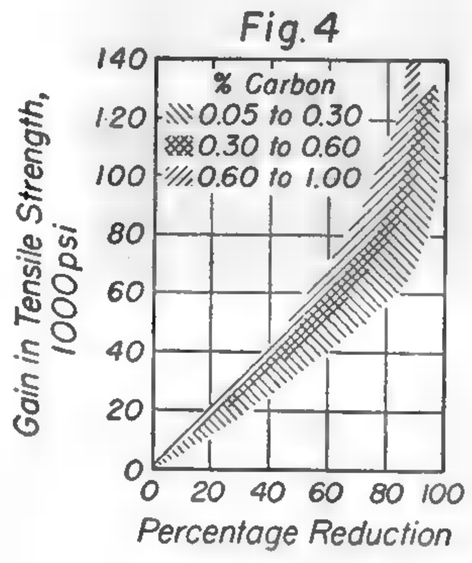
Fig. 3 Microstructures of steel wire

(*a*) 0.10% C steel wire, reduced 85% by cold drawing. Longitudinal section. Etched in nital. × 500. (*b*) 0.10% C steel wire, subcritical process annealed. Longitudinal section. Etched in nital. × 250. (*c*) 0.06% C steel wire, annealed. Longitudinal section. Etched in nital. × 250. (*d*) 0.90% C steel wire, spheroidized. Longitudinal section. Etched in picral. × 500. (*e*) 0.65% C steel wire OP patented (air patented). Longitudinal section. Etched in picral. × 1000. (*f*) 0.65% C steel wire, lead patented, Longitudinal section. Etched in picral. × 1000.

to that of full annealing or pot annealing, will result in tensile properties about the same as with full annealing.

Patenting. Patenting is a form of heat treatment used primarily on medium-carbon and high-carbon steels, and consists in heating continuously strands of rod or process wire to a temperature well above the upper transformation point, and then quenching to obtain definite structures and mechanical properties and also to restore the ductility of hard drawn process wire for further reduction. In one type of patenting called "OP" (Old Process) patenting or "air patenting", the rod strand is heated above the transformation range in a long furnace for about two minutes and quickly cooled in the open air to room temperature. "Metallic hardening" or "MH patenting" consists in heating the strands of rod or wire in a similar furnace and quenching in molten lead at about 1000 F. In "double lead patenting", practiced mostly on process wire, the steel is both heated and quenched in molten lead. The type of patenting used depends on the grade of wire being produced, its particular application and required tensile strength, stiffness, or ductility. Patenting gives a high initial strength with the best characteristics to conform with drawing to high tensile strengths in the finished wire.

The structures obtained by OP patenting and lead patenting are shown in Fig. 3*e* and 3*f*; the approximate tensile strengths obtained by these types of patenting are shown in Fig. 6, for steels of various carbon contents.



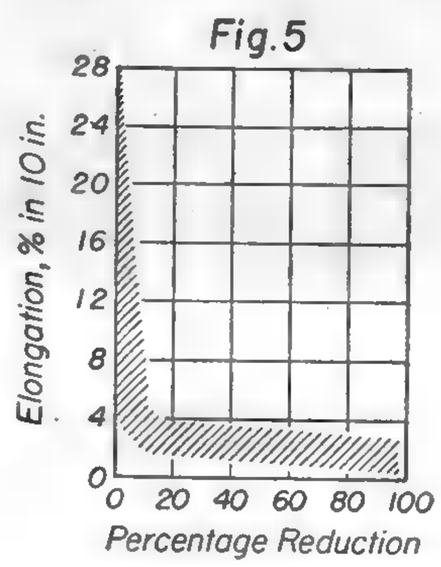


Fig. 4 Increase in tensile strength with increase in reduction
Fig. 5 Effect of reduction on elongation. The carbon content varies from 0.05 to 1.00%.

Mechanical Properties. The initial tensile strengths of rods or wire may be controlled by the chemical composition of the steel. When made of low-carbon steel, hot rolled rods, such as a No. 5 gage (0.218 in. in diam), may have a tensile strength of about 55,000 psi, while similar rods of higher-carbon spring-wire steel may have a tensile strength of about 140,000 psi. Regardless of the initial tensile strength of rod or process wire—whether hot rolled, annealed or patented—the increase in hardness, resulting from cold work in drafting such wire, follows a reasonably definite trend as shown in Fig. 4; the elongation follows a decreasing trend, as shown in Fig. 5.

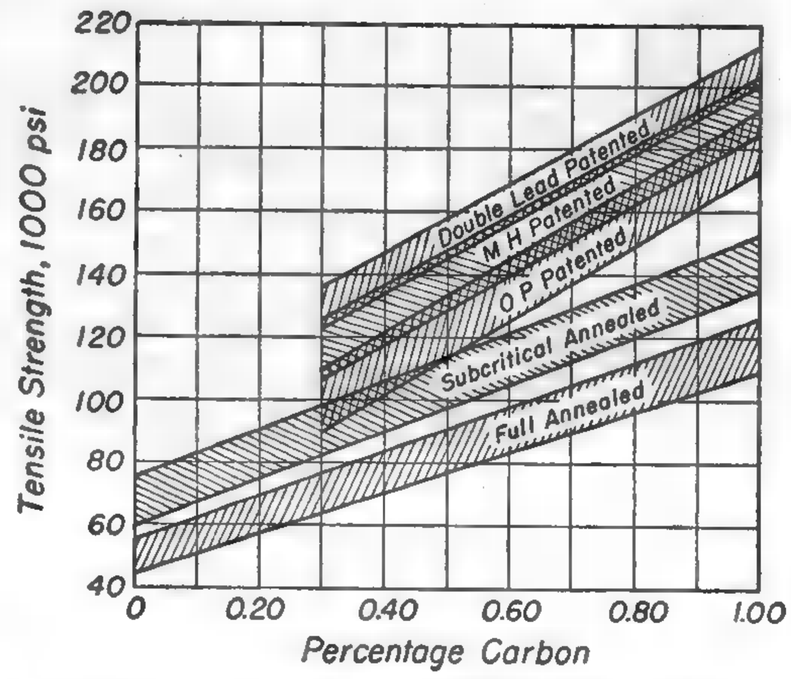


Fig. 6 Approximate effect of heat treatment and carbon content on the tensile strength of steel wire. The bands indicate the effect of wire size.

Applications. Wire may have one of several different surface finishes—either black annealed, bright, coppered, tinned, or galvanized. Wire is fabricated into a wide variety of household articles, including pins, strainers, fly swatters, egg beaters, toasters, window screens and many others. Farmers require bale ties, barbed wire and woven fencing. Industry demands such items as nails, telephone wire, bolt wire, rope wire, piano wire, and various grades of spring wire including oil tempered wire. A large proportion of the special types of wire are designed to meet severe service requirements and the production processes are rigidly controlled.

Machinability of Steel

By O. W. Boston*

IN the machining of metals, the metal being cut, the cutting tool, the size and shape of cut, the cutting fluid, the process, the type of machine tool, and the cutting conditions all influence the results. If any one of these factors is changed, different results will be obtained. It appears impossible to have a set of cutting conditions that will utilize all factors equally and ideally. Therefore, it is necessary to combine factors for the most effective compromise.

"Machinability" is a term used for indicating the relative ease or success with which a material is machined by sharp cutting tools in operations such as turning, drilling, milling, broaching, threading, reaming, sawing or grinding. Machinability is evaluated in several different ways, depending on the objective. In commercial machining, objectives vary widely and machinability may be evaluated in terms of tool performance as represented by the tool life per grind under given conditions; the speed at which the material can be cut, under different conditions, while maintaining a given tool life; the force, energy or power required for the cutting; the surface finish produced; or the dimensional accuracy maintained among like pieces under given conditions.

Values of machinability are usually comparative and represent the behavior of the material under given conditions. The material, shape and size of the tool, the size and shape of the cut, the cutting fluid used, and the cutting speed must be held constant in order that the values may be directly comparative. If any one of these variables is changed for the tests, other directly comparative results will be obtained that may not agree with those of the first test. Also, the machinability rating of a material as determined by one process, may be different from that obtained by another process.

Materials Being Cut. Many materials have optimum cutting conditions in regard to speed, feed, depth, tool shape, tool material, or cutting fluid, some or all of which are different from those for other materials. Ratings of machinability for such materials should be determined under these optimum conditions. The values of machinability for different materials will then be comparative, although the details of the tests are individual.

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Tests for Machinability. The factors of importance in machinability are cutting speed, tool life, power consumption or cutting force, the size and shape of the chips, the finish left on the cut surface, and the accuracy of dimensions of the finished product.

Many types of tests have been developed for indicating the machinability of a given metal. If machinability is to apply to the tool, then the material being cut should be constant; if machinability is to apply to the material, then the tool should be constant. Cutting fluids may be introduced as the variable while the material and tool are held constant. Machinability may be expressed as:

1 The *life* of the cutting tool in turning, milling, drilling, broaching, tapping or sawing, when cutting under fixed conditions of speed, feed, depth of cut, and with a given cutting fluid.

2 The force, energy, or *power* required for cutting by various processes, such as milling, turning, drilling; or the energy required for removing a single chip of a given size or shape in milling.

3 The *torque and thrust* in drilling or counterboring.

4 The *cuttability* as measured by

(*a*) The rate of penetration of a drill in a given time under a constant feeding pressure;

(*b*) The traverse of a turning tool when fed against the work by a constant pressure, as in cutting off;

(*c*) The time in minutes or number of strokes required for cutting off a given cross-sectional area with a hack saw subjected to a given feeding load rather than a positive rate of feed.

5 The condition or surface quality of the *machined surface* produced on the material by the cutting tool.

6 The *temperature* developed at the point of the tool.

7 The *cost* of removal of 1 cu in. of the metal under specific conditions. This would involve both power and cost of the tool.

Factors Affecting Machinability. The factors affecting machinability in accordance with the above classification are, as follows:

1 Material being cut—its composition, structure, shape and size.

2 The cutting speed, size and shape of cut.

3 The cutting tool—its material, quality, treatment, shape, size, surface quality and condition.

4 The condition of the machine tools on which the cutting is done, together with the processes involved.

5 The cutting process. A given material may have different ratings of machinability for the different processes; that is, for turning, drilling, milling, grinding and the like.

6 Rigidity of the tool and work-holding device.

7 The characteristics of the cutting fluid used.

The best cutting condition involves the material being cut, the tool, the mechanical device and the cutting fluid. For any material being machined, obviously one specific combination of conditions is best. In order to secure the greatest production at the least cost, the cutting tool should be of a given material of a certain definite quality. It should have a certain contour of cutting edge, and combination of angles influencing its geometrical shape. A certain cutting fluid should be used, having properties especially suited to the given conditions, and the mechanical equipment for the particular process involved should be suitable. If the physical or mechanical properties of the material are changed, or if another material is substituted, some of the factors involving the tool, cutting fluid, or mechanical equipment should be changed also to maintain optimum conditions. The present state of the art of metal cutting leaves the selection of the various factors for a given problem to be determined largely by cut-and-try methods.

The steel being cut, the cutting tool and the cutting fluid used in any cutting operation present variables that affect machinability. Each is discussed separately below.

Fundamental Principles

Several factors involved in the machinability of steel are closely associated with both the tool and the work material, as discussed separately below.

Chip Formation. Chips of ductile metals are removed invariably by plastic flow. They are of two general forms, the ribbon or elementary type, and the sectional type. The elementary type, Fig. 1, is continuous and of virtually uniform cross-sectional area but is made of very thin transverse slip bands or slip elements. In the sectional type, Fig. 10, the small slip elements are grouped into clusters or sections of approximately equal size. Frequently these sections cling together to form a long, continuous chip, the outer surface of which is saw-toothed; but often the various sections become detached, giving broken-up chips that are more easily disposed of.

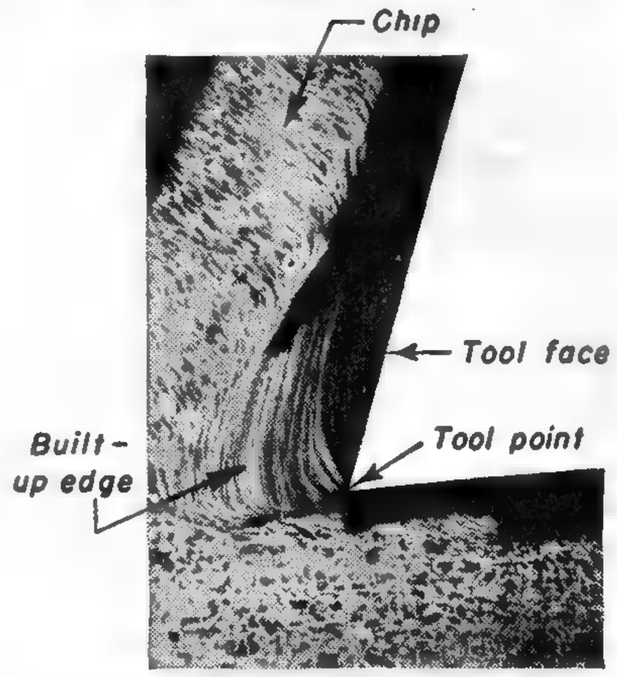

Fig. 1 Chip formation and typical built-up edge formed during the cutting of annealed low-carbon steel with a single-point tool having a 15-deg rake. The depth of cut was 0.020 in. and the speed of cutting, 120 fpm. A mineral oil containing sulfur and chlorine was used.

The bar was stopped suddenly after prolonged cutting and the section at right angles to the cutting edge was prepared for microscopic examination, which revealed the structure that is shown.

Almost immediately after a cut is started, a small particle of the material being cut is trapped on the face of the tool and forms a "built-up edge", somewhat triangular in shape, thickest directly ahead of the cutting edge, and becoming thinner as it extends backward over the face of the tool, as shown in Fig. 1. In all types of metal cutting, such as turning, shaping, drilling, sawing or milling, this built-up edge protects the cutting edge of the tool by causing the undeformed material immediately ahead of the tool point to flow plastically into a chip that slides over the built-up edge and across the face of the tool.

The built-up edge depends on the composition and structure of the material being cut, the rake of the tool, the cutting speed, the cutting fluid, and the size of the cut. The thinner the chip, the smaller the built-up edge becomes and the more nearly the cutting edge of the tool cuts the material to leave a smooth finished surface. This surface is smooth, but appears as a torn surface similar to the face of a very fine file. For thick chips, the cutting edge of the tool transmits directly only a small portion of the total force involved in cutting, since it is protected by the built-up edge. The built-up edge appears to be a rather permanent structure as long as the cut is continuous. Portions of this accumulation may slough off and be carried away on the underside of the chip, and frequently portions of it adhere to the surface of the work material as it passes the flank of the tool (*see* Fig. 1).

In given conditions, the built-up edge is largest at low speeds. As the speed is increased, the edge is reduced in size, particularly in height. At extremely high speeds, the built-up edge is smallest. When metal is cut at a very high speed (with cemented carbide tools, for example), the built-up edge disappears and the cutting edge of the tool actually cuts and forms the machined surface that has the highest surface quality.

Chatter. Often high-frequency vibrations occur in the formation of the chips, because of the sliding of the elements of the chip into sections or because of the periodic sloughing off of the built-up edge. These vibrations may set up a natural period of vibration of the tool, of the work, or even of the whole machine, which may become very

objectionable because of noise, poor surface finish and possible damage to the machine. Rigidity of tooling, or change in speed, feed, depth of cut or tool shape may cause the vibration to cease. Whenever long, thin chips are taken, as with a tool that has a large radius at the nose or ■ long, straight cutting edge, the danger of vibration is increased.

Surface Finish. The finish on the cut surface is improved as the built-up edge is reduced in size. This reduction may be accomplished by increasing the rake of the tool, using high speeds, reducing the size of the chip, changing the structure of the metal being cut, or introducing a cutting fluid. Any one or a combination of these measures is commonly used to secure better finish.

Machining operations of the finishing type are designed to provide flaw-free surfaces that resist fatigue. Surface finish is important not only in connection with surface machining with single-point tools, but with surfaces made by abrasives and other means. The American Standards Association Committee on Surface Quality has been working on this subject for several years. The first report was made to industry in December 1938.

Surface qualities, by definition, are the physical characteristics of a boundary that separates solid substances. These qualities include such factors as the geometry of the surface in three dimensions, crystal structure, appearance, color, resistance to corrosion, hardness, size and shape of surface flaws. The committee report deals particularly with the geometry of the surface deviations from the nominal surface (cylinder, flat, sphere). These deviations are of three kinds—surface flaws, waviness, and roughness, all three of which can be specified in inches. Surface flaws are occasional irregularities; waviness consists of widely spaced irregularities, more than 1/32 in. apart, such as feed marks; and roughness consists of finely spaced irregularities, less than 1/32 in. apart, which determine what is usually called the "finish" of the piece. Flaws and waviness are now measurable, but roughness, being inside the waves, calls for a new measuring technique. The committee has been concerned with the means of specifying roughness and has adopted the average height of the finely spaced irregularities as a measure of roughness. This height is expressed directly in micro-inches (millionths of an inch) across the surface in a direction to give the largest reading. It is recognized that this average height of irregularity is by no means a complete specification of any surface and that other information concerning the character of the irregularities, as well as waviness, flaws, and other surface qualities, will often be required for solving practical problems. Consideration is being given to means of specifying some of these other surface qualities. A preferred set of roughness classes has been suggested by the committee, to be designated by appropriate symbols that range from ¼ micro-inch to 63,000 micro-inches, root-mean-square average.

During the past 20 years a number of investigators have worked on equipment for measuring surfaces. The equipment most widely used is of three types:

1 Profile recorders that draw an enlarged graph of the actual surface profile. Two types of these laboratory instruments have been described: (*a*) the Profilograph, which uses mirrors, lenses, and a light beam;[3,16] (*b*) an electric profile recorder using vacuum and cathode-ray oscillograph.[1]

2 Several arrangements of microscopic observations (profile microscope) have been used with special illumination for observing surface profiles directly.[2,17]

3 A Profilometer is a portable meter that does not draw a record of the profile, but takes an automatic running average of the height of the surface irregularities and indicates that average directly on a meter. This instrument is portable, self-contained, and has found direct application in the shop.[1]

Tool Wear. When steel is being cut with tools of carbon tool steel, or when cast iron is being machined with any type of tool material, tool failure is caused by wear on the flank of the tool directly beneath the active cutting edge. Tools that fail in this manner should be reground when the width of this abraded surface reaches 0.030 in. or causes an appreciable increase in power. When steel is cut with tools of high speed steel, normal tool failure is caused by a gradual cupping on the face of the tool. After the chip has been formed, it slides over a built-up edge that protects the cutting edge, and rubs against the face of the tool some distance back from the cutting edge, as shown at *A* in Fig. 2. The area of sliding contact between the chip and tool becomes heated, decreases in hardness, and is abraded by the flowing chip. A groove, gradually worn into the face of the tool, becomes larger and larger until its edge meets or nearly meets the cutting edge, as shown at *B*, Fig. 2. The flank below the cutting edge may wear also, causing the newly formed cutting edge to move toward the enlarging groove, as shown at *C*, Fig. 2. The built-up edge is gradually reduced in size from the start of the cut until the edge of the groove meets the cutting edge. A new irregular cutting edge is formed, resembling a ridge of mountains. At this point the built-up edge disappears. The tool cuts most efficiently under this condition, but unfortunately the irregular mountainlike peaks break off and then the tool fails quickly.

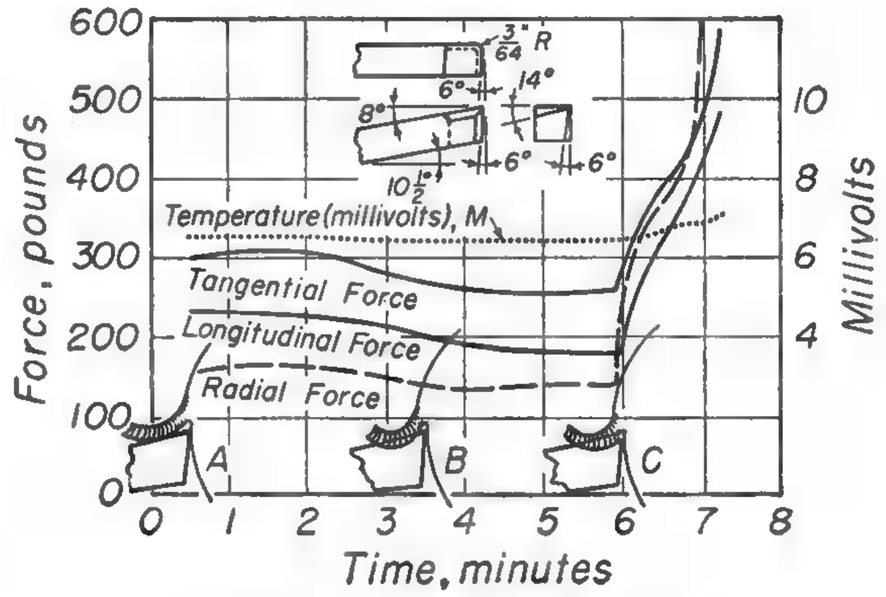

Fig. 2 Failure of a tool by gradual cupping

The progress of tool wear can be estimated readily from the color, shape, and size of the chips produced. In the turning of steel, the chips produced are first long and straight or only slightly coiled and are blue or purple in color at proper cutting speed. The color indicates the development of excessive heat even though the tool has been newly ground and has cut for only a small part of its total life. While the groove is forming in the face of the tool, the chips become coiled either in short spiral or in long helical forms of small diameter. In this condition, the chips are at a lower temperature (are not colored); the tool cuts such chips for the greater part of its life. When the newly formed cutting edge starts to fail, the chips become irregular in shape, rough on the bottom, and again blue in color.

The manner of wear and failure seems to be the same in taking both heavy and light cuts. The time for complete tool failure is easily observed when heavy cuts are being taken, because of the sudden change in shape of the chips, the high blue color, and the burnished surface of the cut shoulder. When light cuts are taken, the failure is similar, but it is more difficult to determine the instant of tool failure. French and Digges[4] used a trailer tool that was set to cut when the leading tool was worn so that the test log became 0.002 in. larger in diameter. However, it has been found that while taking a light cut, there is virtually no change in diameter of the work because of wear on the tool, until tool failure occurs; so the trailer tool, or any device that will indicate the sudden appreciable increase in diameter of the work piece, does give a true value of the time for tool failure under light cuts.

The cutting edge of a tool usually fails first at one point and then at another, long before total failure. This is known as preliminary failure. It may occur on the end of the single-point tool and therefore cause ■ poor finish and a greater diameter of the work piece than is desired. On forming tools, this preliminary failure determines the life of the tool, since the tool must be removed and reground. Single-point tools can be ground with a greater

angle on the side cutting edge or a larger radius at the nose, so that the preliminary failure occurs on the side of the tool and the quality of only the cut shoulder of the work is affected. However, such a tool will cut for a considerable time before complete failure.

Relation Between Cutting Speed and Tool Life. For a given steel, tool, and cutting condition, the life of a turning tool varies inversely with the cutting speed, as indicated by the equation $VT^n = C$, in which V is the surface cutting speed in feet per minute; T is the tool life during cutting, up to the time of tool breakdown measured in minutes; n is the exponent of T and equals the tangent of the angle of slope of the curve of cutting speed versus tool life, when plotted on log-log paper; and C is a constant depending on various conditions, such as type of material; size, shape, and material of tool; size and shape of cut; and cutting fluid. This relation gives a hyperbolic curve on cartesian or rectangular co-ordinates, but a straight line on double logarithmic paper, as shown in Fig. 3.

It is shown below that the constant C and exponent n will vary for virtually every set of conditions as the steel, tool, or cutting fluid is changed, so that no single value of n in the equation $VT^n = C$ can be used safely to represent conditions in general.

Relation Among Forces, Energy and Power. Formulas for cutting forces in turning, and torque and thrust in drilling are given below. These curves indicate that the values of the constant and exponents may vary as the material or tool shape is changed.

Influence of Tool Wear on Cutting Force. The three components of the cutting force and the temperature indicated in millivolts as determined by a thermocouple at all times during the tool life are shown when cutting an annealed SAE 2335 steel dry at 145 fpm. The depth of cut was 0.100 in. and the feed was 0.0125 in. A high speed steel lathe tool was used that had an 8-deg back rake angle, 14-deg side rake, 6-deg end relief, 6-deg side relief, 6-deg end cutting edge angle, 0-deg side cutting edge angle, and 3/64-in. nose radius. The condition of the tool and the built-up edge at ½, 3½, and 6 min after beginning the cut are shown in Fig. 2 at *A*, *B* and *C*, respectively. Tools of cast cobalt-base alloy and of sintered carbide have less rake and therefore require more power.

The Steel Being Cut

The steel being cut presents many factors that affect its machinability, as outlined below.

(1) Composition, such as carbon, alloy, or special steels developed for free-machining that contain sulfur, lead, selenium, or manganese. (2) Melting and casting practice and characteristics of grain size. (3) Fabrication—whether cast, forged, drawn, or rolled (hot or cold finished). (4) Heat treatment. (5) Mechanical properties—tensile strength, hardness, and work hardening capacity. (6) Metallographic structure. (7) Size of the material.

Composition, Heat Treatment and Grain Size.* The machinability of steel varies with its composition, treatment and structure. In cold finished bar stock for screw-machine work, the lamellar pearlitic structure is best for the low-carbon and medium-carbon steels. In the high-carbon steel, such as 1095, a spheroidized condition increases tool life. It is reported that the best machinability of normal cold drawn steels is obtained with an elongation of 13 to 16% in 2 in. and a minimum reduction of area of 40%. There is danger of reduced tool life if the elongation is less than 10% and the reduction of area is less than 35%. Tools will last longer when the steel that is being cut has low hardness and low tensile strength. In screw-stock steels, well broken-up chips, a good finish, and a long tool life at high speed are desirable, but not always obtainable together. High-carbon alloy steels that work harden appreciably are machined in the hot rolled and annealed condition if it is desired to have the tools last as long as possible.

For favorable machinability, a normalizing treatment (or annealing) is recommended by McQuaid[5] for the more highly alloyed steels. It is seldom necessary to normalize carbon carburizing steels, because satisfactory machinability is usually obtained in the hot worked condition. In the fine-grained, shallow-hardening type of low-alloy steels, higher normalizing temperatures are necessary to obtain the lamellar pearlitic structure that is best for machining.

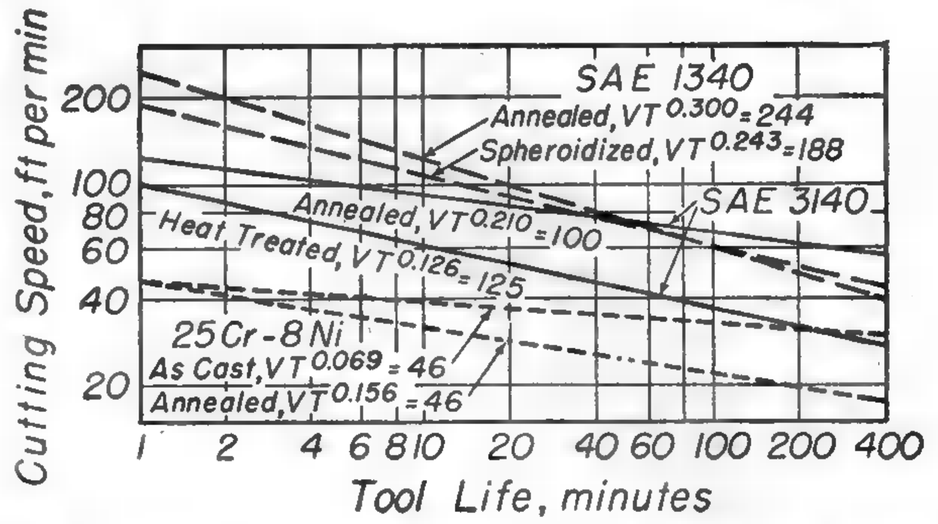

Fig. 3 Curves of cutting speed versus tool life for various types and conditions of steel. Note log-log scale. The curves indicate that each material with a different structure has a curve with a different slope. Thus one equation is not suitable for describing the relation between cutting speed and tool life for all materials. *See* text.

For rough lathe work where surface finish is inconsequential, low hardness is more important than low ductility. For finishing cuts on such steels as 6140, 4140 and 3140, tool life is impaired if the Brinell hardness is more than 207, even though the structure is lamellar pearlite.

Steels of fine grain size (ASTM 5 to 8), when used as oil-hardening or carburized steels, are very ductile, particularly if they are abnormal. These steels show less warpage in heat treatment and appear to be best for producing a fine finish. W. G. Hildorf states: "In general, coarse grain size (ASTM 1 to 5) is better for heavy cuts. Steel of each grain size should be cut with tools appropriately ground. The resulting cost of metal cutting for each steel with favorably ground tools is approximately the same over a long period of time. Difficulty would be encountered, however, should an attempt be made to machine the coarse-grain steels on a machine properly set up for machining fine-grain steels."

For further discussion of grain size of steel, the reader may refer to the articles by Wilson[6,15] and to the article on page 399 of this Handbook.

Cutting Speeds and Feeds in Turning. The cutting speeds listed in Table I* will give satisfactory duration of service from tools when the various steels are being machined in turret lathes with high speed steel tools that have been properly ground for roughing cuts from 1/16 to 3/16 in. deep and feeds from 0.020 to 0.060 in.

Table I. Cutting Speeds Recommended for Turning[a]

Steel	Cutting Speed, surface ft per min
Alloy	
annealed	50 to 60
treated	25 to 40
Castings, miscellaneous	50 to 60
Machine	
hard	35 to 60
medium hard	60 to 85
soft	100 to 120
Threading	25 to 40
Tool	
annealed	60 to 80
unannealed	25 to 35

(a) Recommendations of Warner and Swasey Co. for machining in turret lathes with high speed steel tools, roughing cuts from 1/16 to 3/16 in. deep and feeds from 0.020 to 0.060 in.

Frequently the tools must be ground to produce a certain shape of work that calls for reduced cutting speeds. At best the speeds recommended above are for setting up work and may be modified as experience and conditions indicate. The use of cutting fluids may permit cutting speeds higher than those indicated. If cast cobalt-base

* See also the article on "Metallurgical Factors Affecting the Machinability of Steel", page 369.

* Data as recommended by Warner and Swasey Co.

alloy tools are used, these speeds may be increased from 25 to 75%, depending on the material being cut and the finish desired. If cemented carbide tools of a suitable type are used, speeds as great as 250 to 300 fpm are recommended. If carbon tool steels are used, the values given should be reduced 50%.

Many types of steels are prepared in the form of bars for use in hand and automatic screw machines. For this work, the cuts are usually much lighter than those used in turret lathes, and for that reason the speeds are generally higher, ranging from 100 to 180 surface ft per min.

The machinability of many of these steels is improved by providing some nonabrasive constituent to break up the continuity of the ferrite. Sulfur is used commonly for this purpose. Steels containing sulfur are known as free-cutting steels. For accuracy of dimensions, freedom from rolling mill scale, and improvement in machinability, cold drawing is practiced widely for many low-carbon steels. Usually the hot rolled bars are not equal in machinability to the cold drawn product. Those alloy steels that work harden excessively in cold drawing are often machined in the hot rolled, annealed condition. Good free-machining steel has low ductility and must also have a low order of work hardness. The tools should be ground so that the chips break up into small particles, instead of forming long coils. The article on page 369 lists the machinability ratings of the principal types of carbon and low-alloy steels, based on the rating of AISI-B 1112 steel as 100%. These speeds are suggested only for setup purposes. They may be modified extensively to meet the requirement of the particular operation and cutting fluid used. The article on "Cutting Fluids", page 66, includes an extensive table that gives ratings for the various metals, arranged in groups according to the speed of cutting.

Relation Between Cutting Speed and Tool Life in Turning. Many examples indicate that the analysis or condition of the steel being cut influences the exponent n and and the constant C in the equation of cutting speed versus tool life, $VT^n = C$, described previously. Under Cutting Tools below, it is shown that the tool material and tool shape change this equation; cutting fluids also change it.

In turning cast steel containing 25% Cr and 10% Ni, tool bits ⅜ in. sq were used, ground to 8-deg back rake, 14-deg side rake, 6-deg end relief, 6-deg side relief, 6-deg end cutting edge angle, 15-deg side cutting edge angle, and 3/64-in. nose radius. In taking a cut 0.050 in. deep with 0.0255-in. feed per revolution, it was found that, when the bar was machined as cast, the resulting equation was $VT^{0.069} = 46$, but when a corresponding bar was machined after it had been quenched from 2000 F, the equation was $VT^{0.156} = 46$. These two curves, plotted in Fig. 3, show a considerable change in the value of the exponent merely through the change in structure. For a tool life of 1 min, the cutting speed for each curve is 46 fpm, but for a 60-min tool life, the cutting speed for the heat treated bar is 25 fpm, and that for the as-cast bar is 35 fpm.

Similarly, different bars of 3140 steel 2¼ in. in diam were machined under identical conditions, with a cut 0.0625 in. deep and 0.0377 in. feed, and a high speed steel tool ⅝ in. sq ground to 6-deg back rake, 12-deg side rake, 6-deg end relief, 6-deg side relief, 13-deg end cutting edge angle, 0-deg side cutting edge angle, and ⅛ in. nose radius. The bar was heat treated by quenching in oil from 1525 F and then tempering at 900 F for 1 hr to give a Brinell hardness range of 311 to 340, an elastic limit of about 150,000 psi, a tensile strength of about 165,000 psi, an elongation in 2 in. of about 16%, and a reduction of area of 55%, the resulting equation was $VT^{0.210} = 100$, as shown in Fig. 3. When a similar bar was annealed by cooling from 1575 F, giving a Brinell hardness of 202 to 207, the resulting equation was $VT^{0.126} = 125$, shown in Fig. 3. The cutting speeds for the annealed bar are higher for all values of tool life than corresponding speeds for the heat treated bar.

Similarly, when 1340 steel was machined in the annealed condition with the identical tool and cut outlined in the above paragraph, the equation obtained was $VT^{0.300} = 244$. When the steel was machined in a spheroidized condition, the equation was $VT^{0.243} = 188$. These lines cross at a tool life of 90 min. The annealed bar permits higher cutting speeds for any tool life shorter than 90 min, but the spheroidized bar is better for greater values of tool life. Many other similar examples have proved this point.[7]

For a 20-min tool life, V_{20}, in cutting a 1045 steel under a given cutting condition, high speed steel tools have a cutting speed of 150 fpm for the annealed bar, about 139 fpm for the cold finished bar, about 102 fpm for a bar quenched and tempered at 1000 F, about 93 fpm for a bar quenched and tempered at 600 F, and about 84 fpm for a bar quenched in oil from 1520 F. This wide variation in cutting speed results from the structure and cold finishing.

When cutting dry a 2340 steel annealed with a high speed steel tool of the 8-22-6-6-6-15-3/64 shape, the cutting speeds for 100-min tool life varied as the size of chip was varied, as follows:

A cut 0.0125 in. deep and 0.0125-in. feed gave a cutting speed of 176 fpm and removed 33 cu in. of metal per tool grind for a tool life of 100 min.

For the same tool life, when the cut was 0.035 in. deep and the feed 0.0125 in., the cutting speed was 120 fpm, and 63 cu in. of metal was removed per grind.

When the depth was 0.100 in. and the feed was 0.0125 in., the speed was 72.5 fpm, and 108.8 cu in. of metal was removed per grind.

When the depth was 0.200 in. and the feed was 0.0125 in., the speed was 71 fpm, and 213 cu in. of metal was removed per grind.

For the same cross-sectional area of cut as with the 0.100-in. depth by 0.0125-in. feed, but with the depth reduced one-half and the feed doubled, the cutting speed for a 100-min tool life was changed from 72.5 to 60 fpm, and the metal removed per tool grind was reduced from 108.8 to 90 cu in.

Cutting-Force Relations in Turning. For a given steel and a turning, planing, or shaping tool, the cutting force in pounds (represented by its tangential T, radial R, and longitudinal L components) varies as the feed F and the depth of cut D, as indicated by the following equations:

$$T \text{ (tangential force)} = C_1 F^x D^y$$
$$R \text{ (radial force)} = C_2 F^a D^b$$
$$L \text{ (longitudinal force)} = C_3 F^c D^d$$

C_1, C_2, and C_3 are constants and x and y are exponents. Values of C, x, and y in this equation will vary with the steel or the shape of the tool.

The equations for the three components, when cutting dry a fully annealed low-carbon steel at 80 fpm with a tool ground to 8-deg back rake, 22-deg side rake, 6-deg end relief, 6-deg side relief, 6-deg end cutting edge angle, 0-deg side cutting edge angle, and 3/64-in. nose radius, are as follows: $T = 102{,}500F^{0.80}D$; $R = 704F^{0.46}D^{0.13}$; and $L = 12{,}600F^{0.42}D^{1.35}$.

These equations, determined by Kraus, are shown to vary both in the value of the constants and in that of the exponents, as the shape of the tool is varied, by changing the side and back rake angles, or the nose radius to such an extent that it is difficult to give a general formula.[8]

F. W. Taylor[9] determined a formula for tangential force on a tool having a large nose radius, when turning steel from 30 to 60 fpm, as follows: $T = C\ D\ F^{0.934}$.

The values of C ranged from 230,000 for soft, medium-carbon steel, annealed to a tensile strength of 70,000 psi, to 296,000 psi for hard steel. Taylor used a round-nose tool ⅞ in. wide. The back rake was 8 deg, side rake 14 deg.

The author has found that the equation $T = CD^{0.95}F^{0.79}$ is reliable in the turning or planing of an annealed 3150 steel. The value of the constant ranged from a minimum of 108,200 when a sulfurized mineral oil was used to facilitate cutting, to a maximum of 128,200 during dry cutting. The high speed steel tool had 8-deg back rake, 14-deg side rake, 6-deg relief, 6-deg end cutting edge angle, 0-deg side cutting edge angle, and 1/32-in. nose radius. The setting angle was 90 deg.

It is evident that the change in material affects greatly the value of the cutting force. Figure 4 shows the power resulting from the tangential cutting force when a variety of metals are being machined, as compared with the resistance to cutting by milling and drilling.

Power, Torque and Thrust in Drilling. Values of torque, thrust, and power were determined from drilling a normal-

ized and annealed chromium-vanadium 6150 steel under various commercial conditions, with standard commercial taper-shank drills of high speed steel, the points of which were ground carefully on a machine. For further details regarding drills and for detailed information when drilling other metals, see "Metal Processing".[10] The feed of each drill corresponds, as nearly as could be obtained on the machine, to those generally recommended values shown in Table II. The actual number of rev per minute is based on a peripheral speed of about 60 fpm for all drill sizes, although torque and thrust are not affected by speed. One part of soluble oil to 16 parts of water was used as a cutting fluid in all tests.

These equations are used to determine the torque and thrust for 6150 steel under any cutting condition. The torque and thrust for any drill diameter and feed may be determined graphically from Fig. 5 and 6, respectively. The torque for a drill 1 in. in diam, operating at 0.013-in. feed is shown to be 63 ft-lb. Similarly, the corresponding thrust is shown to be 1820 lb.

Table III also shows factors F_1 and F_2 for torque and thrust by which the torque and thrust, as determined from Fig. 5 and 6, can be multiplied in order to get the torque or thrust for any one of the other forged steels listed. To illustrate, it is desired to know the torque when drilling 2320 steel with a ¾-in. diam drill operating at

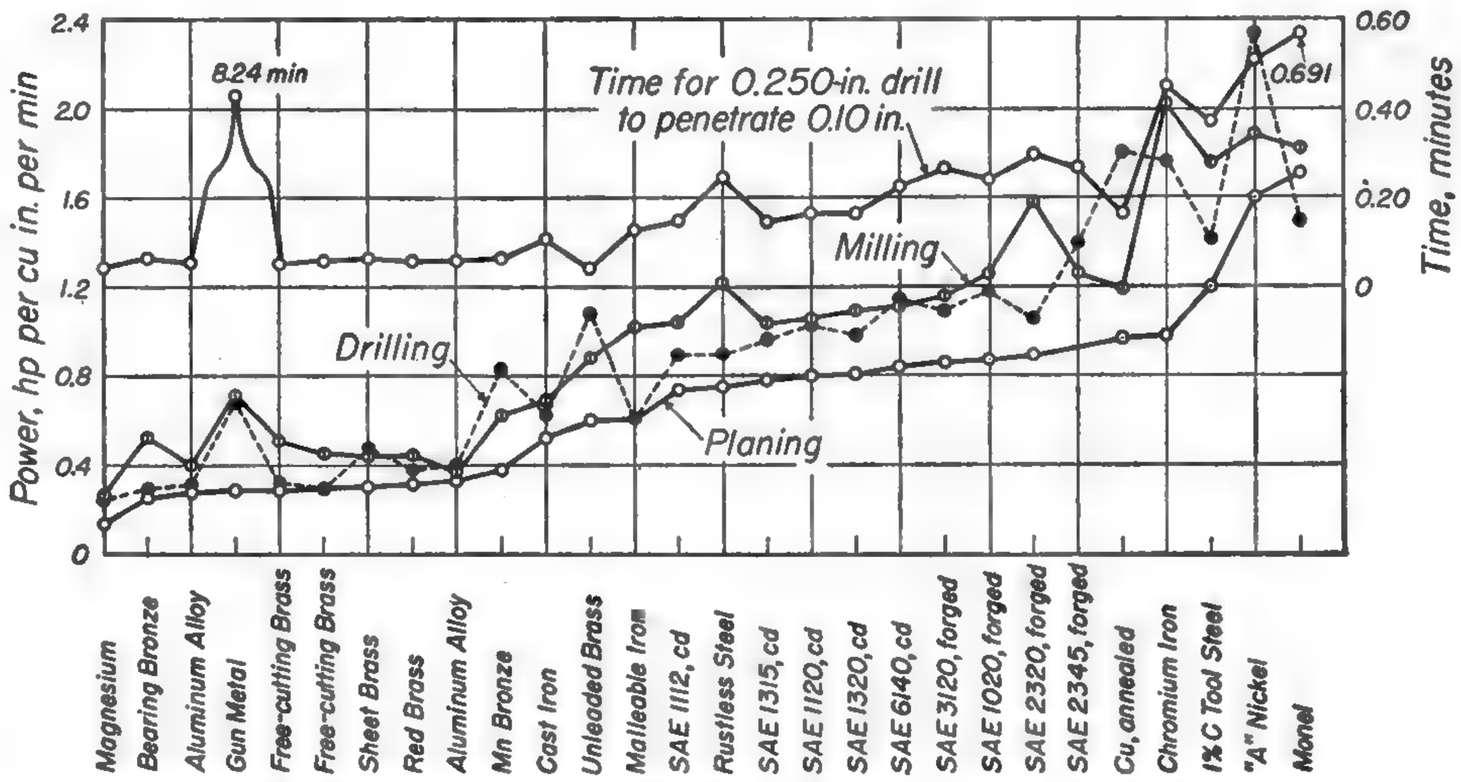

Fig. 4 At the tool point, net values of horsepower per cubic inch of metal cut per minute for various metals. Values were determined for drilling, milling and planing under standardized conditions

In order to make it possible to determine the torque T in pound-feet, the thrust B in pounds, or power, for any other combination of drill diam d in inches and feed f in inches per revolution, the following equations were

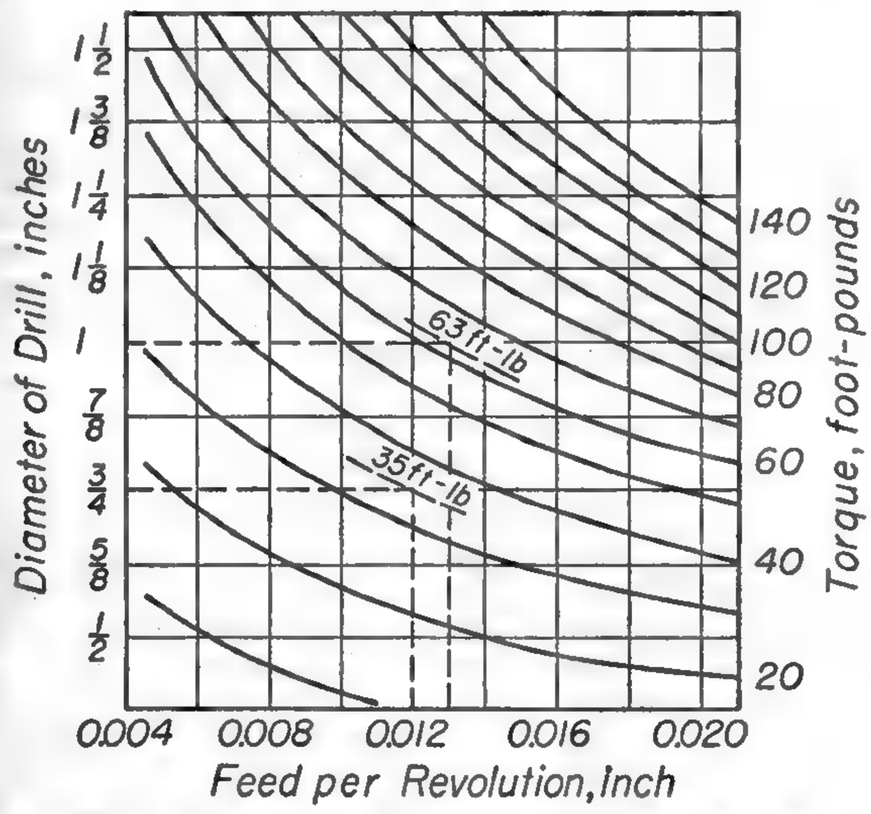

Fig. 5 Torque at the drill point in drilling 6150 steel

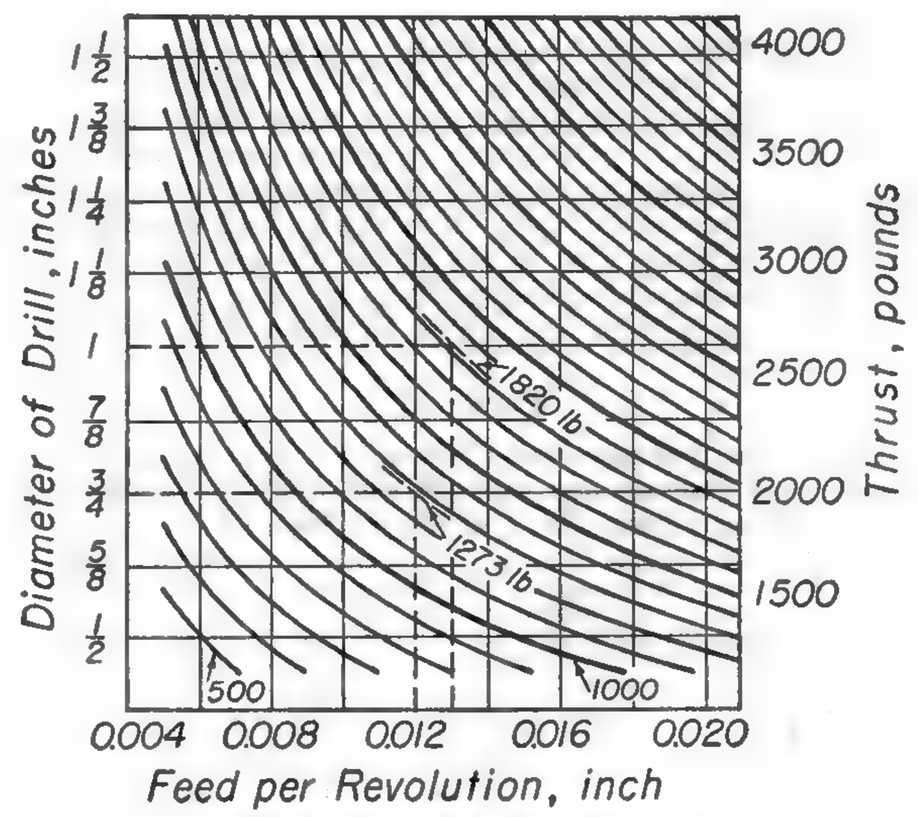

Fig. 6 Thrust in drilling 6150 steel

determined: $T = Cf^{0.78}d^{1.8}$; $B = Kf^{0.78}d$. C is the constant for the material, drill, and cutting fluid in the torque formula, and K is a similar constant in the thrust formula. For drilling 6150 steel that has a Brinell hardness of 186, the formula becomes: $T_{6150} = 1840\ f^{0.78}\ d^{1.8}$. The thrust formula becomes: $B_{6150} = 53{,}400\ f^{0.78}\ d$. The constants for torque and thrust are shown for a number of other steels in Table III.

0.012-in. feed. From Fig. 5 the torque is shown to be 35 ft-lb for the 6150 steel. The torque factor for the 2320 steel is found to be 0.820 in Table III. The resulting torque for the 2320 steel is equal to 35 times 0.820 or 28.7 lb-ft.

The total horsepower developed at the drill point equals the horsepower resulting from the torque plus the horsepower resulting from the thrust as follows:

$$HP = \frac{2\pi TN}{33{,}000} + \frac{B\ f\ N}{12 \times 33{,}000}$$

To illustrate, the drill 1¼ in. in diam with a feed of 0.015 in., rotating at 171.1 rpm (60 fpm) when cutting 6150

Table II

Speeds and Feeds Recommended for High Speed Drills in Various Metals When Cut Using a Suitable Coolant

Size of Drill, inch	Feed per Revolution, inch	Bronze, Brass	Alloy Steel Drop Forging	Cast Iron	Tool and Carbon Steel Drop Forgings	Mild Steel	Malleable Iron	Cast Steel	Hard Cast Iron
		Feet per Minute							
		300	50	140	60	120	90	40	80
		Revolutions per Minute							
1/16	0.003	18320	3056	8554	3667	7328	5500	2445	4889
3/32	0.0035	12212	2038	5702	2442	4884	3666	1628	3258
1/8	0.004	9160	1528	4278	1833	3667	2750	1222	2445
5/32	0.0045	7328	1221	3420	1465	2934	2198	976	1954
3/16	0.005	6106	1019	2852	1222	2445	1833	815	1630
7/32	0.0055	5234	872	2444	1047	2094	1570	698	1396
1/4	0.006	4575	764	2139	917	1833	1375	611	1222
9/32	0.0065	4071	678	1900	814	1628	1222	542	1084
5/16	0.007	3660	611	1711	733	1467	1100	489	978
11/32	0.0075	3330	555	1554	666	1332	1000	444	888
3/8	0.008	3050	509	1426	611	1222	917	407	815
13/32	0.0085	2818	469	1316	563	1126	846	376	752
7/16	0.009	2614	437	1222	524	1048	786	349	698
15/32	0.0095	2442	407	1140	488	976	732	326	652
1/2	0.010	2287	382	1070	458	917	688	306	611
9/16	0.0105	2035	339	950	407	814	611	271	543
5/8	0.011	1830	306	856	367	733	550	244	489
11/16	0.0115	1665	277	777	333	666	500	222	444
3/4	0.012	1525	255	713	306	611	458	204	407
13/16	0.0125	1409	234	658	281	562	423	188	376
7/8	0.013	1307	218	611	262	524	393	175	349
15/16	0.0135	1221	203	570	244	488	366	163	326
1	0.014	1143	191	535	229	458	344	153	306
1⅛	0.015	1017	170	475	204	407	306	136	272
1¼	0.016	915	153	428	183	367	275	122	244
1⅜	0.016	833	139	389	167	333	250	111	222
1½	0.016	762	127	357	153	306	229	102	204
1⅝	0.016	705	118	329	141	282	212	94	188
1¾	0.016	654	109	306	131	262	196	87	175
1⅞	0.016	610	102	285	122	244	183	81	163
2	0.016	571	95	267	115	229	172	76	153

steel, has a torque of 110.8 lb-ft and a thrust of 2430 lb. Substituting these values in the above equation would give the total horsepower as follows:

$$HP = \frac{2\pi 110.8 \times 175.1}{33{,}000} + \frac{2{,}430 \times 0.015 \times 175.1}{12 \times 33{,}000}$$

$$= 3.692 + 0.016 = 3.708$$

The horsepower resulting from the thrust is only 0.016 or only 0.44% of the total power developed; so for ordinary purposes the output of horsepower from the thrust may be neglected. The thrust is important in design, however. Table II shows that the efficiency of the machine, as determined by dividing the input by the output, is highest when small drills are used, operating at high speed with resulting low values of torque and thrust. Similarly, the efficiency is lowest when the torque and thrust are high, even though the speed of the machine is lower.

Table III

Constants for Torque and Thrust Formulas for Various Steels, and Factors for Torque and Thrust Conversion When Using the Curves of Fig. 5 and 6

S.A.E. Number	Bar Number	Brinell Hardness Number	Torque Formula		Thrust Formula	
			C	Factor, F_1	K	Factor, F_2
1020	1	137	1590	0.865	40,000	0.749
1045	2	159	1590	0.865	42,000	0.786
2320	3	163	1510	0.820	44,000	0.824
3120	4	143	1510	0.820	39,000	0.730
3135	5	192	1500	0.815	46,000	0.862
6150	6	187	1840	1.000	53,400	1.000
3250	7	207	1740	0.946	57,000	1.068
3140	8	196	1550	0.843	50,000	0.936
2330	9	202	1780	0.967	66,000	1.235
2340	10	207	1840	1.000	65,000	1.218
6120	11	137	2100	1.140	55,000	1.030
6130	12	156	2000	1.087	56,000	1.049
6140	13	163	2000	1.087	56,000	1.049
9250	14	202	1800	0.978	63,000	1.180
4135	15	156	1560	0.848	43,000	0.805
4130	16	156	1700	0.946	48,000	0.899
1095	19	154	2180	1.184	69,000	1.291

It has been found that torque and thrust are affected little by a change in cutting speed, but the power is a direct function of the speed, as illustrated above.

The horsepower per cubic inch of metal cut per minute is lower for larger values of feed and drill diameter. In drilling 6150 steel with a drill ½ in. in diam at 0.009-in. feed, a value of 1.443 is obtained. For drilling the same steel with a drill 1¼ in. in diam at 0.015-in. feed, the horsepower per cubic inch per minute is 1.075.

In another set of experiments[11] it has been shown that, in the drilling of several steels with 11 different types of cutting fluids, the equation for torque as given above holds true for all steels. When the steels or the cutting fluids are varied, only the constant is changed, as shown in Table IV. The formula given for thrust above in connection with the 6150 steel holds approximately, but for more accurate work, considering the variation in web thickness w of the drills of different sizes, a more accurate formula for thrust has been developed as follows:

$$B = Kf^{0.87}\left(\frac{d}{5} + \frac{w}{d}\right)^{2.12}$$

The performance of one cutting fluid on one steel does not indicate its relative performance on another steel. Actual values of torque and thrust for drilling an annealed 1035 steel with each of 11 cutting fluids, are shown in Fig. 7 and 8. (*Also see* "Cutting Fluids", page 66.)

Table IV shows the values of torque and thrust for standard drills ½ in. and 1¼ in. in diam, operating in each of four steels with three cutting fluids. The equations for torque and thrust and values of the constants are indicated also.

Similar values for torque and thrust are shown in Table V, for drills ranging from ⅛ to ½ in. in diam, when operating in the same steels with an emulsion consisting of 1 part soluble oil to 16 parts water. The equation for torque shown for small drills in Table V is the same as that for larger drills shown in Table IV. The equation for thrust for the small drills shown in Table V is of a simpler form, since it does not account for variations in web thickness.

Table IV

Torque and Thrust Values When Drilling Various Steels with Twist Drills More Than ½ in. in Diam. and Using Three Types of Cutting Fluid

$$T = C\, f^{0.78}\, d^{1.8} \qquad B = K\, f^{0.87} \left(\frac{d}{5} + \frac{w}{d}\right)^{2.12}$$

Material	Cutting Fluid	½ in. Diam Drill[a] Torque	½ in. Diam Drill[a] Thrust	1¼ in. Diam Drill[b] Torque	1¼ in. Diam Drill[b] Thrust	C	K
SAE 1020, annealed	Dry	15.96	875	123.5	3180	2186	906,000
	1 to 50 emulsion	13.00	750	101.0	2750	1786	785,000
	Sulfurized oil	10.62	628	82.4	2285	1457	651,000
SAE 1035, annealed	Dry	13.45	769	104.0	2790	1843	795,000
	1 to 50 emulsion	11.80	678	91.6	2465	1622	702,000
	Sulfurized oil	9.95	618	77.0	2250	1363	651,000
Carbon tool steel, annealed	Dry	15.25	897	118.0	3280	2089	933,000
	1 to 50 emulsion	14.00	895	108.2	3253	1918	927,000
	Sulfurized oil	12.03	732	93.2	2665	1649	759,000
SAE 3150, annealed	Dry	16.17	880	125.0	3200	2215	912,500
	1 to 50 emulsion	14.50	752	112.4	2740	1995	780,200
	Sulfurized oil	12.38	648	95.5	2362	1696	673,200
SAE 1112	Dry	8.90	603	69.0	2190	1222	624,000
	1 to 50 emulsion	8.90	561	69.0	2035	1222	580,300
	Sulfurized oil	8.30	592	64.4	2150	1162	613,000

(a) At 0.009-in. feed and 449 rpm (b) At 0.015-in. feed and 174 rpm

Cutting Tools

The efficiency of a cutting tool is based on the length of time per grind that it will cut at a certain speed under given conditions (termed "tool endurance"); on the power consumed by the tool in removing the metal, and on the finish it produces. The smaller the cutting angle and the greater the rake, the more efficient is the cutting action, from the standpoint of power. When cutting hard metals, the sharp lip will not stand up so well as the blunt lip. The greater the lip angle, the greater the reinforcement to withstand the cutting force and to carry away the heat generated. The tool that has a large rake induces the chip to flow over its face with less distortion, while the tool that has a small rake pushes the metal off with excessive shear and compression. In general, a tool may fail (1) by abrasion on the flank below the active cutting edge; (2) by abrasion on the face behind the cutting edge, causing development of a groove that wears forward to the cutting edge and results in the fairly sudden breaking off of the cutting edge; (3) by a combination of 1 and 2; (4) by spalling or crumbling of the cutting edge; and (5) by a decrease in hardness because of excessive heat generated at the cutting edge.

Table V

Torque and Thrust Values for Drilling Various Steels Using a 1 to 16 Emulsion[13]

Torque in lb-ft $= C\, f^{0.78}\, d^{1.8}$
Thrust in lb $= K\, f^{0.87}\, d$

Steel	Values for the ¼-in. diam drill at 0.006-in. feed per revolution: Torque, lb-ft	Thrust, lb	C	K
SAE 1020, annealed	2.76	306	1740	104,300
SAE 1035, annealed	2.06	281	1300	96,000
0.97% C tool, annealed	2.92	390	1842	133,100
SAE 3150, annealed	2.38	318	1500	108,500
SAE 1112, cold finished	1.58	217	1000	74,100

Types 1, 2 and 3 are normal types of tool failure. Tools made of carbon tool steel usually fail in the first way when cutting steel and cast iron. High speed steel tools fail in the first way when cutting cast iron, but normally in the second or third way when cutting steel, as illustrated in Fig. 2. Carbide tools fail by flank wear, by cupping, or by the two together.

Factors entering into the performance of tools include (1) composition, (2) melting and casting practice, (3) fabrication—whether forged, ground from rolled bars, cast, or sintered, (4) heat treatment, (5) mechanical properties—hardness, ductility and hot hardness, (6) tool form, such as profile of cutting edge, and various tool angles, (7) tool sharpness, (8) metallographic structure, (9) tool setting.

Cutting-Tool Materials. Cutting tools must be formed to meet the requirements of the material of which they are made. Cutting speeds and the size of the cut also must be in accordance with the tool material in order to help obtain satisfactory commercial tool life. Cutting tools are commonly made of carbon tool steel, finishing steel, high speed steel, cobalt-base alloys, sintered carbide, and diamonds. Carbon tool steels are used to some extent where light cuts at comparatively low speeds are permissible, in screw machines on free-cutting materials where the tool is well cooled, or where formed tools are stocked for infrequent use. The great majority of tools being used are made of high speed steel. The 18-4-1 high speed steel is the type most commonly used for all-around work. It is uniform in performance. The 18-4-2 type of

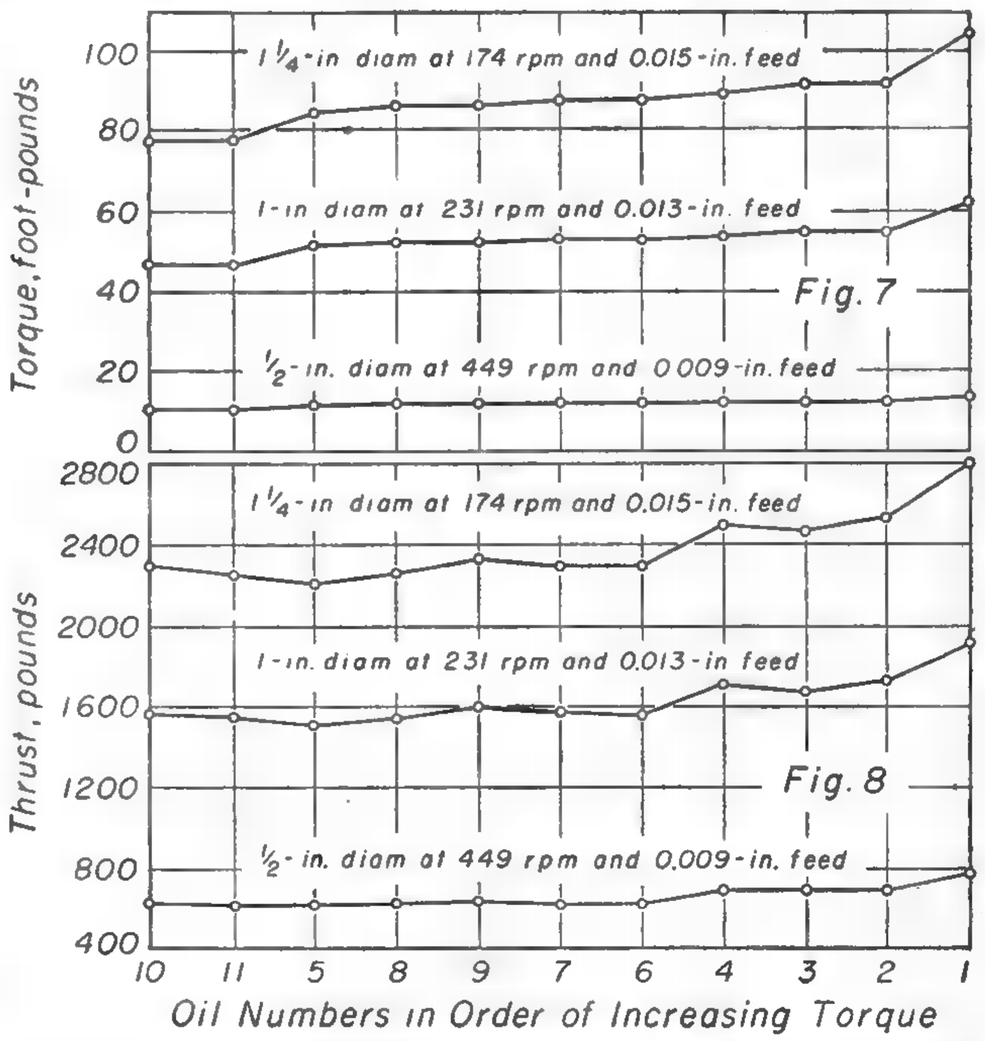

Fig. 7 Torque required to drill an annealed 1035 steel forging with various sizes of drills operating at a speed of 60 fpm and with cutting fluids as indicated by the numbers along the horizontal axis of the graph. These numbers refer to different cutting fluids, as follow: (1) dry cutting; (2) 1½% borax in water; (3) 1 part soluble oil to 50 parts water; (4) 1 part soluble oil to 10 parts water; (5) No. 1 lard oil; (6) light mineral oil; (7) heavy mineral oil; (8) 10% lard oil; (9) mineral 5% oleic acid; (10) sulfurized mineral oil; and (11) sulfurized-base oil, blended 1 to 5 with light mineral oil.

Fig. 8 Thrust values required to drill the 1035 steel of Fig. 7

steel generally gives slightly better performance than the 18-4-1 type. The 18-4-3½ type of high speed steel is coming into favor for heavy-duty work. Molybdenum steels, such as 8-4-1, 8-4-2, and 9-1½-4-1 also are coming into general use where high speed steels are involved. The cobalt high speed steels give as much as 25% greater production for certain heavy-duty jobs.

Cast cobalt-base alloy and sintered carbide tools are nonferrous in character. These alloys are cast or sintered to shape and are finally ground. Neither can be forged or heat treated, and both are used ordinarily in the form of tips welded to the end of heavy steel shanks. Both cobalt-base alloys and cemented carbide are less ductile than high speed steel and serve best when cutting abrasive materials. They must be ground with less clearance and rake in order to provide a greater lip angle to support the cutting edge. Both should be supported rigidly to avoid bending or chattering. Terminology applied to a ground tool is presented in Fig. 9 and 10, which apply to a typical high speed steel, shank-type tool.

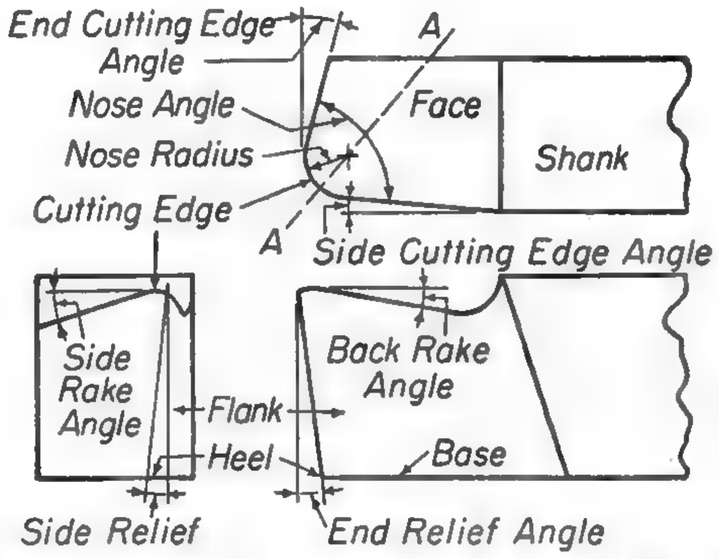

Fig. 9 Nomenclature of a ground right-cut, single-point tool that has a straight cutting edge and straight shank. (American Standards Association)

Performance of Tools. In the cutting of a given steel, the composition or treatment of the high speed steel tool, as well as its geometric shape, has a bearing on its performance. A series of tests for speed of cutting in relation to tool life, was performed on each of four high speed steel tool bits, two of which were of the regular 18-4-1 type of high speed steel; the third was a cobalt high speed steel; the fourth was a molybdenum high speed steel. When these four tool bits were ground to a specific shape for turning dry, annealed 2345 steel, individual equations were obtained, indicating that the constant, as well as the exponent, of the tool life equation is subject to change because of the tool material.[7]

Influence of the Tool Shape on Tool Life. For a 60-min tool life, the cutting speed is increased 125% as the radius of the nose of the tool is increased from zero to ¼ in.[14] Increasing the side cutting angle similarly shows a great increase in cutting speed for the same tool life. Frequently, if side cutting angles are greater than 30 deg on deep cuts where deep thin chips are taken, chatter is likely to occur. This chatter may be eliminated by changing the cutting fluid, the cutting speed, the size or shape of cut, and preferably by reducing the side cutting edge angle. The speed for a 60-min tool life is increased 55% as the side cutting edge angle is increased from zero to 60 deg. The side rake angle similarly indicates an increase in cutting speed for any given tool life, but for cutting an annealed 2335 steel, the maximum speed was reached when using a side rake angle of 22 deg. However a 70% increase in cutting speed was obtained by increasing the side rake angle from zero to 22 deg. In the cutting of soft steel, the greatest tool life for any given speed, is obtained when the tool is ground as follows: 8-deg back rake, 22-deg side rake, 6-deg relief, 6-deg end cutting edge angle, 45-deg side cutting edge angle, and ⅛-in. nose radius. For harder steel, the side cutting edge and side rake angles should be reduced.

Influence of Tool Shape on Cutting Force. For a cut 0.100 in. deep with a feed of 0.0125 in. in a 0.61% steel of 207 Brinell and 99,000 psi, with a basic tool ground to 8-deg back rake, 14-deg side rake, 6-deg end cutting edge angle, 15-deg side cutting edge angle, and $\frac{3}{64}$-in. nose radius, the cutting force varies as follows: As the nose radius is increased from zero to ¼ in., the tangential force remains virtually unchanged at 395 lb; the longitudinal force is reduced from 185 to 95 lb; and the radial force is increased from 25 to 150 lb. As the side cutting edge angle is increased from zero to 60 deg, the tangential force remains almost constant at 395 lb. It decreases slightly for the 30 and 45-deg angles. The longitudinal force is gradually reduced from 173 to 90 lb, and the radial force is increased from 48 to 180 lb. As the side rake angle is increased from zero to 40 deg, the tangential force is reduced from 440 to 335 lb, the longitudinal force is reduced from 245 to 98 lb, but the radial force remains virtually constant. A change in back rake angle from zero to 16 deg produces only a slight reduction in tangential and longitudinal forces, but reduces the radial force from 75 lb to zero.

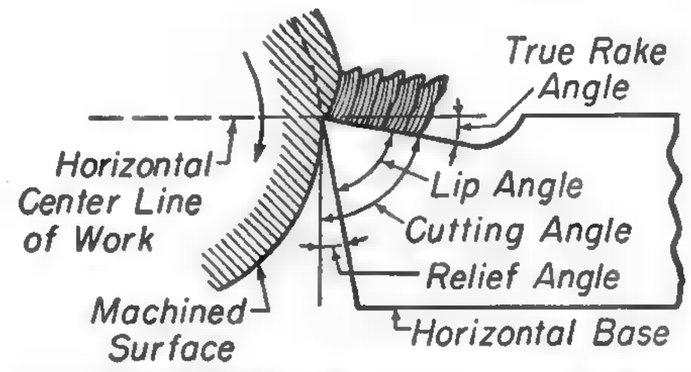

Fig. 10 A section through the active cutting edge *A* — *A* of Fig. 9, including nomenclature

As the cutting speed is varied for an otherwise fixed cutting condition, all components of the cutting force remain virtually constant at the higher speeds. At very low speeds, all values of components vary. The temperature between the tool and work, as determined with a thermocouple, rises rapidly until a speed is reached between 10 and 20 fpm, depending on certain variables, after which it increases in direct proportion to an increase in speed.

Cutting Fluids. See the article on "Cutting Fluids for Machining", page 66 in this Handbook.

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Metallurgical Factors Affecting the Machinability of Steel

BY THE SUBCOMMITTEE ON METALLURGICAL FACTORS AFFECTING MACHINABILITY*

MACHINABILITY may be defined as that property of a metal which governs the performance of the metal in machining reactions. Machinability is a complex, elusive quality, seldom subject to positive control by any single factor. Further, no entirely satisfactory and generally accepted laboratory test has ever been devised to evaluate the machining properties of steel although investigators have made and are continuing attempts to develop such a test. In conjunction with actual machining experience correlated with metallurgical data and manufacturing practices these investigations have brought forth some information on fundamental factors that affect the machining of steel. Factors that arise in the cutting operations are outside the scope of this article; only factors metallurgical in character and inherent in the steel are considered here. They are grouped according to manufacture, composition, processing and physical characteristics.

Steelmaking. Aside from the adjustment of chemical composition, many features in the operation of any steelmaking process will affect the machining characteristics of the final product. It has been learned, for instance, that ease of machining Bessemer steels is generally increased by carrying the steelmaking process to a further point of oxidation of carbon than in making other Bessemer products. Furthermore, any steelmaking procedure that favors the absorption of an appreciable nitrogen content seems to improve machinability. Machining appears to be affected adversely if the final total sulfur content of either Bessemer or open hearth steels consists largely of residual sulfur rather than of sulfur addition.

The Bessemer Process. Acid Bessemer sulfurized carbon steels, commonly known as "Bessemer screw steels", had their origin in the early days of the Bessemer process. Late in the nineteenth century it came to be recognized that high-sulfur blows, erratically produced in the cupola-converter combination, made a product superior to lower sulfur steel in machining qualities. The introduction of the hot metal mixer, the improvement of Bessemer converters and the success of deliberate additions of sulfur to Bessemer steel are now history.

The Open Hearth Process. The addition of sulfur to Bessemer steel led to a similar practice for low-carbon open hearth steel. Thus open hearth screw steels came into existence, having machining quality distinctly better than that of nonsulfurized open hearth steels, though generally poorer in machinability than Bessemer screw steels.

Composition. The chemical composition of a steel has a major influence on machinability, since the composition affects the structure and mechanical properties. Because the effect of composition is obscured by other factors, it is difficult to state the exact influence of each element.

Carbide-forming elements decrease machinability by increasing hardness, but their detrimental effects can be modified by annealing processes. Elements that dissolve in ferrite ordinarily cause poorer machinability on account of the hardness or toughness which they impart. Elements forming inclusions have harmful effects when the inclusion is hard or abrasive, such as alumina or silica. Elements such as sulfur, which form soft inclusions, appear to have a beneficial effect. Best machinability is associated with an optimum hardness and brittleness produced by the combined effect of elements present. Thus an increase of manganese should be accompanied by a decrease of carbon to avoid passing beyond the optimum hardness. General statements concerning the effects of the more important elements and compounds are given below.

Carbon. Very low carbon steels are usually of poor machining quality because they have less than the optimum hardness. The best carbon content for machinability is approximately 0.10% for Bessemer steel and 0.20% for open hearth steel. Cutting quality decreases rapidly with increase of carbon to more than 0.15% in Bessemer and more than 0.30% in open hearth steel.

Manganese. The effect of manganese depends largely on the total content of carbon, manganese and phosphorus. In free-machining steels, the most favorable manganese content is 0.75 to 1.00% in Bessemer steel and about 1.00 to 1.30% in open hearth steel.

Phosphorus. In Bessemer steel phosphorus should be in the range of 0.06% to 0.10%. Added phosphorus, as high as 0.10% in open hearth steel, is mildly effective in improving machinability.

Sulfur. Sulfur is the element most commonly used for obtaining better machinability. As the percentage of sulfur is increased to some limit not yet accurately determined, machinability is improved. From a practical manufacturing standpoint, this limit is approximately 0.30%.

Silicon. Cutting quality ordinarily decreases as the silicon content increases, chiefly because of the silicate inclusions usually present.

Other Elements. The general effect of the other alloying elements is to decrease machinability by imparting hardness and toughness to the steel. For this reason most alloy steels will require a special heat treatment, usually annealing, to secure the best machining properties. Some alloying elements, such as molybdenum, vanadium or chromium decrease machinability less than others, such as nickel. Lead is added to structural steel to improve machinability. Selenium is added to stainless steel to improve machinability; its effect is similar to that of sulfur. Tellurium has also been added to stainless steel to improve machinability.

Inclusions. In accordance with the best accepted practice of screw steel manufacture, every precaution is taken to avoid abrasive inclusions in the finished product. Sulfides, usually occurring in the form of MnS and oxysulfide, variously diluted with FeS, MnO or FeO are generally accepted as benefiting cutting quality; however, it is desirable that such inclusions be small and uniformly distributed. Iron oxides and manganese oxides, either singly or in combination, are believed not to be detrimental. Their presence in high-sulfur steels is usually associated with sulfur (oxysulfides) in which form they are considered distinctly beneficial. The combination of high percentages of these two oxides with SiO_2 is also said to reduce the abrasive and detrimental qualities of silicates. Because of its high hardness and abrasive properties, Al_2O_3 is considered definitely detrimental. Silicates low in FeO or MnO content have a high degree of hardness and are believed to affect machining quality detrimentally.

Processing. Principal processing methods that affect the machining characteristics of steel are hot working, cold working and thermal treatments.

Hot Working. Experience indicates that large structural grain size is ordinarily preferable for most types of machining operations. The desired structural grain size can usually be obtained within reasonable limits by controlling the finishing temperature in hot working. For carbon steels, finishing temperatures are held near 1700 F, or higher when machining characteristics are important and the steel is to be machined before further heat treatment.

For alloy steels that have high hardness when finished at temperatures well above the upper transformation range, temperatures just above A_3 provide somewhat lower hardness (because this decreases the rate of cooling through the transformation range), which may aid machining more than larger grain size with attendant higher hardness.

The effect of hot working on machinability may be considered minor when compared with the effects of such factors as chemical composition and annealing treatment.

Cold Working. Machining characteristics of most steels can be greatly improved by cold working. Machinability is favored by relatively low strength and low ductility. Cold working increases the strength but decreases the ductility. Therefore machinability of steel can be improved by cold working to the point where the cold working increases the

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Table I. Relative Machinability Classification of Cold Drawn Free-Machining and Carburizing Steels
(Based on AISI B–1112 as 100%)

Free-Machining Sulfurized Grades (As rolled)			Nonsulfurized Carbon Grades (As rolled)			Carburizing Steels — Alloy Grades (As rolled)			Alloy Grades (As rolled)		
AISI No.	Per Cent	SAE No.	AISI No.	Per Cent	SAE No.	AISI No.	Per Cent	SAE No.	AISI No.	Per Cent	SAE No.
B-1113	135	1113	C-1019	73	1019	A-4023	73	4023	A-4621	57	....
B-1112	100	1112	C-1016	73	1016	A-4024	73	....	A-1320	55	1320
C-1119	95	1119	C-1018	73	1018	A-5120	70	5120	A-4317	55	....
B-1111	94	1111	C-1022	70	1022	A-8615	67	....	E-4620	55	....
C-1116[a]	91	1116	C-1020	64	1020	A-3115	67	3115	A-8625	51	....
C-1117[a]	85	1117	C-1023	64	....	A-3120	67	3120	A-4320	51	4320
C-1118[a]	82	1118	C-1025	64	1025	A-8617	64	....	A-6120	51	
C-1109	[redacted]	1109	C-1015	61	1015	A-4608	64	....			
C-1120[a]	82	....	C-1017	61	1017	A-4027	64	4027	Alloy Grades (Annealed)		
C-1144	79	1144	C-1012	57	....	A-4028	64	....			
C-1137	73	1137	C-1006	55	1006	A-2317	64	2317	E-2512	48	....
C-1141	70	1141	C-1008	55	1008	A-4615	64	4615	A-2515	48	2515
			C-1010	55	1010	A-8620	61	....	E-2517	48	....
						A-8720	61	....	E-3310	48	3310
						E-4617	61	....	A-4815	48	4815
						A-8622	57	....	E-3316	45	....
						A-4620	57	4620	A-4820	45	4820

(a) Also classified as carburizing steels.

hardness beyond the good machining range of about 187 to 217 Brinell. Cold work brings the greatest improvement in steels that have a low order of work hardening and a high order of work embrittlement.

Thermal Treatments. The machining properties of steel can be affected markedly by heat treatment. Steels that contain less than 0.10% C can be improved in machinability by quenching in water from above A_3, which lowers the ductility and reduces the tendency to drag in machining. Except for these very low-carbon steels, however, quenching and tempering is detrimental to machining properties. The tempered structure is one of the least favorable for machining.

Annealing and normalizing treatments can be very useful in improving the machining properties. In medium-carbon steels they should be designed to coarsen the grain and break up the continuity of the ferrite as much as possible. The carbide should be present as lamellar pearlite. At about 0.50% C with this type of structure, the strength becomes too high for best machinability and it is necessary to modify the annealing cycle so that just enough carbide will be spheroidized to keep the strength within the best machining range, in the vicinity of 100,000 psi tensile strength or about 200 Brinell. Otherwise the structural characteristics should remain the same. As the carbon increases to more than 0.50%, the percentage of spheroidization should increase until, at about 1.00% C, virtually complete spheroidization is necessary to keep the strength factor within the best machining range.

In the alloy steels, the same general principles again apply, but other factors also must be taken into consideration. Alloying elements such as vanadium may form carbides or, like nickel, may form solid solutions. Sometimes the same alloying element may act in both ways; that is, it may go into solution in the ferrite and form a carbide. Examples are chromium and manganese. In this discussion the alloying elements will be considered under two general classifications—those forming carbides and those forming solid solutions.

The elements forming carbides have the same effect as carbon on machining properties; but because of the effect of these elements on hardenability, the carbon content at which the strength factor becomes too high for good machinability is lower than in the plain carbon steels. When heat treatments are used to lower the strength, the annealing cycle should be designed to produce a coarse-grained lamellar pearlite, well broken up. Part of the carbide is spheroidized in the higher carbon alloy steels as in the plain carbon steels. It follows that carbide-forming elements give no particular difficulty in producing good machining properties in alloy steel.

The elements forming solid solutions present a different problem. They toughen and strengthen the ferrite and therefore their tendency is to retard machinability. Attempts can be made to produce a lamellar pearlite structure by thermal treatments (or lamellar with a certain percentage of spheroidized carbide) the same as outlined for carbon steels, but the characteristics of the ferrite matrix cannot be changed much. It is more difficult to produce a lamellar pearlite structure if much of the alloying element is in solid solution in the ferrite, since such elements make the transformation of austenite more sluggish, and if cooling is a little too rapid, the pearlite reaction will be suppressed. If the cooling is a little too slow,

Table II. Relative Machinability Classification of Cold Drawn Steels Suitable for Heat Treating
(Based on AISI B–1112 as 100%)

Alloy Grades (As rolled)			Alloy and Carbon Grades (Annealed for Machinability)								
AISI No.	Per Cent	SAE No.	AISI No.	Per Cent	SAE No.	AISI No.	Per Cent	SAE No.	AISI No.	Per Cent	No. SAE
A-4032	55	4032	C-1045	57	1045	A-8635	57	....	A-9850	51	....
A-4130	51	4130	C-1050	57	1050	A-8632	57	....	A-4150	51	....
A-5130	51	....	A-4032	70	4032	A-9840	57	....	A-3150	51	3150
A-3130	48	3130	A-4130	67	4130	A-4047	57	4047	A-2345	51	2345
A-2330	45	2330	A-5130	67	....	A-4142	57	....	E-4337	51	....
A-3135	42	3135	A-8627	64	....	A-4145	57	4145	A-4340	51	4340
A-2335	39	....	A-4037	64	4037	A-3140	57	3140	A-5152	51	....
A-3140	36	3140	E-4132	64	....	A-3141	57	3141	A-5150	51	5150
A-3141	36	3141	E-4135	64	....	A-2335	57	....	A-8645	48	....
			A-3130	64	3130	A-5145	57	....	A-9445	48	....
Carbon Grades (As rolled)			A-8630	61	....	A-8637	55	....	A-6152	48	....
			A-4042	61	4042	A-9437	55	....	E-6150	48	....
C-1030	57	1030	E-4137	61	....	A-8735	55	....	A-8647	45	....
C-1035	57	1035	A-4140	61	4140	A-8640	55	....	A-8650	45	....
C-1040	55	1040	A-3135	61	3135	A-9440	55	....	A-8745	45	....
C-1045	51	1045	A-2330	61	2330	A-8740	55	....	A-1330	42	....
C-1043	51	....	A-5140	61	5140	A-9845	55	....	A-9747	42	....
C-1050	48	1050				A-8642	51	....	A-8747	42	....
						A-9442	51	....	A-8750	42	....
						A-8742	51	....			

however, the structure may be predominantly spheroidized. When little can be accomplished with heat treatment, machinability of these alloy steels can be improved by cold working to reduce ductility. This is particularly true in the low-carbon alloy steels like 4615, where free ferrite is the predominant structural constituent. Experience has indicated that it is an advantage to cold work the more highly alloyed steels like 2512 to higher hardness than is usually considered best for free machining, in order to reduce the ductility further. This applies to drilling or broaching where steel that has been cold worked to a Brinell number up to 250, or above, may give better results than softer material with high ductility and toughness.

Physical Characteristics. Like other factors affecting machinability, physical characteristics depend on manufacturing and processing practices. Therefore a discussion of some physical details has been included in the preceding sections. In general, the qualities desired, though not clearly defined, seem to be a low capacity for work hardening with a high degree of work embrittlement, under the conditions of cold work that exist during cutting.

Grain Size. There is a divergence of opinion about the relation of structural grain size to machining quality, but it is generally agreed that some improvement in machining performance usually occurs with large structural grain size. However, the improvement is not proportional to the degree of coarsening. Steel that has a small austenitic grain size is usually structurally fine grained as rolled. Certain precautions, such as finishing at a high temperature, tend to coarsen the structural as-rolled grain size and thus aid machining. However, fine-grained steels, made usually by additions of aluminum are generally of poorer machinability because Al_2O_3 present in the steel has an abrasive action on the tool.

Hardness. Many investigators have tried to correlate closely Brinell hardness numbers and machinability; but much of the work has been unsuccessful because composition, structure and mechanical factors are not taken into account in a simple hardness test. Nevertheless, some consider that Brinell hardness is an indication of machining quality and that the range of hardness for ease of machining is about 187 to 229 Brinell.

Tensile Properties. Tensile properties are an index of machinability only in giving comparative values of strength and ductility of different steel compositions. Good machining steels are soft and brittle and have the property of low work hardness. Tensile properties can therefore be used to show the relation of tensile strength to ductility. It is also probable that shearing properties are related to machining properties.

Metallographic Structure. Lamellar pearlite is the most favorable structure in which carbon occurs in steel for free machining, unless there is too much of it, as in very high-carbon steels. The presence of too much pearlite results in strength too high for machining, and it is necessary to spheroidize the cementite as mentioned before.

Many authorities hold the opinion that nonabrasive inclusions that break up the ferrite particles are strong factors for improved free cutting. Sulfides are an outstanding example of this type of inclusion. Perhaps the smaller the inclusions, the more effective they are. The effect of submicroscopic particles is not known, although some have speculated that such particles exert greater influence on machinability than visible inclusions do.

Classification. A study of the factors influencing the machinability of steel indicates that the various steels may be classified in groups that have more or less similar machinability. The various AISI steels with corresponding SAE numbers have been arranged in the Classification Tables I and II.

Those grades having machinability significantly affected by annealing have been rated both "annealed" and "as-rolled" (not annealed). The values given are intended to serve only as a guide. Adjustments should be made to suit specific operations and conditions, since the variation in any one grade may readily overlap similar grades immediately preceding or following in its series. These values are appropriate for turning, forming, drilling and cutting-off operations where high speed tools and a conventional cutting fluid are used.

The Welding of Ferrous Metals

BY THE SUBCOMMITTEE ON WELDING AND CUTTING*

THE METALLURGICAL aspects of fusion welding and certain allied processes are discussed in a general way in the article entitled "Welding Processes", on page 71 of this Handbook. The present article will summarize the application of these methods to ferrous metals.

Table I lists the welding methods that are commonly used and those occasionally used for joining 26 grades of ferrous materials. The welding of these materials will be discussed in the order given in Table I.

Iron

1 Wrought Iron. The low carbon and high slag content have a marked effect on the weldability of wrought iron.

Forge Welding. Wrought iron is an ideal material for forge welding.

Resistance Welding. Spot, seam, projection, flash and resistance butt welding may be applied satisfactorily to wrought iron. To produce solid, clean welds and to prolong electrode life, all scale, oxide and other foreign matter must be removed from the work.

Thermit Pressure and Fusion Welding. Wrought iron can be successfully welded by either of these processes. On old wrought iron that contains heavy layers of slag it may be necessary to make two thermit welds in order to produce a satisfactory joint. The first of these may melt into the laminated iron-and-slag piece, and porosity, caused by the slag layers, may be found in the thermit steel. If so, the collars are trimmed off and the original gap is cut through the section, leaving the porous thermit steel to be remelted in a new weld made on these same ends. The new weld will fuse only as far as the original weld did, from which the slag has been eliminated. Most modern wrought iron sections contain so little slag that this reweld is unnecessary.

Gas Welding. In oxyacetylene welding of wrought iron, the slag content sweats to the surface at a comparatively low temperature. This may deceive the inexperienced operator who may regard it as an indication of fusion. Heating must be continued until the base metal itself actually breaks down into a puddle.

This puddle of molten metal must be maintained and the welding rod must be kept immersed in it to assure fusion and penetration without oxidation. Excessive stirring of the puddle should be avoided since this causes needless exposure and resulting oxidation.

An oxyacetylene welding rod for wrought iron should either be made of low-carbon iron or should contain sufficient manganese and silicon so that a weld metal relatively high in these elements will be obtained. The welding flame should be strictly neutral.

Arc Welding. Arc welding of wrought iron, both in flat and vertical positions, with coated electrodes, is hindered by accumulations of slag that become entrapped in the weld, and care must be taken to melt out this slag. In general practice, as little as possible of the wrought iron is melted, and reverse polarity reduces the formation of slag accumulations substantially but not entirely.

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The welding of wrought iron with bare electrodes is comparable with welding of low-carbon steel. The arcing characteristics of the electrode and the ability to obtain proper fusion between the parent metal and the deposited weld metal are the same as in the welding of mild steel.

Welds made with bare mild steel electrodes have strength approximately equal to that of the parent metal, while welds made with heavily coated mild steel electrodes are stronger than the parent metal.

Bronze Welding. The bronze welding process can be applied readily to wrought iron.

Oxyacetylene Pressure Welding. Wrought iron will respond satisfactorily to standard pressure welding.

Submerged-Melt Welding. A two-pass procedure is necessary to assure consistently sound joints. The first pass, which is approximately the full depth of the V, fuses and fluxes the accumulated slag from the base metal, but is porous because the gas evolved has not been completely eliminated. The second pass re-fuses the first and adds reinforcing. The resulting weld, which is made with materials ordinarily used for low-carbon steel welding, is sound and its strength exceeds that of the base metal.

2 Low-Carbon Iron. Iron with a carbon content of 0.06% max is one of the most readily welded of the ferrous metals.

For welding low-carbon steels, preheating is not necessary and subsequent annealing is not required unless it is desired to eliminate the residual stresses set up during the welding operation.

Forge Welding. Low-carbon iron is readily welded by the forge welding process.

Resistance Welding. Low-carbon irons are readily resistance welded by any of the processes that are suitable for welding wrought iron.

Gas Welding. This process is similar to the gas welding of low-carbon steels, except that the filler rod utilized is necessarily of low-carbon iron in order to retain the corrosion resistance of the parent metal and to obtain a weld of similar characteristics.

Arc Welding. Arc welding of low-carbon iron is accomplished with the use of mild steel electrodes, heavily coated. The welding current and procedures are the same as for welding mild steel. Bare electrodes can be used with a resulting decrease in the corrosion resistance of the weld and adjacent parent metal. Iron with carbon content less than 0.15% absorbs gas readily from the atmosphere during welding. Welds of highest quality require complete shielding.

Bronze Welding. Low-carbon iron may be bronze welded quite readily by either the arc or gas process. One decided advantage is that neither process requires heating the steel to the high temperature necessary for fusion welding.

Thermit Welding. Iron with a carbon content of 0.06% and less can be successfully welded by both thermit fusion and thermit pressure processes.

Submerged-Melt Welding. The use of rod and granulated material of suitable composition makes possible a sound weld having a metalloid content not exceeding 0.40%, and equal in strength to the base metal.

Carbon Steels

1 Low-Carbon Steel (0.30% C and less). These steels are easily welded by all the welding processes and the resultant welds and joints are of extremely high quality.

Gas Welding. The joint edges should be clean and properly prepared to facilitate good fusion and a sound weld. In welding long seams, allowance must be made for the effect of heat along the line of weld, which causes contraction during cooling and tends to pull the unwelded ends of the plates together. The spacing allowed normally in welding is a ¼-in. opening per foot of seam. Fast welding speeds will reduce the amount of contraction substantially. For making fillet welds, the overlapping plates should be held close together.

A neutral flame is frequently used for welding steel of this class. Increased welding speeds are possible, however, by using a slightly reducing flame. This type of flame carburizes the kerf surfaces, thereby lowering the melting temperature and making possible the fusion of the deposited metal to the plates at a temperature lower than would normally be required. Welded joints made in this way are of high quality and the fusion zone is not hard or brittle.

The preference for filler metal is for the so-called "high-test" welding rods with about 0.15 to 0.20% C and certain metallic elements that will insure freedom from included oxides and give the molten metal proper fluidity.

Arc Welding. Low-carbon steels are readily welded by all forms of this process. Many types of electrodes may be used —bare, dust-coated, washed or dipped, shielded-arc, or flux-coated. Carbon-arc welding is also practical for these steels and the results depend on the technique employed.

In the welding of long seams, the progressive shrinkage of the deposited metal tends to pull the plates together. However, this condition is less severe than with gas welding

Table I. Process Chart for Welding Ferrous Metals

Metals and Alloys	Forge	Resistance	Thermit	Thermit Pressure	Oxyacetylene Pressure	Gas	Bronze	Inert-Gas-Shielded Arc	Arc	Submerged Melt
				(See explanation of code at end of table.)						
Iron										
1 Wrought iron	A	A	A	A	A	A	A	..	A	A
2 Low-carbon iron	A	A	A	A	A	A	A	..	A	A
Carbon steels										
1 Low-carbon	A	A	A	A	A	A	A	B	A	A
2 Medium-carbon	A	A	A	A	A	A	A	B	A	A
3 High-carbon	..	B	A	A	A	B	A	B	A	B
4 Tool steel	..	■	B	B	A	B	B	B	B	B
5 Copper-bearing steel	..	A	B	A	A	A	B	..	A	A
Cast steel										
1 Plain carbon	..	B	A	A	B	A	A	..	A	A
2 High-manganese	..	..	B	B	No	A-B	A-B	..	A-B	B
3 Other alloys	..	B	A	A	B	A-B	A-B	..	A-B	A-B
Cast iron										
1 Gray iron	..	..	B	No	No	A	A	B	B	No
2 Malleable iron	..	..	B	B	No	B	A	..	B	No
3 Alloy cast irons	..	..	A	B	No	A	A	B	B	No
Low-alloy steels										
1 Plain nickel	..	A	B	B	A	A	..	B	A	A
2 Nickel-copper	..	A	B	B	A	A	..	..	A	A
3 Manganese-molybdenum	..	A	B	B	B	A	..	..	A	A
4 Carbon-molybdenum	..	..	B	B	B	A	..	..	A	A
5 Nickel-chromium	..	No	B	B	A	A	..	..	A	A
6 Chromium-molybdenum	..	No	B	B	A	A	..	B	A	A
7 Nickel-chromium-molybdenum	..	No	B	B	A	B	..	..	B	A
8 Nickel-molybdenum	..	No	B	B	B	B	..	..	B	B
■ Chromium	..	No	B	B	A	A	..	..	A	B
10 Chromium-vanadium	..	No	B	B	A	A	..	..	A	A
11 Manganese	..	No	B	B	B	A	..	..	A	A
Stainless steels										
1 Chromium	..	A	No	No	B	B	..	B	A	A
2 Chromium-nickel	..	A	No	No	A	A	..	A	A	A

Code: A, commonly used. B, used occasionally, under favorable conditions. No, not used. (..) no information available.

and ⅛ in. per ft is enough to allow for shrinkage. Proper clamping and tacking and special welding procedures, such as the "step-back" and "skip" procedures, are commonly used to prevent distortion and residual stresses. The design of the structure, preparation of the joint, the size of electrode, welding current and voltage all are important.

Carbon-arc welding varies from metal-arc welding in that the arc is drawn between the base metal and a carbon or graphite electrode. The arc heat in this process is used only to melt or fuse the base metal, and the filler metal, when required, must be obtained from a specially prepared flange or upset edge at the joint or from some extraneous source. Filler metal can be added by placing more metal on the seam to be welded or by feeding suitable metal into the weld much as in the oxyacetylene process.

Carbon-arc welding performed without a flux or shielding atmosphere, may result in brittle welds. Shielding the arc, by painting the weld with a special flux or by introducing a suitable fluxing material into the arc, produces welds of high quality.

Bronze Welding. Low-carbon steels may be bronze welded quite readily. The joint surfaces are "tinned" by means of a suitable flux and copper alloy welding rod. The rod is then melted into the space between the tinned surfaces to be joined. This work is ordinarily a continuously progressive operation; the tinning is carried out for a distance and then additional filler metal is deposited before the section becomes cold. With recently developed copper alloy rods, strengths of the order of 55,000 psi can be obtained in the welds. This process does not require the steel to be heated to as high a temperature as in fusion welding, a difference that is often a decided advantage.

Thermit Welding. Fusion thermit welding is successfully carried out on low-carbon steels by using forging thermit. The welds have tensile strengths of 70,000 to 75,000 psi, elongations of 15 to 20% in 2 in., and good impact values. Before welding, the joint surfaces are preheated between 1600 and 1700 F. The purity of the weld deposit eliminates the need for subsequent forging or heat treatment to develop satisfactory physical properties.

Oxyacetylene Pressure Welding. Steel tubing of this carbon content can be welded by the closed butt process with either a plane, flat butt or an 8 to 12-deg included angle preparation, outwardly open. Solid sections are welded with the flat butt preparation. Considerable tolerance is permissible on the quality of face preparation, but clean surfaces are necessary. A holding pressure of 1000 psi of cross section is generally applied during preheating, followed by an upsetting pressure of 4000 psi of cross section. With the open butt process, the surfaces to be welded are held apart during the heating cycle, then brought together under pressure to complete the weld. For this method of pressure welding, the preparation of the faces is less critical than with the closed butt process, but the resulting upset is more uneven. The strength of the joints will equal that of the parent metal.

Submerged-Melt Welding. Butt welds from 16 gage to 2½ in. thick can be made in one pass, using suitable means for backing the joint, or multiple-pass procedures can be used for welding even greater thicknesses. The usual joint design requires that the abutting edges be in contact for the full length of the joint. Tack welds must be used to prevent the joint from opening ahead of the welding zone. This phenomenon, which is the exact opposite of that obtained with gas or ordinary arc welding, is caused by the high rate of heat input and speed of welding, which are the features of the process.

Since the major portion of the fused metal consists of base material, the physical properties of the weld metal more nearly approach those of the base material. Thus a single rod composition and granulated material may be used for welding a variety of base-metal compositions.

The loss of dimension as a result of shrinkage, either parallel to or transverse to the weld, is only one-third to one-half that usually encountered in an ordinary arc weld. Distortion is greatly reduced and is quite uniform in the usual automatic applications of the process. Certain simple procedures can virtually eliminate distortion. Stress patterns of the welds are about the same, in shape and magnitude, as those obtained with ordinary arc-welded joints.

2 Medium-Carbon Steel (0.30 to 0.50% C). Steels in this class can be welded by the various fusion processes. The technique and materials used are dictated by the metallurgical characteristics of the base metal. In some instances, preheating and subsequent heat treatment may be required to produce the desired weld quality, especially in steels containing more than 0.40% C.

Gas Welding. In welding medium-carbon steel, better welds can be obtained if an excess of acetylene is used in the welding flame. The recommended welding procedure is similar to that for low-carbon steels. As a rule, little trouble is caused by the formation of hard and brittle constituents as a result of rapid cooling. The quality of the finished joint will be improved if it is heat treated after welding.

Arc Welding. The weldability of steels of this grade depends on the carbon content of the base metal, because the rapid cooling may produce martensitic or troostitic structures; and the formation of such structures in the fusion zones tends to make these areas hard, brittle, and of an undesirable character. Steels that have higher hardenability and greater carbon content are likely to be susceptible to toe-and-root cracking from electrodes that contain hydrogen.

Preheating temperatures from 300 to 500 F have been found effective for eliminating and reducing the hard and brittle areas. By heating between 1100 and 1200 F after welding, it is possible to restore the desired properties in the areas affected by the welding heat. Modifications of welding technique, especially in heavy sections, can improve weldment properties considerably in this class of steel.

Shielded-arc electrodes of the type used on low-carbon steels are satisfactory for the welding of medium-carbon steels. The use of "hydrogen-free" shielded electrodes will greatly decrease susceptibility to toe-and-root cracking.

Thermit Welding. This process is carried out as successfully on medium-carbon steels as on the lower-carbon grades. Forging thermit is generally used, but the increase in carbon from the parent metal produces a somewhat higher tensile strength and lower ductility than when the lower-carbon steels are being welded.

Oxyacetylene Pressure Welding. Procedures applied to the pressure welding of low-carbon steel are also satisfactory for medium-carbon steel.

Submerged-Melt Welding. Steels of this class are welded somewhat more readily by this process than by ordinary arc welding, because the higher rate of heat input results in a slower quench and a wider and softer heat-affected zone. Heavy sections should be preheated to reduce further the hardness of this zone.

Rods and granulated material normally used for low-carbon steels are generally used for welding the medium-carbon steels. The carburization from the base metal is sufficient to provide the strength desired in the weld metal. Slightly larger V's and slower welding speeds are an advantage in reducing the hardness of the heat-affected zone, although this procedure is not always necessary.

3 High-Carbon Steel (0.50 to 0.90% C). Because of the higher carbon content, these steels are more difficult to weld.

Gas Welding. Since these steels are often heat treated, the welding heat will affect such treatment and produce a joint with properties different from those of the original metal. Care should be taken to prevent overheating the parts and the weld should be completed as quickly as possible. High-carbon steels melt at a lower temperature than the lower-carbon steels and tend to spark when overheated, a condition that helps to avoid overheating the parts.

A carburizing or excess acetylene flame is advantageous in securing strong sound welds. High-carbon filler rods are often used, although satisfactory results can be obtained with medium-carbon filler metal, which produces a weld of only moderate strength; however, the increase in ductility is often beneficial. By heat treating after welding, it is possible to eliminate the effect of the welding heat and to improve the strength of the weld.

Arc Welding. Steels in this group do not have good mechanical properties after arc welding. Hardness and brittleness may be produced in the fusion zone. For the best results, it is recommended that the parts be preheated to at least 500 F before welding, and subsequently heated between 1200 and 1450 F.

High-carbon steels are often welded to rebuild a worn surface or to develop a hard, wear-resistant surface. Unless the carbon content of the parent metal approaches the higher limit, preheating or subsequent heat treatment is not necessary in such instances.

Mild steel electrodes of the shielded-arc type can be used to make joints on these steels. The deposited metal tends to absorb carbon from the base metal and so loses considerable ductility. Austenitic electrodes are often recommended and the resultant welds have good physical properties, but the fusion zone may still be hard and brittle.

The remarks that apply to medium-carbon steel in regard to arc-welding technique and toe-and-root cracking apply as well to high-carbon steels. In special instances where steels are heat treated before welding, the electrodes selected should be of a sort that will permit attaining desirable ratios of weld metal strength to parent metal strength.

Thermit Welding. High-carbon steels are readily welded by the fusion thermit process. Because of the lower melting temperatures of the parent metal, slightly lower preheating temperatures are used than with the lower-carbon steels.

If forging thermit is used, carburization will be sufficient to produce a weld strength of 90,000 to 100,000 psi. Often, however, when hardness or wearing qualities are of prime importance, special thermits are required.

The preheating and inherent characteristics of the thermit process prohibit the rapid cooling that is obtained in arc and gas welding; therefore, subsequent heat treatment of joints even on these high-carbon steels is not required for satisfactory mechanical properties.

Oxyacetylene Pressure Welding. To produce a joint of high quality it is necessary to use the flat butt preparation and to obtain a smooth finish on the abutting surfaces. Care must be taken to avoid overheating high-carbon steels, since hot cracks and checks usually result. Higher pressures are used for upsetting at lower temperatures.

Submerged-Melt Welding. This process is seldom used to make joints in high-carbon steels. Layer deposits have often been made to rebuild worn surfaces on high-carbon base material, and hard, wear-resistant surfaces are possible by choosing suitable rod composition. Preheating is not usually required, nor is subsequent heat treatment.

4 Tool Steels (0.80 to 1.50% C). These steels are relatively difficult to weld.

Gas Welding. Drill rods, available in the various diameters required for welding, and of carbon content sufficiently high to cover the carbon range, are generally used in welding these steels. The use of a carburizing or excess acetylene flame is advantageous in securing sound strong welds. Flux suitable for welding cast iron should be used sparingly. Preheating and annealing are usually necessary.

Arc Welding. Because of the heat effects of arc welding, this process is seldom used for tool steels. If welding is required, one of the following procedures is recommended:

(1) After annealing, preheat the parts and weld with a suitable shielded-arc electrode; then heat treat to restore the desired properties. (2) Preheat the parts and use an austenitic electrode. Preheating will aid in preventing the formation of a hard fusion zone and the weld will not be hard because of its austenitic condition. (3) Preheat the parts and deposit one or more layers on the kerf surfaces of the parts with a shielded-arc electrode. These layers dilute the carbon so that the parts can then be more readily welded together. It should be noted that this process does not produce a high-carbon weld.

The remarks that apply to medium-carbon steel in regard to arc-welding technique and toe-and-root cracking apply as well to tool steels. In special instances where steels are heat treated before welding, the electrodes selected should be of a sort that will permit attaining desirable ratios of weld metal strength to parent metal strength.

Thermit Welding. Fusion thermit welding is not commonly used on these steels, but successful joints have been made on materials containing 1.10% C. Forging thermit can be used but the tensile strength will not be equivalent to that of the parent metal. Higher-carbon thermit can be used if the strength is of prime importance. Heat treating the weld and fusion zone, after welding, is recommended in order to produce the best properties.

Oxyacetylene Pressure Welding. Tool steels are frequently joined to less expensive steels in the production of drills and other machining tools. Pressure welds are made in these steels at relatively low temperature in order to produce on the tool steel no harmful metallurgical effect that cannot be removed by subsequent heat treatment. Heat treatment is usually necessary to produce the desired physical properties in the welded article. Pressure cycles used on tool steels vary with the material and may be considerably higher than for low-carbon steels.

Submerged-Melt Welding. The process has not been used for joining, but has been used for building up punches that have been scored in hot punching operations. A single layer of welding will pick up sufficient alloying elements from the base material to provide as satisfactory service as the original punch.

Copper-Bearing Steels. These steels, ordinarily of the low-carbon variety, contain from 0.20 to 0.30% Cu. The same welding processes are applicable as for ordinary steels of the same carbon range. Welded joints made by the gas or shielded-arc processes are, in general, as resistant to corrosion as the copper-bearing steels.

Oxyacetylene Pressure Welding. Copper-bearing steels are pressure welded by procedures comparable with those used on carbon steels of similar carbon content.

Submerged-Melt Welding. These steels are welded as readily as ordinary steels in the same carbon range. Since welded joints contain a large proportion of the base metal, they are as resistant as the base material to corrosion.

Steel Castings

Welding of low-carbon steel castings presents no particular difficulties if the casting is properly prepared, is reasonably clean, and the ordinary precautions are taken to avoid setting up excessive expansion and contraction stresses in the metal. With castings that contain more than 0.25% C and with special alloy compositions, certain precautions are necessary in welding.

1 Plain Carbon Steel Castings. Before the welding of steel castings, an effort should be made to learn the chemical composition in order to weld successfully the high-carbon and the alloy castings. Castings under this heading should not contain more than 0.25% C and a negligible amount of alloying materials. Castings of such compositions present no difficulties in welding by approximately the same procedures as with low-carbon wrought steel.

Gas Welding. It is customary to use a general-purpose filler rod for welding these castings, although for the best results the chemical composition of the filler metal should be similar to that of the base metal.

Arc Welding. The procedure for the electric-arc welding of steel castings (low-carbon and medium-carbon) is essentially the same as for wrought steel of similar composition. For the best results, a high-grade electrode heavily coated is considered desirable. The surfaces to be welded should be carefully cleaned of sand inclusions, cracks, porosity and dirt. Multilayer welding and high currents should be employed if the carbon content is low, but small-diameter electrodes and low currents are necessary when the carbon content is high; while in some instances preheating and slower cooling are desirable.

Bronze Welding. Bronze welding is satisfactorily applied to steel castings, especially where the difference in surface appearance of the casting is not objectionable. Both gas and electric-arc processes are used. Before being welded, the surfaces should be prepared and cleaned as described above under Low-Carbon Steels.

Thermit Welding. Repairs are readily made and heavy cast steel parts are commonly reclaimed by the thermit process. Where the work consists of applications such as replacing teeth in large gears or pinions, the fact that the tooth is a comparatively small projection on an extremely heavy casting must be taken into account. If the casting were preheated at the weld only, the heat would be carried away into the casting so rapidly that fusion between the weld metal and the parent metal could not be obtained. Therefore it is necessary to preheat the entire casting. Forging thermit may be used for this work, although where

parts are subject to abrasion and wear, "wabbler" thermit may be employed, to provide a hard, wear-resistant machinable steel.

Oxyacetylene Pressure Welding. Applications of joining cast steels are not normally of such a nature as to meet pressure-welding requirements. The material is weldable using procedures similar to those applied to wrought steels of like composition.

Submerged-Melt Welding. The procedure is essentially the same as for wrought steel of similar composition. Sand inclusions, cracks, porosity and dirt should be removed from the surfaces to be welded. The selection of suitable rods and granulated material permits multipass welding in extremely heavy thicknesses. Intermediate stress relief has been found desirable after the joint has been built up to a thickness of about 5 in.

Defects in castings may be repaired either by usual multipass welding or by a deposit made as a continuous puddle, provided the area of the defect is not so large that the melt will solidify during welding.

2 High-Manganese Steel Castings.* Welding these castings is mostly for the purpose of restoring parts that have been worn away, or for the repair of cracked and broken pieces. The manganese content is frequently as high as 12% or more, and the carbon content ranges from 1 to 1.40%.

Resistance Welding. Electric resistance welding has not been used to any great extent on parts made of manganese steel, because of the difficulties that have been encountered in obtaining strong welds by this method. It is possible, however, that resistance welding can be used successfully by proper adjustment of current and time of application.

Gas Welding. In the welding of high-manganese steel castings, a shallow zone must be heated to a temperature close to 2200 F; the filler metal should then be applied. The rod that is selected should have the same manganese content as the casting; and if the rod contains from 3 to 5% Ni in addition, reliable welds can be produced. The high nickel content tends to inhibit embrittlement under slow cooling so that no quench is necessary.

Arc Welding. For arc welding high-manganese steel (12 to 14% Mn and not more than 1.25% C), a shielded electrode should be used, of a type that will produce properties in the deposited metal approximately the same as those of the base metal. The weld should be in an austenitic condition even after slow cooling, and the welded part should not be quenched because of the danger of cracking. In such instances the weld deposit is rather soft but cold working will produce a hardness of 45 to 50 Rockwell C.

Thermit Welding. Thermit welding of manganese steel is not generally practiced, because of the effect caused on the adjacent steel by the heat of the weld. A fairly successful weld can be made if the whole mass can be preheated and then heat treated after welding.

Submerged-Melt Welding. The limited amount of work that has been done in this class of material indicates that chromium-nickel steel rods should be used for welding, in order to maintain the weld in an austenitic condition.

3 Alloy Steel Castings. In general, alloy steel castings are welded by the same process as that used for wrought alloy steel of the same composition. The number and character of the alloying elements have a decided effect on the welding properties of the castings.

Resistance Welding. Electric resistance welding has not been applied commonly to alloy steel castings because of the varying forms and contours encountered. It is possible, however, to use resistance welding methods if the work pieces are held in suitable jigs and there is proper adjustment of current and time of application.

Gas Welding. It is customary to use a filler rod of composition different from that of the type used in welding carbon steel castings, so that the weld deposit will be similar to that of the alloy steel casting. The same requirements for fluidity of deposit are necessary as with carbon steel castings, in order that impurities may be brought to the surface in the melting operation.

Arc Welding. The procedure for electric-arc welding of alloy steel castings is quite similar to that used with carbon steel castings. The only modification is in the coating of the electrode, which should be so proportioned as to influence the deposit of weld metal. It is customary to use heavily coated electrodes for this purpose. The surfaces to be welded should be thoroughly cleaned before welding. In some instances, preheating is considered desirable, and in virtually all instances, a heat treatment is desirable after the welding has been completed.

Thermit Welding. With the thermit weld metal, it is possible to match the composition of the casting by the addition of alloying elements to the thermit mixture.

Oxyacetylene Pressure Welding. Alloy steel castings are generally of such shapes as to make pressure welding impractical. The material may be welded by the procedures applied to low-alloy steels of similar composition.

Submerged-Melt Welding. The procedure with this type of casting is quite similar to that employed for plain carbon steel castings. Preheating is generally desirable in heavier thicknesses of material. The rod composition may be selected so as to develop the full strength of the base metal, and virtually the same response to heat treatment.

Cast Iron

1 Gray Iron. In the welding of gray cast iron, preheating is usually necessary to avoid stresses. Gray iron castings may be welded hot and then allowed to cool slowly so as to maintain their characteristic gray iron structure. Only in certain instances where the structure of the weld metal is of little importance can preheating be avoided.

Forge Welding. Gray cast iron cannot be forge welded.

Gas Welding. Gray iron castings should be preheated to a low red heat and welded while hot, with a cast-iron welding rod containing a high percentage of silicon. A suitable flux should be used to remove oxides. When the weld is completed, the whole casting should be allowed to cool slowly to room temperature. With this procedure the weld will be strong, yet soft and machinable.

Arc Welding. Preheating the casting to a dull red heat accelerates the welding, relieves stress, reduces the tendency toward unmachinable spots and cracks, and helps to retain the characteristic gray iron structure. Excessive strain or breakage, which may occur in the welding of gray cast iron, may be intensified by a hard area, containing iron carbide, outside the weld. For this reason castings thinner than ¼ in. are seldom welded. It is desirable that the casting be annealed after welding.

The electrodes used are special ones, either coated or uncoated, that make a good bond with the casting. A rather low current should be used, and the welding should be done intermittently. Each bead should be slightly peened and allowed to cool somewhat before depositing the next bead. All these considerations reduce the hardening effect along the line of fusion. Where machinability is of primary importance and strength is of secondary importance, nonferrous electrodes such as high-nickel alloy (67% Ni) are available. These electrodes produce a soft, machinable deposit that does not harden at the fusion line. The deposit is also advantageous where appearance is important, since the color matches that of the cast iron.

Bronze Welding. When gray iron castings are bronze welded, comparatively little preheating is necessary. When the temperature of the base metal is increased to between 1500 and 1600 F, the copper alloy will "tin" the cast-iron and make a bond at least as strong as the cast iron.

For bronze welding with the arc, preheating is generally unnecessary. It should be kept in mind that too much current is detrimental to satisfactory welding; the currents used should be as low as possible consistent with the size of the electrode and of the part being welded.

Thermit Welding. Although entirely suitable for welding gray iron, the thermit process cannot be used on all castings because of the difficulty of allowing properly for shrinkage of the weld metal when it cools. Contraction of thermit steel is approximately twice that of cast iron so that, generally, if the length of the crack to be welded is more than eight times the thickness of the section, the difference in shrinkage along the line of fracture will result in small hairline cracks in the weld.

Submerged-Melt Welding. This process has not yet been applied successfully to the welding of any of the cast irons.

* See also the article entitled "Austenitic Manganese Steel", page 526.

2 Malleable Iron. Fusion welding of malleable castings is generally regarded as unsatisfactory (even when the castings are remalleablized afterward). For this reason, repairs to malleable castings are generally made by bronze welding. Malleable iron foundries frequently reclaim defective castings by fusion welding the white iron castings before malleablizing.

Gas Welding. For the oxyacetylene welding of defective white iron castings before malleablizing, white iron welding rods of the same approximate composition are used. The salvaged castings are then malleablized.

Arc Welding. Malleable iron castings can be welded with the arc process, using low heat. In general, these castings should be treated the same as gray cast iron, using the same precautions and procedure. After welding, the castings should be put through the same annealing process by which they were made originally. Annealing is helpful if full heat treatment cannot be given.

Bronze Welding. The temperature of 1500 F required in the base metal for bronze welding is not so high as to affect seriously the properties of malleable iron; consequently, effective repairs can be made by this process. Either the gas or the arc method may be used.

3 Alloy Cast Irons. The welding procedures for most alloy cast irons are essentially the same as for gray iron. Filler material should be of the same alloy content as the base metal, or if such material is not available, the welds should be made with high-quality gray iron rod. Arc welding is discussed under Gray Iron.

Low-Alloy Steels

The low-alloy steels are readily welded by the various welding processes. The amount of alloying element in these steels is only slightly greater than in ordinary mild steels and is considerably less than in many alloy steels. These steels have higher mechanical properties than carbon steels and usually possess higher resistance to atmospheric corrosion. When low-alloy steels are being welded by a process wherein metal is added, it is not necessary for the metal to have the same composition (provided it has the same physical properties), unless resistance to corrosion is a factor; in such situations the weld metal should be of a composition similar to the base metal. Heat treatment is desirable for the various alloys, to develop the required mechanical properties.

Included among the low-alloy steel classifications are the proprietary compositions known as high-strength low-alloy steels, and described in the article on page 534 of this Handbook. These steels, which are not quenched and tempered, include the manganese-titanium and manganese-vanadium steels used by the navy. These steels have been the subject of considerable research in recent years. They have been designed generally to have yield strengths of 50,000 psi min, and to be weldable by ordinary methods without special precautions. Low-alloy steels approximate the mild carbon steels in weldability.

Gas Welding. Where strength is important, a welding rod of the high-test steel type will give satisfactory results in oxyacetylene welding. Where corrosion resistance is a factor, the welding rod should be of the same composition as the base metal.

Arc Welding. For arc welding these materials, a shielded-arc type of special electrode is generally used.

Thermit Welding. Through the addition of metallic elements to the thermit mixture, either by means of metallic pieces, which are melted during the reaction, or in the form of combinations of oxides of the required elements with aluminum, a wide variation in the composition of thermit steel is made available so that it is entirely possible to match the compositions of a number of low-alloy steels. The following are chemical formulas of the aluminum reduction of several oxides used for this purpose:

$$3Mn_3O_4 + 8Al = 4Al_2O_3 + 9Mn$$
$$Cr_2O_3 + 2Al = Al_2O_3 + 2Cr$$
$$3V_2O_5 + 10Al = 5Al_2O_3 + 6V$$
$$3NiO + 2Al = Al_2O_3 + 3Ni$$

Since these steels are used mainly for developing strength, ductility and resistance to shock, it is usually desirable to heat treat the welds made in these steels. The heat treatments for these alloys are given below.

Oxyacetylene Pressure Welding. Low-alloy steels are readily joined by the pressure-welding process. Sometimes the basic welding cycle must be varied to weld steels high in chromium content. The principal variation consists in the application of a high initial pressure for a small percentage of the total upset, followed by a lower upsetting pressure for the remainder of the cycle. Joint faces are preferably prepared immediately before welding, in order to reduce the possibility of forming an oxide film.

Submerged-Melt Welding. Low-alloy, high-strength steels of proprietary compositions are generally welded with the same rod, granulated material and welding conditions as are used for welding ordinary low-carbon steels. Because of their enrichment in alloying elements from the base metal, the welds develop the desired mechanical properties and resistance to corrosion.

For welding the other alloys listed below, satisfactory physical results can be obtained by selecting rod and granulated material from the various standard materials available. These standard materials will produce a weld of chemical composition identical with the base metal for steel in the manganese-molybdenum and carbon-molybdenum class. If identical weld-metal composition is desired for any of the other alloys, then rods of similar composition should be used.

1 Plain Nickel Alloy Steels. While the 3 to 3½% Ni alloy steels do not necessarily need heat treatment if the carbon content does not exceed 0.25%, such alloy steels with carbon contents greater than 0.25% require a preheat in the range from 300 to 600 F. Steels in this class have a tendency toward air hardening and require slow cooling in order to retain the desired mechanical properties.

2 Nickel-Copper Alloy Steels. The alloy steels in this class contain from 1 to 2% Ni and 1 to 1.6% Cu, while the carbon content is usually limited to 0.25% max. No preheating is required for the ordinary welding of these alloys except when the carbon content exceeds 0.20%; then in some instances preheating is considered desirable. Preheating such alloys within the range between 250 and 300 F makes the desired mechanical properties obtainable.

3 Manganese-Molybdenum Alloy Steels. The steels in this class are alloyed with 0.60 to 1.60% Mn and 0.30 to 0.70% Mo, and the carbon content is usually kept at less than 0.25% max. These steels do not ordinarily require preheating except in certain instances where the carbon content approaches the higher end of the range. In such alloys and for heavy or difficult sections, preheating at 250 to 300 F is an advantage.

4 Carbon-Molybdenum Alloy Steels. This class of steel is similar in many respects to the manganese-molybdenum alloys, except that the manganese content is held to a normal range from 0.30 to 0.60%; the molybdenum content is a little high, ranging from 0.30 to 1% and the carbon content is limited to the same maximum of 0.25%. Here, also, preheating is not required under ordinary conditions, although when the molybdenum content approaches the higher end of the range (more than 0.50%), preheating at 350 F is considered desirable for best results in welding. Similar preheating is also considered desirable if the carbon content approaches or exceeds the limit of 0.25%.

5 Nickel-Chromium Alloy Steels. This classification includes several compositions in which the nickel content ranges from 1% min to 3½% max, while the chromium content ranges from 0.40% min to 1.75% max; the carbon content varies from a maximum of 0.20% for the lower tensile ranges to 0.55% for the higher tensile ranges. These steels cannot be welded safely without preheating. For the lower tensile ranges in steels that contain 0.20% C max, preheating between 200 and 300 F is all that is necessary, but with the higher carbon contents that accompany the increased percentages of nickel and chromium, preheating between 600 and 800 F is considered desirable, followed by slow cooling. For steels that have the highest carbon, nickel, and chromium contents, it is even desirable to raise the preheating temperature to the range between 900 and 1100 F.

6 Chromium-Molybdenum Alloy Steels. These steels are similar in many respects to the nickel-chromium steels. A

much used series of alloys in this classification contains 0.25 to 0.55% C; 0.15 to 0.25% Mo; and 0.50 to 1.10% Cr. Because of such chromium contents, these steels, designed especially for service at high temperature, require a considerable degree of preheat, ranging from 300 to 800 F, and slow cooling is desirable after the welding operation.

7 Nickel-Chromium-Molybdenum Alloy Steel. This steel contains 1½ to 2% Ni, 0.20 to 0.40% Mo, and 0.30 to 0.90% Cr. Although the alloy is used extensively, it has not been welded in enough instances to warrant a statement.

8 Nickel-Molybdenum Alloy Steels. In these steels the carbon content is kept low, the nickel content ranges from 1.65 to 3.75%, and the molybdenum content ranges from 0.20 to 0.30%. Welding has not been applied often enough to furnish the desired data.

9 Chromium Alloy Steel. This steel is used in two ranges of carbon contents—one 0.25% or less, and the other from 0.35 to 0.55%. With the lower range of carbon contents the chromium range is 0.60 to 0.90%, whereas with higher carbon contents, the chromium range is from 0.80 to 1.10%. Preheating is essential before welding. The temperature range recommended is 200 to 800 F.

10 Chromium-Vanadium Alloy Steel. This steel has two ranges of carbon contents—one 0.25% C or less, and the other 0.25 to 0.55% C. Regardless of carbon content, the chromium content is from 0.80 to 1.10% and the vanadium content is from 0.15 to 0.20%. These steels all require preheating in order to obtain satisfactory results from welding. The preheating range is from 200 to 800 F. With this alloy, sample welds may be required in order to ascertain the properties that can be obtained from the welding operation, and particularly the effect of the heat treating operation.

11 Manganese Alloy Steels. These steels contain 1.6 to 1.9% Mn and 0.25 to 0.55% C. For satisfactory welding of these alloys preheating is essential; the desirable range is from 400 to 800 F.

Stainless Steels

The stainless alloys may be grouped into two classifications for welding considerations: (1) stainless irons that contain from 3 to 28% Cr, with or without traces of nickel, and that are essentially magnetic and ferritic in character, and (2) stainless steels that contain chromium and nickel, with or without smaller amounts of molybdenum, manganese, columbium, silicon, or titanium, all of which are in proportions that give an essentially austenitic structure.

1 Iron-Chromium Alloys. The materials in this classification contain from 12 to 28% Cr as the essential alloying constituent, and are termed "stainless irons". They show a tendency toward grain growth in and near the weld. This coarsening of the grain increases markedly with the chromium content and frequently results in undesirable brittleness in the welded equipment made from the higher ranges of chromium content. Small additions of nitrogen decrease this tendency toward grain growth.

Probably the most widely used compositions for fabricated equipment contain between 15 and 18% Cr with 0.10% C max. This material is readily welded and when the fabricated equipment is properly heat treated (to 1450 F, and then slowly cooled) it possesses a satisfactory combination of physical properties in both weld and plate and sufficient corrosion resistance to meet the needs of the majority of applications.

Gas Welding. Chromium irons may be welded by the oxyacetylene method provided adequate precautions are taken; best results are obtained with a flame that is virtually neutral. A slightly reducing flame will result in brittleness of the weld area on account of carbide formation, caused by the affinity of chromium for carbon. A slightly oxidizing flame will result in the formation of refractory chromium oxides, which sometimes cause insufficient penetration of the heat, with consequent reduced weld strength and slag inclusions.

Arc Welding. Electric-arc welding, mainly the metal-arc method, is successfully used in welding stainless irons. A coated wire electrode is recommended, with the metal wire of composition similar to the plate metals, but preferably with slightly higher chromium content, in order to provide for the loss of metal during welding.

Oxyacetylene Pressure Welding. These alloys are welded by the procedures applied to low-alloy steels.

Inert-Gas-Shielded-Arc Welding. Limited experience indicates that the stainless irons are readily welded by the inert-gas-shielded-arc process. The welds appear to be very similar to those made on the iron-chromium-nickel alloys by the same process. More extensive data are currently available showing the suitability of this method of welding. Present practice uses direct current, straight polarity, with argon or helium as the shielding gas. On thin sections, alternating current has been employed—usually with superimposed high-frequency current to start and maintain the arc. When high-frequency current is used, the equipment must be especially designed and insulated.

Submerged-Melt Welding. Stainless irons of the 5% Cr class, with 0.5% Mo and with or without columbium, are welded readily. A preheat of 300 F is recommended, followed by heat treatment for stress relief, grain refinement and maximum ductility. The rod used is of the same general composition as the base metal, while the granulated material, edge preparation and welding conditions are approximately the same as those used for similar thicknesses of low-carbon steel.

Stainless irons containing between 15 and 18% Cr with 0.10% C max are readily welded, using rod and granulated material of compositions that maintain the chromium, manganese and silicon in the weld within the desired limits. When properly heat treated (to 1450 F and then slowly cooled), the weld develops mechanical properties and corrosion resistance equal to those of the base metal.

2 Iron-Chromium-Nickel Alloys. Alloys in this classification contain sufficient nickel and manganese in addition to the chromium, with or without small amounts of other metals, to maintain an essentially austenitic condition. The composition that probably represents the major tonnage of plates and sheets fabricated into equipment by welding, is 18% Cr, 8% Ni, and 0.10% C max. These chromium-nickel steels are also furnished commercially in ratios of 25 to 12 and 25 to 20, all of which have been successfully welded by methods described below.

All stainless steels, except those stabilized by columbium or titanium, will show an accumulation of carbides at the grain boundaries when exposed to temperatures between 700 and 1500 F. This "carbide precipitation" is found also in lines approximately parallel to the weld bead and perhaps a quarter inch distant, even in stainless plates that have been properly heat treated before welding. This accumulation, resulting from the heat of the welding operation, is evidence that the plate metal in that narrow zone has been heated to a temperature range wherein carbide precipitation can take place.

This accumulation of carbides at the grain boundaries in the narrow zones adjacent to the weld bead will, in most instances, show less resistance to many corrosive mediums than will the metal at some distance from the weld and where it has not been held in this susceptible temperature range. It is coming to be standard practice, therefore, in fabricating stainless steel vessels by welding, to heat treat the equipment after completing the welding, with all compositions except those in which columbium or titanium is present as a stabilizing element. The treatment commonly used involves heating to approximately 1950 F and quenching in water. The heat treatment increases the over-all resistance of these alloys to corrosion and also puts the metal in its softest, most ductile and impact-resistant form.

Gas Welding. This method is generally applied to the lighter gages. On the thinner sections, a flange type of weld is used and the edges are joined without the addition of welding rod. On gages where metal must be added, a bare (uncoated) rod is used with a flux applied as a thin paste to the work.

The wider distribution of heat from the acetylene flame, as contrasted with the intense and local effect of the arc methods, makes it desirable to use chill blocks when welding with gas. Likewise, as a result of the more general heating and expansion of the metal sheet (since stainless steel has a 50% higher coefficient of expansion than carbon steel) jigs and clamps will be found convenient for holding the work piece.

In the gas welding of stainless steel it is of paramount importance to adjust the flame so that it is virtually neutral, thus avoiding excessive carburization of the metal, which would reduce materially the corrosion resistance of the resultant weld.

Arc Welding. The usual methods of arc welding are successfully applied in joining the stainless steels. Satisfactory electric welding is done by means of direct current in preference to alternating current. Reversed polarity is normally used; that is, work negative and electrode positive. Coated metallic electrodes are preferred. The composition of the welding wire should be similar to the composition of the plate, preferably with the chromium content of the wire slightly higher.

As pointed out previously, austenitic steels are susceptible to grain growth at high temperature; therefore overheating is to be avoided. When the current has been adjusted to give a smooth arc, the bead may be laid down as rapidly as is consistent with good welding practice.

Oxyacetylene Pressure Welding. The 18-8, 25-20, 25-12 and other stainless compositions are pressure-welded with good results. Welding characteristics permit corrosion resistance equal to that of the base metal when stabilized materials are used and joint and parent metal are chemically homogeneous. Smooth, clean joint faces are necessary for the welding of these high-alloy materials. No oxide should be allowed to form on the joint faces before welding. Welding cycles used are the same as those applied to low-alloy steels.

Inert-Gas-Shielded-Arc Welding. The inert-gas-shielded-arc process has been found to be especially well suited for the welding of stainless steels. Depending on the application, these steels can be welded manually; or with suitable equipment the process can be mechanized, the holder being adjusted either manually, or by electronic means.

Welds made on stainless steel by the inert-gas-shielded-arc process show a minimum of discoloration, or oxidation, requiring very little finishing. There is no spatter to be removed, and the amount of reinforcement can be controlled to some extent, again reducing finishing costs. Virtually no chromium, nickel, or stabilizing elements are lost when stainless steels are welded by this method.

Welds can be made with or without filler metal, as dictated by the application. Direct current, straight polarity is used, with argon or helium as the shielding gas. Alternating current has been used to some extent on thin material; superimposed high-frequency current is employed, when necessary, to start and maintain the arc. Equipment used with superimposed high-frequency current must be suitably insulated.

Submerged-Melt Welding. These alloys can be welded almost as readily as low-carbon steels of the same thickness. Joint preparation and welding speeds are similar to those used for low-carbon steels, but some reduction in welding current and voltage is necessary. The compositions of both rod and granulated material are selected to provide weld metal of desired chemical composition, mechanical properties and resistance to corrosion. In the columbium-stabilized types, the process is not recommended for welding butt joints less than $\frac{3}{16}$ in. thick, nor for fillet, plug or multipass welds, since with existing procedures such welds crack as a result of the hot shortness of these alloys.

The Cutting of Ferrous Metals by Gas and Electric Arc

BY THE SUBCOMMITTEE ON WELDING AND CUTTING*

THIS ARTICLE describes the cutting of ferrous metals by means of a gas flame. Cutting by means of an electric arc is much less common; such cutting is discussed briefly at the end of the article. "Cutting", as the term is used here, includes not only severing, but also "flame machining", which refers to the planing, milling, turning, drilling and boring of metal by a gas flame.

Gas Cutting of Ferrous Metals

Gas cutting of ferrous metals is a process of preheating material to its kindling or ignition temperature and then oxidizing it rapidly by means of a closely regulated jet or stream of oxygen issuing from a special tool called a "cutting blowpipe" or "torch". Hence, the process is primarily a chemical one, based on the chemical affinity of oxygen for ferrous metals that have been heated to the kindling temperature or higher.

The chemical reaction that results when commercially pure oxygen is brought into contact with most steels or iron at the kindling point, is an active one. Carbon steel is preheated in daylight to a bright red color, a condition reached between approximately 1400 and 1600 F. For accurate control, the gases supplied and the rate of progression of the cutting should be closely regulated.

Only the metal within the direct path of the oxygen jet is acted upon. In linear cutting, or severing, a "kerf" is formed; that is, a narrow race, having uniformly smooth and parallel walls. Under skilled workmanship, using mechanically guided cutting torches or blowpipes, cutting tolerances, with respect to squareness and longitudinal alignment of the cut surface, may be held closely.

The faces or walls of the kerf, in the commonly used carbon steels, are not injured by the cutting operation. On the contrary, the strength and toughness of the faces are slightly increased. The effect of heat on the metal, as a result of normal cutting operations, rarely penetrates farther than approximately 0.1 in. below the cut surface, except in the so-called "stainless steels", where precipitation of carbide may extend as far as 0.375 in.

In addition to linear gas cutting or severing, other types of controlled oxidation are in use, employing the free-burning reaction of oxygen with ferrous metals that have been heated to kindling temperature, in order to sever, shape and work such materials. One application, known generally as "oxygen-lance cutting", utilizes a relatively long section of small-diameter iron pipe. A pipe with a stream of oxygen flowing through it is ignited and kept aflame, thus forming a lancelike cutting tool that furnishes preheat as well as free oxygen for cutting and is used primarily for emergency and heavy-duty cutting, such as opening furnace tap holes.

Another application of gas cutting is known as "flame machining". This method is used primarily to surface ferrous metals in much the same way as a planer or milling machine. The cut does not penetrate the work as in severing or linear gas cutting.

Chemistry of Cutting. The oxide of iron formed in gas cutting is a black, brittle substance, identical in composition with hammer scale or magnetite ore; the chemical formula is Fe_3O_4. This substance contains a proportion of oxygen smaller than in rust or red iron oxide, Fe_2O_3. For cutting as in Fig. 1, the completed equation for the oxidation reaction in gas cutting is:

$$3\,Fe + 2\,O_2 = Fe_3O_4 + 26{,}691\ cal$$

The following data may be computed:

1 lb oxygen will oxidize 2.618 lb or 9.186 cu in. of pure iron.
1 cu ft oxygen will oxidize 0.217 lb or 0.761 cu in. of pure iron.
1 lb of pure iron requires for oxidation 0.382 lb or 4.610 cu ft O_2
1 cu in. of pure iron requires for oxidation 0.109 lb or 1.314 cu ft O_2

In actual gas cutting, the iron or steel removed from the kerf is, as already noted, not entirely oxidized or consumed by the oxygen, but because of the eroding effect of the cutting oxygen jet, about 30 to 40% of the metal is

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washed out of the cut as unconsumed or metallic iron. As a result of this fortunate circumstance, it is not uncommon to obtain satisfactory cuts with a consumption of cutting oxygen even somewhat less than one cubic foot of oxygen per cubic inch of material removed from the kerf. As may be seen from the above data, this rate of consumption is more than 30% better than the theoretical figure, based on chemical reaction alone.

Combustion of Fuel Gases. A number of fuel gases of higher flame temperature have been employed for cutting ferrous metals, with varying degrees of success. The more important of these are: acetylene, hydrogen, city gas, natural gases, coke-oven gas, ethylene, and the lighter petroleum distillates, including methane, ethane, propane and butane. Table I gives combustion constants for certain of these fuel gases.

Table I. Combustion Constants of Fuel Gases

Name of Gas	Chemical Equation for Complete Combustion	Heat Value, Btu per cu ft (net)	Flame Temp with O_2, deg Fahr
Acetylene	$C_2H_2 + 2\frac{1}{2}\ O_2 = 2\ CO_2 + H_2O$	1433	6300
Hydrogen	$H_2 + \frac{1}{2}\ O_2 = H_2O$	275.1	5400
City gas	Typical mixture	300 to 800	4600
Natural gas	Typical mixture	800 to 1200	4600
Coke-oven gas	Typical mixture	500 to 550	4600
Methane	$CH_4 + 2\ O_2 = CO_2 + 2\ H_2O$	913.8	5000
Ethane	$C_2H_6 + 3\frac{1}{2}\ O_2 = 2\ CO_2 + 3\ H_2O$	1631	5100
Propane	$C_3H_8 + 5\ O_2 = 3\ CO_2 + 4\ H_2O$	2309	5300
Butane	$C_4H_{10} + 6\frac{1}{2}\ O_2 = 4\ CO_2 + 5\ H_2O$	2999	5300
Ethylene	$C_2H_4 + 3\ O_2 = 2\ CO_2 + 2\ H_2O$	1530	5100

Aside from hydrogen, all these fuel gases are hydrocarbons and, as shown in Table I, give off carbon dioxide (CO_2) and water vapor (H_2O) as products of complete combustion. They may be burned in different manners but, when used for gas cutting, the combustion is made to take place in the way that will develop maximum flame temperatures. For quick starting and rapid progress of a cut, hot preheating flames are a prime essential. This requirement is fulfilled by designing cutting torches or blowpipes that burn the fuel gases according to the Bunsen principle and premix commercially pure oxygen instead of air with the gases before combustion. The substitution of oxygen for air, in the primary combustion, results in a notable increase of flame temperature of the fuel gas, because the nitrogen, constituting nearly four fifths of the air, does not need to be heated by the flame when oxygen is used. Acetylene produces a hot, short flame, with an easily distinguished, bright inner cone; the hottest point is at the tip of the inner cone. Flame structures of hydrocarbon gas are complex in nature, with a multiplicity of cones as a result of the successive chemical reactions that take place in different stages of combustion.

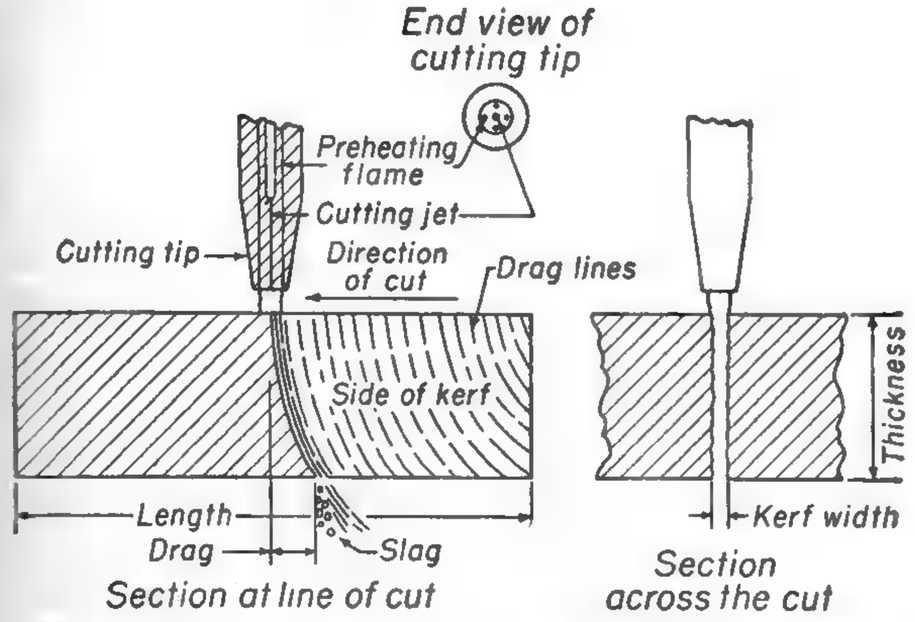

Fig. 1 Sections during oxyacetylene cutting

Depending on the ratio of oxygen to fuel gas in the mixture, the characteristic of the flame produced may be carburizing, neutral, or oxidizing. The neutral flame results when just sufficient oxygen is supplied to complete the primary combustion in the inner cone of flame, yielding carbon monoxide (CO) and hydrogen (H_2) as products. Neither of these two gases carburizes or oxidizes molten metal; in fact, both are neutral to it. Regardless of the amount of primary oxygen supplied, complete combustion in the inner cone of flame is impossible since, at such extremely high temperatures, carbon dioxide and water vapor are unstable and dissociate or revert in part to carbon monoxide, hydrogen and oxygen. This dissociation limits maximum temperatures attainable in a flame of oxy-fuel gas; otherwise these temperatures might go much higher.

Maximum flame temperatures are obtained with strongly oxidizing flames; therefore, this type is generally used for gas cutting. Oxidizing flames preserve the general appearance of neutral flames, but their inner cone is shorter, "necked in" on the sides and more sharply defined. Because of dissociation, the products of the primary combustion in the inner cone of excess oxygen flames consist of carbon monoxide, carbon dioxide, hydrogen, water vapor, and free oxygen, in proportions that depend on the amount of excess oxygen premixed with the fuel gas.

The secondary combustion of the fuel gas takes place in the outer or envelope flame. Here, any carbon monoxide and hydrogen contained in the primary combustion products complete their combustion to carbon dioxide and water vapor, respectively, since the lower temperature is insufficient to cause dissociation of these latter compounds. The necessary oxygen required for completing the secondary combustion in the envelope flame is taken from the surrounding air by diffusion into the zone.

Table II gives optimum gas ratios and equivalent volumes of oxygen and acetylene, city gas, natural gas, and propane required for gas cutting the same work at the same speed.

Table II. Equivalent Volumes of Fuel Gas and Preheating Oxygen for Cutting

Name of Fuel Gas	Optimum Ratio of Oxygen to Fuel Gas	Gas Consumption: Preheating Oxygen, cu ft per hr	Gas Consumption: Fuel Gas, cu ft per hr
Acetylene	1.7 to 1	17	10
City gas	0.75 to 1	56	75
Natural gas	2.0 to 1	56	28
Propane	4.5 to 1	54	12

The data in Table II apply only when each fuel gas is utilized at maximum efficiency. In practice it is difficult for the operator to adjust the ratio of gases other than acetylene to even approximately correct values. Because there is no definite starting point, such as the neutral flame in the burning of acetylene, even an experienced operator frequently adjusts the gas ratio of the flames that utilize other fuel gases, to much higher gas ratios than the best values indicated by Table II. Obviously this involves the use of much more oxygen than would otherwise be required. With acetylene, the change in the size and brilliance of the flame when adjusted to the oxidizing side of the neutral flame, is great enough to make it quite unlikely that any operator will employ oxygen-acetylene ratios appreciably higher than necessary.

Furthermore, when certain other fuel gases are used, the oxygen requirements for the cutting jet are greater than when acetylene is used. This is particularly true when the consumption of preheating gas is large and the resulting gases of combustion are sufficient to pollute the jet of cutting oxygen. In such instances a noticeable deterioration in the cutting efficiency may ensue.

Combustion of Acetylene. Because acetylene is the fuel gas most widely used for cutting, its combustion will be described in greater detail. Tables I and III show the reaction for complete combustion of acetylene as:

$$C_2H_2 + 2\frac{1}{2}\ O_2 = 2\ CO_2 + H_2O + 542{,}700\ \text{Btu}$$

In other words, 1 molecular volume of acetylene unites with 2½ molecular volumes of oxygen to form 2 molecular volumes of carbon dioxide and 1 of water vapor, with a liberation of 542,700 Btu of heat.

Most hydrocarbons are exothermic, generating heat during formation and absorbing the same amount of heat during combustion. But acetylene is highly endothermic, absorbing heat during formation and liberating it during burning or decomposing. The endothermic heat liberated by acetylene is in addition to that produced by the com-

bustion of its component elements. The total heat generated is given in Table III.

Table III
Heat Produced by Complete Combustion of Acetylene

Reaction Formula	Btu per Molecular Volume	Btu per cu ft at 60 F and 1 atm	Percentage of Total
Endothermic ... $C_2H_2 = 2\,C + H_2$	86,600	228	15.9
Carbon ..... $2\,C + 2\,O_2 = 2\,CO_2$	352,000	928	64.8
Hydrogen ..... $H_2 + \frac{1}{2}\,O_2 = H_2O$	104,100	277	19.3
Total heat of combustion.....	542,700	1433	100.0

Acetylene contains the highest percentage of carbon (92.3% by wt) of any common gaseous hydrocarbon compound. This, coupled with its exceptionally large endothermic heat, gives it the highest flame temperature of any known fuel gas, by a wide margin.

Oxygen Purity. High-purity oxygen is essential for rapid and efficient cutting. Even a small percentage of impurities in oxygen causes a great loss in the cutting quality. Tests made by machine cutting 12-in. mild steel billets in the laboratory, under identical conditions, using oxygen from 97.5 to 99.5% pure, gave results summarized in Table IV. The results demonstrate clearly the importance of using high-purity oxygen for cutting.

Table IV. Effect of Oxygen Purity on Consumption

Percentage Purity	Oxygen Consumption — Cubic Feet per Linear Foot Cut	Oxygen Consumption — Percentage Increase
99.5	45.5	...
99.0	49.5	8.8
98.5	55	20.9
98.0	63	38.5
97.5	73	60.5

Effect of Gas Cutting on Steel. In gas cutting, the temperature of a slight depth of metal immediately adjacent to the cut face is raised to considerably above the transformation range. As the cut progresses, the steel cools again through this range. The speed of cooling depends on the heat conductivity of the surrounding metal, radiation losses, and the fact that the heat is applied only momentarily at any given point, since the cutting torch is kept in constant motion while cutting. When the steel being cut is at room temperature, the rapidity of the cooling is sufficient to have an actual chilling or quenching effect on the cut edges, particularly in heavier cuts involving large masses of cold metal.

When polished and etched specimens are taken from gas-cut edges and examined under the microscope, the material is found to be altered when compared with the original metal. However, the change is largely a physical one, concerned with crystalline grain structure. The normal pearlitic steel is transformed into one or more of several structures ranging from spheroidized carbides in ferrite to the harder constituents, depending on the particular chemical composition of the steel cut and the rate of cooling after the cutting operation, as well as the carbon content and the alloying elements present. Also, the heat developed by the cutting makes the grains at the edge of the cut either larger or smaller than the unaffected grains behind the cut edge.

Low-Carbon and Mild Carbon Steels. At normal temperatures, gas cutting of carbon steels that contain less than 0.30 or 0.35% C is not detrimental unless alloying elements are present. Gas-cut edges of such steels are suitable for any uses where edges are employed that are prepared by any of the mechanical methods of severing; for example, planing, milling, shearing, friction sawing and grinding. Gas-cut edges are adapted to applications involving stresses, such as mechanical calking and holes in which tubes are to be expanded or rivets driven. Clean, smooth gas-cut edges of low-carbon or medium-carbon steel plates or forgings have physical properties that render them actually superior to edges that are sheared, planed, or otherwise prepared mechanically.

A few years ago when the ASME Boiler Code Committee conducted an investigation of the conditions that develop when the fusion welding process is applied to gas-cut edges, such conclusive results were produced that all restrictions pertaining to welding on gas-cut surfaces were removed from the Boiler Code. The wording of the Code requirement, adopted in 1935 for incorporation in the Power Boiler and Unfired Pressure Vessel Sections, follows:

> *"Preparation for Welding.* The plates may be cut to size and shape by machining or shearing, or by flame cutting if the carbon content does not exceed 0.35%. If shaped by flame cutting, the edges must be uniform and smooth and must be freed of all loose scale and slag accumulations before welding. The discoloration which may remain on the flame-cut surface is not considered to be detrimental oxidation."

Where edges are gas-beveled to form a V for welding, and later are welded together by either oxyacetylene blowpipe or electric arc, the heat of the welding operation acts to dissolve all marginal structures previously formed and operates to anneal the metal for an appreciable depth below the cut surface. Any change in structure that the preceding cutting may have produced in and adjacent to the cut surface is therefore obliterated.

Tests of flame-cut edges of low-carbon and medium-carbon steels to determine their physical properties (such as hardness, ductility, microstructure and resistance to impact) have shown that they are satisfactory for almost any type of mechanical treatment or character of service.

Higher-Carbon and Alloy Steels. Gas cutting of higher-carbon and alloy steels, particularly at room temperature, may produce a thin layer of hard material on the cut surfaces, which may not be sufficiently ductile to withstand the stresses set up in cooling, without cracking, or the stresses imposed by the subsequent use of the part cut. The torch heats the steel at the cut edges to a high temperature momentarily, but normal thermal expansion is prevented by the adjoining cold metal. The action called "upsetting" results. Later, when cooling occurs, contraction of the upset metal may develop severe stresses in tension along the cut edges. With these steels, the ductility may not be sufficient to prevent incipient cracks and checks that can prove dangerous in service, since they are likely to develop into large fractures.

Preheating and Annealing. Experience has shown that if these higher-carbon and alloy steels are preheated and, in certain instances, annealed afterward, no cracks will occur on the cut edges. Naturally, with the adjoining metal preheated, the difference in expansion is less between it and the metal heated during cutting, and "upsetting" is greatly reduced or eliminated.

Certain steels may be preheated as high as 1000 F or more for gas cutting. However, care must be taken not to carry the preheating too far, because the metal may develop too great an affinity for the jet of cutting oxygen at elevated temperatures, thus causing it to act erratically and prevent proper control of the cut. In cutting particularly thick preheated sections, special precautions should be taken to complete the work as quickly as possible after the piece has been withdrawn from the furnace, in order to avoid having the interior considerably hotter than the metal at the surface, a condition that may arise if the piece is allowed to cool partially in air before cutting. If partial cooling does occur, the oxygen jet may start to penetrate without much difficulty, but on entering the interior of the section the jet may fail to go through and may cause a flare-up in the cutting. The factor responsible for this stoppage is the hot center, which oxidizes so readily that a cavity or pocket may form on the inside of the piece. Where this occurs, a slight lowering of the cutting oxygen pressure will often rectify the trouble.

When equipment is used that delivers large volumes of oxygen through large tips at low pressures, large billets and rounds are successfully cut at rolling temperatures (1700 to 1800 F). Occasionally very high cutting speeds are obtained. Evidently, at temperatures above the transformation range, steel reacts more vigorously with the cutting oxygen, producing slags with great amounts of iron and relatively little Fe_3O_4.

To obtain the most efficient use of the oxygen and, at the same time, leave the steel in the best condition, a preheat temperature of 500 to 600 F should ordinarily suffice for carbon steels. The additional expense that accompanies preheating is compensated for by the more rapid rate at which preheated steel can be cut.

Annealing completely restores the original pearlitic structure of the steel at the cut edges, wherever this may be desired, and removes any residual stresses set up in the metal. The majority of steels do not require annealing if they have been preheated before the flame cutting.

Flame Softening. Flame softening is a localized and progressively applied oxyacetylene heat treatment, similar in physical aspects to flame hardening, but directly opposed in the objective. The results of flame softening are similar to those obtained by preheating in a furnace, but the effect can be restricted to a small area and the process is comparatively simple and economical. Flame softening is discussed in an article on page 651.

Mechanical Effects of Gas Cutting. Properly performed, gas cutting on carbon steels and low-alloy steel produces accurate results. Top and bottom edges of the cut are sharp and the width of the kerf is uniform. Surfaces of the cut may be smooth and square and may be produced without "drag" lines. The precision obtainable depends on (1) the cutting equipment and procedure employed and (2) the suitability of the material for cutting. Other mechanical effects of the gas cutting result from warping, caused by the expansion and contraction of the steel in heating and cooling.

When heated locally, as in gas cutting, a part may warp unless (*a*) its stiffness or cross-sectional strength is sufficient to resist the forces set up; (*b*) it is held in place by clamps or weights during cutting and cooling; (*c*) it is multiple-cut simultaneously or in rapid succession around its neutral axis, thus equalizing the forces set up and neutralizing their effect; (*d*) the cutting operation is followed immediately and progressively by rapid cooling or quenching in a suitable medium.

Plates ½ in. thick or more seldom warp or buckle from gas cutting, unless unduly long and narrow. In such simple operations as cutting off rods, bars, rails, piping, structural shapes, and similar materials of considerable length, warpage is not involved. So-called "skip-cutting" is frequently used in splitting narrow materials, such as flat bar stock and structural I-beams and channels to prevent warpage. In this method, the cut is made to skip at intervals, depending on the work, leaving a series of uncut sections along the line of cut, each about ½ in. to 1 in. long. These uncut ligaments hold the material in line until cooled; then they are cut through to separate the parts. Sometimes two or more torches are moved together along parallel lines, thus making simultaneous cuts, to eliminate warpage, increase production and reduce costs. During some operations, such as beam splitting, water quenching is an effective check to warpage. Where great accuracy is demanded in over-all dimensions of larger cut parts, suitable correction factors must be applied in making the cutting layout, particularly where the steel is preheated.

Gas-Cutting Equipment. Gas-cutting equipment consists ordinarily of the cutting torch or blowpipe with separate cutting tips of different sizes, oxygen and fuel-gas hose with connections, oxygen and fuel-gas pressure regulators, and gas cylinders. The pressure regulators are usually equipped with cylinder and working-pressure gages. Regulators for the cutting oxygen are designed especially to deliver oxygen in large volumes and at higher pressures and, hence, are usually fitted with gages that measure working pressures as high as 400 psi.

Where large quantities of oxygen are required, oxygen cylinders are often manifolded. Acetylene generators, rather than cylinders, are used where the consumption justifies it. In such installations, distribution pipe lines are frequently employed to carry both gases to the various points of consumption throughout the premises. For gas cutting by machine, the torch is held and operated mechanically, but its essential features and the accessory equipment remain unchanged. To ensure safety and efficient results, the manufacturer's instructions for setting up and operating the equipment should be followed closely.

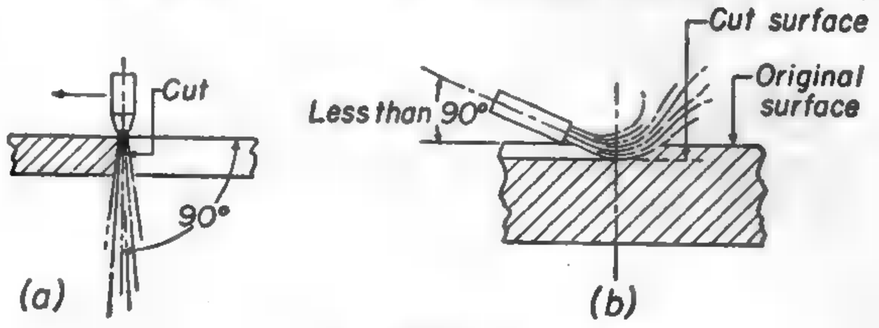

Fig. 2 Flame cutting

Gas-Cutting Processes. *Flame Cutting.* Gas cutting is used primarily for severing. With this process, the cut is made through the material as at (*a*), Fig. 2, leaving the cut edges in a plane usually at 90 deg to the surface of the part cut. The cutting tip is held preferably perpendicular to the surface, as shown, although in certain work it may be tilted somewhat along the line of cut. For bevel cutting, the tip is tilted to the required angle or a bent tip is used, but the cut still penetrates through the material. These processes are widely known as "flame cutting".

Flame Machining. This process utilizes the same fundamental principle of chemical reaction, but the cutting oxygen stream is made to impinge on the work at a more or less acute angle, as at (*b*), Fig. 2—in some instances almost tangentially. The cut is not permitted to penetrate through the work, as in severing, but is restricted to removal of a predetermined depth and width of material from the surface by oxidation. The various gas-cutting processes are classified in Fig. 3.

Fundamental Principles of Flame Cutting. In flame cutting, the jet of cutting oxygen usually enters the cut in line with the axis of the cutting oxygen orifice (*a*) in Fig. 2. After traversing about one-half the thickness of the cut, however, the jet may curve backward in a direction opposite to the travel (Fig. 1). When this occurs, the amount by which the oxygen jet falls behind the perpendicular in passing through the material is known as the "drag" of the cut. Faint markings or ridges called "drag lines", left on

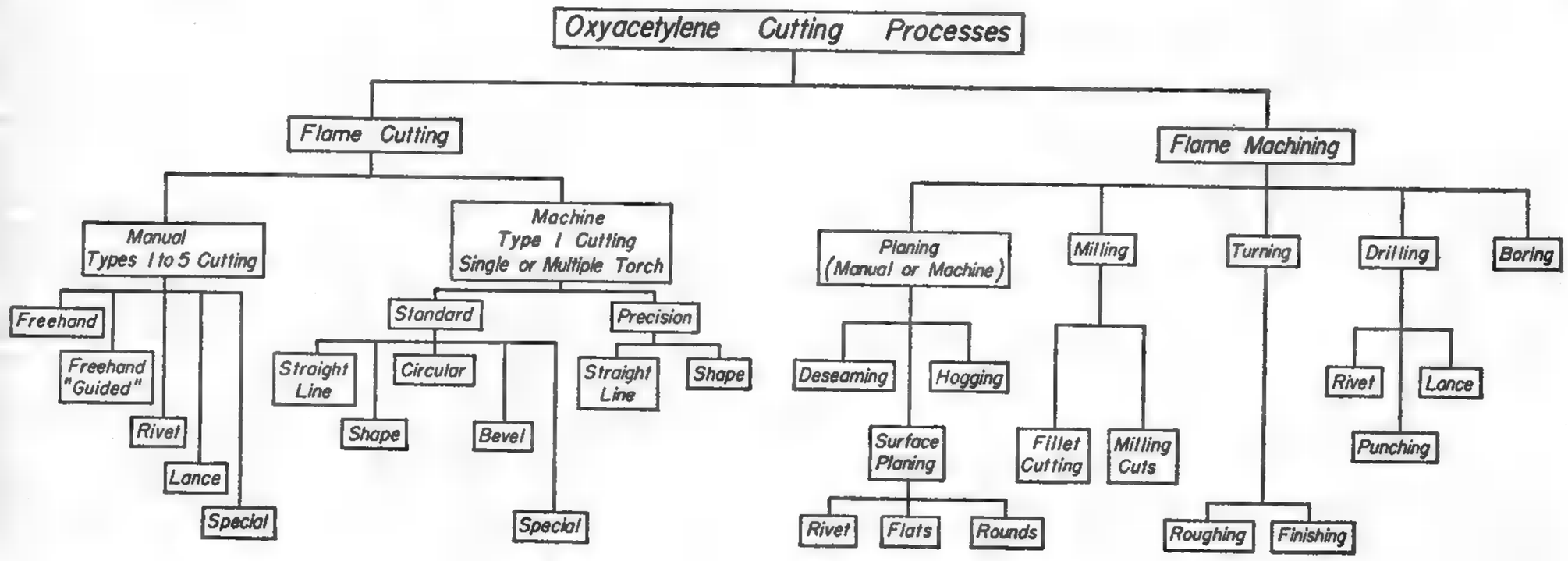

Fig. 3 Classification of gas cutting processes

the face of the cut, enable the drag to be measured, as shown in Fig. 1. In heavy cuts, these drag lines are more pronounced. Cuts with short or negligible drags are known as "high-quality" cuts; those with long drags are termed "low-quality" cuts.

Cutting studies have shown the following facts: (1) As the drag is decreased, the oxygen consumption is increased. For very short drags, a slight decrease in drag length can be procured at the expense of increased oxygen consumption. (2) Except for low cutting speeds, a certain minimum length of drag is characteristic of a given tip and speed regardless of the operating pressure (or the oxygen consumption). (3) An increased drag may result if an attempt is made to obtain a drag shorter than the minimum by increasing the operating pressure beyond that at which the minimum drag is obtained.

In considering the costs of flame cutting, therefore, it is essential to determine how short the drag must be to fulfill the requirements. If it is too long, a final corner will remain uncut and this is usually not permissible. Straight-line cuts can frequently be made with considerable drag, without a particularly detrimental effect, since the drag lines lie within the plane of the cut and do not prevent both top and bottom edges of the cut from being left clean and sharp. This procedure, which saves considerable oxygen, is also applied in cutting scrap, where cut quality is nonessential as long as severing is accomplished. However, in cutting shapes, when rounding curves or corners, less drag is permissible, because the bottom contour of the cut will tend to come out different from the top, with the edges not square. Such cuts must be made with short drag. They require a good deal more oxygen than long-drag cuts that barely penetrate the material. Precision-machine flame cuts are necessarily of high quality.

Satisfactory Commercial Flame Cuts. These must fulfill the following requirements: (*a*) The drag must be sufficiently short; that is, the line markings on the face of the cut should approach the straight up-and-down condition. The drag should not be long enough to prevent the final corner from being cut and the piece from dropping. (*b*) The sides of the cut should be sufficiently smooth—not grooved, fluted or ragged. (*c*) There should be no firmly adhering slag on the bottom of the cut, because considerable labor is required for its removal. With proper adjustments, only loose slag is obtained, or none at all. (*d*) The upper and lower edges of the cut should be sufficiently sharp to meet the requirements of the particular job. (*e*) The cost must be moderate.

The following conditions are necessary to obtain smooth cuts: (1) suitable cutting tip, with cutting orifice of correct size and proper degree of preheat; (2) suitable oxygen and fuel-gas pressures and uniform regulation of them; (3) correct cutting speed; (4) uniformity of torch movement; (5) smooth and uniform bore and proper type of cutting orifice; (6) cleanliness in the exit of the orifice; (7) cleanliness of preheat holes; no slag adhering to the end of the tip; (8) high-purity oxygen; (9) proper angle of incidence of the cutting oxygen stream in relation to the upper edge.

Selection of Cutting Tip or Nozzle. Widely varied cutting tips or nozzles of different styles and sizes are available for flame cutting. They provide for cutting various thicknesses of most ferrous materials, and for different surface conditions—clean, painted, rusty or scaly—as well as for various special types of work. The thickness of the material to be cut determines the diameter of cutting orifice of the tip to be selected. The condition of the surface and the composition of the metal determine the intensity of preheat flames that should be used. Rusty or scaly surfaces are often cleaned or "descaled" along the line of cut before cutting, by cracking the scale loose, either with the preheating flames or the torch, or mechanically with scrapers or chipping hammers.

Starting Flame Cuts. Flame cuts are usually started at the edge of the piece. The cutting torch is held so that the ends of the inner cones in the preheating flame just clear the surface of the material. When a spot of metal at the top of the edge has been heated to a bright red, the jet of cutting oxygen is turned on. The metal in the immediate path of the cutting jet oxidizes, and as the torch moves slowly and steadily along the line to be cut, separation is effected. In flame cutting ordinary steel, the tip should be held vertically at a correct distance above the surface and advanced steadily at the proper speed.

Piercing Holes. When starting a flame cut in the metal away from the edge, or when piercing a hole, more time is usually consumed in bringing the spot to the kindling temperature than in starting the edge. When a spot has been heated to a bright red, the torch is raised about ½ in. above the normal position for line cutting and the cutting oxygen is turned on slowly. As soon as the work material is perforated, the torch is lowered again to the normal height above the surface and the cutting is continued if necessary. Drilled holes are used for some work, particularly to form a straight, smooth starting edge for a heavy internal cut.

Cutting Round Bars. When round bars of steel are to be cut, gas pressures are set for the maximum thickness or diameter, and the cut is started at the side. As the cut progresses, the torch is raised to follow the circumference. Starting is facilitated by nicking the bar with a chisel to create a burr at the point where the cut is to begin, so that the oxygen can take hold more easily.

Heavy Cutting. In heavy cutting, the greatest care must be used in selecting the proper operating pressure. Not only is the range of suitable pressures considerably narrower for the heavier cuts, but the pressure decreases at the hose-line connections and a larger torch should be used with the increasingly greater flows of oxygen required for heavy cutting. The large volumes of oxygen needed are better supplied through the use of lower pressures and torches with large cutting orifices. Extreme preheating is necessary. Attempts to obtain the quantity of oxygen required by the use of high pressures in common machine cutting torches results in gouges and pockets in the kerf. Variations in the quality of steel are more important in heavy cutting.

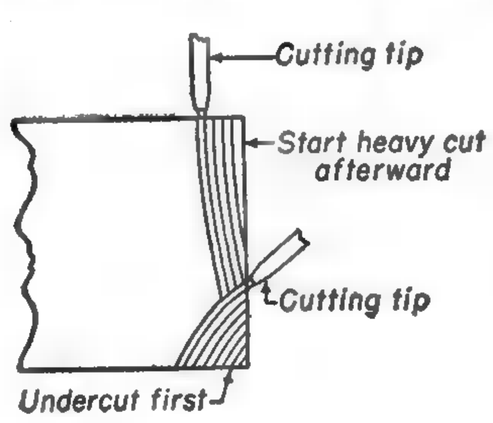

Fig. 4

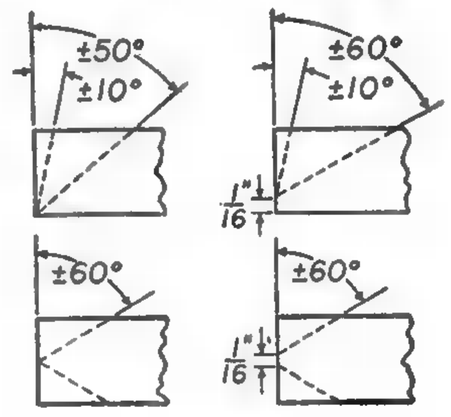

Fig. 5

Fig. 4 Undercutting as an aid in starting a cut
Fig. 5 Limits in the cutting of bevels and fillets

Considerable skill is sometimes required for starting a heavy cut, in order to sever the initial lower corner completely and to avoid pocketing the stream of cutting oxygen in the lower portion of the cut. It is essential that the front edge of the cut be very clean, particularly the lower portion of the front face. To align the axis of the tip with the front edge of the material, the stream of cutting oxygen should be turned on with preheating flames burning to render it visible. In starting the cut, the movement of the torch should be retarded just long enough to allow the cutting stream to attack the material actively throughout almost the entire depth. Then the torch is permitted to proceed normally. If the piece is very heavy, the lower portion of the front face is sometimes heated with a large welding flame. In certain instances, starting is facilitated by first undercutting the forward edge of the material with a hand cutting torch (Fig. 4). However, unless the operator is experienced, the resulting cuts may be poor and ragged.

Care is required also in completing the final corner of heavy cuts. A slight retardation of the forward movement of the torch is desirable here as well.

Scope of Flame Cutting. *Thickness.* When the standard cutting torches are not assisted by oxygen lances, present limits of penetration are about 36 in. for manual cuts and 54 in. for machine cuts. Particularly for freehand flame cutting, the upper limit depends largely on the skill and steadiness of the operator. With oxygen lances it is possible to penetrate virtually any thickness of metal.

Materials. Almost any ferrous material can be cut by gas; however, certain steels contain sufficient alloying elements to offer considerable resistance to the process. The uncombined carbon in cast iron has a similar effect. For such materials, special flame-cutting techniques must be applied, as described later. Oxygen lances permit penetration of virtually any metal, ferrous or nonferrous.

Cross-Cut Tolerances. Where the torch is held firmly and advanced at uniform speed, as in machine flame cutting, cross-cut tolerances can be kept within narrow limits. In ordinary steel 6 in. thick, cut surfaces can be held to cross-sectional squareness accurate within $\frac{1}{32}$ in. Cuts in thinner sections can be held to proportionately smaller limits. The degree of longitudinal precision of a machine cut depends on the trueness of the guide rails of the cutting machine, the clearance of the operating mechanism and the regularity of the propelling unit. Machine cuts can be made so smooth and square and can have such sharp edges that they require no further finishing of any kind.

Bevels. Angular or bevel flame cuts are accomplished by inclining the torch and tip sideways to the desired angle, or by using a bent tip. Such cuts may be either by hand or by machine, in straight or irregular lines, and with the same range of depth as in normal cutting at right angles. The usual angular limits of bevel and straight-faced fillet cutting are indicated in Fig. 5.

Shapes. Straight lines, circles or contours of the utmost complexity are flame-cut with equal ease by either mechanical or hand-guided torches. Flame cutting, in sharp contrast with most machine tool processes, has almost unlimited flexibility in this respect.

Multiple-Torch Cutting. In many applications of machine flame cutting, as many as 20 torches are used to cut a like number of identical shapes simultaneously. Concentric circles for flanges and the like are often cut in one operation, with two or more torches.

When the sheets are thin and level enough to be clamped economically into a tight pile, stack cutting is indicated for multiple production. When the plate is heavy or wavy, multiple cutting is used—sometimes along with stack cutting.

Stack Flame Cutting. The operation known as "stack flame cutting" offers a means of cutting several thicknesses of metal simultaneously with a single torch, instead of employing multiple-torch cutting.

The plates in the stack should be clean and flat, with edges in alignment where the cut is started. The number varies with the thickness of individual plates, to keep the thickness of the stack within reasonable limits. The plates should be clamped together firmly, as nearly as possible along the line of cut. When thin plates are to be flame cut in stacks, a "waster plate" that has sufficient rigidity to lie flat while the cut is being made, is usually clamped on to prevent the top thin plate from buckling with the heat. A waster plate serves also to maintain ignition in the cut by its own combustion, thereby increasing the speed of cutting in this kind of work.

Flame-Cutting Techniques. Several different flame-cutting techniques have been developed for performing various cutting operations and for cutting different grades of ferrous metals. The International Acetylene Association in its Oxyacetylene Committee Publication, Section I, entitled "Oxyacetylene Cutting", defines five distinct flame-cutting techniques. These are typified in Fig. 6 from the standpoint of flame movement and may be described as follows:

Type 1 Flame Cutting. This is the simple progressive type, widely used for carbon steels and other ferrous metals that are easily cut. The cut proceeds freely and regularly in a line and at the will of the operator. The technique consists in first preheating a spot to kindling temperature (1400 to 1600 F) with the several preheating flames surrounding the orifice for the cutting oxygen. Then the cutting oxygen is turned on and the cut is started. Theoretically, preheating should be necessary only for starting. In practice, however, preheating flames are maintained throughout the cutting operation, to ensure continuity of cutting and high speed. The torch is manipulated merely by holding it at correct height above the surface and advancing it at proper uniform speed along the line of cut (Fig. 6). The high velocity of the stream of cutting oxygen confines it to a narrow path and holds the oxidizing action within close limits. This makes accurate control possible. In practice, a considerable portion of the metal removed from the kerf is blown out in molten metallic form, unoxidized—particularly from heavier cuts. Figure 7 illustrates the relationship among thickness, metal removed and oxygen consumed in Type 1 flame cutting.

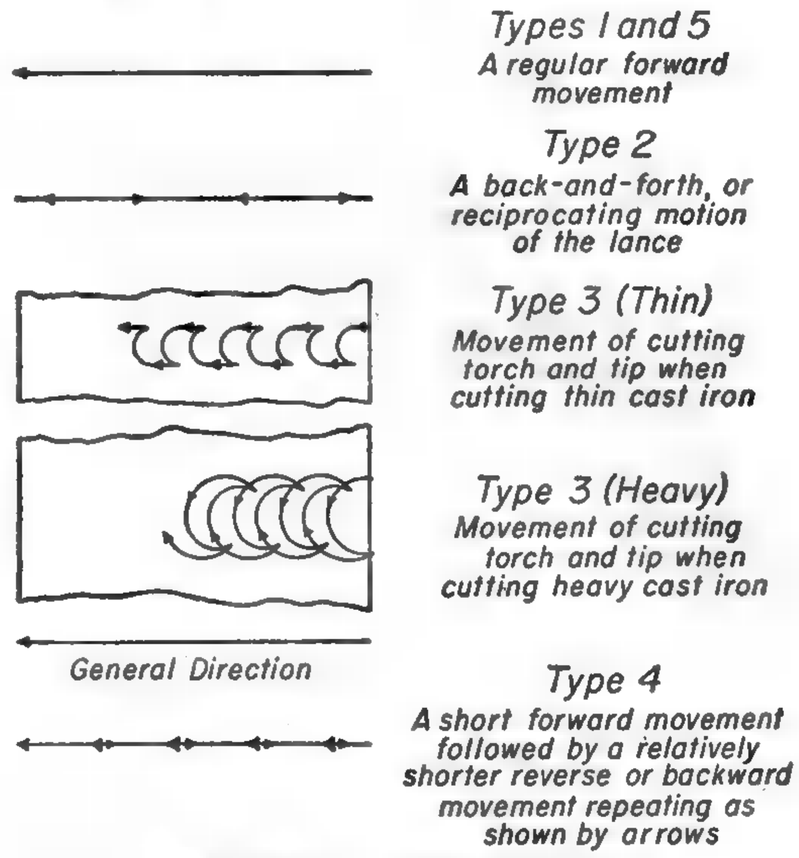

Fig. 6 Types of cutting techniques

Type 2 Flame Cutting. Commercially, this is known as "oxygen-lance cutting". Virtually all ferrous metals and many other materials can be cut or pierced with the oxygen lance. The lance ordinarily consists of a length of black iron pipe (¼ or ⅜ in. inside diam) with a globe valve on one end, connected to an oxygen hose, regulator and cylinder or manifold, so that only oxygen flows through the lance pipe.

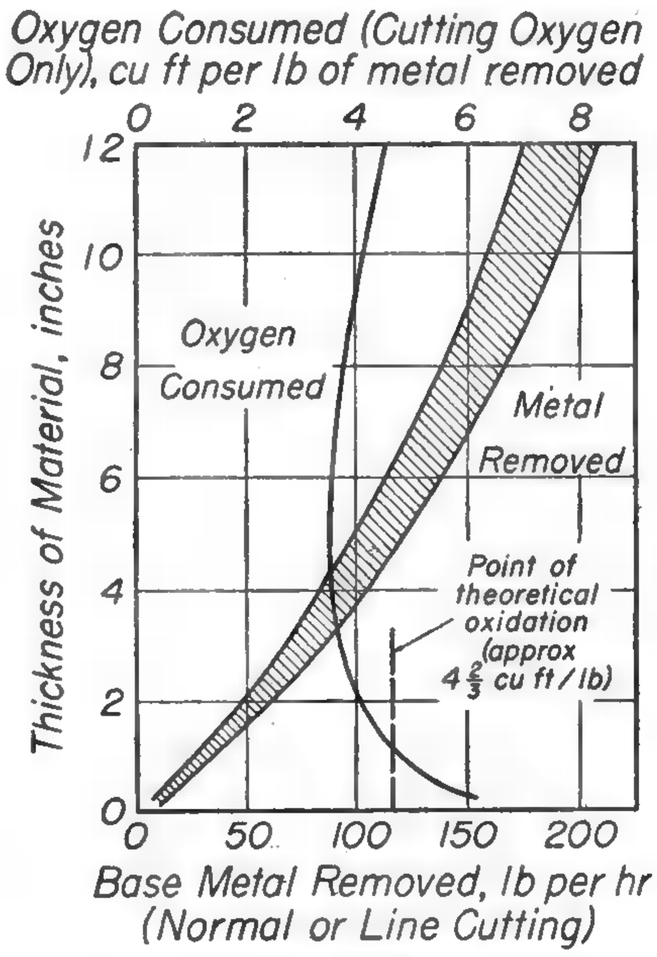

Fig. 7 Relationship among thickness, metal removed, and oxygen consumed

As in Type 1 flame cutting, a spot is first preheated to kindling temperature, usually by means of a welding torch with large tip. Then the end of the lance is brought against the heated area and oxygen is turned on at about 40 to 50 psi. This oxidizes the metal and sufficient heat is produced to continue the cut or hole with oxygen alone, without oxy-fuel gas flames to facilitate the progress. The end of the lance is held in the cut or hole so that the stream of cutting

oxygen emerges at the point of cutting or oxidation. This heats the end of the lance pipe, causing it to burn also. As the operation proceeds, the lance is consumed, ultimately requiring replacement by a new length of iron pipe. Oxidation of the lance itself requires only a minor portion of the oxygen consumed, while the heat of the burning lance assists in the cutting.

Once started, the oxidation reaction is vigorous. It may be intensified further, if desired, by using a lance pipe of greater wall thickness, or by inserting one or more steel rods into the pipe. Both the thicker pipe and the rod inserts furnish additional fuel and heat, while the rods decrease the area of the effective opening in the lance pipe, thereby imparting greater velocity to the oxygen stream and increasing the eroding effect.

Oxygen-lance cutting acts to extend the range of penetration in standard cutting-torch operations. This method is seldom used alone but is an aid to Type 1 flame cutting in severing thick or heavy masses of metal. However, under proper conditions and setup, oxygen lances can be employed independently. With various modifications, they are used for flame cutting large sections of cast iron, steel and other materials. For example, oxygen lances serve to burn holes in salamanders and ladle chills, in which, after cooling, dynamite is inserted and exploded for final demolition. It has become standard practice to open tap holes in blast furnaces and open hearth furnaces with the oxygen lance. In this operation, a spot of metal in the tap hole and the end of the lance pipe are both heated red hot with an oxy-acetylene welding torch. Oxygen is then allowed to flow through the pipe and impinge on the hot metal, which is quickly pierced, allowing the molten metal to flow out.

Lancing usually consumes more oxygen per pound of metal removed than other types of flame cutting. This, however, is offset by the greatly increased value of the cutting service as compared with other methods that can be used for such work. Obviously, the surface produced by Type 2 flame cutting, or lancing, is not so smooth as the surface obtained with Type 1 flame cutting. Nevertheless, surprisingly accurate holes can be pierced with the lance. Oxygen lance cuts should be made so that the slag and molten metal can flow out of the cut freely by gravity wherever possible.

Type 3 Flame Cutting. This technique was developed especially for cutting cast iron. Considerably more preheat is used than in Type 1 flame cutting, both in starting and in continuing the cut. A definite flame oscillation is used, which is necessary for cutting the cast irons, particularly those possessing carbon in the uncombined or graphitic state resistant to flame cutting. The sidewise motion or oscillation of the flame is approximately in the form of half circles or new moons, advancing in short and regular intervals, as shown in Fig. 6, Type 3 (heavy), when cutting heavy cast iron. A slight modification of the flame oscillation, shown in Fig. 6, Type 3 (thin), has been found more advantageous for cutting thin cast iron.

The resulting cut, therefore, may be termed a "worked cut", for the cast iron originally in the kerf has, in reality, been "worked out" by the oscillating technique. If this technique is regularly maintained, it causes a constant stream of slag and molten metal to flow through the kerf, preheating the base metal in the kerf and preparing it for further oxidation and displacement as the molten products are removed. The cut is naturally somewhat rougher than a Type 1 flame cut, because more of the metal has been removed by the mechanical eroding effect of the jet of cutting oxygen. A wider kerf is produced; therefore more metal must be oxidized and oxygen and acetylene consumptions are greater than for Type 1 flame cutting.

Highly carburizing preheating flames are used in Type 3 flame cutting of cast iron; that is, the flames are adjusted to carry a considerable excess of acetylene, which appears as a long whitish feather in the flames, beyond the small brilliant inner flame cone (Fig. 8). The length of the excess streamer of acetylene should be approximately equal to the thickness of the cast iron. This flame adjustment helps to maintain preheat in the cut, since the excess acetylene combines with cutting oxygen beyond the tip.

Type 3 flame cutting, or cast-iron cutting, appears to be limited at present to the alteration and repair of machinery and to the demolition of castings, usually in basements or other inaccessible locations where they must be broken up before removal, or otherwise reduced in size.

Type 4 Flame Cutting. For severing stainless steels, which resist ordinary techniques, a distinctive cutting technique has been developed, utilizing a flame motion or oscillation different from that in Type 3 flame cutting. In this method also the flame is moved continually while cutting, but in short strokes back and forth along the line of cut (Fig. 6) instead of sideways. When a cut is started in stainless steel, the entire face or leading edge of the cut is preheated from top to bottom, until the edge has been brought to a bright red color. The usual spot at the top edge is preheated also. Then the cutting operation is started. The forward and backward reciprocating motion already described, advances the cut through the part in short forward increments.

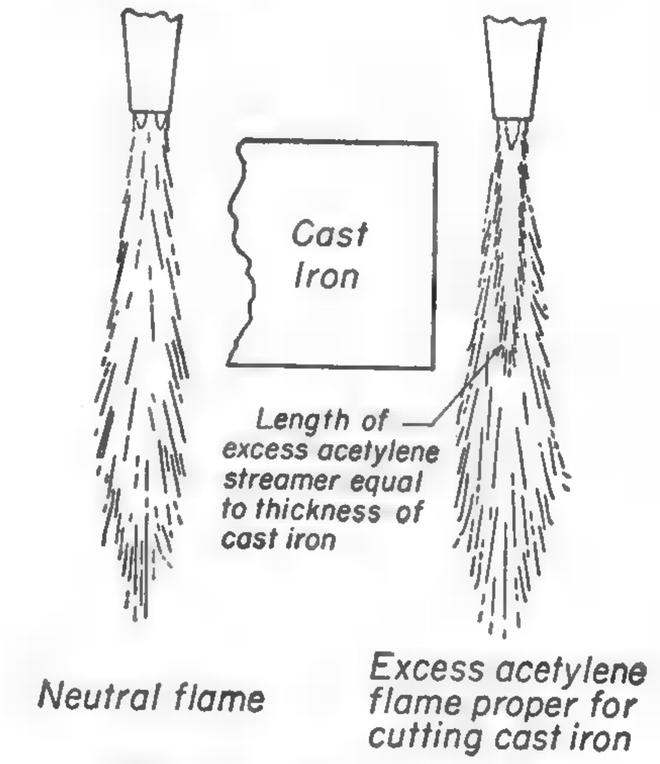

Fig. 8 Flame for Type 3 cutting

As in Type 3 flame cutting, the maintenance of a steady stream of liquid slag and molten metal is essential for a successful cut. Erosion by slag is probably as important as any other single factor in cutting stainless steels. It determines the degree of uniformity attainable in the cutting of these metals. Naturally, Type 4 cutting leaves a rough surface, necessitating subsequent machining or grinding if a smooth finish is desired.

Type 5 Flame Cutting. This technique involves the use of powdered additive materials in the cutting zone and supplants Type 4 cutting when the necessary equipment is available, enabling cuts of Type 1 to be made on metals such as stainless steels that are difficult to cut. The principal trouble in cutting these steels is the formation of highly refractory chromium oxide. One form of the Type 5 technique introduces iron powder into the reaction zone where it combusts with a portion of the oxygen, thus liberating intense heat that removes the oxides of chromium by a combination melting and fluxing action, and also permits cutting on very high alloy materials and cast iron in addition to stainless steels. Another type of equipment feeds a flux through the cutting oxygen stream. This flux combines with the chromium oxides to form a slag of low melting point—an action similar to that of the flux in oxy-acetylene welding of stainless steels.

The possibilities of this type of flame cutting have been investigated less thoroughly for cutting other metals than for cutting stainless steels. However, there are definite indications that cast iron, tungsten, and possibly other metals and alloys of low cuttability will yield to this technique.

Regardless of whether the iron-powder method or flux-injection method is used, the speed of cutting compares favorably with that reached in cutting mild steel and the cut faces are remarkably smooth. At times, the addition of flux enables resistant materials to be cut by Type 1 flame cutting instead of by a more tedious technique.

Cuttability of Ferrous Metals. Certain alloy steels contain chromium, nickel and other elements in amounts sufficient to render these steels considerably more difficult to

cut than carbon steels. The effect of various alloying elements on the cuttability of steel, as reported by various authorities, is summarized in Table V.

Types of flame-cutting techniques that are employed with various ferrous metals are given in Table VI.

Hand Flame Cutting. Many variables affect the performance of freehand flame cutting. However, the range of fair average practice in freehand oxyacetylene flame cutting of mild steel, not preheated, is given in Table VII. Oxygen and acetylene consumptions for cutting the various thicknesses as great as 12 in. are listed, both in cubic feet per hour and in cubic feet per linear foot of cut.

Freehand "Guided" Flame Cutting. This includes such operations as cutting circles and drawing the torch head along a bar or straight edge that acts as a guide. Circles or disks can be cut accurately with a hand torch that has a straight head, by using a circle-cutting attachment consisting of a clamp, radius rod and adjustable center point. Another attachment has small wheels that rest and roll on the surface of the work.

Flame-Cutting Machines. Flame-cutting machines are comparable with machine tools. As flexible as a jigsaw, flame-cutting machines are capable of making flame cuts of such high quality and accuracy that the edges frequently require no further finishing.

Straight-Line Machine Flame Cutting. Straight-line machine flame cutting is even simpler than freehand flame cutting. Once the machine and gas pressures have been set, the torch follows the line of cut automatically. As the cut progresses, the operator watches the drag and the flow of slag or oxide to prevent pocketing or other defects from developing. For oxyacetylene machine flame cutting of mild steel, speeds and gas pressures should be adjusted within the ranges given in Table VIII.

Machine Flame Cutting of Shapes. Regular or irregular shapes, of almost any size or thickness, no matter how complex, are flame-cut with ease by machine. The process has jigsaw flexibility. Most shape-cutting machines are driven by a motor. Some have tracing devices that are guided by hand around the outline of a drawing.

Circular Flame Cutting by Machine. Most flame-cutting machines can be adapted to circular cutting. A radius rod that has an adjustable center point is furnished with some of these machines. The point is placed in a punch mark at the center of the circle and the machine and cutting torch travel around the circumference at the radius set. Ordinarily a short "lead in" cut is made through the scrap, so as to have the finished cut smooth and unmarred at the starting point.

Precision Flame Cutting by Machine. One technique for machine flame cutting that produces especially high quality and accurate cuts is sometimes distinguished by the name "precision machine flame cutting". It will be noted in Fig. 3 that this type of cutting has been set up as a separate division of machine flame cutting, to distinguish it from standard machine flame cutting, which is a less refined process.

Although the technique described under Type 1 cutting is, in general, the one followed for precision machine flame cutting, closer adjustments of pressures and speed are required than for standard machine flame cutting. Cut surfaces have been attained by this method that have the cross-sectional squareness accurate within 0.003 in. for a 1-in. thickness. For thicker material, cross-cut tolerances increase approximately in proportion to the thickness. The cross-cut tolerances for thicknesses of 1, 2, 4 and 6 in. when precision flame-cut by machine, are shown in Fig. 9. These tolerances are not generally available commercially (1947).

Machine Flame-Cutting Table. The range of fair average practice in machine oxyacetylene flame cutting of mild steel, not preheated, is given in Table VIII.

Flame-Machining Operations. In flame machining, each operation is a problem in itself, calling for a co-ordination of nozzle tooling and metallurgical control. Various types of flame-machining operations have been included at the right-hand side of Fig. 3. It will be noted that these are termed planing, milling, turning, drilling and boring, like the corresponding machine tool operations. Subclassifications of these operations also are given in the chart. Not all these operations have been commercialized up to the present time; some are still in the development stage.

Flame Machining. Several types of tangential cuts may be classified under the heading of "flame machining". The principal differences are primarily the character of application and the tolerances or degrees of surface regularity attained or permitted. Flame machining can be either manual or mechanical. The subclassifications are:

1 *Deseaming or Scarfing.* This process of flame machining is used in the steel mills for removing cracks or seams in billets, slabs and rounds.* It is employed also in steel foundries for exploring and cleaning out cracks and sand holes in castings.
2 *Hogging.* This type of flame machining, applied to steel castings, removes superfluous metal that has been either provided purposely or caused by defective conditions at the time of pouring. Hogging also removes risers and sprues of such location or character as to make it difficult or impossible to dispose of them by ordinary or Type 1 flame cutting.
3 *Surface Planing.* This operation is a step beyond the practice of deseaming, in that the cuts are adjacent to one another, thus enabling the removal of wide surfaces. When surface planing is done mechanically, the tolerances as to depth and width of cut can be kept to within $\frac{1}{16}$ and $\frac{1}{8}$ in. of the surface.

* For information concerning torch scarfing, the reader may refer to the article "Conditioning of Semifinished Steel", page 343.

Table V. Effect of Alloying Elements in the Gas Cutting of Steel

Element	Effect
Aluminum	A low aluminum content does not hinder flame cutting. However, an aluminum content of 10 to 15% resists flame cutting either hot or cold, except where a special technique is used.
Carbon	In unalloyed steels, 2% C or less permits flame cutting by simple progressive procedure (Type 1 technique). However, steels containing more than 0.30% C should be preheated between 500 and 600 F before cutting, or heated after cutting, before the cut surface cools to normal temperature, in order to prevent hardening and cracking at edges. The quality of the cut is affected by both amount and form of carbon content. Graphite and cementite (Fe_3C) tend to hinder cutting, but cast irons containing 4% C are cut successfully by a special technique (Type 3).
Chromium	Chromium contents of 1½% or less have no adverse effect. Steels with 4 to 6% may also be cut by Type 1 technique, provided carburizing preheating flames of low intensity are used. Where the chromium content is 10% or more, a special cutting technique is required to produce a complete cut (Types 4 and 5).
Copper	Copper contents of 3% or less in steel permit easy flame cutting.
Manganese	Manganese contents of 14% or less, with 1.3% C, allow for good cutting. However, high-manganese steels require preheating before cutting, in order to prevent cracking.
Molybdenum	A molybdenum content of 0.25%, as in chromium-molybdenum aircraft steels, does not hinder cutting. But a steel with 5.5% Mo, 8% W and 1% C is uncuttable, either hot or cold, unless special techniques are employed.
Nickel	As much as 7% Ni in steel does not hinder good flame cutting. Steels with 34% Ni have been cut in instances where the carbon content was lower than 0.50%.
Phosphorus	Phosphorus contents of 2% or less do not prevent good gas cutting.
Silicon	Silicon contents of 2.90% or less permit cutting by the simple progressive method. Transformer iron, containing 4% Si or less, can be gas cut, but a high silicon content reduces speed. Precautions in preheating and cooling are necessary with certain of these steels in the higher ranges of carbon and manganese contents to prevent or modify tendencies toward air-hardening.
Sulfur	Small amounts, such as are normally present in steels, have no effect. With higher percentages of sulfur, the rate of gas cutting is reduced and sulfur dioxide (SO_2) fumes are produced.
Tungsten	Tungsten contents of 10% or less do not hinder flame cutting of steels that contain also 5% Cr, 0.2% Ni and as much as 0.8% C. A tungsten content of 17% necessitates preheating before cutting and a procedure similar to the cutting of cast iron (Type 5 technique).

Table VI. Data for Flame Cutting of Ferrous Metals,[a] Cutting Techniques[b] and Heat Treating Practices[c]

Metal	Approximate Carbon Content, %	Cutting Technique[b] Type 1	2[k]	3	4	5	Pre-heating Flames[d]
Iron (low-carbon)	0.04	C	...	...	...	...	...
Carbon steels[e]							
Low-carbon	0.10 to 0.30	C[f]	...	...	...	...	...
Medium-carbon	0.30 to 0.50	P or HT	...	...	...	...	...
High-carbon	0.50 to 1.60	HT	...	...	...	...	...
Tool steel	0.90 to 1.10	HT	...	...	...	...	...
Cast iron							
Gray iron	2.75 to 3.75	...	C[n]	C[n]	...	C[n]	Car
Malleable iron	2.50	...	C[n]	C[n]	...	C[n]	Car
Alloy cast iron	Any	...	C[n]	C[n]	...	C[n]	Car
Duriron (approx 15% Si)	0.75	...	C[n]	C[n]	...	C[n]	Car
Manganese steels							
SAE T-1330 (including Mn structural)	0.25 to 0.35	P or HT	...	...	...	...	...
SAE T-1350	0.45 to 0.55	HT	...	...	...	...	...
Hadfield's (10 to 14% Mn)	1.00 to 1.50	P	...	...	...	...	...
Silicon-manganese (0.80 to 2.20% Si)	0.45 to 0.70	HT	...	...	...	...	...
Silicon steels							
Structural (0.20 to 0.30% Si)	0.25 to 0.40	HT	...	...	...	...	...
Transformer (4.00% Si or less)	0.10 max	P or HT	...	...	...	...	...
Nickel steels							
SAE 2015 (0.40 to 0.60% Ni)	0.10 to 0.20	C	...	...	...	...	...
SAE 2115 (1.25 to 1.75% Ni)	0.10 to 0.20	C[g]	...	...	...	...	...
SAE 2315 and 20 (3.25 to 3.75% Ni)	0.10 to 0.25	C[g]	...	...	...	...	...
SAE 2330 to 50 (3.25 to 3.75% Ni)	0.25 to 0.35	HT	...	...	...	...	...
High-nickel (34.0% max Ni)	0.50 max	...	...	C[h]	...	C	...
Nickel-chromium steels							
SAE 3115 (0.45 to 0.75% Cr)	.....	C	...	...	...	...	...
SAE 3120 to 50 (0.45 to 0.75% Cr)	.....	HT	...	...	...	...	...
SAE 3215 to 50 (0.90 to 1.25% Cr)	.....	HT	...	...	...	...	...
SAE 3312 to 40 (1.25 to 1.75% Cr)	.....	HT	...	...	...	...	...
SAE 3415 to 50 (0.60 to 0.95% Cr)	.....	HT	...	...	...	...	...
Molybdenum steels							
SAE 4130 to 50 (0.50 to 1.10% Cr)[i]	0.25 to 0.55	HT	...	...	...	...	...
SAE 4615 (1.65 to 2.00% Ni)	0.10 to 0.20	C[h]	...	...	...	...	...
SAE 4620 to 40 (1.65 to 2.00% Ni)	0.15 to 0.45	HT	...	...	...	...	...
SAE 4815 to 20 (3.25 to 3.75% Ni)	0.10 to 0.25	HT	...	...	...	...	...
Chromium steels							
SAE 5120 (0.60 to 0.90% Cr)	0.15 to 0.25	P or HT	...	...	...	...	...
SAE 5140 to 50 (0.80 to 1.10% Cr)	0.35 to 0.55	HT	...	...	...	...	...
SAE 52100 (1.20 to 1.50% Cr)	0.95 to 1.10	HT	...	...	...	...	...
4 to 6% Cr steel	0.25 max	HT	...	...	...	...	Car
Stainless steels							
Low-carbon chromium (12 to 18% Cr)	0.12	....	...	...	C[l]	C[l]	Car
High-carbon chromium (12 to 18% Cr)	0.30 to 0.60	....	...	...	C[l]	C[l]	Car
Chromium-nickel (7 to 10% Ni) (16 to 20% Cr)	0.05 to 0.20	....	...	...	C[l]	C[l]	Car
Chromium-vanadium steels							
SAE 6115 to 20 (0.80 to 1.10% Cr)	0.10 to 0.20	C[g]	...	...	...	...	...
SAE 6125 to 95 (0.80 to 1.10% Cr)	0.20 to 1.05	HT	...	...	...	...	...
Tungsten steels							
SAE 71360 (12 to 15% W)	0.50 to 0.70	....	...	C[h]	...	C	...
SAE 71660 (15 to 18% W)	0.50 to 0.70	....	...	C[h]	...	C	...
SAE 7260 (1.50 to 2.00% W)	0.50 to 0.70	C[h][j]	...	...	...	...	...
Vanadium steel (0.15% V min)	0.90	HT	...	...	...	...	...
Aluminum steel[m] (less than 10% Al)	.....	C	...	...	...	...	...

(a) The data apply to metal in the forged, rolled, and cast condition unless otherwise noted. Preheating of any steel will ordinarily improve the economy of cutting and prevent acute hardening. For carbon steels, heat treatment in one form or another is usually employed where the carbon content exceeds 0.30%, provided the cutting is conducted at normal temperatures (60 to 80 F). If the temperature of the metal is lower than this, heat treating may have to be employed at a lower carbon content to preserve or re-establish desired physical properties. The letters P or HT are used to designate material that is cuttable cold, but requires either preheating or reheating to prevent damaging the cut surface or to preserve or restore commercial properties.

(b) The technique of cutting varies for different grades of steel. See the description of the five distinct types in the text.

(c) Heat treating practices employed for grades that are unduly hardened by the normal application of flame cutting are listed in the table under the following classifications:

C denotes that metal may be safely cut at room temperatures.

P denotes that metal should be preheated before cutting in order to prevent hardening of the metal in the face of the cut. Usual preheating temperatures range from 500 to 900 F. Preheating is also used for certain grades to facilitate cutting.

HT denotes heat treatment, in a furnace or by other means, after cutting, in order to improve or recondition the structure of the cut surface, provided the material is kept warm between the time of cutting and the heat treatment.

Car denotes carburizing flame. A carburizing flame is one carrying more fuel gas than is required for complete combustion.

(d) Unless otherwise indicated, neutral preheating flames are desirable. However, appreciably higher preheating temperatures may be obtained by adjusting these flames for an excess of oxygen (oxidizing). Therefore, where additional preheating is desired, oxidizing preheating flames may be used wherever neutral flames are indicated. Considerable economies are sometimes obtainable with oxidizing flames in which the ratio of oxygen to acetylene is about 1.7 to 1 or 1.8 to 1.

(e) The addition of normal amounts of copper (3% or less) does not interfere with the type of cutting normally employed for the grade of steel in question. The addition of copper, however, does increase hardening of the cut surface, necessitating introduction of heat treatment at a lower point in the aggregate of hardening alloys than would otherwise prevail.

(f) Grades SAE X-1314 and X-1315 may harden perceptibly if carbon contents are high and the metal is cut at normal or lower temperatures.

(g) After cutting, heat treatment may be necessary if carbon contents are high.

(h) No data are available as to heat treatment, if necessary.

(i) Including SAE 4340 and 4315.

(j) Evidently the tungsten contents may be as high as 10% with Type 1 cutting technique.

(k) All grades that respond to Type 1 cutting technique will respond readily to Type 2 technique, either in conjunction with Type 1 technique or separately. The heat treatment for Type 2 corresponds to that for Type 1.

(l) Heat treatment is usually necessary to counteract harmful effects of the heating produced during the cutting operation, unless the metal contains a stabilizing element to prevent such heat effects.

(m) Aluminum steel containing approximately 1% Al, 1% Cr and 0.50% Mo is reported to be cuttable by Type 1 technique. Heat treatment would depend on the carbon content.

(n) The cut surfaces in heavy sections of cast iron are hardened by the cutting operation and should be heat treated if they are to be machined after cutting.

Flame Drilling and Punching. Figure 10 shows a method used for flame drilling a round hole in the end of a billet, for centering or piercing purposes. The dimensions of the finished hole can be made uniform and the walls straight if the nozzle or tip is held properly during drilling.

The oxygen lance, described under Type 2 flame cutting, is also a valuable tool for flame-drilling operations, particularly those too deep for a cutting tip to reach.

Rivet Cutting. Flame drilling has proved successful for rivet cutting by surface oxidation of heads. Cutting tips

Table VII. Data for Hand Flame Cutting of Clean, Mild Steel ⅛ to 12 In. Thick, Not Preheated. Type 1 Cutting Only

Thickness of Steel, inch	Diameter of Cutting Orifice, inch	Oxygen Pressure, psi	Cutting Speed, in. per min[b]	Gas Consumptions[a] — Per hr — Oxygen, cu ft	Per hr — Acetylene, cu ft	Per linear ft[b] — Oxygen, cu ft	Per linear ft[b] — Acetylene, cu ft
⅛	0.0380 to 0.0400	15 to 23	20 to 30	45 to 55	7 to ■	0.37 to 0.45	0.06 to 0.07
¼	0.0380 to 0.0595	11 to 20	16 to 26	50 to 93	9 to 11	0.63 to 0.72	0.08 to 0.11
⅜	0.0380 to 0.0595	17 to 25	15 to 24	60 to 115	10 to 12	0.80 to 0.96	0.10 to 0.13
½	0.0465 to 0.0595	20 to 30	12 to 22	66 to 125	10 to 13	1.10 to 1.14	0.12 to 0.17
¾	0.0465 to 0.0595	24 to 35	12 to 20	117 to 143	12 to 15	1.43 to 1.95	0.15 to 0.20
1	0.0465 to 0.0595	28 to 40	9 to 18	130 to 160	13 to 16	1.78 to 2.89	0.18 to 0.29
1½	0.0595 to 0.0810	40	6	.....	.....	.....	.....
2	0.0670 to 0.0810	22 to 50	6 to 13	185 to 231	16 to 20	3.55 to 6.16	0.31 to 0.53
3	0.0670 to 0.0810	33 to 55	4 to 10	240 to 290	19 to 23	5.80 to 12.00	0.46 to 0.95
4	0.0810 to 0.0860	42 to 60	4 to 8	293 to 388	21 to 26	9.70 to 14.64	0.65 to 1.05
5	0.0810 to 0.0860	53 to 70	3.5 to 6.4	347 to 437	24 to 29	13.66 to 19.83	0.91 to 1.37
6	0.0980 to 0.0995	45 to 80	3.0 to 5.4	400 to 567	27 to 32	21.00 to 26.70	1.19 to 1.80
8	.... to 0.0995	60 to 77	2.6 to 4.2	505 to 615	31.5 to 38.5	29.30 to 38.84	1.83 to 2.42
10	.... to 0.0995	75 to 96	1.9 to 3.2	610 to 750	36.9 to 45.1	46.90 to 64.20	2.57 to 3.84
12[c]	.... 0.1200	69 to 86	1.4 to 2.6	720 to 880	42.3 to 51.7	67.70 to 103.00	3.98 to 6.05

(a) Because the pressure of acetylene for the preheating flames is more a function of blowpipe or torch design than of the thickness of the part being cut, the pressure data have been omitted from this table. For acetylene pressure data, see charts of manufacturers of apparatus.

(b) Lowest speeds and highest gas consumptions per linear foot are for inexperienced operators, short cuts, dirty or poor material. Highest speeds and lowest gas consumptions per linear foot are for experienced operators, long cuts, clean and good material.

(c) Beyond 12-in. thickness, the critical data of manual cutting practices are greatly affected by the condition of the metal and the skill of the operator, resulting in wide ranges of data. In view of this, the table has been terminated at the 12-in. thickness.

The reader is referred to Table VIII, which gives data on machine cutting wherein the range of thickness has been extended to 36 in.

Table VIII. Data for Machine Flame Cutting of Mild Steel ⅛ to 36 In. Thick, Not Preheated. Type 1 Cutting Only[c]

Thickness of Steel, inch	Diameter of Cutting Orifice, inch	Oxygen Pressure, psi	Cutting Speed, in. per min[b]	Gas Consumptions[a] — Per hr — Oxygen, cu ft	Per hr — Acetylene, cu ft	Per linear ft[b] — Oxygen, cu ft	Per linear ft[b] — Acetylene, cu ft
⅛	0.0250 to 0.0400	15 to 23	22 to 32	40 to 55	7 to 9	0.34 to 0.36	0.05 to 0.06
¼	0.0310 to 0.0595	11 to 35	20 to 28	45 to 93	8 to 11	0.34 to 0.66	0.07 to 0.08
⅜	0.0310 to 0.0595	17 to 40	19 to 26	82 to 115	9 to 12	0.86 to 0.89	0.08 to 0.09
½	0.0310 to 0.0595	20 to 55	17 to 24	105 to 125	10 to 13	1.04 to 1.24	0.11 to 0.12
¾	0.0380 to 0.0595	24 to 50	15 to 22	117 to 159	12 to 15	1.45 to 1.56	0.14 to 0.16
1	0.0465 to 0.0595	28 to 55	14 to 19	130 to 174	13 to 16	1.83 to 1.86	0.17 to 0.19
1½	0.0670 to 0.0810	55	12 to 15	240	14 to 18	3.20	0.23 to 0.24
2	0.0670 to 0.0810	22 to 60	10 to 14	185 to 260	16 to 20	3.70 to 3.72	0.29 to 0.32
3	0.0810 to 0.0860	33 to 50	8 to 11	240 to 332	18 to 23	6.00 to 6.04	0.42 to 0.45
4	0.0810 to 0.0860	42 to 60	6.5 to 9	293 to 384	21 to 26	8.53 to 9.02	0.58 to 0.65
5	0.0810 to 0.0860	53 to 65	5.5 to 7.5	347 to 411	23 to 29	10.97 to 12.62	0.77 to 0.84
6	0.0980 to 0.0995	45 to 65	4.5 to 6.5	400 to 490	26 to 32	15.10 to 17.78	0.98 to 1.16
8	0.0980 to 0.0995	60 to 90	3.7 to 4.9	505 to 625	31 to 39	25.52 to 27.30	1.59 to 1.68
10	0.0995 to 0.1100	75 to 90	2.9 to 4.0	610 to 750	37 to 45	37.50 to 42.10	2.25 to 2.55
12	0.1100 to 0.1200	69 to 105	2.4 to 3.5	720 to 880	42 to 52	49.70 to 60.00	2.97 to 3.50
12[d]	0.1935	30	[e]	1274	85	[d]	[d]
14	0.221	25	[e]	1458	98	[d]	[d]
16	0.221	30	[e]	1683	98	[d]	[d]
18	0.250	25	[e]	1838	134	[d]	[d]
20	0.250	30	[e]	2098	134	[d]	[d]
22	0.250	35	[e]	2358	134	[d]	[d]
24	0.290	25	[e]	2467	174	[d]	[d]
26	0.290	30	[e]	2772	174	[d]	[d]
28	0.290	35	[e]	3077	174	[d]	[d]
30	0.332	25	[e]	3125	204	[d]	[d]
32	0.332	30	[e]	3425	204	[d]	[d]
34	0.332	35	[e]	3775	204	[d]	[d]
36	0.332	40	[e]	4125	204	[d]	[d]
¼[f]	Tapered	120	26	70	14	0.54	0.109
½	Tapered	100	22	100	18	0.91	0.163
¾	Tapered	100	20	120	18	1.00	0.18
1	Tapered	110	18	130	18	1.44	0.20
1½	Tapered	100	16	170	25	2.11	0.31
2	Tapered	100	13	230	25	3.52	0.39
3	Tapered	85	10	270	32	5.4	0.64
4	Tapered	85	9	330	35	7.3	0.78
5	Tapered	110	8	395	35	9.7	0.87
6	Tapered	125	7	435	35	12.4	1.00
7	Tapered	80	6	495	36	16.5	1.20
8	Tapered	100	5½	580	36	21.2	1.32

(a) Because the pressure of acetylene for the preheating flames is more a function of blowpipe or torch design than of the thickness of the part being cut, the pressure data have been omitted from this table. For acetylene pressure data, see charts of manufacturers of apparatus.

(b) Lowest speeds and highest gas consumptions per linear foot are for inexperienced operators, short cuts, dirty or poor material. Highest speeds and lowest gas consumption per linear foot are for experienced operators, long cuts, clean and good material.

(c) The apparent inconsistencies that will be noted in some of the columns in the table result from the fact that straight-line relationships do not exist among pressure, speed, and orifice sizes for the range of apparatus data for which this table was devised.

(d) The generally accepted point at which heavy cutting begins is 12 in. The data for 12 to 36 in. are for torches with large tips, using large volumes of oxygen at low pressures. Because the speed depends on the conditions of the material being cut and the skill of the operator, no figures are given for gas consumption per linear foot.

(e) Cutting speeds per minute vary from 4 in. for light sections to 2 in. for heavy sections.

(f) These data are for divergent orifices that have controlled expansion tips, permitting the use of relatively high oxygen pressures so as to expand the cutting oxygen through the orifices. Thus the gas stream has high velocity and is relatively narrow. Higher speeds and lower specific consumption of oxygen result.

used for this operation have large cutting-oxygen orifices of the expanding type, low in pressure and velocity, together with preheating flames of high intensity. The tip is held in line with the rivet, close to the head, so that preheating flames impinge on the center. As soon as a spot is heated bright red, the cutting oxygen is turned on slowly. This quickly oxidizes a crater in the head and consumes the head. The rivet shank is then knocked from the hole.

Flame Boring. Rough boring can be accomplished by means of a compound setting of the cutting flame. Application of this process depends largely on tooling so that the slag and molten metal from the cuts will not interfere with the cutting and the operation of the cutting nozzle.

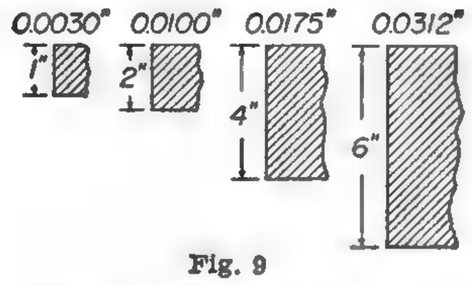

Fig. 9

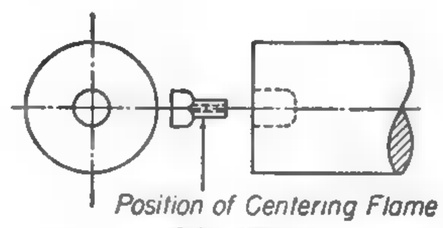

Fig. 10

Fig. 9 Cross-cut tolerance for precision machine-cutting practices
Fig. 10 Flame drilling

Underwater Cutting. Equipment for underwater cutting has been highly developed. Although oxyacetylene is used for shallow work, the pressure of acetylene needed soon rises to more than 15 psi because of the hydrostatic head. As a result oxyhydrogen torches are used at depths greater than 25 ft. Operation under water involves the creation of an artificial atmosphere or "bubble" in which the preheating flames burn and in which the actual cutting is done. Some torches create such a bubble by the use of a skirt around the tip. The skirt is filled with the combustion gases, in order to keep the water away from the flame. The most successful equipment for deep-water operation requires a supply of compressed air to form the bubble in the skirt.

Operating pressures are determined largely by the hydrostatic head to be overcome. The chilling effect of the water on the work requires heavier preheats. Because of the difficulties under which the diver must work—such as clumsy dress, darkness, insecure footing, cold, and high pressure—only severing cuts are made, and oxygen and acetylene consumption figures are meaningless, although the specific cutting speed may be higher than in the open air.

The torch may be lighted on the surface and lowered to the diver in that condition or it may be sent down unlighted, to be ignited by a spark.

Another form of underwater cutting equipment uses the electric arc for preheating. The apparatus embodies a holder with an oxygen valve and means for gripping a hollow electrode. In operation, the diver calls for current, draws an arc against the work and, as soon as there is a molten pool of metal, he opens the oxygen valve, permitting a stream of oxygen to flow down the hollow electrode. Simplicity is the chief advantage of this equipment, since only the oxygen hose and the cable carrying the current need to go to the surface. However, the diver's telephone must be in perfect order and elaborate precautions must be taken to protect him from the electric current.

Safety Rules. Certain precautions must be observed for the safe handling and operation of gas cutting tools and appurtenant equipment. Standard rules and regulations have been promulgated by the cutting industry in co-operation with regulatory bodies that deal with the safety of the public and of workers. In "Safe Practices Bulletin No. 23", published by the National Safety Council, and in "Regulations for the Installation and Operation of Gas Systems for Welding and Cutting", issued by the National Board of Fire Underwriters, the subject of general safety is well covered, with regard to gas-welding and gas-cutting processes. The American Standards Association pamphlet, War Standard Z 49.1, is also recommended.

Electric-Arc Cutting

The process of electric-arc cutting consists in applying the heat energy of the electric arc to melt the metal along the desired line of cut. Because of the extremely high temperature developed in the electric arc, it can be used to fuse almost any material that conducts electricity, and in this way it is employed for cutting metals. Arc cutting is not a true cutting process, since the metal is merely melted away. Arc cutting does not equal gas cutting from the standpoint of smoothness, quality, or accuracy of cut surfaces, and hence, is not used where high-quality, accurate cuts are required. However, it is useful where smooth, uniform cut surfaces are not essential and mere severing is the main object, as in scrapping operations. Arc cutting is used also for metals not easily cut in any other manner, such as cast iron, manganese steel, and large sections of nonferrous metals. It is applied particularly to the cutting of risers from large manganese steel castings. Arc cutting is also used for the cutting of rivets and piercing of holes.

Carbon-Arc Cutting. This process consists essentially of drawing an arc between a carbon or graphite electrode and the material to be cut. Direct current is generally used, with the carbon electrode negative (straight polarity), although alternating current can be used also. Graphite electrodes are preferred to carbon electrodes, because they have a much longer service life and retain a point longer. A point is essential for clean, smooth cuts. The heavy currents used for arc cutting make ordinary electrode holders unsuitable except for light work. Special holders are recommended that have a long shank, a special mechanism for gripping and a shield for protecting the hands.

Manipulation of the cutting arc, when cutting plates ½ in. thick or less, consists simply in advancing along the line of cut at a rate equal to that at which the metal is being melted away. The most smooth and uniform cuts are made when the plate is in a horizontal plane, but the operation may be performed when the plate is in an inclined or vertical position. For horizontal cutting, the electrode is held vertical or pointed slightly forward. For inclined or vertical cutting, the electrode is pointed downward. When materials heavier than ½ in. are being cut, the vertical face of the cut is melted away progressively from top to bottom. Thus the bottom of the cut is advanced slightly ahead of the top of the cut, producing an undercut that permits the molten metal to run out more easily. Skilled operators can make narrower cuts. The width and speed of the cut increase with the current and the diameter of the electrode. Recommended current values for graphite electrodes of different sizes are in Table IX.

Table IX. Current Values for Arc Cutting

Electrode Diameter, inch	Current, amperes
¼	200 or less
⅜	200 to 400
½	300 to 600
⅝	400 to 700
¾	600 to 800
⅞	700 to 1000
1	800 to 1200

Arc Cutting With Coated Electrodes. The application of heavily coated electrodes to cutting is not always an economical process, but has certain merits, particularly where no oxyacetylene cutting torch or graphite electrode is available. Electrodes with either a gaseous or slagging type of coating can be used, but the slagging type gives better results because it will handle higher current densities. Plates ⅜ in. thick or less can be cut simply by advancing the electrode along the line of cut. On heavier plates the electrode is pointed forward and moved from the top to the bottom of the cut, so as to keep the bottom slightly ahead. Electrodes smaller than $\frac{5}{32}$ in. in diam are not suitable for arc cutting. The width of the cut is approximately constant for all electrodes ¼ in. in diam or less. Alloy steels and many nonferrous metals can be cut readily by the coated-electrode cutting process.

Oxygen-Arc Cutting With Hollow Electrodes. Using the equipment and technique described for underwater cutting with an oxygen arc, rough cuts at high speeds can be made in air if the work piece is moderate in thickness. However, the electrode must be changed at frequent intervals and the speed decreases when the sections to be cut are heavy.

TESTING OF FERROUS METALS

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Macro-Etching of Iron and Steel

By the Subcommittee on Macro-Etching*

MACRO-ETCHING of iron and steel consists in subjecting the surface of the metal to the action of a reagent in order to bring out the internal and surface structure for visual examination.

Preparation of Sample. The preparation of the surface of the test specimen is governed by the intensity of the action of the reagent employed. Weak etching solutions require polished surfaces. Solutions strong enough to produce a deep attack require less care in sample preparation.

Unless otherwise noted, the samples should be in a soft, annealed condition. However, when hardened material is to be etched, great care should be taken to protect the metal from the effects of heat of grinding or cutting.

In Table I, the surface required for each reagent is designated by the letters *A*, *B*, or *C* under the heading "Remarks". Type *A* represents a saw-cut or machined surface; *B*, an average ground surface; and *C*, a polished surface. When type *A* surface is used, consideration must be given to the type of steel. For the higher-carbon steels and for tool steels in general, a cleanly sawed disk will produce very good results. On the very soft steels, it is desirable to have a machined surface, not too coarsely cut, or a sawed surface, rough ground to remove all traces of flowed metal. It is important to make sure that the metal has not been smeared or flowed over the surface in order to conceal internal defects.

The compilation of etching solutions for macro-etching (Table I) has been taken largely from Berglund's "Metallographers' Handbook of Etching". In the present compilation an effort has been made to list the reagents alphabetically according to the purposes for which they are intended. Different conditions will be revealed in the same steel by etching with different solutions, and it is well to be familiar with each reagent in order to interpret the results correctly.

Recommended Practice for a Standard Macro-Etch Test for Routine Inspection of Iron and Steel

The macro-etch test reveals readily and quickly many of the characteristics of steel but, in some instances, further examination by standard testing methods is required to evaluate the characteristics properly. The knowledge that a piece of steel is dendritic or that it contains metallic and nonmetallic segregates is not sufficient evidence on which to base definite conclusions concerning the properties of the steel. The macro-etch test is of real value in separating metals that are obviously defective from those that are not. The test is easily made, but experience and judgment are required to interpret results.

Preparation of Sample. When it is desired to reveal surface defects, such as seams, laps and grinding checks, preparation of the sample is frequently unnecessary. Any oil or grease on the surface should be removed for best results. Scale on the surface of the material will be removed by the acid, so that the surface defects will become visible. In order to reveal the internal structure or defects, a section must be prepared by cutting through the metal at a point where inspection is desired. For best results, the samples to be etched should be in a soft, annealed condition, and the method of preparation such that no metal is smeared or flowed over the surface.

The surface finish necessary for the specimen depends on the etching solution to be used. A machined surface is recommended as the standard in this practice. A smooth ground and polished surface is not necessary and in many instances a fairly smooth sawed cut is satisfactory—for example, on the higher-carbon steels and tool steels in general. On the very soft steels, a machined surface is desirable, if not too coarsely cut, or a sawed surface, rough ground to remove all traces of flowed metal.

Etching Solution. A solution of one part commercial hydrochloric acid and one part water is recommended. The advantage is that this solution can be heated with little or no change in concentration. The fumes of this mixture are corrosive so the work should be done under a hood. A solution consisting of 38% hydrochloric acid, 12% sulfuric acid and 50% water, is sometimes used in the same manner as the recommended hydrochloric acid solution. This solution has been used extensively by a number of forging manufacturers, and was suggested originally by the Watertown Arsenal. The advantages appear to be a more sharply defined etched pattern and less susceptibility to rusting.

It is not necessary to throw away the acid after each test, but for the best results, a fresh solution should be used for each test. Irregular etching effects are obtained if the etching solution is dirty or contaminated, or if the sample is oily.

For containers, pyrex glass, porcelain dishes, or corrosion-resistant metals can be used. Satisfactory results have been obtained with hydrochloric acid and particularly with sulfuric acid in a lead-lined iron pan or wooden tank, provided care is used in the application of heat. However, a wooden tank is the least satisfactory type of container and should not be employed unless absolutely necessary. For heating the solution, the method that permits the best control of temperature should be used.

Temperature of Acid. A temperature of 160 F is recommended. At this temperature the reaction of etching is vigorous and the solution does not evaporate too rapidly.

* The members of this subcommittee are C. B. Post, *Chairman* (The Carpenter Steel Company), C. T. Hewitt (The Fafnir Bearing Company), T. B. Reynolds (Ingersoll-Rand Company), E. S. Rowland (The Timken Roller Bearing Company) and A. O. Schaefer (The Midvale Company).

Table I. Etching Solutions and Recommendations for Macro-Etching

The compositions of various etching solutions are given below. When acids are mentioned, the concentrated strengths are intended. Muriatic acid may be used satisfactorily where hydrochloric acid is mentioned. When the ingredients of an etchant are all liquids, the proportions are by volume. When one or more of the ingredients is a solid, the proportions are by weight unless the actual weights and volumes are given.

Water or alcohol should never be poured into an acid; rather, the acid should always be poured into the other liquid. Unless otherwise stated, the etching should be done at room temperature.

After the etchant has been removed by washing and drying, the etched surface may be preserved by covering it with clear lacquer. The lacquer should be removed if it is desired to study the macro-etched specimens further.

"Surface A" in the column headed Remarks, means a saw-cut or machined surface; "Surface B", an average ground surface; "Surface C", a polished surface.

Purpose	Composition	Remarks	Uses
Blowholes	10% sulfuric acid in water	Use cold on large sections for 24 hr. Surface B	Shows blowholes, porosity, pipe, and inclusions.
Blowholes	50% hydrochloric acid in water	Use at 160 to 175 F for ½ hr. Surface A	Shows blowholes, porosity, pipe, and inclusions.
Carburized case	5% solution of nitric acid in alcohol	Etch at room temperature. Surface B	Shows depth of carburized case
Contrast	1 part iodine, 2 parts potassium iodide, and 10 parts water	Use at room temperature. Surface B	Produces contrast for photographing
Cracks	5% solution of nitric acid in alcohol	Etch at room temperature. Etches within ½ hr. Surface B	Detects fatigue, service, hardening and grinding cracks
Cracks	Hydrochloric acid	Apply cold with swab	Detects embrittlement cracks in steam boiler drum
Cracks	50% hydrochloric acid in water	Use at 160 to 175 F for ½ hr. Surface B	Detects fatigue, service, hardening, grinding, and internal cracks. If hardened, material should be softened before etch.
Cracks	Kerosene and whiting test	Wash surface with kerosene. Wipe off. Paint with thin mixture of whiting and water. Let dry. Kerosene in cracks, if present, will discolor whiting. Surface B	Detects fatigue, service, hardening and grinding cracks
Cracks	120 g copper ammonium chloride, 50 ml conc hydrochloric acid, 1000 ml water	Etch first with a neutral solution to remove machine marks. Use cold for 20 min to ½ hr. Surface B	Produces a strong relief effect. Shows up dendrites and may indicate cracks
Decarburization	5% nitric acid in alcohol	Etch at room temperature. Surface C	The decarburized areas will be light. Area not decarburized dark
Defects	10% sulfuric acid in water	Use cold on large sections for 24 hr. Surface B	Shows porosity, pipe, blowholes, and inclusions
Defects	50% hydrochloric acid in water	Use at 160 to 175 F for ½ hr. Surface A or B	Shows porosity, pipe, blowholes, and inclusions
Defects	2 parts conc sulfuric acid, 1 part conc hydrochloric acid, 3 parts water	Use at 160 to 175 F for at least ½ hr. Surface A	Shows general structure and defects
Dendrites	2 parts conc sulfuric acid, 1 part conc hydrochloric acid, 3 parts water	Use at 160 to 175 F for at least ½ hr. Surface A	Shows general dendritic structure and defects
Dendrites	50% hydrochloric acid in water	Use at 160 to 175 F for at least ½ hr. Surface A	Shows general dendritic structure and defects
Dendritic pattern	25% sulfuric acid in water	Use cold, 8 to 16 hr. Surface B	Shows dendritic pattern and flow lines
Dendritic pattern	40 g ferric chloride, 3 ■ cupric chloride, 40 ml hydrochloric acid, 500 ml water	Etch first with 10% nitric acid. Surface B	Shows dendritic pattern or structure
Etch, universal	500 ml hydrochloric acid, 70 ml sulfuric acid, 180 ml water	Use at 160 to 175 F for 1 to 2 hr. Surface A	Good universal etch
Fiber	10 to 20% solution of ammonium persulfate in water	Swab on freshly made solution for ½ min. Surface B	Shows fiber and grain contrast
Flow lines	25% sulfuric acid in water	Use cold, 8 to 16 hr. Surface B	Shows flow lines and dendritic pattern
Flow lines	50% hydrochloric acid in water	Use at 160 to 175 F. Surface A	Shows flow lines
Ghost lines	10 to 20% solution of ammonium persulfate in water	Swab on freshly made solution for ½ min. Surface C	Shows ghost lines
Grain contrast	10 to 20% solution ammonium persulfate in water	Swab on freshly made solution for 1 to 2 min. Surface B	Shows grain contrast and fiber
Grain contrast	1.5 g cupric chloride, 30 ml hydrochloric acid, 95 ml water, 30 ml ethyl alcohol	Polish specimen carefully. Surface C	Shows good grain contrast
Grain size	10 to 20% solution ammonium persulfate in water	Swab on freshly made solution for 1 to 2 min. Surface B	Shows grain size especially in low carbon steels, wrought iron, and welded sections
Hardness penetration	5% nitric acid in alcohol	Etch at room temperature on smooth ground surface. Surface B	Shows depth of hardness penetration of heat treated samples
Hardness penetration	50% hydrochloric acid in water		(*See* NOTE A)
Heterogeneity	50% hydrochloric acid in water	Immerse specimen in solution at 160 to 175 F from ½ to 1 hr. Surface A	Shows heterogeneity in general
Heterogeneity	Undiluted hydrochloric acid	Use hot (212 F). Surface A	Shows heterogeneity in 3 to 3.5% Ni steels
Impurities in ferrite	1 g cupric chloride, 0.5 g stannous chloride, 30 g ferric chloride, 30 ml hydrochloric acid, 500 ml distilled water, 500 ml ethyl alcohol	Etch only well polished surface that has been thoroughly dried. Surface C	Plates out copper on ferrite containing impurities. Gives a good even etch
Internal cracks	50% hydrochloric acid in water	Use at 160 to 175 F for ½ hr or longer. Surface B	Shows internal cracks or thermal checks
Inclusions	10% sulfuric acid in water	Use cold on large sections for 24 hr. Surface B	Shows inclusions, porosity, pipe, and blowholes
Inclusions	10 to 20% sulfuric acid in water	Use at 160 to 175 F. Surface B	Etches sulfide inclusions
Inclusions	50% hydrochloric acid in water	Use at 160 to 175 F. Surface B	Etches sulfide inclusions

Purpose	Composition	Remarks	Uses
Pipe and porosity	10% sulfuric acid in water	Use cold on large sections for 24 hr. Surface B	Shows pipe, porosity, blowholes, and inclusions
Pipe and porosity	50% hydrochloric acid in water	Use at 160 to 175 F. Surface B	Shows pipe, porosity, blowholes, and inclusions
Rail Sections	9 parts hydrochloric acid, 3 parts sulfuric, 1 part water	Use at 160 to 175 F for 2 hr. Surface A	Use for etching rail sections.
Segregation	3% solution picric acid in ethyl alcohol	Etch at room temperature for 4 to 5 hr. Surface B	Shows segregation
Segregation	1 g picric acid, 1 drop conc hydrochloric acid in 25 ml alcohol	Use hot. Surface B	Shows segregation
Segregation	10 to 15% solution nitric acid in water or alcohol	Etch at room temperature. Surface B.	Shows heavy segregation
Segregation	5% solution nitric acid in water or alcohol	Etches within ½ hr. Surface is black when etched. Surface B	Shows segregation in low-carbon, low-chromium, nickel steels
Segregation	2 to 10% solution nitric acid in water	Etch first with weak acid to remove machine marks and then increase concentration for structure. Surface B	Shows segregation in ingot sections and large pieces
Segregation	50% hydrochloric acid in water	Use at 160 to 175 F. Surface A	Shows segregation in ingot sections and large pieces.
Segregation	1 g cupric chloride, 0.5 g picric acid, 1.5 to 2.5 ml hydrochloric acid, 10 ml water, 100 ml ethyl alcohol	May be used for electrolytic etching. Surface B	Shows segregation
Segregation, carbide	2% nitric acid in alcohol. For high speed steel, use 5% nitric acid in alcohol.	Use cold on a polished longitudinal section. For high speed steel, etch until matrix is darkened. Surface C	To detect carbide segregations, particularly in high speed steels
Segregation, carbon and phosphorus	1 part copper ammonium chloride, 12 parts water	Immerse finely ground, clean sample in solution for 1 min, wash with water, and rub off copper. Surface C	Shows phosphorus and carbon segregation
Segregation, phosphorus	0.5% solution picric acid in water	Etch at room temperature until staining occurs. Surface C	Uneven staining represents phosphorus segregation
Segregation, phosphorus	30 g ferric chloride, 100 g hydrochloric acid, 1 g cupric chloride, 0.5 g stannous chloride, 1000 ml water	Polish as for microscopic work, use etch cold for 10 sec to 2 min. Surface C	Shows phosphorus segregation
Segregation, phosphorus	10 ■ cupric chloride, 40 g magnesium chloride, 20 ml hydrochloric acid; 1000 ml ethyl alcohol (Steads No. 1 reagent)	Dissolve salts in small amount of hot water, then add alcohol. Apply solution to polished surface drop by drop. Surface C	Areas not coated by copper show phosphorus segregation
Segregation, phosphorus	5 ■ cupric chloride, 4 ■ magnesium chloride, 1 ml hydrochloric acid, 20 ml water, 100 ml alcohol (Steads No. 2)	Etch for 1 min. Surface C	Shows phosphorus segregation
Segregation, phosphorus	4 ■ cupric chloride, 20 ml hydrochloric acid, 40 ml water, 20 ml ethyl alcohol	Polish specimen carefully. Surface C	Shows phosphorus segregation
Segregation, phosphorus	1.5 g cupric chloride, 5 g nickel nitrate crystals, 6 g ferric chloride, 12 ml water	Immerse specimen for 90 sec or more. Surface C	Shows phosphorus segregation
Segregation, sulfur		(*See* NOTE B)	
Segregation, sulfide inclusions	10 to 20% sulfuric acid in water	Use at 160 to 175 F. Surface A	Etches sulfide inclusions
Soft spots	5% nitric acid in alcohol	Etch at room temperature. Surface B	Nondestructive test for hardened tools
Soft spots	50% hydrochloric acid in water	Use cold on ground surface. Surface B	Shows soft spots
Strains	90 g cupric chloride, 120 ml hydrochloric acid, 100 ml water	(*See* NOTE C)	Shows strain lines
Strains	6 ■ cupric chloride, 6 g ferric chloride, 10 ml hydrochloric acid, 100 ml ethyl alcohol	Heat specimen to 400 F and immerse ground surface. Surface B	Shows strain lines
Strauss test	3% cupric sulfate; 10% sulfuric acid, 87% distilled water	(*See* NOTE D)	To measure intergranular corrosion of 18-8 Cr-Ni corrosion-resisting steel
Structure	25% nitric acid in water	Etch at room temperature. Surface B	Shows general structure
Structure	50% hydrochloric acid in water	Use at 160 to 175 F for at least ½ hr. Surface A	Shows general structure and defects
Structure	2 parts conc sulfuric acid, 1 part conc hydrochloric acid, 3 parts water	Use at 160 to 175 F for at least ½ hr. Surface A	Shows general structure and defects
Thermal cracks	50% hydrochloric acid in water	Use at 160 to 175 F for ½ hr or longer. Surface B	Shows thermal checks or internal cracks
Weld examination	50% hydrochloric acid in water	In testing large sections, the acid may be added by building a dam with paraffin wax around the part to be tested. Surface A	For testing the soundness of welds

NOTE A. *Hardness penetration.* Use at 160 to 175 F for about 15 to 60 sec. To preserve surface after etching, scrub in running water, dip in weak NH_4OH, dip in solution of soluble cutting oil, dry with a rag and compressed air. Surface B or C

Shows depth of hardening, especially in carbon steels; produces distinct contrast between martensitic and troostitic zones

NOTE B. *Segregation, sulfur.* Soak ordinary sensitized photographic silver bromide paper in a 2% aqueous solution of sulfuric acid. Apply emulsion side of paper to smooth-ground, clean sample for a minute or two. Do not move the paper once in contact with the specimen. Air bubbles should be rubbed out with a squeegee or roller. Rinse paper, fix in hypo, wash thoroughly.

The brown pattern formed on the paper indicates the relative distribution of sulfides. The darker and heavier the marks, the more sulfur is indicated to be present. Surface B. Best results are obtained only on the first or second prints made from a surface.

Shows the distribution of sulfur. Can also be used to distinguish machinery steel from screw stock.

NOTE C. *Strains.* Copper does not precipitate with this etch. Heat specimen to between 400 and 475 F for ½ hr, then etch ground surface for 1 to 3 min. Rub with powdered cupric chloride, then rinse with alcohol. Surface B

NOTE D. *Strauss test.* Specimen ½ by 1 by 4 in. is sensitized by actual welding, or artificially by heating to between 900 and 1300 F (generally 1250 F). Immerse in the boiling cupric sulfate solution for 72 hr. Specimen is then bent 180 deg around a ½-in. pin. Cracking indicates disintegration, caused by migration of carbides to grain boundaries. Surface B. (120° fine emery)

If the temperature rises much above 175 F, the etching solution may lose selectivity and a reaction may occur over the entire surface rather than only at the localized points of attack that it is desired to reveal. On the other hand if the solution is at a temperature below 160 F, the etching operation will generally be prolonged unnecessarily with little gain in the results. A suitable thermometer should be used for determining the temperature.

The ordinary procedure is to put the cold specimens into hot acid at 160 F and then to adjust the process carefully so that a temperature of about 160 F is maintained at all times. Methods for maintaining this temperature are different in different laboratories and depend on the number of specimens that are etched in the pan at one time, the volume of etching solution used, and the heat conductivity of the container. For extreme consistency of results, it is advisable to clean the specimens first and then to heat them in hot water to the same temperature as the acid. The specimens are then transferred to the acid bath, which has first been heated to the proper temperature. This practice makes the duration of etching much easier to control than if the specimens were put into cold acid and brought up to temperature with the solution, or if cold specimens were put into hot acid, with resulting fluctuation in the temperature of the acid.

Duration of Etching. The duration of etching depends on the type of steel to be etched, the condition of the surface, and the physical condition of the steel—for instance, whether it has been annealed or hardened. For best reproducibility of results, it is extremely important that the time be measured accurately and maintained from batch to batch. If the steel is not etched long enough, the sample will not reveal all the information desired; if the steel is etched too long, some of the more delicate details will be masked by the general destruction of the surface.

When the specimens are in a soft, annealed condition, the etching periods listed in Table II have been found to produce good average results. However, this table has a limited value, and should serve only as a guide in determining the length of time that may be required for producing a properly etched surface. Marked variation in the susceptibility of steels to attack by acid, will be found among different heats of steel and among different methods of heat treatment. This variation in susceptibility to acid attack depends also on the position of the specimen in the ingot as influenced by the extent of segregation, and depends particularly on the machined finish of the specimen. A little practice with the macro-etch test will enable the operator to develop a surface that will be macro-etched deeply enough to bring out the structure fully, but not overetched with consequent development of excessive pitting that masks the structure and frequently deceives the examiner.

Washing and Preserving Specimens. After the test specimen has been etched, it should be removed from the hot acid, washed under running water, and then scrubbed with a stiff brush in order to remove the deposit of "smut" from the surface. Live steam is also an excellent medium for washing etched pieces. The piece is first rinsed thoroughly and then placed under the nozzle that directs the steam. By this method the specimen can be dried rapidly and completely with freedom from rust. After being washed, the specimen can be blotted with a paper or cloth towel or dried with a blower.

As a simple temporary means of avoiding rust, the specimen may be rinsed in water to remove the acid, then dipped in ammonia and washed in hot water. For longer preservation, after the specimen has been dried, it should be covered with a thin coat of transparent lacquer or with a film of oil that may be applied with the palm of the hand. Rusting may be delayed temporarily and small amounts of rust may be removed from a dried sample by the application of a solution of 50-50 syrup of phosphoric acid and water to which a little sugar has been added. The excess solution may be blotted up with a cloth or paper towels. Caution is recommended because this solution will roughen the hands and disintegrate cloth, if allowed to remain in contact for an extended time.

Interpretation of Results.* The results obtained on properly etched samples are of great value if interpreted correctly. Surface seams, internal cracks and pipe are easily recognized. It is the incorrect interpretation of the evidences of segregation and dendritic structures, as revealed by deep etching, that affords the greatest possibility of expensive errors and the needless rejection of material. For instance, every pit does not indicate an inclusion, since pitting may also result from acid attack around carbide particles. Irregular etching effects are obtained if the surface being examined has retained any oil or

* The article on page 412 includes macrographs that illustrate most of the defects discussed here.

Table II. Recommended Duration of Macro-Etching for Various Steels

(See text for recommended composition and temperature of the etching solution.)

Steel	Duration of Etching, minutes
SAE Carbon Steels	
1010	60 (%S <0.020)
1050	20 (%S <0.020)
1070	20 (%S <0.020)
1095	20 (%S <0.020)
SAE Nickel-Chromium Steels	
3115	45
3150	20 to 30
3215	60
3250	20 to 30
3312	45
3340	30
3450	20 to 30
SAE Tungsten Steels	
71360	20
7260	30
SAE Silicon-Manganese Steels	
9255	20 to 30
9260	20 to 30
SAE Manganese Steels	
T1330	20
T1335	20
T1340	20
T1345	20
T1350	20
SAE Nickel Steels	
2015	60 (%S <0.015)
2115	60
2315	60
2350	30 to 45 (%S <0.015)
2515	60 (%S <0.015)

Steel	Duration of Etching, minutes
SAE Molybdenum Steels	
4130	20 to 30
4150	20 to 30
4340	20 to 30
4615	20 to 30
4640	20 to 30
SAE Chromium Steels	
5120	30
5140	30
5150	30
52100	20
SAE Chromium-Vanadium Steels	
6115	30
6140	20 to 30
6150	20
Stainless Irons and Steels	
Chromium type	30
Chromium-nickel type	60 or more, depending on carbon content (%C <0.10)
Free-Machining Stainless Steels	
Chromium type	20
Chromium-nickel type	20
Tool Steels	
Carbon and carbon-vanadium	20
Manganese oil-hardening steel	20
Tungsten hot die steel	20
Chromium hot working die steel	20
High-carbon high-chromium steel	20
High speed steel	20

grease; if the surface was prepared by an unsuitable machining method that caused a smearing or rubbing action of the metal; if the piece was in contact with other specimens in the etching bath; or if the etching solution was dirty or contaminated.

Cracks from Etching. Before etching, hardened or otherwise highly stressed steels should be tempered sufficiently to prevent cracking, since otherwise sound steel may crack in the etching solution and thus lead to false conclusions.

Grinding Cracks. Grinding cracks can be distinguished easily in a short-time macro-etch test and are usually, but not always, identified by a pattern of some symmetry. Again it must be emphasized that hardened pieces should be softened by tempering before hot etching.

Surface Cracks. As revealed by deep etching, surface cracks usually follow an irregular path and may result from wrong handling during heating, forging, rolling, or cooling from the finishing temperature. On heat treated material, surface cracks may be caused by incorrect treatment, by improper grinding, or by surface stresses.

Seams. Seams in rolled material are of varying depth and usually extend in a straight path parallel to the direction of rolling. In forged material, seams generally follow the contour of the forging and the flow of the metal. The most detrimental result of seams is that they may serve as a point of origin for fatigue failures or may open into deep cracks if the metal is subsequently quenched during heat treatment. This detrimental effect may be avoided if, during manufacture, the surface is machined to a sufficient depth to remove the seams.

Surface Appearance. Steels may be etched with a comparatively smooth surface or with a very rough or pitted surface, depending on variables in manufacture and composition. Therefore, a highly roughened surface is not necessarily detrimental. It has been found that smoother surfaces can be obtained by adding to the hot etching solution several drops of triamylamine, an organic inhibitor. Inclusions are then attacked in preference to the metal, thereby eliminating the general roughness and consequently producing better etch patterns.

Irregularity in pitting may usually be attributed to one or more of the defects described below. Certain manganese, oil-hardening steels are attacked more readily by the acid and are often decidedly roughened without being defective in any way.

Center Porosity. If porosity is the result of an actual discontinuity within the metal, it is probably more accurate to classify the defect as a pipe. Usually, however, the porosity is not visible until the specimen has been etched. This condition may be found in widely varying degrees, and the question of whether the steel should or should not be used is one for experienced judgment. The term "porosity" is generally restricted to segregations that are partially torn open during hot rolling, or forging.

Pipes and Bursts. Pipes are internal cavities formed during solidification of the ingot and carried through the various manufacturing processes to the finished product. Pipe is invariably associated with segregated impurities, which are deeply attacked by the etching reagent. Cavities in the center that are not associated with deeply etched impurities, are often mistaken for pipe but such cavities can usually be traced to bursts caused by incorrect processing of the steel during forging or rolling. Either pipes or bursts should be visible after deep etching; they can generally be distinguished from each other by the degree of sponginess surrounding the defect. Piped material usually shows considerably more sponginess than burst material.

Unsound Steel. Numerous blowholes and nonmetallic inclusions visible as the result of the deep etch usually indicate that both gases and oxides were distributed throughout the steel at the time of casting.

*Nonmetallic Inclusions and Metallic Segregates.** Nonmetallic inclusions usually appear as pits and must not be confused with pits that result from the etching out of metallic segregates. When nonmetallic inclusions are suspected in highly alloyed steels that may contain metallic segregates, a comparison should be made of an annealed specimen and a hardened specimen, etched in the same way. If the etching pits are the result of nonmetallic inclusions, they will appear similarly in both the annealed and the hardened specimens. If they are the result of a metallic segregate they will differ. The macro-etch test is not recommended as a test for "cleanliness" of steel, since unambiguous results are obtained only when large slag inclusions are present in the steel.

Segregations are revealed by the severity of the acid attack on the affected areas. Segregations at the center may be attacked so deeply after etching that they appear as a pipe, or the segregation may be grouped in some fairly regular form about the center, depending on the shape of the ingot and the mechanical work done on it.

Segregation at the corners of ingots can sometimes be detected in macro-etched disks obtained from large forgings. It should be emphasized that evidences of this type of segregation sometimes appear as cracks, whereas actually they may represent a segregate that has been dissolved by the acid during the test.

Segregation, as revealed by macro-etching, is not always an indication of defective material. A polished specimen should be examined under the microscope to determine whether the revealed segregation is metallic, a crystalline arrangement, or a concentration of impurities. The microscopic identification of segregation may be supplemented by chemical means, such as analysis of center drillings for carbon, phosphorus and sulfur, or analysis of inclusions separated chemically from the metallic matrix of the steel.

Internal Cracks. Internal cracks, sometimes called "flakes", "cooling cracks", or "thermal cracks", can be detected by the macro-etch test and their identity can be verified by a fracture test of a hardened specimen in which the cracks are revealed as brightly crystalline spots. These cracks are an actual discontinuity in the metal and, depending on their nature and distribution, may make the steel unfit for use unless closed by further hot reduction.

Dendritic Pattern. Etching often reveals a dendritic structure that results from the crystalline characteristics of the ingot. Dendritic patterns are detected even in steel that has been subjected to repeated mechanical reduction. It has not been proved that dendritic patterns are associated with surface failures, provided the material has been subjected to sufficient mechanical working and provided the segregation accompanying the dendritic formation is not in the form of nonmetallic inclusions incapable of being dispersed.

In the formation of dendritic crystals, the intercrystalline material contains minute metallic segregations that can be eliminated by diffusion. However, nonmetallic inclusions thus segregated cannot be eliminated by diffusion. The microscope should be used in conjunction with macro-etching for distinguishing metallic from nonmetallic segregates.

Pattern Effect. Pattern effect is almost entirely the result of the crystallization of the ingot, and is found in the part of the bar that was the columnar structure of the ingot. This part of the bar etches differently from the part that was the granular structure of the ingot. If the steel contains considerable inclusions of sulfide and silicate, then the area of contact between the columnar structure and the granular structure may be particularly noticeable. In the absence of large amounts of sulfides and silicates, the pattern effect is probably of no serious consequence.

Grain Size. Although the deep-etch test is of no definite value in determining grain size, nevertheless the manner in which many specimens etch may provide some indication of the grain size. Generally the larger the grain size, the coarser the appearance of the etched surface.

Decarburization and Carburization. Ordinarily areas that have been either decarburized or carburized, etch differently from the remainder of the specimen; the chief difference is in color. Decarburized parts appear lighter in color and carburized parts, darker.

If the section to be examined is small enough, it can be given a final polished finish and then etched cold for ▮ to 30 sec in nital (3% nitric acid, 97% ethyl alcohol). This will usually result in excellent contrast and if the polish is good enough, the same sample can be examined microscopically as well as visually.

* *See also* "Nonmetallic Inclusions in Steel", page 445.

Etching to Determine Soft Spots and Penetration of Hardness. The hardened case and the unhardened core of a heat treated section of shallow-hardening steel will contrast in color after etching. This fact is valuable in determining the depth to which a sample has hardened.

To show the penetration of hardness best, the sample should have a finish equivalent to that produced by polishing with 00 emery cloth, or finer. The sample can then be etched in either hot or cold acid. If hot acid is used, the ground sample is dipped for 15 to 60 sec in a solution of 50% hydrochloric acid in water at 160 to 175 F. If it is desired to etch cold, the ground sample is etched for 5 to 10 min in a cold solution, 10% nitric acid in water. On a polished surface, nital produces excellent results. After either method of etching, the sample should be washed thoroughly in warm water with a cloth or sponge, and then dried with an air blast. If it is desired to preserve the etched surface of the specimen, the procedure suggested earlier in this article should be followed.

Soft spots, which often result during the hardening of carbon or low-alloy tool steels, can generally be distinguished by either of the macro-etching methods mentioned above. The soft spots invariably etch in relief and are not so dark as the harder surrounding areas. Troostitic areas on hardened alloy steels appear darker than the surrounding areas when etched in nital.

Etching to Reveal Flow Lines. When macro-etched, a longitudinal section will show more or less well-defined flow lines, which result from elongation of structural constituents. These flow lines indicate the directions in which the steel was worked during rolling or forging, and do not signify defective material. The longitudinal face on which the flow lines are to be developed, should have a smooth surface, either machined or ground. The etching procedure is carried out in a solution of 50% hydrochloric acid in water at 160 to 175 F, in the same manner as outlined under Recommended Practice. The length of time required for development of flow lines is variable; therefore it is necessary to inspect the piece from time to time while it is etching, in order to determine when the etch has progressed far enough.

When it is difficult to develop flow lines on a particular piece, the etched surface may be painted with India ink. Then, when the ink is dry, the surface may be rubbed lightly with fine abrasive cloth. This procedure removes the ink from the high portions of the surface and leaves the "valleys" darkened, thus providing the contrast needed to show up flow lines.

Etched surfaces that reveal flow lines can be preserved in the same manner as other etched surfaces, as noted above. For an illustration of flow lines revealed by macro-etching, see page 416.

Etching Reagents for the Microscopic Examination of Iron and Steel

COMPILED BY THE SUBCOMMITTEE ON ETCHING REAGENTS FOR IRON AND STEEL*

IN THE preparation of etching solutions that are listed in Tables I to V, only reagents of high analytical purity should be used.

Etchants that are used for more than one purpose are listed in more than one of the tables; for example, chromic acid (Reagent 4) is included in Tables I, II and V, with explanatory remarks concerning the use of the reagent for each of three purposes.

The references listed after Table V, may be consulted for more detailed discussion of the recommended reagents, and for information concerning reagents that are used less commonly than those listed in the tables.

Table I. General Reagents for Irons and Steels (Carbon, Low-Alloy and Medium-Alloy Steels)

No.	Etching Reagent	Composition	Uses	Remarks
1	Nitric acid (Nital)	Nitric acid (sp gr 1.42) ..... 1–5 ml Ethyl or methyl alcohol (95% or absolute) ..... 100 ml (also amyl alcohol)	(1) To darken pearlite and give contrast between pearlite colonies; (2) to reveal ferrite boundaries; (3) to differentiate ferrite from martensite. Extensively used in studies of microstructures of medium-alloy as well as low-alloy and plain carbon steels.	Etching rate is increased, selectivity decreased with increasing percentages of HNO_3. 4% in amyl alcohol useful for grain boundary and contrast of low-carbon steels. Etching time, a few seconds to a minute.
2	Picric acid (Picral)	Picric acid ..... 4 g Ethyl or methyl alcohol (95% or absolute) ..... 100 ml (Use absolute alcohol only when picric acid contains at least 10% moisture.)	For carbon steels and some low-alloy steels (1) annealed (2) normalized (3) quenched (4) quenched and tempered (5) spheroidized (6) austempered	More dilute solutions occasionally useful. Does not reveal ferrite grain boundaries as readily as No. 1. (Reference 2)
3	Hydrochloric and picric acids	Hydrochloric acid .. 5 ml Picric acid ..... 1 g Ethyl or methyl alcohol (95% or absolute) ..... 100 ml	For revealing the austenitic grain size in quenched, and quenched and tempered steels	Best results are obtained when the martensite is tempered for 15 min at 400-475 F.
4	Chromic acid	Chromic acid ..... 10 g Water ..... 100 ml	For various structures except grain boundaries of ferrite. Attacks cementite very rapidly, austenite less rapidly, ferrite and phosphide very slowly, if at all.	Used electrolytically, the specimen as anode, the cathode stainless steel or platinum, ¾ to 1 in. apart; 6 volts usually used. Time of etching 30–90 sec depending on specimen. (Reference 5)
5	Heat tinting	Heat only	Pearlite first to pass through a given color, followed by ferrite; cementite less affected, iron phosphide still less. Especially useful for cast irons.	Clean, dry, polished specimen heated face up on hot plate to 400–700 F. Time and temperature both have decided effects. Bath of sand or molten metal may be used. (Reference 1)

* The members of this subcommittee are W. D. Forgeng, *Chairman* (Union Carbide and Carbon Research Laboratories, Inc.), M. Baeyertz (Armour Research Foundation), G. F. Comstock (Titanium Alloy Manufacturing Company), G. A. Ellinger (National Bureau of Standards), A. R. Elsea (Battelle Memorial Institute), C. F. Lottier (Chicago), M. R. Norton (Watertown Arsenal) and J. R. Vilella (United States Steel Corporation Research Laboratory).

Table II. General Reagents for Alloy Steels, Including Heat-Resisting, Stainless and High Speed Steels

No.	Etching Reagent	Composition	Uses	Remarks
6	Mixed acids in glycerol...	(A) Nitric acid ..... 10 ml Hydrochloric acid .....20-30 ml Glycerol .....20-30 ml	Structure of iron-chromium base alloys, high speed steels, and austenitic manganese steel. Etches nickel-chromium alloys satisfactorily.	Warm specimen in water before etching. For best results use method of alternate polishing and etching. If given sufficient time, will etch totally austenitic alloys, but better results are obtained by using Reagent 6 C.
		(B) Nitric acid ..... 10 ml Hydrofluoric acid. 20 ml Glycerol .....20-40 ml	Structure of high-silicon alloys of the Duriron type	Amount of glycerol may be varied to suit metal.
		(C) Nitric acid ..... 10 ml Hydrochloric acid. 20 ml Glycerol ..... 20 ml Hydrogen peroxide (30%) . 10 ml	For etching iron-chromium-nickel, iron-chromium-manganese, and all other iron-chromium base alloys	Amount of hydrochloric acid may be varied if reagent acts too rapidly or slowly. For best results employ method of alternate polishing and etching.
7	Chrome regia	Hydrochloric acid. 25 ml Chromic acid (10% water solution) 5-50 ml	Heat treated 18-8 stainless steels	Activity is controlled by amount of chromic acid. Can also be used electrolytically by diluting with 2 parts of alcohol and 2 parts of glycerine.
8	Acid ferric chloride.....	(A) Saturated solution of ferric chloride in hydrochloric acid, to which a little nitric acid is added	Structure of stainless steel	Use full strength.
		(B) Ferric chloride .. 5 g Hydrochloric acid 50 ml Water ..... 100 ml	Structure of austenitic nickel steels	
9	Oxalic acid	Oxalic acid..... 10 g Water ..... 100 ml	For austenitic stainless steels and high-nickel alloys. Carbides and general structure revealed, depending on etching time	Used electrolytically, the specimen as anode, the cathode stainless steel or platinum, about 1 in. apart; 6 volts usually used. Precipitated carbides in stainless steels may be revealed in 10-15 sec, the general structure in about 1 min. For study of carbides 1.5-3 volts may be used, thus increasing the etching time and improving control of etch.
10	Mixed acids and cupric chloride	Hydrochloric acid 30 ml Nitric acid ..... 10 ml Saturate with cupric chloride and let stand for 20-30 min. before use.	For stainless alloys and others high in nickel or cobalt	Apply by swabbing.
11	Cupric chloride and hydrochloric acid in alcohol	Hydrochloric acid 100 ml Cupric chloride.. 5 g Ethyl Alcohol... 100 ml	For austenitic and ferritic steels	Kalling's Reagent. In mixed structures, ferrite is most easily attacked, carbides are not attacked and austenite is attacked appreciably only when it has begun to decompose to martensite.
12	Hydrochloric acid in alcohol	Hydrochloric acid 10 ml Ethyl alcohol ... 90 ml	For chromium and chromium-nickel steels	Used electrolytically to show delta ferrite and the general microstructure
13	Hydrochloric and lactic acids in alcohol.....	Hydrochloric acid 10 ml Lactic acid ..... 45 ml Ethyl alcohol.... 45 ml	For chromium steels	Used electrolytically for general microstructure
14	Ammonium persulfate....	Ammonium persulfate .... 10 g Water ..... 100 ml	For austenitic stainless steels and high nickel alloys. Carbides and general structure revealed depending on etching time	Used electrolytically. Similar to oxalic acid, Reagent No. 9, but slower in action and provides better control in the case of fast-etching steels.
15	Nitric and acetic acids....	Nitric acid ..... 30 ml Acetic acid ..... 20 ml	For stainless alloys and others high in nickel or cobalt	Apply by swabbing.
16	Hydrochloric and nitric acids in alcohol.....	Hydrochloric acid 10 ml Nitric acid ..... 3 ml Methyl alcohol .. 100 ml	To reveal the grain size of quenched, or quenched and tempered high speed steel	Etch 2–10 min. (Reference 6)
17	Ferricyanide solution.....	Potassium ferricyanide ... 30 g Potassium hydroxide .... 30 g Water ..... 60 ml	To distinguish between ferrite and sigma phase in iron-chromium, iron-chromium-nickel, iron-chromium-manganese and related alloys. Colors sigma phase light blue, ferrite yellow	Must be fresh. Use boiling. (Reference 7)
18	Cupric sulfate.....	Cupric sulfate... 4 g Hydrochloric acid 20 ml Water ..... 20 ml	Structure of stainless steels	Marble's reagent
3	Hydrochloric and picric acids	Hydrochloric acid 5 ml Picric acid ..... 1 g Ethyl or methyl alcohol (95% or absolute) ..... 100 ml	For etching many steels of the iron-chromium, iron-chromium-nickel, and iron-chromium-manganese types	(Reference 2)
4	Chromic acid	Chromic acid.... 10 g Water ..... 100 ml	For austenitic steels. Attacks carbides very rapidly, austenite less rapidly and ferrite very slowly, if at all. Attacks the sigma phase more rapidly than carbides in iron-chromium base alloys	Used electrolytically (Referenee 5)
5	Heat tinting	Heat only	For identifying constituents in high-alloy steels. Carbides remain white while ferrite is darkened more rapidly than austenite.	Clean dry polished specimen, heated face up on hot plate to 1000–1400 F. for 10–60 sec. For distinguishing between austenite and ferrite, it is often useful to apply a chemical etch first.

Table III. Reagents for Revealing Segregation, Phosphides and Strain Lines

No.	Etching Reagent	Composition	Uses	Remarks
19	Cupric chloride	(A) Cupric chloride.. 1 g Magnesium chloride ..... 4 g Hydrochloric acid 1 ml Water ..... 20 ml Ethyl alcohol (absolute) .... 100 ml	For showing segregation of phosphorus or other elements in solid solution; copper tends to deposit first on areas lowest in phosphorus	Dissolve salts in least possible quantity of hot water. Etch for about 1 min, repeating if necessary. Stead's reagent.
		(B) Cupric chloride.. 5 g Hydrochloric acid 40 ml Water ..... 30 ml Ethyl alcohol.... 25 ml	To reveal strain lines, microstructure, and precipitation hardening in steel	May be used cold. Etching time, about 10 sec. Fry's reagent
20	Sodium picrate, neutral..	Sodium picrate .. 1 g Water ..... 100 ml (Wash salt well with alcohol to remove excess acid or alkali)	In cast iron, shows difference between phosphides and cementite. Iron phosphide attacked, cementite unattacked.	Use boiling. Etching time 20 min
21	Chromic acid and heat tinting	Chromic acid.... 8 g Water ..... 100 ml Followed by heat tinting.	Distinguishes between iron phosphide and cementite in phosphide eutectic of cast iron. Iron phosphide is colored darker.	Etch first in picric acid (No. 2) then for 1 min in chromic acid; heat tint by heating face up on hot plate at about 500 F for 1 min.
22	Alkaline chromate	Chromic acid .... 16 g Distilled water.. 145 ml Sodium hydroxide 80 g	Shows oxygen segregation. Darkens martensite rapidly, ferrite more slowly, and zones of high oxygen content much more slowly	Add sodium hydroxide slowly, and use when not over 1 day old by boiling at 118–120 C. for 7–20 min. (Reference 8)

Table IV. Reagents for Revealing the Structure and Depth of Case of Nitrided Steels

No.	Etching Reagent	Composition	Uses	Remarks
23	Cupric sulfate and cupric chloride	Cupric sulfate .....1.25 g Cupric chloride.....2.50 g Magnesium chloride 10 g Hydrochloric acid .. 2 ml Water ..... 100 ml Dilute above solution to 1000 ml with 95% ethyl alcohol.	For showing total depth, structure, and various zones of nitrided chromium-vanadium steels and nitralloy	Proportions must be accurate. Etch by immersion to avoid confusing edge effects.
24	Picric and nitric acids	4% picral (Reagent No. 2) 10 parts 4% nital (Reagent No. 1) 1 part	For depth of case and structure of nitralloy	Best results are obtained when specimen is annealed in lead at 1475 F before etching.
1	Nitric acid (Nital)	Nitric acid ..... 2 ml Ethyl or methyl alcohol (95% or absolute) ..... 100 ml	For structure and depth of case of nitrided steels	
18	Cupric sulfate	Cupric sulfate ..... 4 g Hydrochloric acid .. 20 ml Water ..... 20 ml	Total depth of nitrided case	Marble's reagent

Table V. Reagents for Differentiating Carbides, Nitrides and Tungstides

No.	Etching Reagent	Composition	Uses	Remarks
25	Alkaline sodium picrate	Picric acid ..... 2 g Sodium hydroxide ..... 25 g Water ..... 100 ml (Add sodium hydroxide slowly to picric acid and water.)	Colors cementite but not carbides high in chromium; in tungsten steels, iron tungstide and iron tungsten carbide are colored more rapidly than cementite, but tungsten carbide is unaffected; attacks sulfides. Delineates grain boundaries in hypereutectoid steels in slowly cooled condition	Use boiling, 5–10 min, or preferably, electrolytically at room temperature; for the latter, the specimen is the anode, cathode is stainless steel or platinum, with 6 volts about 40 sec is usually sufficient.
26	Hydrogen peroxide and sodium hydroxide	Hydrogen peroxide 10 ml Sodium hydroxide (10% solution in water ..... 20 ml	Attacks and darkens iron tungstide in carbon-free iron tungsten alloys; tungsten carbide is darkened.	Must be fresh. Etching time 10–12 min
27	Ferricyanide solution	(A) Potassium ferricyanide ... 1–4 g Potassium hydroxide .... 10 g Water ..... 100 ml (7 g of sodium hydroxide may be substituted for the potassium hydroxide.)	Differentiates between carbides and nitrides; cementite is blackened, pearlite turned brown, and massive nitrides remain unchanged.	Must be freshly made; etch 15 min. in boiling solution.
		(B) Potassium ferricyanide .. 10 g Potassium hydroxide ..... 10 g Water ..... 100 ml (7 g of sodium hydroxide may be substituted for the potassium hydroxide.)	Darkens carbide containing chromium, carbides and tungstides in tungsten and high speed steels. At room temperature colors ternary carbide (Fe_3W_2C or Fe_4W_2C) in a few seconds, iron tungstide (Fe_3W_2) in several minutes, and barely colors cementite	May be used cold, but preferably hot, should be freshly made, etching time 5–10 min. Murakami's reagent

(*continued*)

Table V. (continued)

No.	Etching Reagent	Composition	Uses	Remarks
28	Sodium cyanide	Sodium cyanide.. 10 g Water ..... 90 ml	Darkens carbides without attacking austenite or grain boundaries	Used electrolytically, the specimen as anode, cathode, similar material, about 1 in. apart; 6 volts (not less than 5). Etching time 5 min or more. (Reference 9)
29	Potassium permanganate.	Potassium permanganate .. 4 g Sodium hydroxide 1-4 g Water ..... 100 ml	For high speed steels, and alloys high in chromium or cobalt. Causes a differential attack on carbides and tungstides	Use boiling 1–10 min. (Reference 10)
4	Chromic acid	Chromic acid .... 10 g Water ..... 100 ml	Attacks carbides in stainless steels very rapidly, austenite less rapidly, and ferrite very slowly if at all. For various structures of stainless steels	See solution No. 4 in Table I.
9	Oxalic acid	Oxalic acid ..... 10 g Water ..... 100 ml	To reveal carbides in stainless steels	See No. 9 in Table II. If strongly etched, general structure is revealed; therefore for study of carbides reduced voltage is used for etching, giving better control of etch.

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The Spark Testing of Steel

By W. G. Hildorf* and C. H. McCollam*

THE spark test is a method for the classification of steels according to their chemical composition, by visual examination of the sparks that are thrown off when the steels are held against a high-speed grinding wheel. The test is valuable as a safeguard against the accidental mixing of steels of different compositions, or as a method for separating steels known to be mixed. Spark testing is fast, convenient, economical and, when applied with proper regard for its limitations, reliable and accurate.

Spark testing is essentially a method for the separation of steels that have different compositions. It is not a substitute for chemical analysis, and is not intended for the identification of "unknown" samples. The character of sparks should be similar when spark streams are examined from a number of specimens supposedly of the same material. If one or more of the specimens exhibits a spark stream of different character, the presence of "foreign" material is indicated. Chemical analysis can be used for positive identification in such instances.

One of the advantages of the spark test is that it can be applied to steels in virtually all stages of production, as billets, as bar stock in the racks, as partly machined forgings, or frequently even as finished parts. Because spark testing is performed directly on the pieces themselves, expensive sampling methods are avoided, along with attendant possibilities of mix-ups in numbering and handling. Small pieces of mixed material that could not be sampled, even if the cost of analysis were not prohibitive, are frequently salvaged quite economically by the spark test.

Theory. When a piece of steel is held in contact with a moving abrasive wheel, small particles of the metal are torn loose. With a high-speed wheel, this tearing process is so rapid that the temperature of the particles is raised to incandescence. As the particles are hurled through the air, the trajectory is quite easily followed, particularly against a dark background. This trajectory is called a "carrier line". If the metal is either ingot iron or wrought iron, the result is a small sheaf of single lines, termed a "spark picture". If a piece of carbon steel of about 0.20% C is held in contact with the wheel, a lightening of the color of the line will be noted, as well as a number of short single "forks" or "primary bursts", caused by the presence of carbon (Fig. 1).

While a spark is incandescent and in contact with the oxygen of the air, the carbon present in the particle is burned to carbon dioxide. The transition of solid carbon to gaseous carbon dioxide is accompanied by an increase in volume. Although the particle of hot steel is plastic, it offers resistance to this volume increase, thus building up an internal pressure that is relieved only by an explosion of the particle. There are some observations to support this explanation of the bursts. For instance, the examination of the small steel particles when they are cold, reveals in the residue numerous hollow spheres with one end completely blown away. The relation of carbon content to the frequency of bursts also marks carbon as the element responsible for the forking of the carrier line. A 0.20% C steel exhibits a slight forking effect (Fig. 1); a 0.40% C steel, a pronounced burst (Fig. 2); and steel that contains about 1.00% C, a minute explosion (Fig. 3). Moreover, greater intensity of bursting is noticed as the carbon content of the steel is increased.

Examination of the Spark Stream. The technique of the visual examination of the spark stream is quite important. When this technique is properly learned, variations in the stream become more readily distinguishable.

Wheel Pressure for Spark Testing. When using the spark cabinet, which will be described later, the operator should hold the pieces on the wheel in such a manner as to throw the spark stream about 12 in. horizontally and at a right angle to his line of vision. At this point, it is well to spend a little time in determining precisely the pressure required for maintaining a stream about 12 in. long, without reducing the speed for most efficient performance of the wheel. Wheel pressure is important, whether the piece is held against the wheel, as in cabinet work, or the wheel against the piece, because increasing the pressure will raise the temperature of the spark stream and bursts, and will give the appearance, to the inexperienced eye, of a higher carbon content. Experience will dictate later, to the trained spark tester, the length and volume of the spark stream required for the various steels that will be encountered.

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When the optimum wheel pressure has been determined, it is suggested, for the introductory tests, that the operator select two steels of widely different carbon content, preferably plain carbon steels. An SAE 1020 and 1050 (or a steel of higher carbon content) will be satisfactory. First one and then the other should be held against the wheel. The operator should always be careful to strike the same portion of the wheel with each piece. When the eyes of the operator are focused on a point about one-third of the distance from the tail end of the stream, and are watching only the sparks that cross the line of vision, he will find that after a short while a mental image of the individual spark will be formed. As soon as an operator can fix spark images in this manner, he is prepared to examine the character of the "spark picture".

Sections of Sparks. The entire sheaf of sparks may be divided into three equal sections: (1) the wheel sparks, which are the third of the stream nearest the wheel; (2) the center area; and (3) the tail sparks, which represent the third of the stream farthest from the wheel.

The components to be observed are the carrier lines, the spark bursts and the "characteristic sparks". The carrier lines will vary in length, breadth, color and number. The spark bursts will vary in intensity, size, number, shape, and distance from the wheel or from the end of the carrier lines. Carrier lines are the incandescent streaks that trace the trajectory of every glowing particle. They are discussed more fully in connection with the characteristic sparks to which they are closely related.

The Spark Burst. The spark burst, that is, the "carbon spark", is the most useful characteristic of the spark picture, since the variations in the number and intensity of the bursts indicate the changes in the carbon content. Steels that have the same carbon content but different amounts of alloying elements are not always so easily identified; most of the alloying elements have some influence on the spark picture. They may affect the carrier lines, the bursts, or the form of characteristic sparks. Their effect may be, for example, to retard or to accelerate the carbon spark, or to make the carrier line lighter or darker.

Effect of Molybdenum. One of the most easily recognized of all the characteristic sparks is that of molybdenum, which appears as an orange-colored spearhead on the end of every carrier line. Other features of the molybdenum spark are that the spearheads are detached from the carrier lines, and that they are always present, regardless of the length of the lines (Fig. 4). Sometimes, when the carbon content is high, the spearhead is difficult to distinguish; but if a decarburized surface can be found, the characteristic spark immediately becomes quite distinct. Low-carbon high-sulfur screw stock will generally show a spearhead at the end of the carrier line; however, with practice, this grade can be distinguished from the molybdenum steels with little difficulty.

Effect of Nickel. Nickel gives a characteristic spark identified by tiny blocks of brilliant white light. This characteristic spark from nickel steel may be the result of the suppressing effect of nickel on the carbon burst. In low-carbon steels (0.10 to 0.20% C and 3.5 to 5% Ni) these blocks are located in the spark stream quite near the wheel, but in higher-carbon steels they are located in the burst. When present with molybdenum, nickel partly suppresses the carbon spark, and the nickel spark is in turn suppressed in the 4600-series steels. The chemical spot-test method is generally used for distinguishing among various nickel contents because of inherent difficulties in spark testing for this element.

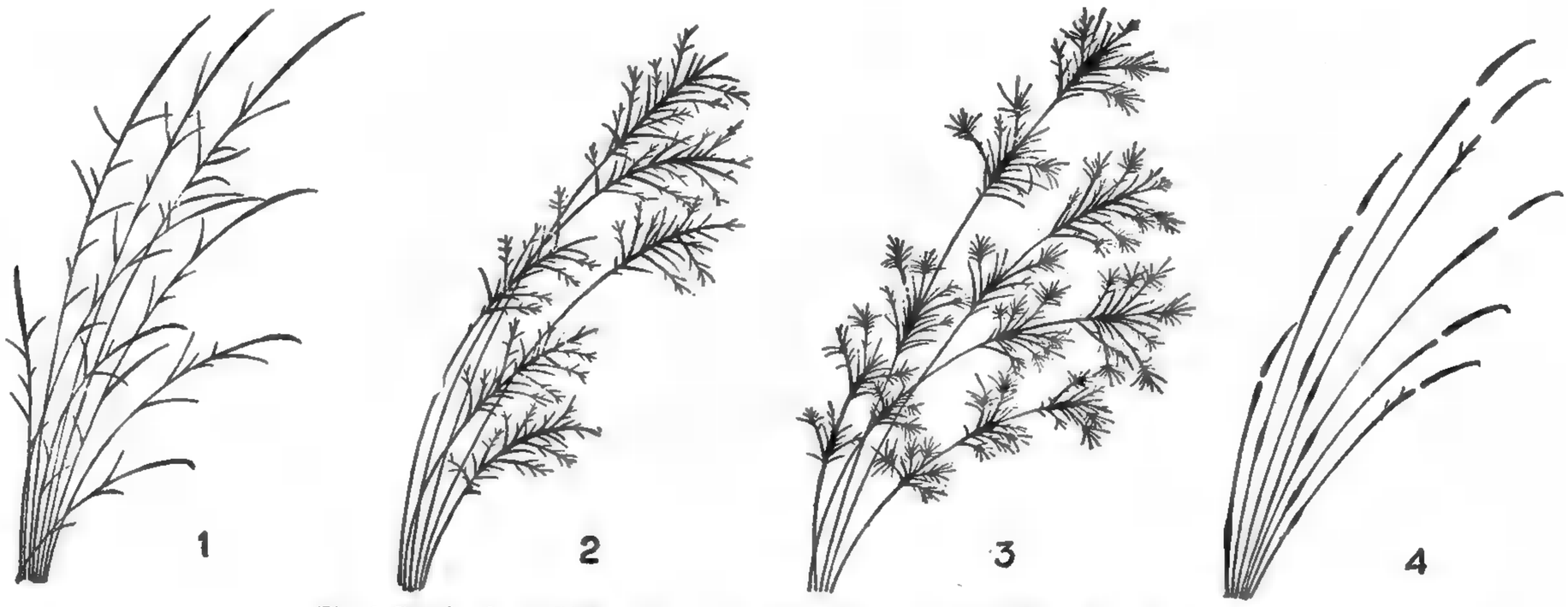

Fig. 1 Sparks from SAE 1015 steel (0.15% C), showing simple "forking effect"
Fig. 2 Sparks from SAE 1045 steel (0.45% C), showing "secondary burst"
Fig. 3 Sparks from SAE 1095 steel (1.0% C), showing the intensity of bursts that is characteristic of high-carbon steel
Fig. 4 Sparks from SAE 4615 steel (0.15% C, 1.75% Ni, 0.25% Mo), showing a detached "spearhead" that is characteristic of molybdenum, and the swelling in the spark line indicating nickel with molybdenum

Effect of Silicon. Silicon suppresses the carbon spark to a more marked degree. The carrier line from silicon steels of the SAE 9200 series is much shorter than from a plain carbon steel of the same carbon content, and usually ends abruptly in a white flash of light.

Effect of Tungsten. The spark streams for 18-4-1 and molybdenum high speed steels, as shown in Fig. 5 and 6, were prepared by J. V. Emmons. He states: "18-4-2 high speed steel sparks the same as the 18-4-1 type. With light wheel pressure, 4% W steel is similar in appearance to 18-4-1, but with heavy pressure the 4% grade shows an occasional secondary burst not found in the 18% W type. Observations are based on a 9-in. Alundum wheel, grade 46M, 1750 rpm."

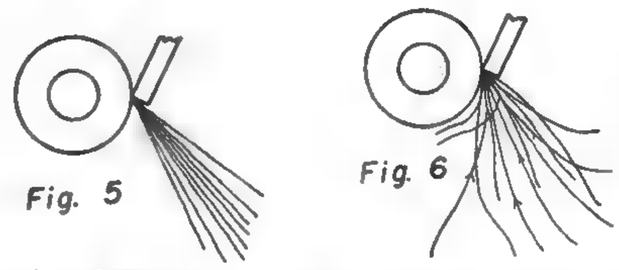

Fig. 5 Sparks from 18-4-1 high speed steel. Red color with numerous red lines
Fig. 6 Sparks from molybdenum high speed steel. Red and orange. Numerous orange spearheads have a few primary bursts.

Equipment for the Spark Test. *The Spark Cabinet.* A cabinet makes possible the examination of spark streams under ideal conditions. It is convenient both in training men for spark testing and in examining spark streams from steels that have spark characteristics still unknown to the operator.

A substantial wooden cabinet, about 40 in. long, 36 in. wide and 36 in. deep, will be suitable for this purpose. The cabinet should be placed on a bench or table at a

height convenient for the operator. The inside should be stained a flat black and should be equipped for artificial illumination. The spark cabinet should be located where no direct light will strike either the operator's eyes or the inside of the cabinet. The grinder may be mounted in the left front of the cabinet, and should throw a spark stream across the front of the cabinet at right angles to the operator's line of vision.

The Grinder. If the spark stream is to be satisfactory for examination, a grinder for spark testing should have a peripheral wheel speed of not less than 4500 fpm.

If parts in production are to be lightly ground, the grinding wheels should be of small diameter. Since the operator should not be handicapped by unnecessary fatigue, the weight, bulk and balance of the grinder are important considerations. Portable grinding equipment, with approximately 7 lb of well-distributed weight, has been found very satisfactory. The shaft bearings should be readily replaceable.

The grinding wheels should be rather coarse, very hard and approximately 1¼ by ⅜ by ¼ in. in size. Norton's wheel No. A 46-PV is suggested for general use, including testing of hard steels, and A 46-SV for soft steels.*

Spark-Test Goggles. Protection of eyes during spark testing is very important, both to avoid injury from steel and abrasive particles and to minimize the effects of certain light rays. Several optical companies have developed goggles that satisfy these requirements of spark testing.

Standard Spark-Test Specimens. Standard specimens can be prepared from bar steel. A convenient size is 1 in. in diam by 3 in. long. One end should be stamped with the identification marking of the steel, and a specimen number. Chemical compositions of these specimens should be kept for reference. Specimens should cover as wide a range of chemical compositions as possible, to permit the operator to familiarize himself with the manner in which the character of sparks is affected by various carbon contents and alloying elements.

For training purposes, a dozen or more specimens should be cut from bars of the materials with which the spark tester will have occasion to do most of his work. For example, if experience in identifying the molybdenum spark is desired, 12 pieces of SAE 1020 steel, 1 in. in diam, stamped **1**, and 12 pieces of SAE 4615 steel of like size and appearance, stamped 2, will provide the standard specimens necessary. These specimens are consulted only as a means of verifying the correctness of the classification of the "unknown" samples.

Spark-Testing Personnel. Personnel for spark testing should be selected with care. It is advisable to select a man whose eyes are sensitive to light and who has a fair knowledge of the compositions of various steels.

If a spark tester possesses the necessary physical and mental attributes, his efficiency should develop with experience in the examination of sparks. The more rapidly that experience is acquired, the sooner he will be available for duty.

Strict supervision of spark-testing work is advisable. The spark tester should be held at his highest possible efficiency. It should be understood by each operator that his work must be 100%, that not a single piece of foreign steel can be passed in error. Occasional decisions must be made as to when the spark test can be used safely, and also when it must not be used. The reputation of the spark test for reliability depends largely on the wisdom of such decisions.

Plant Spark Testing. Proper lighting conditions are necessary for satisfactory spark testing. Strong direct light, either natural or artificial, is a distinct disadvantage. Spark testing should be done in a shadow, and against a dark background.

It is advisable to protect the spark stream from heavy drafts of air, since this will cause a decided hooking of the tail sparks, which may be confusing.

Bar and tube stock, carefully racked, can frequently be spark tested without removal from the racks. Similar material in bundles can be spread out on inspection benches; small pieces of regular size and shape are generally placed on work benches. If a large number of pieces must be tested in a limited time, laborers can be used to arrange the parts in uniform rows for the spark tester, so that his time can be applied entirely to examination of sparks.

In tests of hot rolled or heavily scaled material, care must be used to make certain that the spark stream is not from a decarburized area. Bar stock is more safely ground on the cut end, and forgings are ground preferably at the point from which the tong-hold was removed.

* For an explanation of these identifying symbols, refer to the article on page 64 of this Handbook.

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Austenitic Grain Size in Steel

By E. C. Bain* and J. R. Vilella†

PROBABLY no other subject relating to the heat treatment of steel received more attention at one time than did austenitic grain size. This interest in grain size developed in response to the need for a better understanding of those subtle but important factors of steel quality that cannot be explained by the composition of the steel as ordinarily reported in the usual analysis. In brief, the explanation was found to lie largely in the grain size of the austenite, established during the final heating above the transformation range. The *extra-analytical* properties finally secured depend largely on the actual grain size of the austenite that transforms to set up the microscopic structure existing in heat treated steels as tested and used. Once the trends of austenitic grain growth in steel were understood, it was apparent that a clear-cut, positive correlation existed between properties or behavior and the austenitic grain size established in the final heating. This relationship seems not to exist between the securable properties and any grain size that might have been established at some other temperature, or with some treatment not used in the final heat treatment that is responsible for the properties. This reasonable circumstance was seemingly overlooked for a time, perhaps because of a lack of confidence in means of ascertaining quickly the austenitic grain size of any specimen of steel about to be quenched in any suitable manner. Yet this is the grain size that would be expected to have a direct, rather than fortuitous, significance. Throughout this article, *grain size* will always mean the actual austenitic grain size established at elevated temperature in an indicated significant heating.

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The pioneer contributions to this advance in the technology of heat treated steels, both in manufacture and in use, came from several sources. In Sweden the study[1] progressed as an inquiry into the characteristic attributes, particularly of acid open hearth tool steel. Another approach[2] was that which related to the hardenability of comparatively low-alloy, low-carbon, carburizing steels quenched directly from the carburizing box. A more advanced development[3] of this subject, on the part of manufacturer and user, was that of carbon tool steels of controlled hardenability (and toughness) produced without significant changes in composition, and the subsequent extension of these achievements to the steels of greater tonnage. All these studies converge, building a simple concept of grain-size effects and the purpose of this article is to set forth this simplification as applied to medium- and high-carbon and low-alloy steels that are heat treated.

The Usefulness of the Older Observations. It has been known for decades that a coarse fracture of a hardened and broken piece of steel accompanies excessive brittleness, and that equally hardened steel which requires greater effort in breaking, exhibits a finer, "silky" fracture. The many individual facets of the broken surface are large in the first instance and small in the second. With what the size of the individual facets is related, and on what this corresponding coarseness or fineness depends, was not

Table I

Effects of Previously Existing Austenitic Grain Size

Property	Trends in Heat Treated Steel Products: From Coarse-Grained Austenite (No. 5 and Above)	From Fine-Grained Austenite (Finer than No. 5, 5 to 8)
Hardenability	Deeper hardening	Shallower hardening
Toughness at same hardness	Less tough	Tougher
Distortion	More distortion	Less distortion
Quenching cracks	More prevalent	Usually absent
Grinding cracks	More susceptible	Less susceptible
Residual stress	Higher	Lower
Retained austenite	More	Less
For Annealed and Normalized Products		
Machinability	(Rough) better	(Rough) inferior
Machinability (special cases)	(Fine finish) inferior	(Fine finish) better
Formability (special cases)	Superior	Inferior

obvious, however, and was not understood until more recently. Another observation was probably made long ago; similar steels, in sections too large to be hardened throughout, harden more deeply, in a given medium, whenever the fracture appearance is coarse, and less deeply when the fracture is fine. Some twenty-five years ago certain manufacturers were introducing an alloying element to preserve the fine fracture and its attendant toughness, and were adding extra manganese to restore the deeper hardening characteristics. When a single bar or heat of steel was under consideration, it was observed long ago that high heating temperatures, as in the Metcalf test, induced the deeper hardening and the attendant coarser fracture, but any cause-and-effect relationship between coarseness and depth of hardness penetration in the quenched piece was not specifically mentioned until more recently. Indeed it was erroneously supposed by some that the quenching rate in any medium was accelerated if the steel was quenched from a higher temperature. This is now known to be untrue[4] in any general sense. Since steels of almost identical composition (as far as ordinary chemical analysis is concerned) are available, each of which will develop its own particular grain size at a certain temperature, grain-size variation may be studied independent of the heating temperature, which may thus be the same for all. When interest centers in a particular steel, then heating temperature or heating schedule is varied to produce the grain-size contrast. By the use of both methods of grain-size control, the broad effects have become familiar.[5] In a general way the effects of the previously existing austenitic grain size can be summed up in Table I.

The Formation and Growth of Austenite Grains. When a piece of carbon or low-alloy steel is heated above the so-called critical point, the ferrite and carbide react with each other to form austenite. The austenite is a crystalline phase differing distinctly from both the carbide and ferrite of which the steels under consideration are inevitably composed. Like any metal composed of a solid solution, austenite exists in the form of polyhedral grains. This reaction begins at a number of points, in the interface of the carbide (particles or plates) and the ferrite. In each such growing particle of newly formed austenite, carbon and iron and other elements from the carbide particles are dissolved, as well as iron and other elements from the ferrite. Each little island of austenite grows until finally it reaches its similarly growing neighbors.[6] In an ideally simplified formation there would be just as many grains of austenite as there were separate original nuclei, and this is nearly realized in a fairly coarsely spheroidized steel. In actuality, some of the islands of austenite grow more rapidly than others; therefore, when a large grain encounters a small one, the small one is forced to shift its orientation, layer by layer, thus losing its identity while being absorbed into the larger grain. Probably this happens frequently in certain steels and rarely in others. Now if the steel is far from eutectoid in composition and is heated below the Ac_3 or Ac_{cm} temperature, some islands of ferrite or cementite will remain unabsorbed regardless of the period of heating. These undissolved proeutectoid constituents appear to block grain growth so that this initial set of austenite grains is preserved even after long heating. When the temperature of heating is above Ac_3 or Ac_{cm}, any ferrite usually disappears quickly enough, but the carbide, although ultimately soluble, dissolves rather slowly so that, depending on its coarseness, more or less of the carbide persists even after surprisingly long intervals of time. It is important to note here that the first grain size of the austenite depends largely on the number of nuclei and that as long as any moderate amount of carbide remains these grains do not change greatly.

In pearlitic steels the effective nuclei are often located in the interior of a region of lamellae; in spheroidized steel each spheroid of carbide is a potential nucleus. When the spheroidization is fine, many such nuclei are ineffective because of the mechanism mentioned above. However, at ordinary quenching temperatures the original pattern of austenitic grain size is largely retained; this is termed the "uncoarsened grain size" to which almost all practical heat treating of carbon steel relates. The number of nuclei seems to depend on the following factors:

1 Previous mechanical and heat treatment, as it affects
   (*a*) Distribution of carbide, lamellar or spheroidal; that is, the structure
   (*b*) Fineness of carbide dispersion
   (*c*) Homogeneity of steel
   (*d*) State of stress or deformation
2 Composition of ferrite and carbide
3 Nonmetallic inclusions
   (*a*) Submicroscopic
   (*b*) Microscopic

Subsequent changes in the grain size of the austenite occur when heating reaches toward and beyond the normalizing range of temperature. Many steels not made in a way to restrict grain growth begin to undergo mild coarsening about as soon as the major part of the carbide (or ferrite) is dissolved. With rising temperature, such steels appear to coarsen rather regularly without any abrupt changes, presumably by the successive coalescence, here and there, of two or sometimes three grains to form one new grain. There is no marked disparity of grain size at any point. When a special, less soluble carbide exists, as for example in vanadium steels, the carbide particles persist to high temperatures such as 1750 to 1800 F, and little grain growth occurs as long as many such vanadium-rich carbide particles remain.

In similar manner certain nonmetallic substances appear to accomplish this same inhibition to grain growth. This broad effect of inert particles has long been known in the manufacture of tungsten filament wire, in which the extremely inert and refractory oxide of thorium present as visible particles, at least in part, acts as the grain-growth inhibitor.

An interesting effect of these so-called "grain-growth inhibitors" is that when they finally become ineffective at some elevated temperature, as a result either of solution or of coalescence, or by mere inefficacy or insufficiency, the amount of grain growth is then likely to be greater than in a steel free from such restraint. Such steels retain a fine grain almost unchanged during heating at successively higher temperatures until abruptly, here and there, a single large grain forms from as many as 100 or more former small grains. Prolonged heating, or a rise in temperature, will ordinarily convert the remaining fine grains to the same type of large grain as first formed upon reaching the coarsening temperature. Inhomogeneities of the steel tend to broaden the temperature range of two distinct grain sizes. This state of affairs in the range of marked grain growth is sometimes spoken of as "duplexing". It has no special significance, merely marking a natural transition stage from fine to coarse grains, when the change is large, fairly abrupt and unfinished.

It should be remembered that the persistence of carbide and attendant retention of small grains is often a matter not of equilibrium but of rate of solution, and carbide frequently remains undissolved for 30 min or more in eutectoid or even hypoeutectoid steel heated well into the austenite temperature range (above Ae_3).

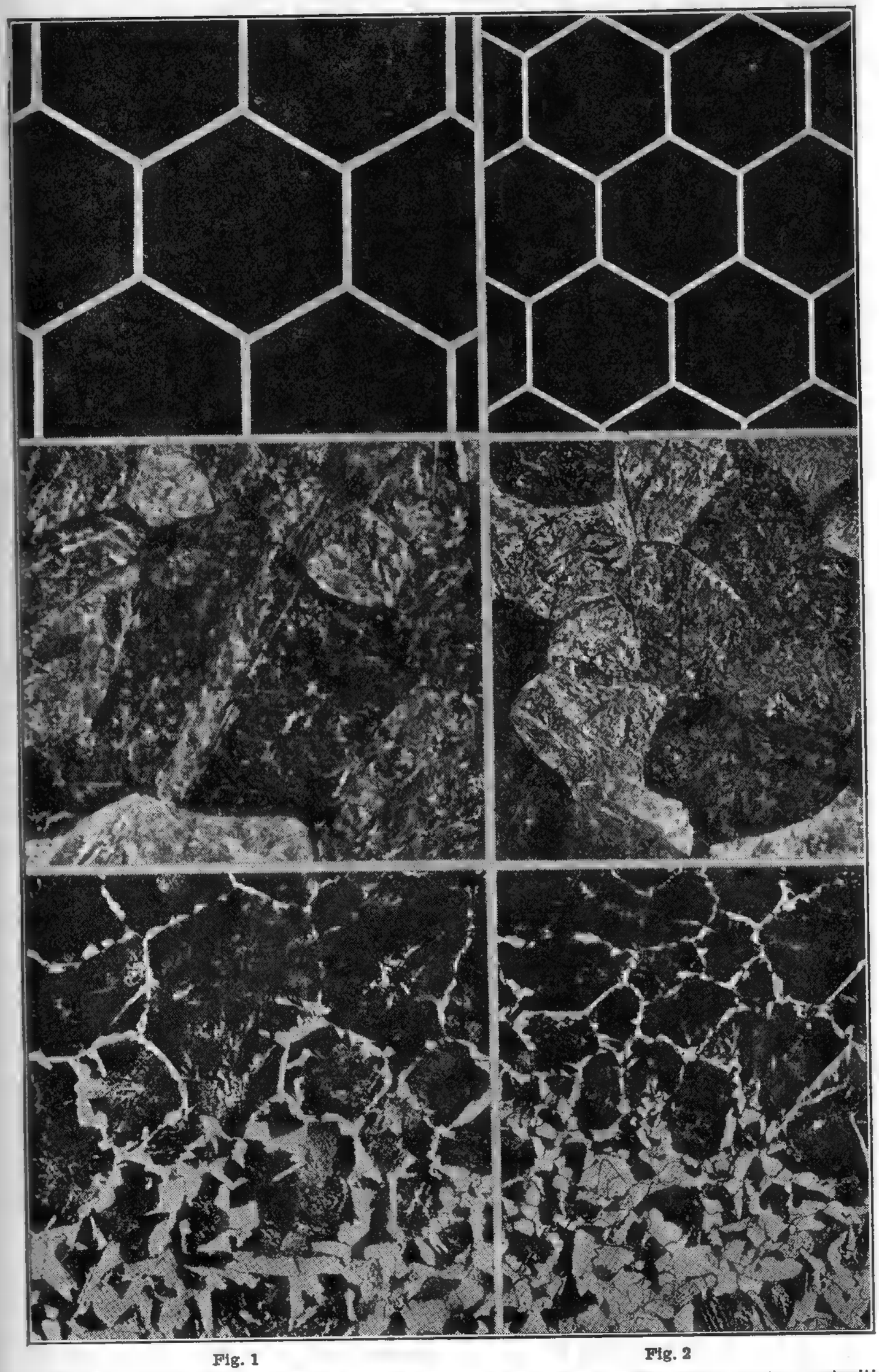


Fig. 1 Fig. 2

Fig. 1 *Upper*, idealized hexagonal network for mean grain size 1, ASTM scale. *Center*, austenitic grain size 1, that is, up to 1½ grains per sq in. of image at × 100 as revealed in quenched and lightly tempered structure. Etched with Vilella's martensite reagent. *Lower*, from ASTM Specification E 19-33, hypoeutectoid structure in carburized steel (8 hr at 1700 F) with grains up to 1½ per sq in. at × 100.

Fig. 2 *Upper*, same as Fig. 1, but for mean grain size 2. *Center and lower*, same as Fig. 1, but for 1½ to 3 grains per sq in.

Determination of Austenitic Grain Size

The grain size established in austenite at various temperatures has been discussed above in a qualitative or comparative way. It now becomes necessary to go into greater detail and to choose some quantitative basis for estimating grain size. Grains are solid bodies, and to be entirely correct one should speak of an average grain size in terms of volume, such as fractions of a cubic inch or a cubic millimeter; or one could better use the reciprocal, a certain number of grains per cubic inch or cubic millimeter. Actually, this is unnecessary and probably confusing. Estimation of grain size or grain counting is finally accomplished by viewing a polished *plane* section under the microscope; the boundaries of the grains as viewed lay out a network on a *plane* surface. The number of grains per unit area so sectioned on a plane, or the average area of these rough polygons, serves as well, as a measure of grain size, as would a number based on three dimensions or volume. It is possible to consider the grains as solid bodies while reporting in terms of their mean sections on a representative plane. The actual units employed in such estimates of grain size are not uniform for different metals in different countries. The common terms for reporting grain size are:

1 Grains per sq mm
2 Average area of grain (in sq mm)
3 Mean diameter of grain (in mm)
4 Arbitrary numbers (exponential), Timken, ASTM, index based on the formula Number of grains per sq in. at × 100 = 2^{N-1}, in which the index of grain size = N

The designation "mean diameter" (3) is fortunately not much used, since it is not easily estimated directly and, as a derived number, is ambiguous and less useful than the direct observation. Any scheme showing number of grains per unit area (either of specimen or microscopic image at known magnification) is vastly preferable.

In America, virtually all studies and specifications of austenitic grain size refer to the Timken, ASTM index numbers. For convenience they are tabulated with corresponding dimensions in Table II, and extended somewhat beyond the usual range employed. In Table II, the last column, headed "Grain Boundary Area, sq mm per cu mm", shows the minimum possible interface area. The effective intergranular surface will be greater, particularly in the finer grain sizes, because of the surfaces of undissolved carbide particles and because of irregularities in the boundaries of austenite grains.

It is often desirable to match the microscopic image discussed below with the standard network charts, such as are included herewith (Fig. 1 to 8), using a magnification either lower or higher than ×100, respectively, for coarse or fine grains. These rules apply:

For × 50, report ■ numbers lower than matching chart.
For × 200, report 2 numbers higher than matching chart.
For ×400, report 4 numbers higher than matching chart.
For × 800, report 6 numbers higher than matching chart.

Idealized grain boundaries in a hypothetical hexagonal network are shown in Fig. 1 to 8 for the corresponding ASTM grain sizes as tabulated in Table II. These are probably the best standards for general comparison and estimation of grain size.

Preparation and Microscopic Examination of Specimens for Grain-Size Rating. Thus far it has been assumed that the grains could be rendered clearly visible in a microscopic specimen and an estimate of their size arrived at either by counting over a known area of image at known magnification, or by comparing such images on the ground glass of the microscope with charts that have standard graded patterns of grain size marked out. In general, this is easily done, especially for grain sizes No. 6 or coarser. For finer grain sizes counting or comparing is more time-consuming but never impossible. In principle, the problem of determining grain size of austenite is rendered more complex than in brass, for example, because it is necessary to estimate the grain size of a constituent which is no longer present. If it were possible to examine under a microscope the heated steel ready to be quenched, this complication would not arise, but such technique is not practical. Fortunately, austenite transforms in such a way as to reveal the former grain boundaries unequivocally. This comes about because:

1 Proeutectoid rejections in either hypereutectoid or hypoeutectoid steels can usually be forced to the grain boundaries to form a complete, or nearly complete, network.
2 Transformation reactions, even in eutectoid steel, begin dominantly in the grain boundaries and may be interrupted when a network is developed.
3 Martensite has limits of orientation that depend on the orientation of the parent austenite grain and hence can, with suitable agents, be etched much like a pure metal to develop contrast among grains.

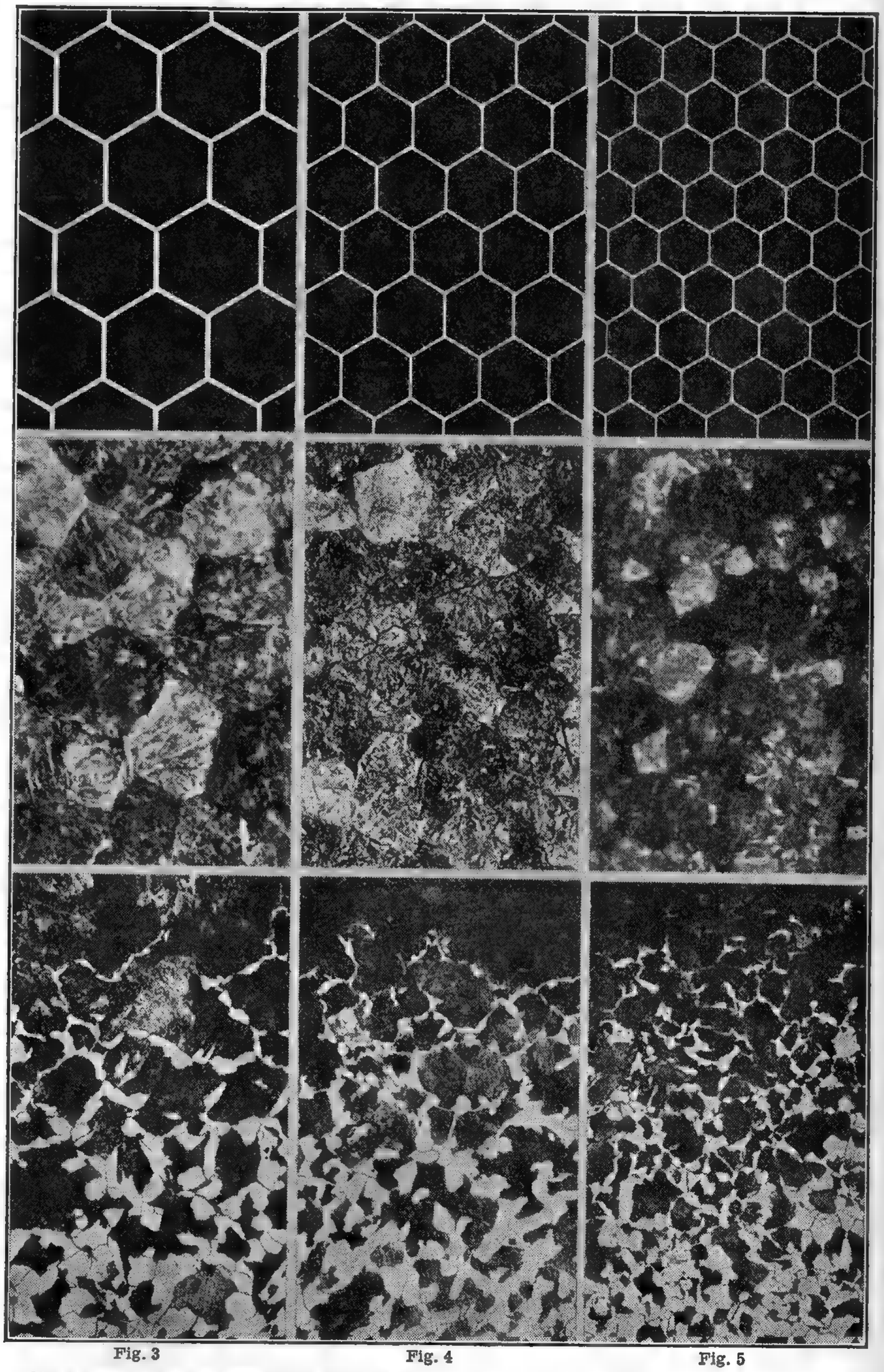


Fig. 3 Fig. 4 Fig. 5

Fig. 3 *Upper*, idealized hexagonal network for mean grain size 3, ASTM scale. *Center*, austenitic grain size 3, that is, 3 to 6 grains per sq in. of image at × 100 as revealed in quenched and lightly tempered structure. Etched with Vilella's martensite reagent. *Lower*, from ASTM specification E 19-33, hypoeutectoid structure in carburized steel (8 hr at 1700 F) having 3 to 6 grains per sq in. at × 100.

Fig. 4 *Upper*, same as Fig. 3, but for mean grain size 4. *Center and lower*, same as Fig. 3, but for 6 to 12 grains per sq in.

Fig. 5 *Upper*, same as Fig. 3 and 4, but for mean grain size 5. *Center and lower*, same as Fig. 3 and 4, but for 12 to 24 grains per ■ in.

In some respects it is advantageous that the grain size of austenite is estimated on the basis of its decomposition products and not of the constituent itself, for this circumstance permits outlining the grain boundaries with constituents that may have great visual contrast with the main portion of the grains. Even under the worst conditions the problem, however unique, is not more difficult than for brass or other single-constituent metals. It happens that while cooling slowly through the transformation range, carbon or low-alloy steels with a carbon content somewhat remote from the eutectoid (that is, distinctly hypoeutectoid or hypereutectoid) reject either ferrite or carbide, respectively; the rejection of these proeutectoid constituents occurs largely at the grain boundaries, after which the remainder of the austenite transforms to a black-etching pearlite. The transformation of eutectoid austenite, beginning characteristically in the grain boundaries, makes possible the formation of some fine pearlite (nodular troostite) in the grain boundaries, after which the remainder of the austenite may be caused to transform to light-etching martensite. Thus eutectoid steels, from which no separate boundary constituent can be rejected, may have the grain boundaries clearly outlined. It is obviously of no consequence which is darker, the boundary or the interior body of the grain.

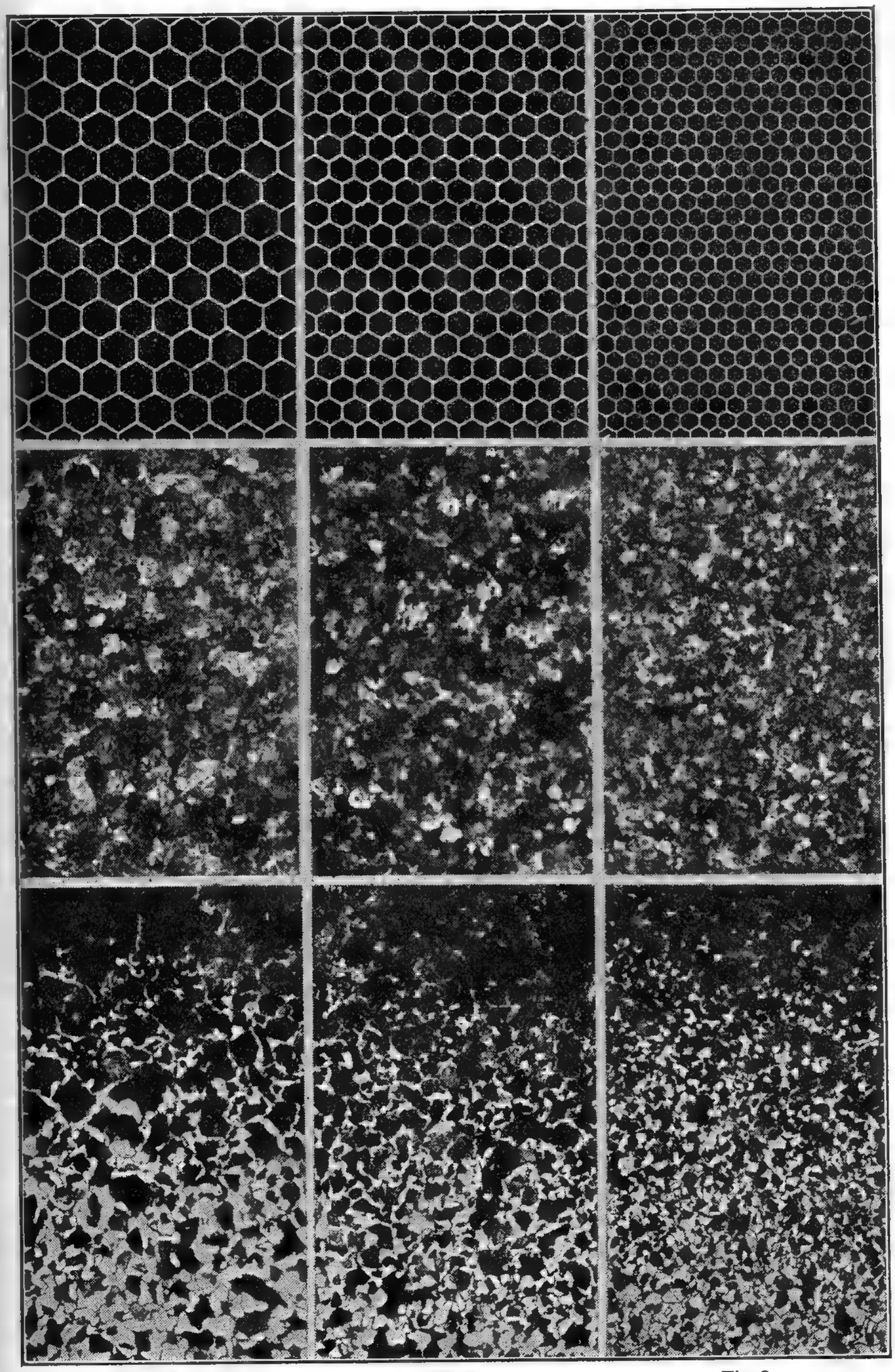


Fig. 6 Fig. 7 Fig. 8

Fig. 6 *Upper,* idealized hexagonal network for mean grain size 6, ASTM scale. *Center,* austenitic grain size 6, that is, 24 to 48 grains per sq in. of image at × 100 as revealed in quenched and lightly tempered structure. Etched with Vilella's martensite reagent. *Lower,* from ASTM Specification E 19-33, hypoeutectoid structure in carburized steel (8 hr at 1700 F) with 24 to 48 grains per sq in. at × 100.

Fig. 7 *Upper,* same as Fig. 6, but for mean grain size 7. *Center and lower,* same as Fig. 6, but for 48 to 96 grains per sq in.

Fig. 8 *Upper,* same as Fig. 6 and 7, but for mean grain size 8. *Center and lower,* same as Fig 6 and 7, but for 96 grains or more per sq in.

Any sample of steel heated at any temperature, depending on carbon content, above Ac_3, Ac_1 or Ac_{cm}, is made of austenite (in which carbide may be present or not), composed of grains, and an interest may exist in the size of those grains; the foregoing paragraph shows how it is always possible to learn what this grain size is. Often the steel may be normalized in handling; then it will be the high-temperature austenitic grain size in which interest centers. If so, it is possible either to simulate the normalizing treatment in a small laboratory furnace, thus establishing the grain size in question, or to carry a piece along in the commercial furnace. The grain size is established at the conclusion of either type of heating and the only problem thereafter lies in cooling the specimen in a manner that will make the grain size clearly readable under the microscope. More often the interest lies in the grain size in the steel as heated for the final quench (water, oil, or air). Only the austenitic grain size actually established in the particular heat treatment under consideration can be correlated with the steel properties to be secured. The austenite grain size is not affected in any way by the kind of cooling applied; however, a specimen selected from the heating furnace for examination should be cooled so that the grain size will be made apparent.

For example, if a steel is desired which will not coarsen beyond a No. 5 grain size, and the customary austenitizing temperature is from 1475 to 1500 F, then it is advisable to cut a specimen of dimensions suitable for the application and to heat it, either along with a commercial batch or in a small furnace for the same period, and then to cool it, as indicated below, in a way that will give the best

delineation of grain size. If the steel is normalized or homogenized prior to such heating for hardening, then this treatment should preferably precede the heating for test. To take care of possible furnace irregularities, some prefer to heat to a temperature 50 F or even 100 F higher than the commercial schedule, assuming that if a steel does not coarsen at 1550 F, it certainly will not do so at 1475 F, a conclusion that is generally true. Testing at much higher temperatures than those employed in practice is not helpful in the study of grain size, because the test then departs too far from the conditions in which interest centers and valuable information is lost.

Another example might be cited in which a certain degree of coarsening is desired in the normalizing range. Then the proper preferred normalizing temperature should be used either in the commercial furnace or in a laboratory furnace, for the customary period of time.

The essential point is that for pertinent information regarding quenching and tempering and the final properties of heat treated steel, the grain size should be established at the approximate quenching temperature. For useful information concerning grain size effects in other heating operations, such as normalizing or forging, the higher temperatures employed therein should be used in the determination of grain size also. Failure to observe this consistent procedure may result in erroneous conclusions.

When the grain size has been developed in the properly heated —and therefore austenitic—steel, the steel is cooled in whatever way will best reveal this grain size. The procedure will vary with the type and carbon content.

Hypoeutectoid Carbon Steels. In most steels with a carbon content between 0.25 and 0.60%, it will be sufficient merely to cool a specimen about ½ in. in diam in air. The ferrite will form chiefly in the grain boundaries and mark out the grains as in Fig. 9. When the grain size is small, complete envelopes (particularly of ferrite) ordinarily will not form, but this offers no difficulty. Generally one austenite grain still forms only one area of dark pearlite so that the eye readily recognizes the grains either for counting or for comparison.

When the composition is only slightly hypoeutectoid, the steel may be treated according to directions below for eutectoid steel, or may be cooled to about 1340 F and held there for 10 or 15 min before final cooling. This cooling will usually form a very good network of ferrite.

Hypoeutectoid Alloy Steels. With the exception of carburizing steels (discussed below) these steels should generally be cooled by the second method for hypoeutectoid carbon steels, allowing still more time at about 1340 F. Otherwise they may be treated as for eutectoid steels (below). An excellent improvement of this method is to hold at some temperature near 1300 F long enough to establish a ferrite network, and then quench. Subsequent tempering at approximately 800 F (one minute is sufficient) develops a black-etching "sorbite" in the body of the grains. The most brilliant contrast develops during etching. Higher alloy steels require longer holding time; the optimum can be determined once for all by a series of specimens held for three or four different periods.

Hypereutectoid Steels. These steels are easily cooled to develop a fine carbide network; the best rate depends on composition. Unless the carbon content is more than 1.10%, they are best treated as eutectoid steels (below). Equally satisfactory results are secured by the method of holding at 1300 to 1340 F, quenching, and reheating at approximately 800 F. The hypereutectoid zone of a carburized steel is handled in the same way, as discussed below. Figure 10 shows a carbide network marking out the grains.

Eutectoid Carbon Steel. A specimen of ⅝ to 1 in. in diam is properly heated in the range in question and quenched in water; one end may be kept out of the water. The center, or the unquenched end, will be uniform fine pearlite, in which grain size is not discernible; the outer zones will be martensitic. Between the two will be a zone in which the martensitic body of the grains will etch lightly, while the many nodules of fine pearlite in the grain boundaries will etch black and mark out the grains. When this method becomes somewhat ambiguous in the

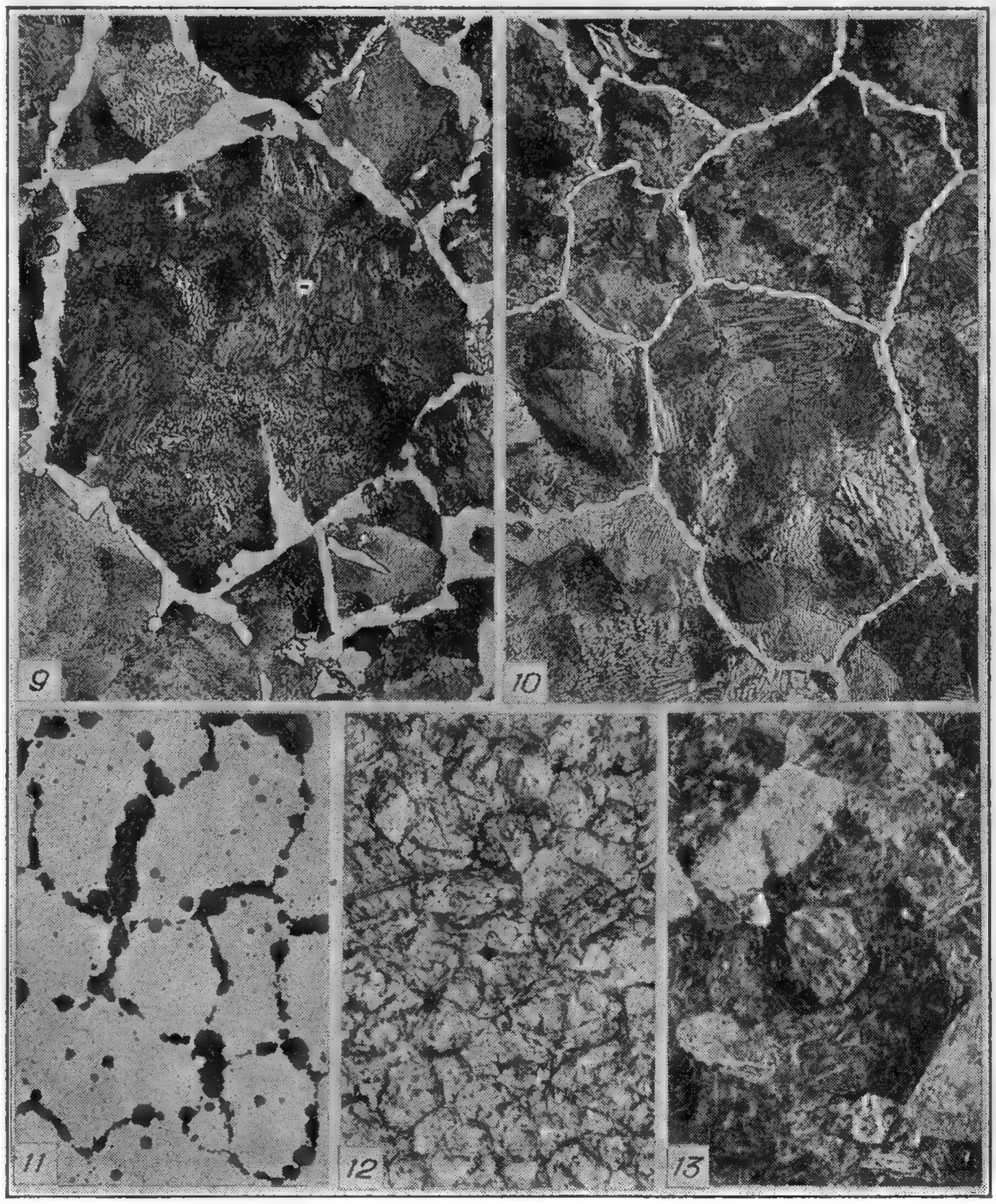


Fig. 9 Ferrite network properly developed for estimation of grain size in hypoeutectoid steel (× 300).
Fig. 10 Carbide network properly developed for grain-size estimation in hypereutectoid steel (× 300).
Fig. 11 Black etching network of fine pearlite properly developed for estimation of grain size in incompletely hardened eutectoid steel (× 125).
Fig. 12 Grain size developed in fully hardened steel (martensite) for estimation of grain size (× 100).
Fig. 13 Grain size developed in fully hardened and tempered steel (troostite or sorbite) for estimation of grain size (× 100).

Table II. Comparison of Systems for Reporting Grain Size[a]

Timken, ASTM No.	Grains per sq in. of Image at × 100 Max	Min	Mean	Grains per sq mm	Mean Area per Grain, sq mm	Grains per cu mm, approx	per cu mm Area, sq mm Boundary Grain
—3	0.09	0.05	0.06	1	1	0.7	2.4
—2	0.19	0.09	0.12	2	0.5	2	3.3
—1	0.37	0.19	0.25	4	0.25	5.6	4.7
0	0.75	0.37	0.5	8	0.125	16	6.7
1	1.5	0.75	1	16	0.062	45	9.5
2	3	1.5	2	32	0.031	128	13.4
3	6	3	4	64	0.0156	360	19
4	12	6	8	128	0.0078	1020	27
5	24	12	16	256	0.0039	2900	38
6	48	24	32	512	0.00195	8200	54
7	96	48	64	1024	0.00098	23000	76
8	192	96	128	2048	0.00049	65000	107
9	384	192	256	4096	0.000244	185000	150
10	768	384	512	8200	0.000122	520000	215
11	1536	768	1024	16400	0.000061	1500000	300
12	3072	1536	2048	32800	0.000030	4200000	430

(Usual Range)

(a) Some of the data of this table are from unpublished work of R. H. Aborn and J. J. B. Rutherford.

finest grain sizes, and it is still desired to have an accuracy of one grain size number, the estimation should be made in the fully hardened zone as for hardened steel. Figure 11 shows grain size marked out by black etching fine pearlite in the boundaries in the transition zone.

Fully Hardened Steel. It may be desirable to know the grain size established in heating a steel that has already been quenched—and even perhaps tempered, which would make the problem more difficult. This determination can be accomplished also by suitable etching of the wholly martensitic structure. Two or more slight repolishings and etches may be necessary. The etching agent (Vilella's martensite reagent) that develops contrast between the martensite of individual austenite grains, is made up as follows: Dissolve in 95 ml of ethyl alcohol 1 g of picric acid and 5 ml of concentrated hydrochloric acid.

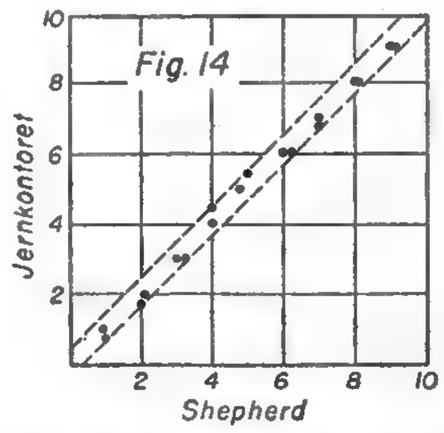
The prior austenitic grain size may be determined in hardened steel that has been tempered definitely and softened moderately. Indeed, there is an optimum degree of tempering that provides the greatest contrast among the grains. Figure 12 shows the structure of hardened steel etched for estimation of grain size, and Fig. 13 shows a hardened and tempered steel.

Carburizing Steels. When the steel under consideration is to be case carburized and quenched directly from the carburizing box, the important grain size is that established under conditions precisely like those that prevail when the steel is removed from the carburizer; the grain-growth characteristics of the steel are often greatly altered by the infusion of carbon, and an examination of the original low-carbon steel heated to the carburizing temperature would be misleading (that is, the core of carburized pieces). Accordingly the specimen should be properly cooled, so as to develop a carbide network in the high-carbon zone when removed at the conclusion of carburization; in brief, the specimen should be handled thereafter exactly as for any hypereutectoid steel. When, however, the carburized steel is to be reheated, the carburized grain is not significant and the specimen should be reheated according to the practice before cooling to mark out the grains.

Observations on the grain size of the hypereutectoid zone of carburizing steels are interesting. In the first place, estimation of grain size under the microscope is, perhaps, easiest in hypereutectoid compositions because of the extra contrast of the usually clear carbide envelopes or network. Certain other features* of the carburized structure are metallographically fascinating, and the examination of carburized specimens of various steels not commercially carburized has sometimes been carried out as a regular test. For details of this procedure the reader is referred to page 407. The only point that must be remembered is that steels indistinguishable in properties and grain size when properly heat treated may possess vast differences in grain size when carburized.

Section-Size Distribution. Inevitably some grains of the mean size or larger will be sectioned in such a way as to show a small polygonal surface in the image. Hence an occasional small polygon should not be reported as indicating mixed structure. When, however, a cluster of small grains is found, they should be taken into consideration, because it is not possible to section more than about three adjacent large grains to yield small plane grain sections. Generally speaking, when grain size is uniform, about three-fourths of the field will show "grains" within one grain-size bracket. Most of the remaining quarter of the field will consist of the next smaller size with a few still smaller polygons.

Austenitic Grain Size from Fracture. In the first section, mention was made that long ago the properties of hardened steel had been correlated with the coarseness or fineness of the fracture surface of a break on the hardened steel. As early as 1926 this relationship was used at the Uddeholm Steel Works in Sweden, as a quantitative measure of certain aspects of steel quality. At first only five recognized grades of fracture were employed, but later the work was extended through the supervision of Jernkontoret, and in 1927 a 10-step scale was recommended as a suitable measure of tool steel quality; sets of standard fractures in specimens 22 mm sq were prepared under the direction of Dr. Ragnar Arpi. These specimens covered the full range of coarseness and fineness usually encountered, by steps which to the eye appeared evenly spaced.



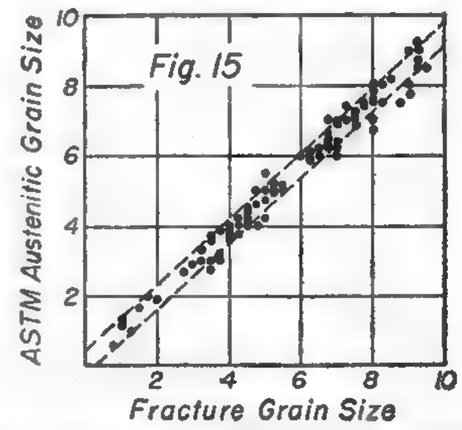


Fig. 14 A comparison of the Jernkontoret and Shepherd fracture standards 1 to 10, each in terms of the other. Note similarity.

Fig. 15 Relation between fracture rating and the true prior austenitic grain size in hardened and broken specimens.

In America, also, B. F. Shepherd employed an examination of hardenability and fracture appearance as a measure of the probable suitability of steels for certain purposes. Shepherd prepared a set of graded standard fractures in which the entire cross section of the standard

* An interesting structural feature of carburized steels becomes apparent when they are cooled in exactly the same way. It has to do with the regularity of the pearlite and the extent to which this pearlite fills the envelopes of the grains marked out by proeutectoid carbide and is designated "normality" or "abnormality". It is sufficient to note here that this feature is controlled by composition and grain size in the carburized condition of steels amenable to the classification. When composition is constant, fine grains infallibly favor abnormality; coarse grains favor normality. With constant grain size the normality is then a measure of effective content of deep hardening elements in solution, these elements favoring normality.

bars was hardened. To gain an adequate impression of different bars of steel, he generally hardened the specimens (of definite section) from four heating temperatures, 1450, 1500, 1550 and 1600 F, and secured thereby a pattern for the coarsening of the steel at increasing temperatures. The fracture was compared with the series of standards similar indeed to the Swedish standards. The latest standard fractures (hardened throughout in both instances) of Shepherd and Jernkontoret, numbered serially 1 to 10, each as compared with the other, are shown in Fig. 14. For most practical purposes these standards may be regarded as the same.

It will have become almost obvious by this time that there is a marked degree of parallelism, more than fortuitous, between coarseness of fracture and the austenitic grain size that existed in the fracture specimen before it was quenched and broken. This relationship proves to be closer than was at first supposed. The estimation of a great many fractures shows that the relationship between the Shepherd or Jernkontoret fracture numbers and the austenitic grain size responsible for the fracture appearance is about as shown in Fig. 15. It should be remembered that the eye is able to arrive at a mean value of the coarseness of a fracture and that for correlating fracture number with austenitic grain size, the mean value of the austenitic grain size should be used. Thus, if a specimen were accurately rated 65% No. 6 and 35% No. 4, its mean grain size would be about 5.3 and it would exhibit a fracture about midway between 5 and 6. There is one interesting fact about estimating prior austenitic grain size by fracture. The eye is more *sensitive* to slight changes in fracture appearance than is the corresponding mean grain size estimation on the microscope. Experienced observers of fractures will agree within one-half, and often within one-quarter, of a single step in the fracture series. There is probably no urgent need even for as many steps as exist in either the ASTM grain size rating or the fracture rating. The properties that are influenced by grain size are not sufficiently modified by small changes to warrant great accuracy in reporting grain size either by fracture or by microscopic examination.

A word should be said about the fracture appearance from mixed grain sizes. Actually there will be large facets mixed with the fine on the fracture surface but the eye does not recognize this at once unless the fracture is fairly coarse; instead, undue influence is exerted by the few coarse facets. Nevertheless, an experienced observer can distinguish "duplexed" specimens reliably from fracture appearance, once he acquaints himself with a few known specimens of mixed grain size. (The mixed grains must really have existed at the time of quenching, and not have been found only after some other unrelated heating.) A few rare anomalous instances are found, in which considerable experience is necessary to estimate actual grain size from fracture. The most notable of these is an austenite grain that coarsens abnormally at elevated temperature, having been inhibited until high temperature is reached. The surface of each grain is slightly matte, not brilliant, suggesting a fine grain size, while the large grain size is also apparent from a faint appearance of large facets. This condition occurs too rarely to be serious. The reasons for it have been suggested.[5]

It is easy and practical to combine a hardenability test with the evaluation of grain size by fracture as Shepherd has done. A standard size of specimen must then be adopted and rigidly maintained and the grain size at the fracture must be estimated on the fully hardened or martensitic rim. The depth of this rim can be measured (by 64ths of an inch in Shepherd's technique) after it is rendered visible by etching. Shepherd reports eight numbers that largely classify certain grades of carbon steel as to their suitability for hardened parts. The first four numbers are depths of hardened zone in 64ths of an inch as quenched from 1450, 1500, 1550 and 1600 F, respectively, while the second four numbers are the fracture numbers (Shepherd or Jernkontoret scale) of the hardened zone of the same specimens. It should be stressed that the information secured by this *P-F* (*P* = penetration of hardened structure; *F* = fracture rating) test goes far toward giving a full account of the behavior of carbon steel. Obviously alloy steels may harden throughout such large sections that the hardenability feature is inapplicable; the estimation of fracture grain size is still valid, however.

The most rapid examination of a steel for significant grain size characteristics consists of rating the fracture first;* if it is not indicative of mixed grain size, the ASTM grain size may be reported at once, or if the fracture shows the probability of such a condition, it may be polished, etched and rated microscopically by the charts of Fig. 1 to 8 inclusive. (*See also* page 413.)

Summary. The grain size established in the austenite of a bar of steel ready to be cooled or quenched plays an important part in determining the properties secured. This grain size is generally fine at ordinary quenching temperatures but is coarser at higher temperatures; for example, normalizing temperature, or higher.

Grain size is not altered by the method of cooling; hence estimation may be made for any suitably heated specimen cooled in such a manner as to reveal the grain size in the transformed microstructure.

The cooling schedule for best estimation of grain size depends on the composition of the steel. Either hypo- or hypereutectoid steels may be cooled slowly enough during the first part of the transformation to cause proeutectoid ferrite or carbide to be rejected in the grain boundaries as a thin network. Eutectoid carbon steels have the grain boundaries nicely marked out by black-etching fine pearlite (nodular troostite) in the zone not quite fully hardened; or in any fully hardened steel a special etch may be given the polished specimen to differentiate by selective attack the separate original austenite grains now converted to martensite.

A close approximate estimate of austenitic grain size in any hardened steel may be made by examining its fracture surface. A chart showing approximate relation between austenitic grain size and either Shepherd or Jernkontoret standard fracture number is included here (Fig. 15).

Eutectoid or hypereutectoid carbon steels (and even hypoeutectoid alloy steels) usually retain considerable undissolved carbide at low temperatures employed for hardening by best practice. Such austenites are fine grained, making it somewhat difficult to estimate actual grain size. This is not serious since the grains are obviously fine and since the carbide-ferrite interface has all the influences that grain boundaries exert on hardening characteristics.

Interest focuses principally on the grain size established in the temperature range of the operation to be carried out and correlated with grain size effects. It is therefore recommended that the grain size be estimated on regular pieces heated according to commercial operations up to the time of cooling or quenching.

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* Austenitic grain size by fracture rating may not be reliable unless the fracture is in a hardened specimen broken without substantial attendant deformation.

The McQuaid-Ehn Test

By H. W. McQuaid*

THE McQuaid-Ehn test was developed in 1922 as a result of an extensive investigation into the effect of melting furnace practice on the hardenability of plain carbon case-hardening steels. It was found that by carburizing at 1700 F in a solid carburizer that would develop a definite hypereutectoid zone, and then permitting the material to cool slowly enough to develop a pearlite structure with free cementite in the hypereutectoid zone, a definite structure would be developed, depending on the practice used in the melting furnace. By this means it became possible to predict from the carburized specimen the reaction of the final carburized product to quenching.

Since this test was first introduced, it has been extended to cover not only plain carbon carburizing steels, but also alloy steels in all the commercial grades, and the plain carbon steels, including the tool steel ranges.

The importance of having methods of associating properties inherent in a given heat of steel with the results to be expected in heat treatment and in the finished product, has resulted in many investigations into the characteristics developed by the McQuaid-Ehn test. Other methods developed for the same purpose are given on page 399.

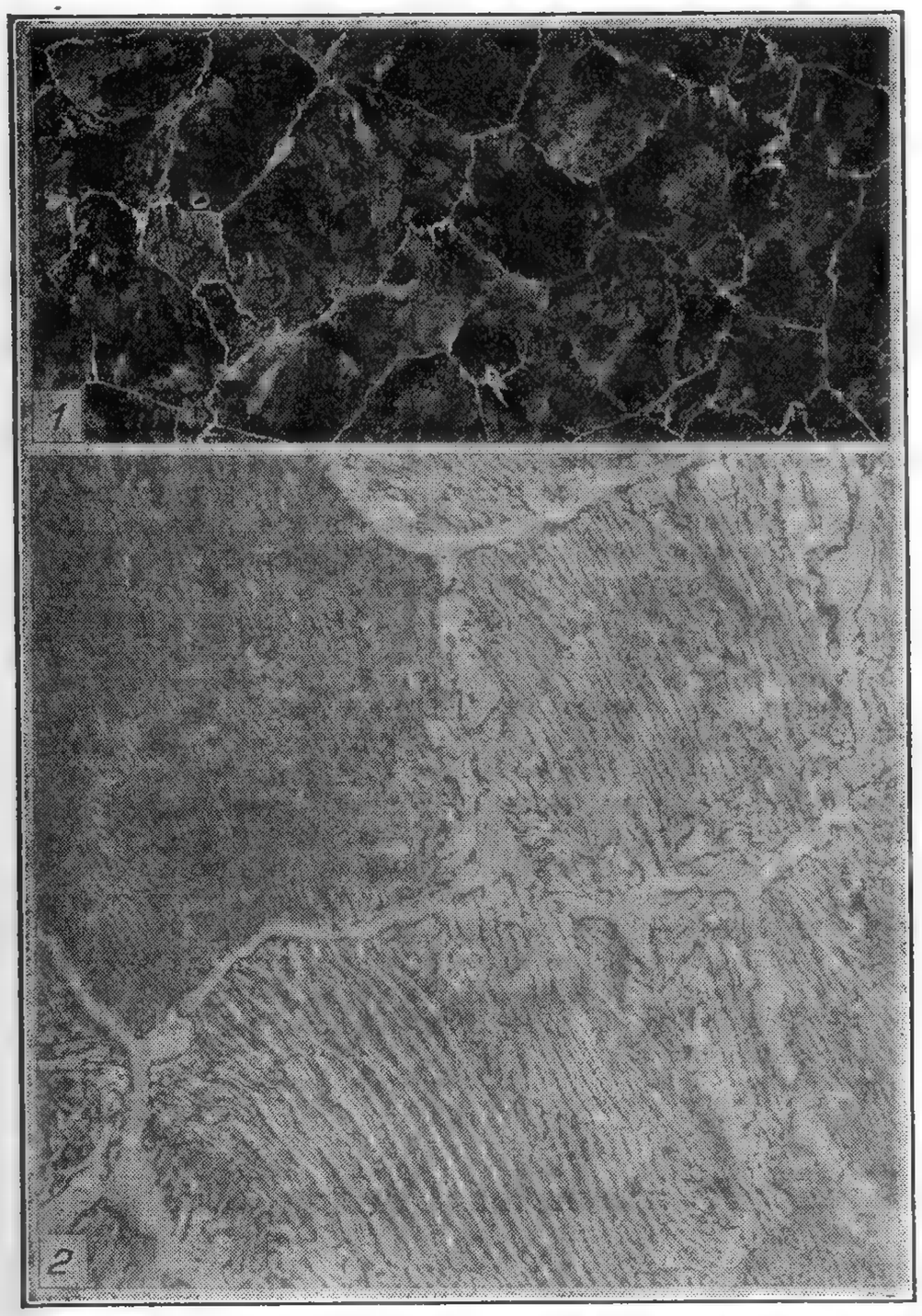

Fig. 1 Case structure of normal steel after McQuaid-Ehn test. White cementite network around dark pearlitic grains (× 100).
Fig. 2 Same as Fig. 1, at × 1000.

Pearlitic Structure Required. In order to make the McQuaid-Ehn test properly, it is necessary to develop a pearlitic structure within the grain of the hypereutectoid zone after case carburizing. This requires the use of a carburizing compound that will develop an excess of cementite sufficient to permit a clear indication of the disposition of the proeutectoid cementite after the formation of pearlite within the grain. The work to be tested should, therefore, be carburized in a solid carburizer containing sufficient energizer to give a carbon content in the case, well above the eutectoid range. Many available commercial carburizing compounds can be used for this purpose. The compound used in the average plant will be found satisfactory.

Carburizing Temperature and Time. The work material should be carburized at a temperature as near 1700 F as is commercially possible. However, little difference will be found with variation in temperature from 1675 to 1725 F.

The time at temperature is determined by the depth of case desired; for most purposes it is necessary to hold at temperature only long enough to develop a hypereutectoid zone sufficient to be studied readily at ×100 magnification. It is better, for most purposes, to carburize until a case approximately 0.050 in. deep is obtained, which will provide a hypereutectoid zone ample for satisfactory study.

Cooling from Carburizing Temperature. The cooling time is governed to a large extent by the alloy content. In order to develop a satisfactory pearlitic structure in the hypereutectoid zone, the cooling rate must be very slow for high-alloy air-hardening steels, but it can be relatively fast for the low-carbon, low-manganese steels containing no other alloying elements. The cooling rate can be determined only by experience, and depends not only on the composition of the steel but also on such factors as the size

Fig. 3 Case structure of abnormal steel after McQuaid-Ehn test. White cementite network with free ferrite (white) around dark lamellar pearlitic grains (× 100).
Fig. 4 Same as Fig. 3, at × 1000.

* Consulting Engineer, Cleveland

of carburizing container, size of specimen and of heating furnace. Plain carbon steels can be carburized in a commercial furnace and air-cooled in the standard carburizing container. The air-hardening steels, such as the high-nickel and Cr-Ni-Mo series, must be cooled in the furnace. Where the work material is carburized in a laboratory furnace, it is quite common to cool all test specimens in the furnace, and it has been found necessary to cool high-alloy steels in the furnace at a definite maximum rate.

The following minimum cooling periods through the transformation range may be found satisfactory: 4 hr for SAE 2315 and 4615; 8 hr for SAE 2512; 16 hr for Krupp steel (Ni 4%, Cr 1.5%); and 3 hr for the other steels, such as the plain carbon, 3115 and 6115.

Interpretation of Results. The interpretation of the test results depends on the examination of the pearlite and cementite in the hypereutectoid zone. In a strictly normal steel, the structure within the grain boundaries is completely pearlitic and, if the grain is coarse, the cementite exists as well-defined lines of fine but continuous formation at the crystal boundary, as shown in Fig. 1 and 2. In a strictly abnormal steel, the pearlite, if present at all as such, will be very coarsely and irregularly lamellar and will have broken down completely at the grain boundaries to form massive cementite and free ferrite (Fig. 3 and 4). Here the cementite will be distinguished as ridges, having a white background of ferrite. Between these two extremes will be found many types in which the pearlite becomes more coarsely lamellar as the steels become more abnormal and an increasing amount of free ferrite surrounds the cementite at the grain boundaries. It will also be noted that there is a tendency for the cementite to become thicker and, in some steels, to become a discontinuous series of elongated particles.

Consideration of Grain Size. It was noticed, at the time when this test was first developed, that variation occurred in the size of the grain in the hypereutectoid zone from one heat to another, and that this variation in grain size also served as an indication of the characteristics of the finished heat treated piece, with regard to hardenability, distortion and mechanical properties.

Usually coarse-grained steel (Fig. 5) will be quite normal—particularly plain carbon steel—with an increasing tendency toward abnormality as the grain size decreases. The coarse-grained normal steels respond better to quenching, harden more deeply and tend to distort considerably more than the finer-grained, more abnormal steels. The coarse-grained normal steels usually have much lower resistance to impact and for this reason the finer-grained steels (Fig. 6) are preferred for applications where resistance to shock-loading is necessary. Because fine-grained steels exhibit a greatly reduced tendency toward grain growth, they are usually preferred, especially in the alloy grades, for quenching directly from the carburizing temperature. In the plain carbon grades, the probability of having soft spots after hardening, is greatly increased with the fine-grained, more abnormal steels, so it is often necessary to quench these steels in a caustic or similar solution after carburizing.

The steels of coarser grain respond more readily to the usual normalizing temperature by forming a coarsely lamellar pearlite; hence they are preferred in some plants because of the improved finish obtained in machining. By using a higher normalizing temperature, approximately 1800 F, to overcome the inherent resistance to grain growth in steels of finer grain, it is possible to improve the machinability of the fine-grained steels so that it equals that of the coarse-grained steels.

At present there is some difference in opinions concerning the relative effects of normality and grain size. It is evident that normality and grain size are two independent characteristics and that steel can be made, if desired, which is fine-grained normal or coarse-grained abnormal. This is entirely a matter of furnace practice, but under present conditions most of the fine-grained steels are slightly abnormal, the coarse-grained steels are normal, and the desired characteristics can be obtained commercially by proper selection according to grain size. For this purpose grain-size charts are available, permitting classification according to grain size as revealed by the McQuaid-Ehn test.

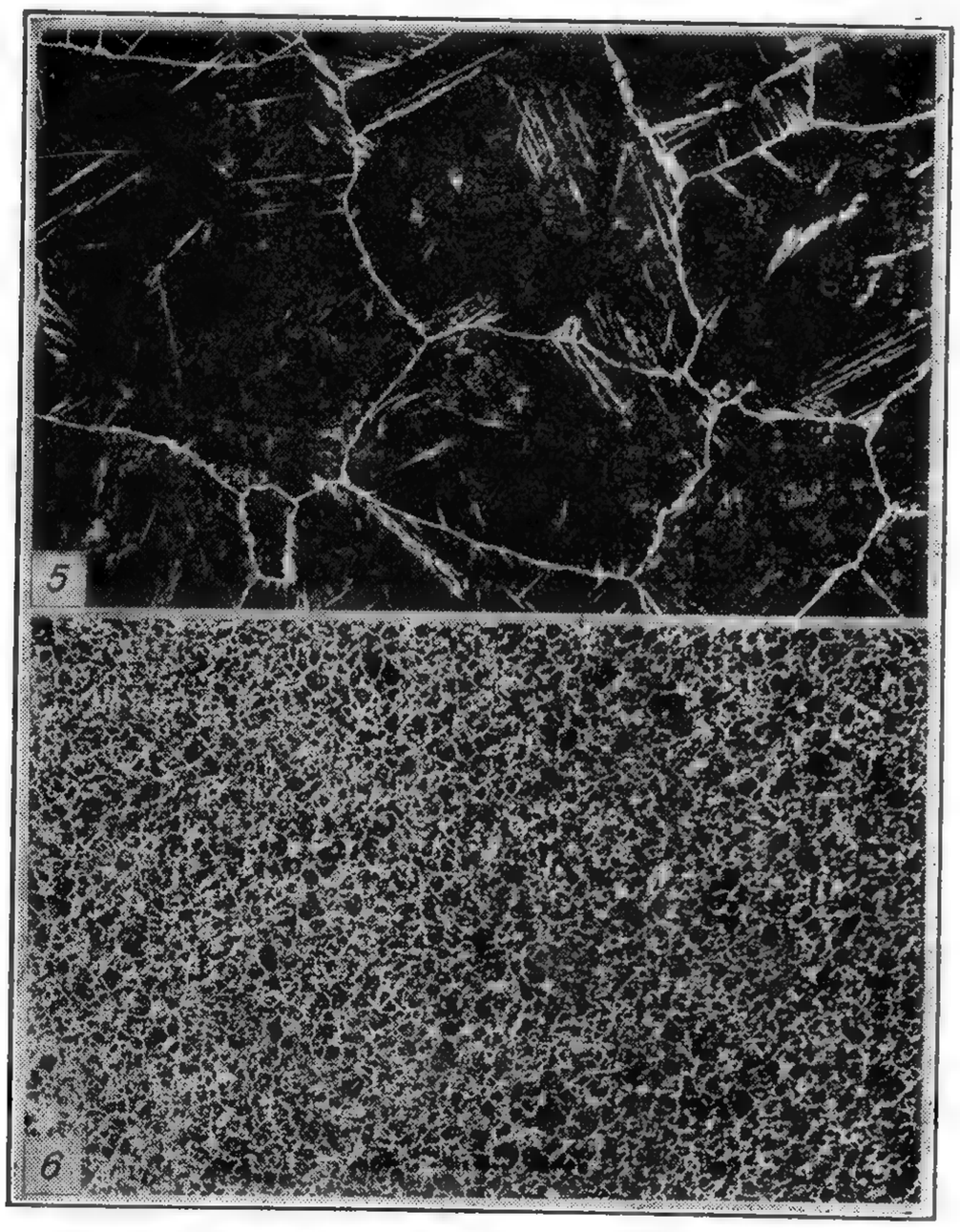

Fig. 5 Case structure of coarse grains after McQuaid-Ehn test (× 100).

Fig. 6 Case structure of fine grains after McQuaid-Ehn test. Same composition as Fig. 5 (× 100).

The Determination of Oxygen, Nitrogen and Hydrogen in Ferrous Metals

BY THE SUBCOMMITTEE ON GASES IN METALS*

OXYGEN, nitrogen and hydrogen exist in solid steel in small amounts but in a variety of forms. Oxygen occurs chiefly as inclusions, that is, as oxides and silicates of iron and other elements, but small amounts may exist in solid solution in the iron, or in special cases—in rimmed ingots and certain castings, for example—as gaseous compounds trapped in small pockets in the metal. Oxygen contents normally encountered in ferrous materials range from about 0.1% by weight (chiefly as FeO) in open hearth ingot iron to negligible amounts in completely deoxidized clean steel, with 0.005 to 0.020% of oxygen usually present in the general run of tonnage steels.

Nitrogen occurs chiefly as nitrides of iron and the alloying elements. The nitrogen content of ferrous materials normally will be about 0.005% for open hearth carbon

* The members of this subcommittee are J. G. Thompson, *Chairman* (National Bureau of Standards), J. B. Austin (United States Steel Corporation), B. M. Larsen (United States Steel Corporation), D. W. Murphy (Bethlehem Steel Company), M. A. Scheil (A. O. Smith Corporation), and F. W. Scott (Marquette Manufacturing Co., Inc.).

steels and about 0.015% for Bessemer steels. Alloying elements such as chromium absorb nitrogen readily, with the result that alloy steels ordinarily contain more nitrogen than the plain carbon steels. Furthermore, nitrogen may be intentionally added to high-chromium steels, so that nitrogen contents of 0.2% or more may be encountered.

The hydrogen content of ferrous materials is usually less than 0.001%. The mode of occurrence of these small amounts of hydrogen is not definitely known, but stable compounds or stable solutions of hydrogen apparently do not exist in steel.

In such a situation it is natural that methods of analysis differ widely in basic principles and in intent. In the determination of oxygen, for example, some methods are intended for the isolation and separate determination of one or more individual oxides, whereas others yield a single value for total oxygen without attempting to determine its distribution among the various combinations that are present. An effort to correlate results obtained by different methods, and thereby to establish the accuracy and limitations of the different methods, was the basis for a project of co-operative analysis, international in scope, which was completed in 1937. The results of the co-operative analysis[1] have been extended by further work in this country and abroad, particularly as described in the Reports of the Oxygen Subcommittee[2] of the Committee on the Heterogeneity of Steel Ingots, of the British Iron and Steel Institute.

The present discussion is confined to individual methods for the quantitative determination of oxygen, nitrogen and hydrogen in ferrous materials. Methods that yield qualitative rather than quantitative data—for example, microscopic and petrographic methods—are discussed elsewhere in this Handbook. (*See* page 445.)

Sampling. When the material under investigation is solid steel, sampling is a routine matter of selecting chips, millings or solid pieces that will be truly representative of the mass of material. However, if the investigation is concerned with the composition of molten steel, sampling is more difficult. Proposed expedients for sampling molten steel without loss of gaseous elements include using a spoon or bomb sample killed with an excess of aluminum,[3,4] arranging for the sample of molten metal to solidify in an evacuated steel tube,[5] and casting the sample in a heavily chilled, wedge-shaped mold.[6] These procedures and the determination of finely divided Al_2O_3 by measurements of turbidity have been discussed by Brower and Larsen.[20]

Methods for the Determination of Oxygen and Oxides. Methods for the quantitative determination of oxygen and oxides in solid steel fall into two groups: reduction methods and residue methods. The first group includes vacuum fusion, hydrogen reduction and aluminum reduction methods, involving reduction of the oxide constituents of the sample at elevated temperatures, with subsequent analysis of the products of the reduction. The second group includes several procedures for solution of the metallic constituents of the sample, leaving an insoluble residue from which individual compounds can be isolated and determined.

Vacuum Fusion Method. The vacuum fusion or hot extraction method consists of heating the sample to temperatures well above the melting point, in a previously degassed graphite crucible in a highly evacuated furnace. Under these conditions, all the oxides in the sample are reduced to gaseous oxides of carbon, which are removed from the melting chamber and analyzed for oxygen.

Samples for analysis by vacuum fusion usually consist of 5 to 20 g of clean material, preferably in one piece of minimum surface area, to reduce errors caused by the presence of an oxide film on the surface of all ferrous materials. For example, recent work by Sloman and Rooney[2d] shows that this surface film varies from about 1 to approximately 100×10^{-6} grams of oxygen per sq cm of surface, depending on the composition of the metal and the manner of preparation of the sample.

Minor variations in details of construction and operation of the different vacuum fusion installations[1,2] are matters of personal preference and do not affect the accuracy of results, as long as certain basic principles are observed. The blank correction should be as low and as constant as possible. The pumping system should maintain a pressure of less than 0.001 mm Hg in the furnace at operating temperature, and should extract the evolved gases from the furnace rapidly and completely.

The vacuum fusion method, properly operated, yields accurate results for the total oxygen content of a wide variety of plain carbon and alloy steels, and is generally accepted as the standard with which the results of other methods are compared. Its principal limitation arises from the presence, in the sample, of volatile elements, the vapors of which react with carbon oxides in the upper portions of the furnace chamber and thus lead to low recoveries of oxygen evolved from the sample. Manganese and aluminum are the principal offenders; other elements, such as zinc and calcium, would cause interference but are not usually encountered in ferrous materials; high sulfur contents, that is, more than 0.05%, contaminate the copper oxide and may necessitate frequent renewal. The maximum permissible amount of manganese or aluminum varies with different installations; some operators believe that as much as 3% Mn or 2% Al can be tolerated, whereas others have reported interference from manganese or aluminum contents of less than 0.5%. In some laboratories, tin is added to the melt to reduce the manganese effect. Another possible source of error is the spattering that frequently occurs during the melting of a sample with high gas content and results in a loss of sample material before the reduction is completed. A third source of error is the occasional presence of unusually large particles of alumina, silica or other refractory compounds that may require extended operation for their complete reduction.

Two attempts to develop rapid methods for determining oxygen content, based on the principles of vacuum fusion, have been reported recently. Singer[7] suggested melting the sample in nitrogen instead of in a vacuum, to simplify maintenance of high-vacuum apparatus, and Derge[6] described a modified apparatus and procedure for rapid analysis. In both instances it appears that increased speed has been obtained at the expense of accuracy and reliability.

Fractional Vacuum Fusion Method. The method was developed to obtain more information than the single value for total oxygen, which is derived from the "standard" vacuum fusion operation. In the fractional procedure, tin is added to the sample in the graphite crucible to lower the melting point. The temperature of the molten metal is then raised in stages and the gases evolved in each stage are collected and analyzed separately. The carbon oxides evolved at the lowest temperature are ascribed to the reduction of FeO, and the gases evolved at progressively higher temperatures to MnO, SiO_2 and Al_2O_3, respectively.

The fractional procedure developed by Reeve and by Hoyt and Scheil[1] in this country has been studied recently by workers in England. Operation is correspondingly slower than a single determination of total oxygen and the accuracy of the various fractions has been questioned. After extended study of the fractional procedure, Swinden, Stevenson and Speight[2c,2d] concluded that the total content of oxygen is equal to that obtained by direct vacuum fusion, and the separation of easily reducible oxides from SiO_2 and Al_2O_3 is complete, but the separation of FeO and MnO is uncertain.

Hydrogen Reduction Method. The oxides present in steel can be reduced by hydrogen at temperatures of about 1200 C, and determination of the oxygen content of the exit gases indicates the amount of oxides reduced.

A major difficulty in the operation of the hydrogen reduction method is to insure exposure of all the oxides in the sample to the action of hydrogen. Early workers added antimony and tin to obtain the sample in the molten state, but this was unsatisfactory because of uncertainty in the blank correction. If solid samples are used, reduction of oxides in the interior depends on diffusion of hydrogen through the metal. Consequently the sample must be very finely divided to insure completion of the reaction in a reasonable time.

Brower, Larsen and Shenk[1] recommended the use of very fine millings, a preliminary stripping operation at 500 to 550 C to remove surface oxygen, and the use of high-fre-

quency induction heating to raise the temperature to 1200 C for the determination of "body" oxygen. This procedure has been applied to alloy and simple steels, resulting in complete reduction of FeO and MnO and in some instances, of SiO_2 and Al_2O_3. Large amounts or large particles of silicates and alumina are incompletely reduced under these conditions. Difficulty has been encountered in the analysis of material with a high content of FeO (Armco iron, for example), because of inability to separate the surface from the body oxygen in this type of material. On the other hand, the presence of manganese and aluminum should cause less interference in the hydrogen reduction method than in vacuum fusion at higher temperatures. Under optimum conditions, results are reproducible to about 0.002% of oxygen, but according to Stevenson,[2c] accuracy of this order is not always obtainable.

Baker[8] proposed a modified hydrogen reduction procedure, using a small amount of hydrogen at reduced pressure, to keep the blank correction low. The hydrogen was purified by diffusion through palladium.

Aluminum Reduction Method. Gray and Sanders[2a] suggested that the total oxygen content of steel samples might be determined by melting the sample with an excess of aluminum at 1150 C, in a neutral atmosphere or in vacuum, with subsequent solution of the cooled fusion in acid and determination of its Al_2O_3 content. Operating in vacuum is usually preferred to operating in hydrogen or other neutral atmospheres.

British investigators[2c] have reported that the results were in satisfactory agreement with results by vacuum fusion and that complete recovery of oxygen was obtained from samples of SiO_2, $Al_2O_3.2SiO_2$, Fe_2O_3 and MnO. The procedure has been applied to the analysis of plain carbon and simple alloy steels, slags, pig irons and cast irons.

Residue Methods. The chief claim for the residue methods is that they determine oxides as they exist in steel. Results of the residue analyses usually are reported as FeO, MnO, SiO_2 and Al_2O_3; other oxides (for example, Fe_2O_3 or the oxides of alloying elements) may be determined when their presence is indicated. Disadvantages of the residue methods lie in the necessarily complicated procedure of purifying and analyzing the residue, and in the varying degrees of insolubility of the different oxides in the different solvents. Results that were available for these methods previous to the co-operative analysis indicated that most of the methods needed further study. The benefits derived from further study are evident in the improved reproducibility of results and in the agreement of results by different methods in the subsequent work of British investigators.[2]

Iodine Method. When a sample of steel is treated with a suitable solution of iodine, the metallic constituents are dissolved, leaving a residue of unattacked oxides, usually contaminated by carbides and other materials.

An aqueous solution of iodine in ferrous iodide, as recommended by Cunningham and Price, has been used in this country. It is claimed that sulfides and nitrides are completely dissolved and do not interfere with analysis of the insoluble residue. Results of the co-operative analysis[1] indicated that good results for SiO_2 and Al_2O_3 may be obtained by this method, properly operated, but that the values obtained for FeO and MnO are less certain. Some of these difficulties have been overcome by subsequent research in England,[2] particularly in the analysis of pig and cast irons.

The use of a solution of iodine in anhydrous methyl alcohol was proposed by Rooney and Stapleton and this alcoholic iodine method has been studied extensively in England. Rooney[2c] concluded that the method can be used for the determination of oxides in low and medium carbon steels that do not contain appreciable amounts of elements which form stable carbides (for example, chromium, vanadium and titanium) or which form insoluble iodides (for example, titanium and molybdenum). Variable results for MnO are obtained sometimes, special precautions must be observed in the analysis of rimming steel, and difficulties are encountered in the analysis of aluminum-killed or aluminum-containing steels, because of the presence of aluminum carbides and nitrides. According to Pearce,[2c] the alcoholic iodine method is not suitable for the analysis of cast irons because of interference by phosphorus.

Electrolytic Method. In this method, the soluble metallic constituents are separated from the insoluble residue by making the sample anode in a suitable electrolyte. Purification and analysis of the residue are similar to operations in the chemical solution methods.

Solutions recommended for use as electrolytes include ferrous sulfate plus sodium chloride; sodium citrate plus potassium bromide; ferrous chloride; and magnesium iodide. Results obtained in the co-operative analysis[1] indicated that electrolytic methods in general were more reliable for determinations of SiO_2 and Al_2O_3 than for FeO and MnO. Scott's method, using a magnesium iodide electrolyte and a carefully controlled procedure, yielded the best results of any of the electrolytic methods.

Electrolytic methods appear to be even more complicated and difficult to control than the chemical residue methods. Perhaps because of this, electrolytic methods have received less attention recently than other methods. Hare and Soler[9] used Scott's electrolytic method in combination with petrographic examination to study the relation of inclusions to furnace practice for alloy steels.

Chlorine Method. If a sample of steel is heated at moderately elevated temperatures in a stream of purified, dried chlorine, the metallic constituents are converted to soluble or volatile chlorides and the unattacked oxides may be determined in the insoluble residue. If the temperature is too low, the residue is contaminated by particles of metal; if it is too high, some of the oxides are attacked by the chlorine. Alloying elements generally require higher temperatures to react with chlorine, and some alloying elements form insoluble chlorides.

Investigators for the Heterogeneity Committee[2c,2d] used 350 C as the chlorination temperature for a number of simple steels. For killed steels, the results were reproducible and the total oxygen values agreed with those obtained by vacuum fusion. Low recoveries of oxygen were obtained from basic Bessemer rimming steel, and difficulties were encountered with a steel that contained 0.75% Cr.

Mercuric Chloride Method. Separation of oxides from the metallic constituents by solution of the latter in an aqueous solution of mercuric chloride has been described by Maurer, Klinger and Fucke.[10] The procedure is intended particularly for the determination of FeO and MnO, which are the least satisfactory determinations by most of the residue methods. Difficulties of purification and analysis of the residue are comparable to those of other methods, and the available data indicate that satisfactory results may be obtained for MnO but that results for FeO are consistently high.

Hydrochloric and Nitric Acid Methods. These methods depend on the solubility of metallic constituents and relative insolubility of certain oxides in approximately 10% hydrochloric or nitric acid. The hydrochloric acid method,[11] somewhat faster and more convenient, is an integral part of the aluminum-reduction method of Gray and Saunders.

Either method furnishes a relatively simple means for the accurate determination of Al_2O_3. Results for SiO_2 are less reliable and neither method is applicable to the determination of FeO or MnO.

Methods for the Determination of Nitrogen. Nitrogen exists in steel primarily in combination, as nitrides of metallic elements. Other possible forms are nitrogen in solution in the metal, or molecular nitrogen in cracks or blowholes, but the amounts ordinarily present in these forms are insignificant. Of the various methods that have been proposed for the determination of nitrogen in steel, two methods of proven worth are available—the vacuum fusion method and the solution-distillation method. It has been shown repeatedly, in England[2d] as well as in this country, that both methods yield accurate results for nitrogen in a wide variety of plain carbon and alloy steels.

In the vacuum fusion method, nitrides in the sample are decomposed by the action of graphite at high temperatures in a high vacuum, forming molecular nitrogen, which is subsequently determined by appropriate analytical means. Some of the nitrides present, particularly in alloy steels, are decomposed slowly. Consequently, it may be advisable to continue the vacuum extraction beyond the minimum time required for reduction of the oxides, to insure complete decomposition of all the nitrides.

In the solution-distillation method, also known as the Allen method or chemical distillation method, the sample is dissolved in acid to convert the nitride nitrogen to ammonium salts. The acid solution is made alkaline and distilled and the ammonia in the distillate is determined by titration or by colorimetric means. Properly operated, this simple procedure indicates correctly the total of the nitrogen present in the specimen as metallic nitrides for a wide variety of steels. However, it has been shown that modern alloy steels may contain nitrides (for example, nitrides of columbium, vanadium, titanium or zirconium) which are not completely decomposed by the simple treatment. To remedy this, variations of the decomposition treatment have been proposed.[2d] For example, Cunningham and Hamner[12] used a mixture of hydrochloric and hydrofluoric acids to decompose the sample, filtered the insoluble residue and digested it with sulfuric acid plus addition agents. The two solutions may be combined for a single determination of total nitrogen or may be analyzed separately for "soluble" and "insoluble" nitrides. Johnson[13] treated the steel with hydrochloric acid, digesting the residue in a mixture of perchloric and sulfuric acids. With these modified procedures, even the alloy steels yield the same results for nitrogen by solution-distillation as by vacuum fusion.

Suggestions to simplify or to hasten the operation of the solution-distillation procedure have been offered by Morrison and Gill[14] and by Beeghly.[15]

Methods for the Determination of Hydrogen. The amount of hydrogen present in solid ferrous materials is seldom as much as 0.001% and the possible importance of such amounts of any constituent has been recognized only recently. Consequently, the determination of hydrogen in steel has received less attention and is less firmly established than the determinations of oxygen and nitrogen. The Fourth Report of the Oxygen Subcommittee in 1943 showed a satisfactory agreement in results obtained by vacuum fusion and by vacuum extraction, and presented other evidence that both methods recover all the hydrogen present. On the other hand, the symposium conducted in this country in 1944 by the American Institute of Mining and Metallurgical Engineers, indicated that the determination of hydrogen is a highly controversial matter. A major difficulty is the uncertainty that the hydrogen content of the sample at the time the analysis is made is the same as the content when the sample was taken. Hydrogen diffuses readily through steel at elevated temperatures and even at room temperature it can diffuse out slowly. The sampling of molten steel presents additional problems, including how to prevent loss of dissolved hydrogen during solidification of the sample.*

The presence of hydrogen in the gases evolved in analysis of steel by vacuum fusion has been recognized for a long time, but the accurate quantitative determination of these very small amounts of hydrogen is not practical in the ordinary operation of the vacuum fusion method. The blank correction for hydrogen is frequently too large and variable to permit determination of a few ten-thousandths of one per cent of hydrogen, and the difficulty of determining a minute amount of hydrogen is increased by the presence of much larger amounts of oxygen and nitrogen. In addition to the analytical difficulties, it is uncertain that all the hydrogen originally present in the sample is recovered in the analysis.

The availability of the vacuum fusion method for hydrogen may be summarized as follows: Satisfactory results are obtained if the hydrogen content of the specimen is high and stable; that is, if there is a large amount of hydrogen to be determined and this hydrogen all stays in the specimen until the latter is dropped into the melting crucible.

The vacuum extraction procedure depends on the ability of hydrogen to diffuse in solid steel at moderately elevated temperatures. Newell[16] recommended vacuum extraction for 1 hr at 600 C. Holm and Thompson[17] preferred to operate at 800 C for more rapid extraction of the gas. Fifteen minutes at 800 C appeared to be ample for the complete extraction of hydrogen from specimens of plain carbon steel but subsequent experience showed that other types of steel required longer extraction periods. Advantages of the vacuum extraction procedure include rapid operation, analysis of a hydrogen-rich mixture, and a low blank correction. The rate of evolution of hydrogen from the specimen tapers off, sometimes making it difficult to determine when extraction has been completed, but evidence submitted in the papers cited, and in others,[2d] shows agreement with results by vacuum fusion; that is, complete extraction of hydrogen was obtained by vacuum extraction, for the samples examined. However, some evidence presented at the AIME symposium does not confirm this conclusion. Further work is needed to establish the limitation of the method.

Reports have been made of several attempts to determine hydrogen in ferrous materials by combustion in purified oxygen, with subsequent determination of the water formed. Schwartz and Guiler[18] described a procedure for white cast-iron samples, but the application of combustion methods to the determination of the small amounts of hydrogen found in commercial steel has not been satisfactory. However, some recent experiments at the National Bureau of Standards indicate that the high results frequently obtained by combustion may be corrected by the observance of special precautions, with the result that values for hydrogen by combustion are at least of the same order of magnitude as the results by vacuum fusion and vacuum extraction. Further work is needed to determine the applicability of combustion procedure for the determination of hydrogen in steel.

Moreau, Chaudron and Portevin[19] reported that hydrogen could be extracted from metallic specimens by ionic bombardment at low temperatures, but the procedure has not been developed as an analytical operation.

Summary. The present status of the determination of oxygen, nitrogen and hydrogen in ferrous materials is briefly as fcllows:

1 For the determination of total oxygen, the vacuum fusion method yields reliable results for a wide variety of plain and alloy steels. Satisfactory determinations of total oxygen have been obtained by the reduction and residue methods; but, in general, reduction methods are most successful in the determination of easily reducible oxides, whereas residue methods are most reliable for the determination of Al_2O_3 and SiO_2.

2 Accurate results for the nitrogen content of a variety of ferrous materials are obtained by either the vacuum fusion or solution-distillation methods.

3 The determination of hydrogen is still in an early stage of development.

* Editor's Note. A recent paper,[21] published since the proof of this article was read, gives a detailed account and a comparison of five methods of sampling the liquid steel bath.

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Physical and Mechanical Testing of Tool Steels

BY THE SUBCOMMITTEE ON TOOL STEEL*

THIS article deals with the physical and mechanical tests applied to tool steels. The practical value of such tests depends on the interpretation of them. The principal objective of this article is to assist in the selection of tests for evaluating tool steel in relation to service conditions.

Fracture Tests. Visual examination of fractured surfaces may provide information concerning (1) internal defects and (2) the effects of previous thermal treatment, especially the grain size.

1 Fracture Tests for the Determination of Internal Defects. Either hardened or annealed steel may be examined in a fracture test for internal defects. However, the conditions to be described can usually be recognized more easily in hardened than in annealed steel.

Hardened test disks of suitable thickness (usually ¼ to ⅜ in., depending on the other dimensions) can be fractured by applying a load at the center of the disk either by pressure or by a blow. Short pieces of bars 1 in. or less in diam are fractured transversely in the same manner. Proper precautions should be taken to avoid danger from flying pieces. Hardened disks or tools may be nicked with a thin cutoff wheel to assist in obtaining satisfactory breaks. The use of macro-etched disks for hardening is not recommended. Segregation and nonmetallic inclusions may be distinguished by heat-tinting the fractured specimens.

The various defects that may be recognized on a fractured surface are discussed below.

Decarburization. Decarburization is determined by the difference in grain size between outer edges and the interior of a specimen. The decarburized zone will exhibit a grain larger in size and brighter in color than the interior of the specimen. All hot rolled bars have a decarburized surface, so acceptance of material is based on whether the amount present may be detrimental (Fig. 1).

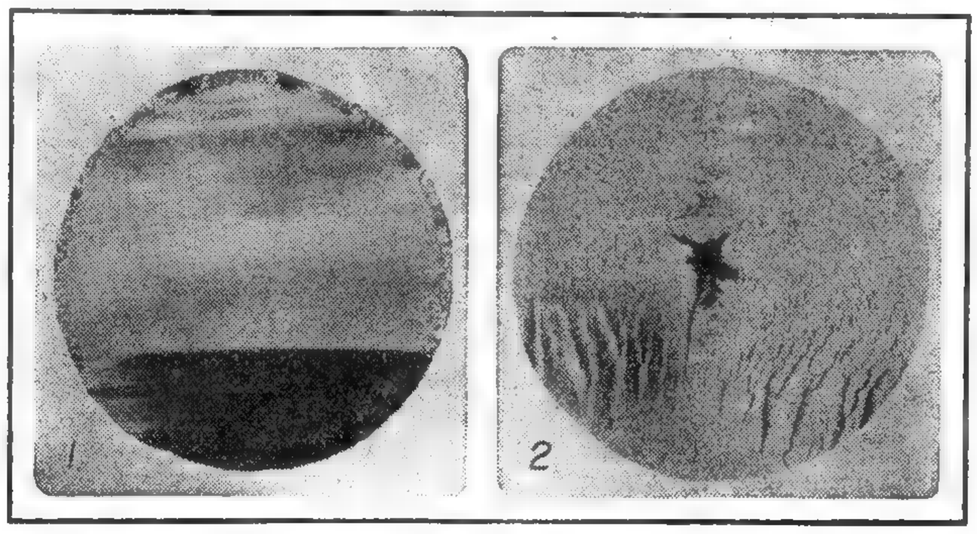

Fig. 1 Decarburized surface
Fig. 2 Pipe

Pipe. Piped steel, caused by shrinkage cavities in the ingot, will be recognized from an actual discontinuity at or near the center of the specimen. When this condition has been largely removed, a coarser or brighter grain may appear in the center (Fig 2).

Bursts. Ruptures produced by forging or rolling resemble pipe somewhat. Distinction may sometimes be made from the shape of the defect or from deep-etch tests.

Flakes. Flakes will appear as short ruptures or bright spots in longitudinal fractures. When fractures are made through, rather than across the flakes, the bright colored spot will appear somewhat conchoidal in form. Care should be taken not to confuse this defect with areas that have been made bright by rubbing during fracturing, or with sections that have been elongated during breakage.

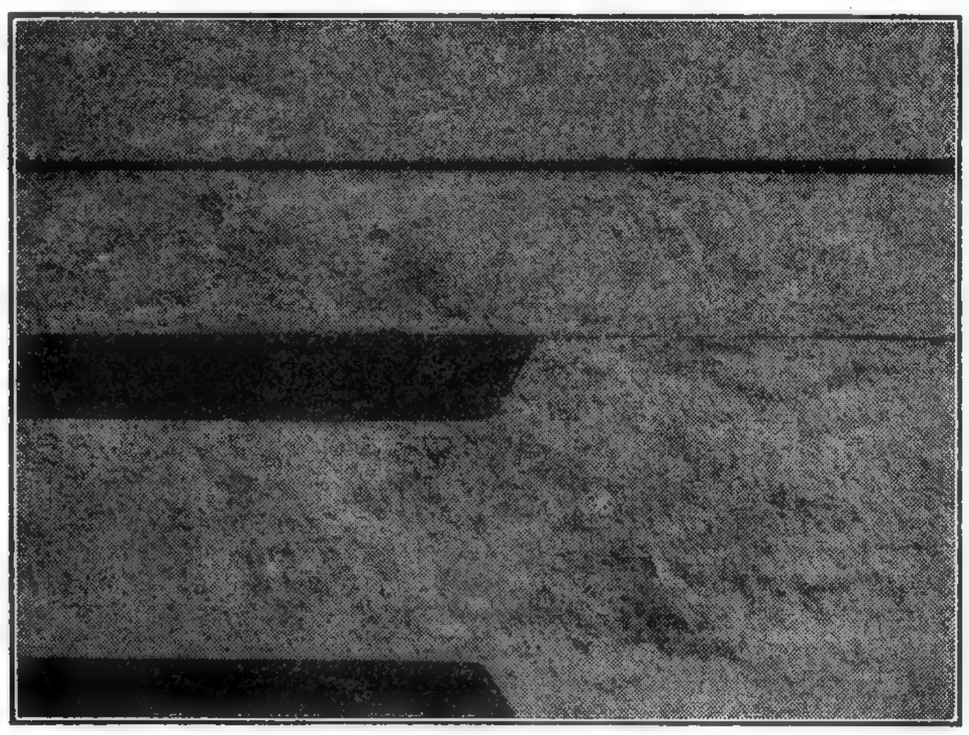

Fig. 3 Woody structure

Woody Structure. Fractures taken in the direction of rolling or forging often have a fibrous appearance. Since all steels are heterogeneous, the fibrous appearance will depend on several factors, such as composition, cleanliness, amount and direction of working. Steels so highly alloyed as to be segregated, such as high speed steel, may reveal a fibrous structure, especially in larger sections where there has been comparatively little reduction from ingot to finished bar. The effect of the fibrous structure can be interpreted only when the general characteristics of the steel are known. Figure 3 shows a woody structure.

Inclusions and Carbide Segregation. Excessive inclusions or carbide streaks may be detected by examination of longitudinal fractures of hardened disks (Fig. 4 and 5).

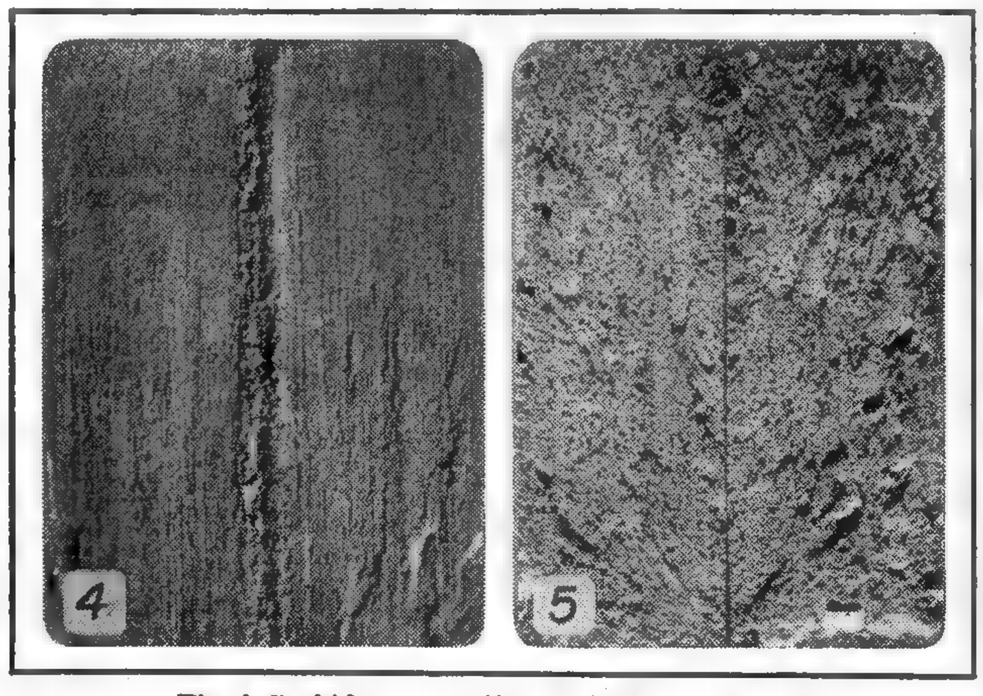

Fig. 4 Carbide segregation in high speed steel
Fig. 5 Inclusions in high speed steel

2 Fracture Test for Grain Size. This test consists of hardening the specimen (machined to ¾ in. in diam by 3 in. long), notching it in the middle and fracturing by impact. The surface of the fracture is then examined for grain size, in comparison with the Shepherd grain size standards illustrated in Fig. 6. (*See also* Grain Size and Hardenability Tests, below.)

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Hardness Tests. Descriptions of the several methods of hardness testing and data for hardness conversion are given in the article on page 93 of this Handbook. The so-called "microhardness testers" are used to determine the hardness of small tools or to detect nonuniformity of hardness caused by variation of structural constituents. Machines using the principle of indentation by a spherical ball are preferred for testing tool steels of medium or low hardness. For testing steel of high hardness, the machines employing diamond indenters are generally used. The file test is used on hardened steels only. Hardness tests at elevated temperatures are of interest, especially with high speed and hot work steels.

Macro-Etch Tests. The procedures for macro-etching are presented in the article on page 389. Too strong concentration of the etching solution, too high temperature, or too long immersion of the specimen in the etchant may result in overetching and should therefore be avoided. Macro-etching is ordinarily applied to steels in the annealed condition.

The deep-etch test reveals readily and quickly many of the characteristics of tool steel, but in some instances, further examination by standard testing methods is required to evaluate the characteristics properly. The knowledge that a piece of steel is dendritic or contains metallic and nonmetallic segregates is not sufficient evidence on which to base definite conclusions concerning the properties of the steel. The deep-etch test is of real value in separating materials that are obviously defective from those that are not. The test is easy to perform; however, experience and judgment are required for interpretation of the results.

Cracks From Etching. Before being etched, hardened or otherwise highly stressed steels should be tempered sufficiently to prevent cracking, because they may crack in the etching solution.

Surface Appearance. Steels may etch with a comparatively smooth surface or with a very rough or pitted surface, depending on composition and variables in manufacture. A roughened surface is not necessarily detrimental.

Irregularity in pitting may usually be attributed to one or more of the defects discussed below. Certain manganese, oil-hardening steels are more readily attacked by the acid than are most other tool steels, and are often decidedly roughened without being defective in any way.

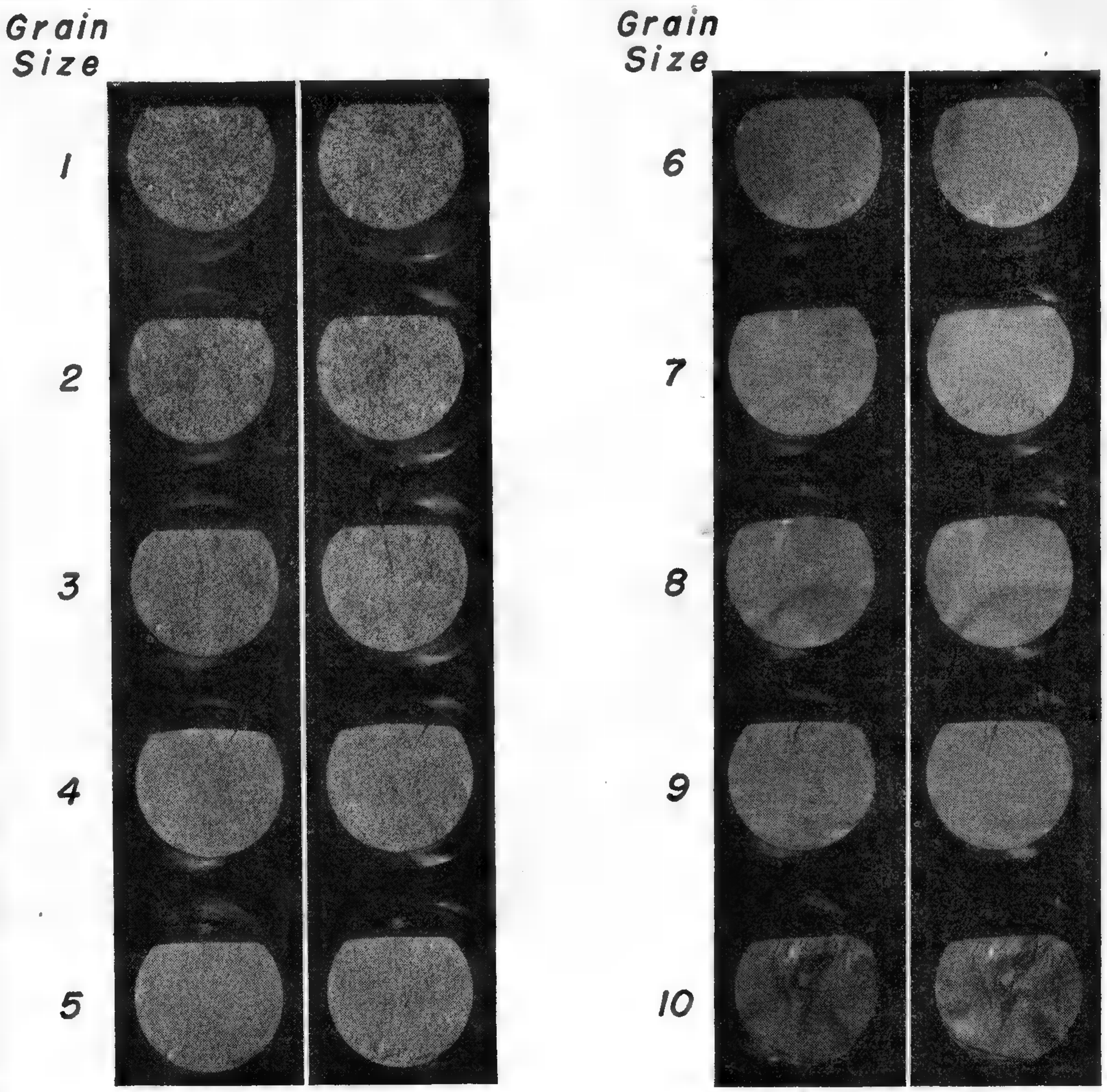


Fig. 6 Shepherd grain size fracture standards

These photographs may be viewed to obtain a three-dimensional or stereoscopic effect by placing a light piece of cardboard, 6 to 10 in. square, so that one edge rests on the center line between the prints and the other edge touches the observer's nose. The eyes should then be adjusted so that there appears to be only one print rather than two. The lighting should be adjusted so that the intensity on each side is approximately the same.

(Metal Progress Data Sheet 78, 1946; stereoscopic photographs by George K. Manning)

Center Porosity. When porosity results from an actual discontinuity within the metal, the defect should probably be classified as "pipe". Usually, however, the porosity is of such a nature that it is not visible until the specimen has been etched. This condition can be found in widely varying degrees, and the question of whether the steel should or should not be used is one for experienced judgment (Fig. 7).

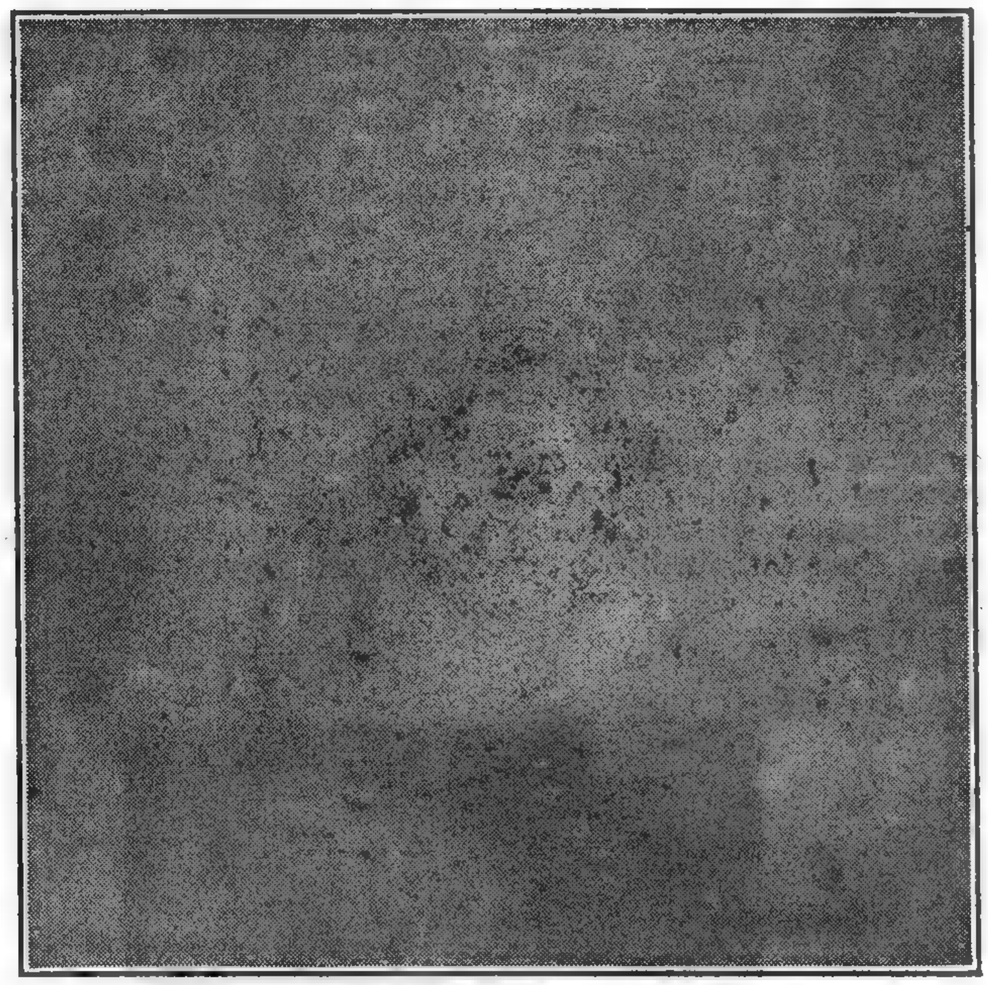


Fig. 7 Porosity

Pipes, Bursts and Center Segregation. Usually such defects are visible before deep etching. After etching, it is often possible to distinguish among the three by the degree of sponginess surrounding the defect. Piped material usually shows considerably more sponginess than burst material (Fig. 8, 9); Fig. 10 illustrates center segregation.

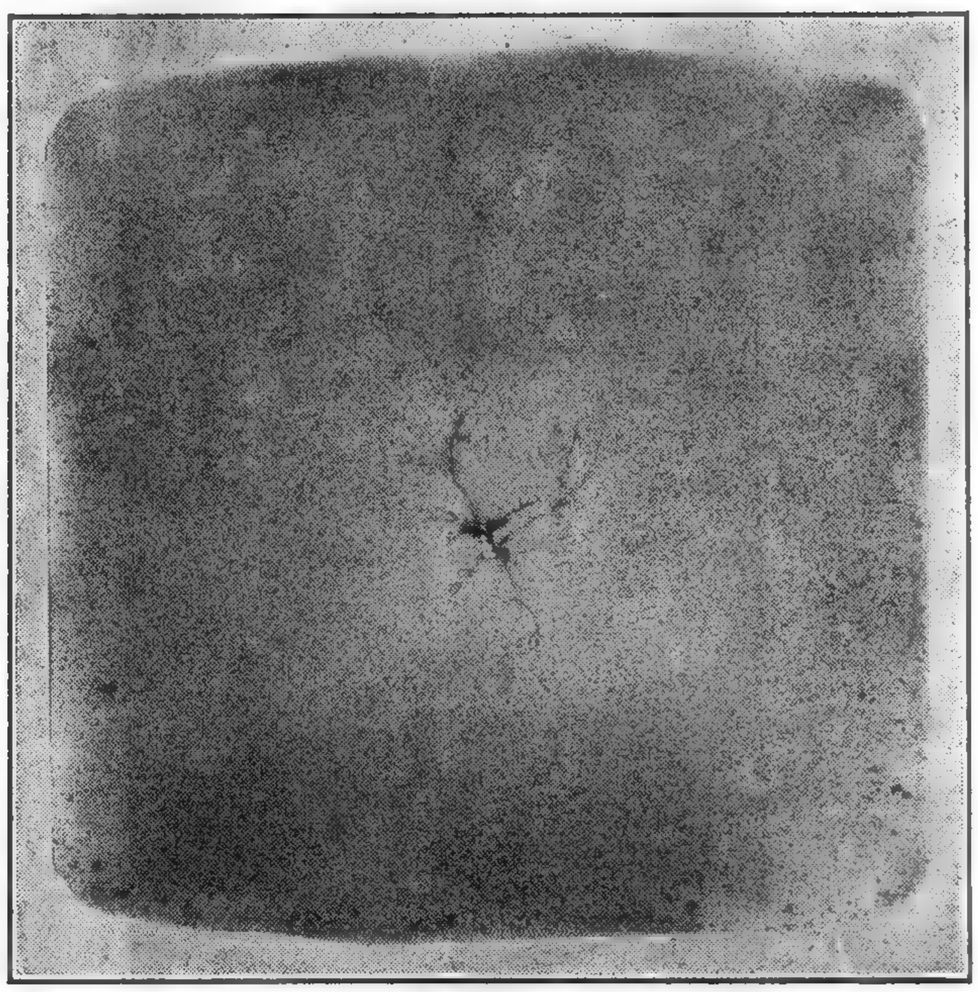


Fig. 8 Pipe

Unsound Steel. When numerous blowholes and nonmetallic inclusions are visible as a result of the deep etch, they usually indicate that both gases and oxides were distributed throughout the steel at the time of casting.

*Nonmetallic Inclusions and Metallic Segregates.** In killed steels, nonmetallic inclusions usually appear as pits, which should not be confused with pits that occur from the etching out of metallic segregates. When the presence of nonmetallic inclusions is suspected in highly alloyed steels that may contain metallic segregates, a comparison should be made of an annealed specimen and a hardened specimen etched alike. If the etching pits are the result of nonmetallic inclusions, the appearance of them will be similar in both the annealed and the hardened specimens; if they are the result of a metallic segregate, they will differ. Microscopic examination is preferable for determining the true character of the segregates.

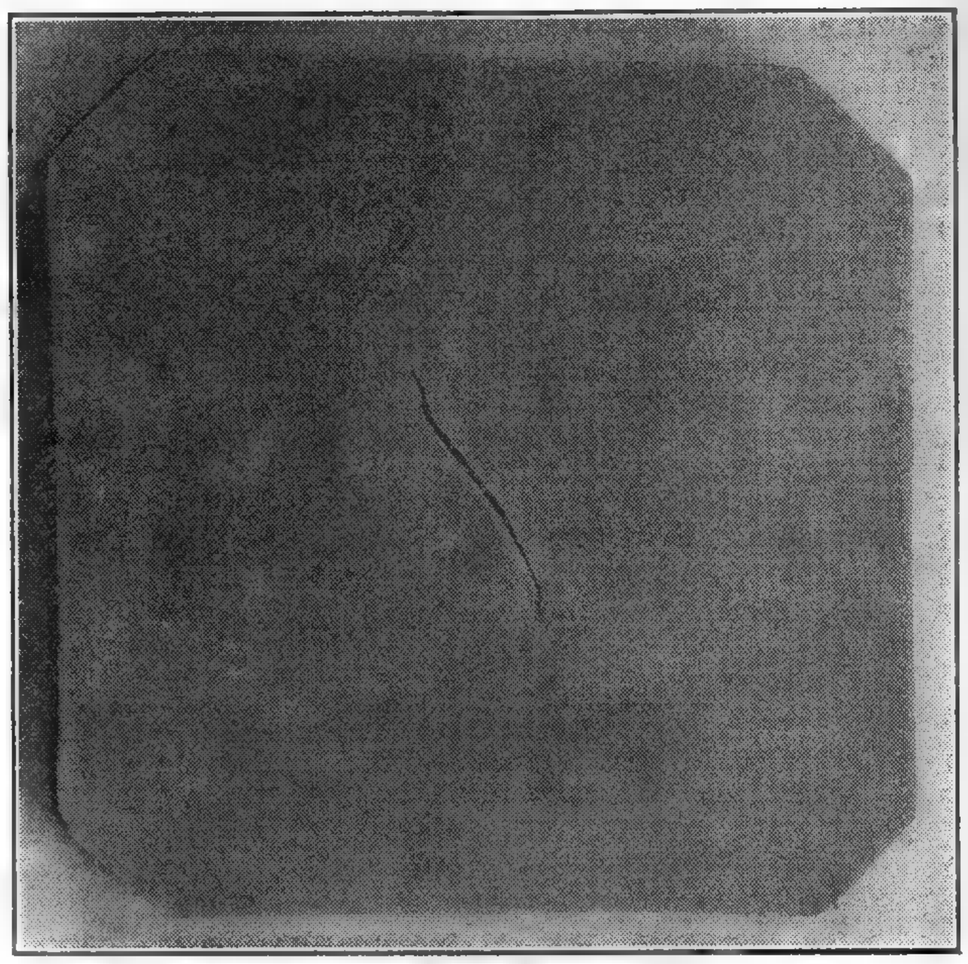


Fig. 9 Hammer burst in high speed steel

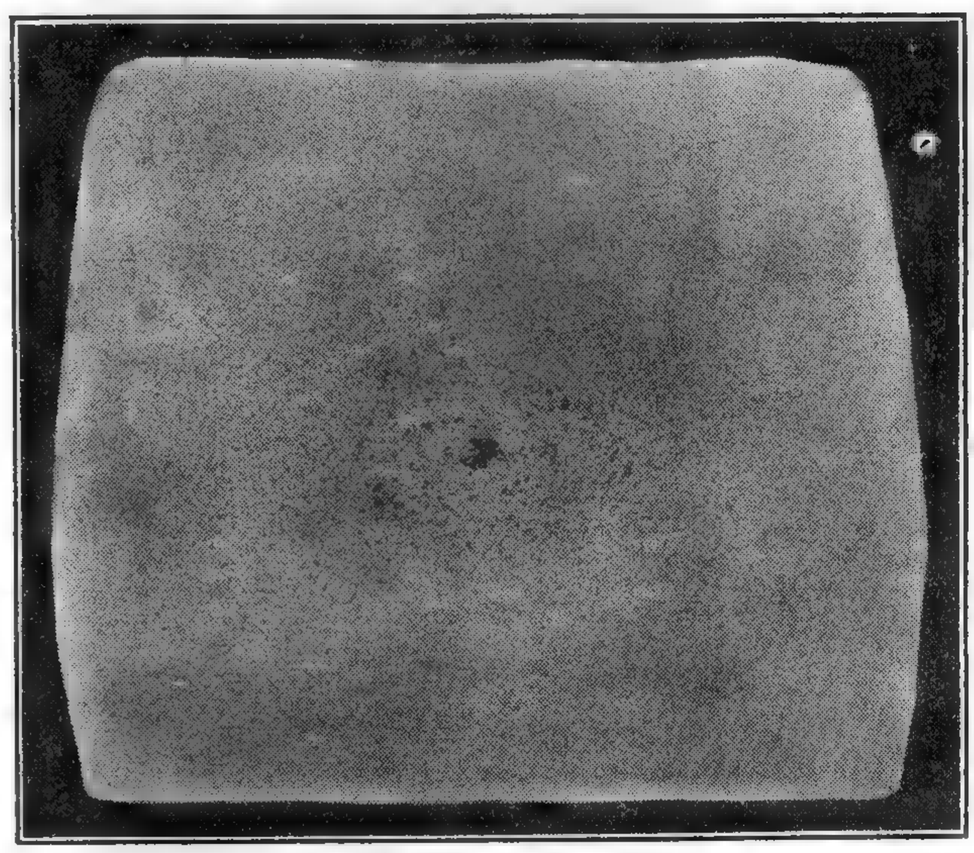


Fig. 10 Center segregation

Internal Cracks. Internal cracks, sometimes called "flakes" or "cooling cracks", can often be observed as the result of the deep-etch test. These cracks are an actual

* *See also* the article "Nonmetallic Inclusions in Steel", page 445.

discontinuity in the metal and, depending on their nature and distribution, may make the steel unfit for use (Fig. 11).

Dendritic Structure. Etching often reveals a dendritic structure, which is the result of the manner of crystallization of the ingot. A dendritic structure is not detrimental

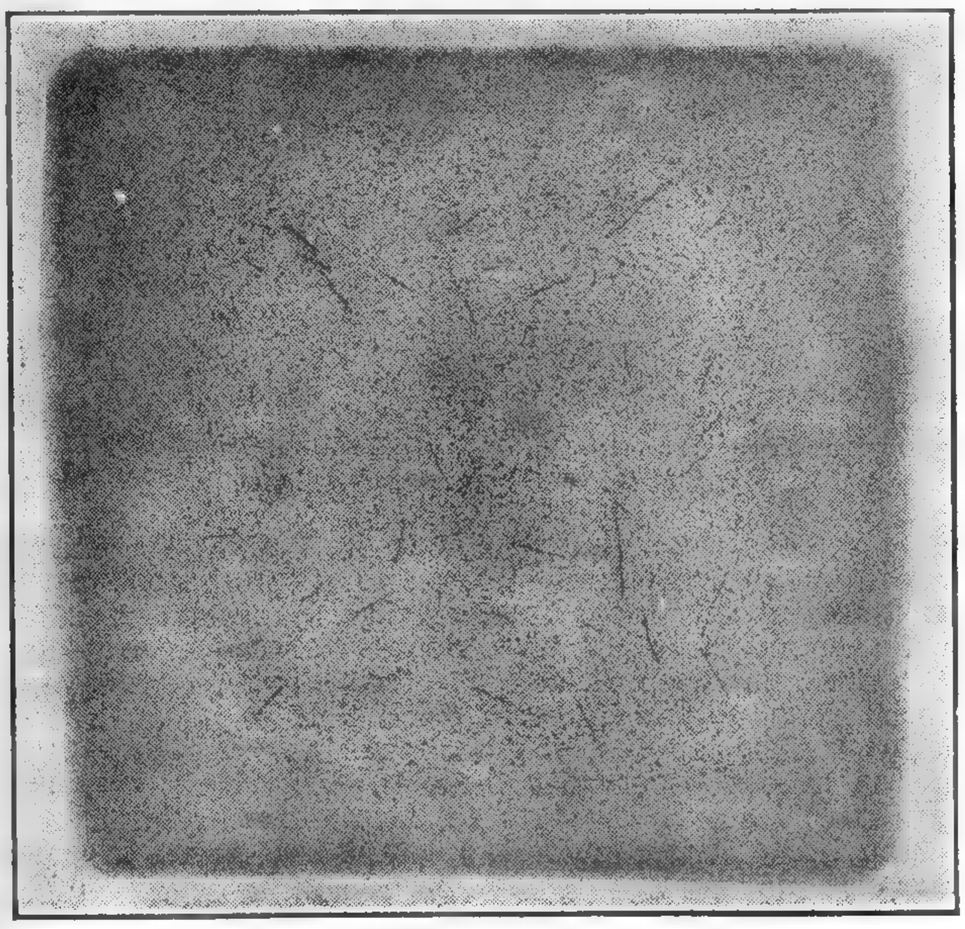


Fig. 11 Cooling cracks

in most instances. The permissible degree depends on the application (Fig. 12).

Pattern Effect. Pattern effect is caused almost entirely by the crystallization of the ingot and generally results when the part of the bar that was the columnar structure of the ingot etches differently from the part that was the granular structure of the ingot. If the steel contains

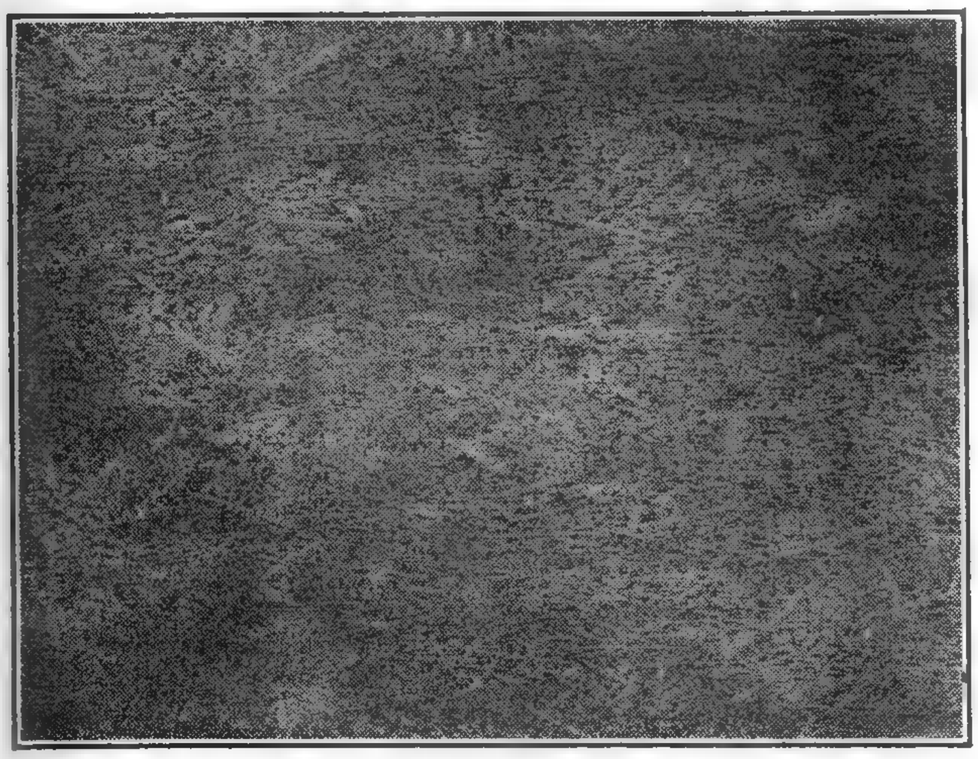


Fig. 12 Dendritic structure

numerous sulfide and silicate inclusions, then the area of contact between the columnar structure and the granular structure may be particularly noticeable. In the absence of large amounts of sulfides and silicates, the pattern effect probably has no serious consequence (Fig. 13).

Grain Size. Although the etch test is of no definite value in determining grain size, nevertheless the manner in which many specimens etch may indicate something of the grain size. Generally, the larger the grain, the coarser is the appearance of the etched surface.

Decarburization and Carburization. Ordinarily the areas that have been either decarburized or carburized, etch differently from the remainder of the specimen; the chief difference is usually in color. Decarburized parts appear lighter in color and carburized parts appear darker (Fig. 14).

Hardened Case. In shallow-hardening steels, a contrast

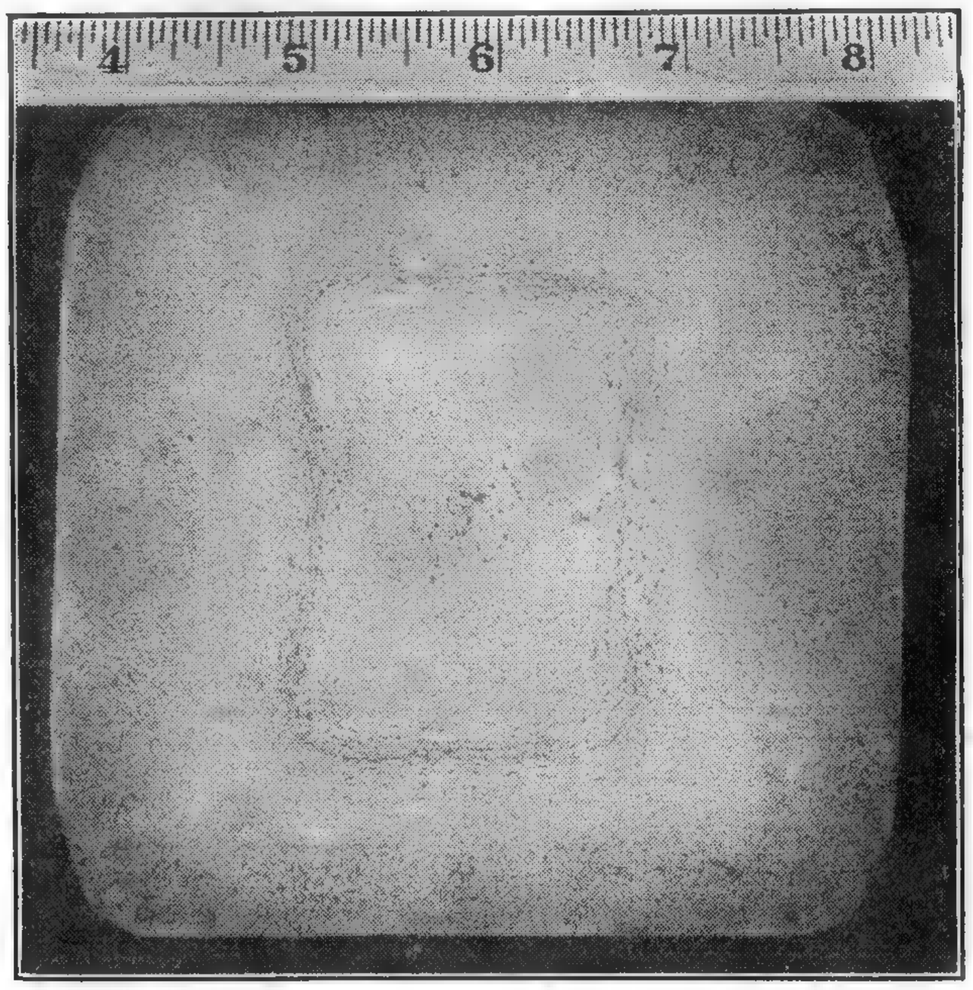


Fig. 13 Ingot pattern

in color between the case and the core appears as a result of mild etching (Fig. 15).

Flow Lines From Forging or Rolling. When subjected to macro-etching, often a longitudinal section shows flow lines because of the elongating of structural constituents. Such flow lines, always more or less visible, indicate the directions in which the steel was worked and do not signify defective material (Fig. 16).

Surface Defects. Seams, laps, cooling cracks and other

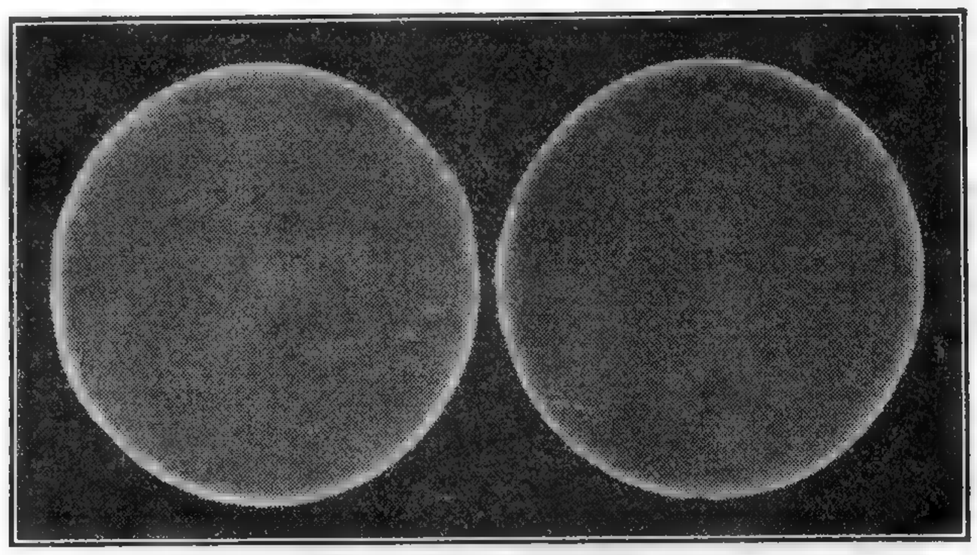


Fig. 14 Decarburization

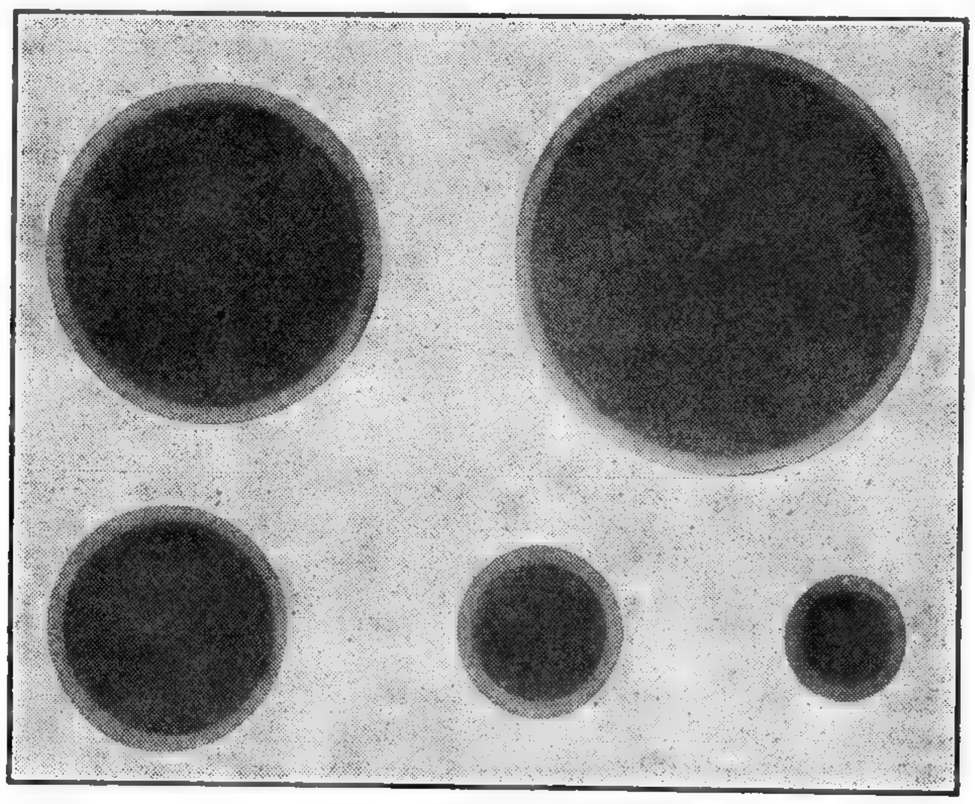
surface defects are revealed and exaggerated in the surface of bars that have been deeply etched (Fig. 17). Therefore, a short-time etch is recommended.

Soft Spots. Soft spots, which often are present after hardening of carbon or low-alloy tool steels, can be distinguished readily by the macro-etch test. The soft spots invariably etch in relief and are not so dark in color as the harder surrounding areas (Fig. 18).

Grinding Cracks. Grinding cracks can be distinguished easily by the standard macro-etch and are usually identified by a pattern of some symmetry (Fig. 19).

Grain Size. The "grain size" of a tool steel usually refers to the size of the austenite grains formed when the steel is heated to the recommended austenitizing temperatures for hardening. A complete discussion of austenitic

grain size, the significance of it and the general methods for measuring it, are presented in separate articles on page 399 and page 407.



Diameter, inches	Chill Penetration, inch	Rockwell C Hardness of Chill	Rockwell C Hardness of Core
2½	10/128	67	35
2	11/128	67	36
1½	12/128	67	37
1	13/128	67	39
¾	14/128	67	41

Fig. 15 Hardness penetration in different sizes of 0.80% C shallow-hardening tool steel

For the determination of grain size in tool steels, the following methods are recommended:

1 The sample is fractured, and the exposed grain structure is compared with the standard (Fig. 6), visually or at a low magnification. The fracture number of the standard that the sample matches most closely is designated as the grain size of the sample. Care must be taken to fracture the sample cleanly, exposing the true grains and not the distorted ones that were pulled apart rather than cleaved. Although particularly well adapted to the carbon tool steels, this test will give a reliable measure of the grain size of any tool steel.

2 The so-called "intercept method" for measuring the austenitic grain size was developed by Snyder and Graff. This method is widely used on high-alloy tool steels such as high speed steels and high-carbon high-chromium steels, because it offers an open scale of measurement in the range of fine grain size. This makes for sensitivity to

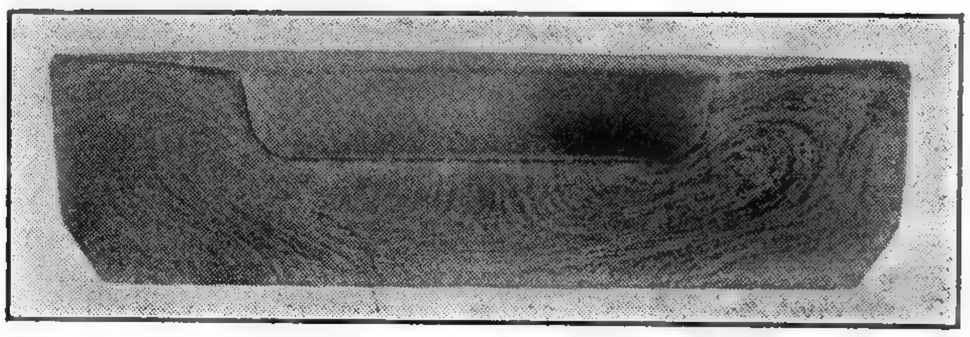


Fig. 16 Flow lines

the slight changes in fine grain size that these steels exhibit and that other tests might not detect. The test may be applied to any steel having prior austenite grains that can be outlined by an etching reagent on a metallographic surface. The sample to be tested is polished as for microexamination, and etched. In the as-quenched state, high speed steel, for example, can be etched in the stronger nital solutions (5 to 10% HNO_3 in alcohol). If the sample has been tempered so that the dark martensite would obscure the grain, hydrochloric acid, added to the nital, will generally attack the grain boundaries sufficiently to leave them defined, after a light repolishing. The sample is then examined through a microscope. The average num-

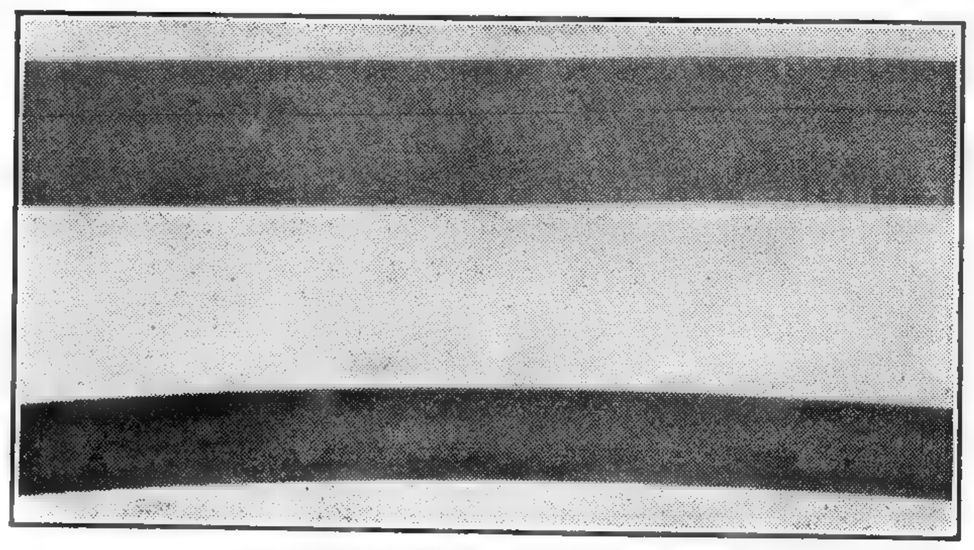


Fig. 17 Surface defects (rolling laps)

ber of grains intercepted by a 0.005-in. line on the sample at ten random points is the grain size of the sample. These counts are usually made by observing the image at ×1000 on the ground-glass screen of the metalloscope, upon which a 5-in. line has been drawn. Illustrations of typical effects of austenitizing temperatures on the intercept grain size of 18-4-1 high speed steel are shown in Fig. 20 to 23. In general, intercept numbers above 15 designate a very fine grain size; from about 12 to 15, a fine grain size; from 9 to 11, a fairly coarse grain size; and 8 and lower, a coarse grain size.

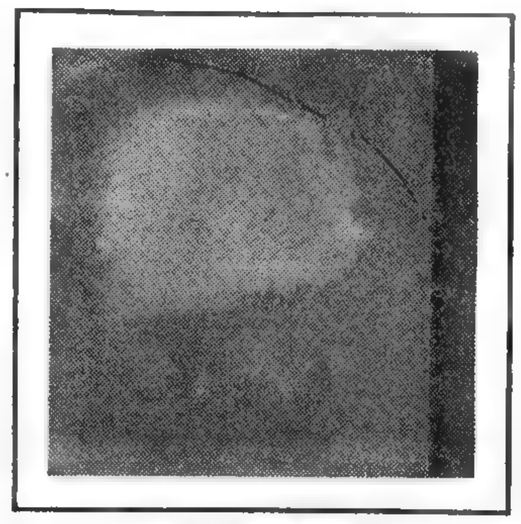


Fig. 18 Soft spot

The knowledge of grain size in tool steels has become increasingly important in recent years, because the actual grain-size number may be used to advantage for the following purposes:

a A guide to determine the correctness of a given heat treatment.
b An indication of toughness (fine grain size is usually associated with improved toughness).
c In conjunction with other tests, such as microexamination, as an aid in establishing the sensitivity of a given steel to heat treatment; that is, a stable grain size over a range of austenitizing temperatures usually indicates a wide range of hardening temperatures.
d An indication of variation in composition or structure, as in a decarburized area, which will have a different fracture grain size and a different luster.

Microscopic Tests. The examination of polished sections of tool steel under the microscope is a common method

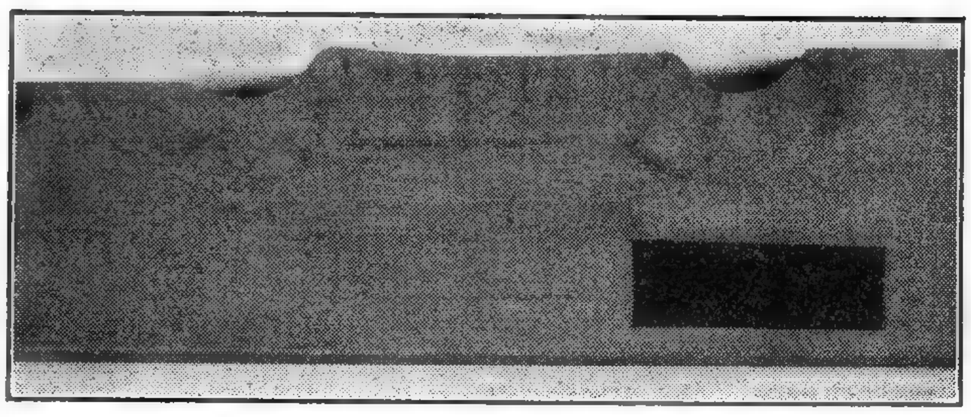


Fig. 19 Grinding cracks on hardened die steel

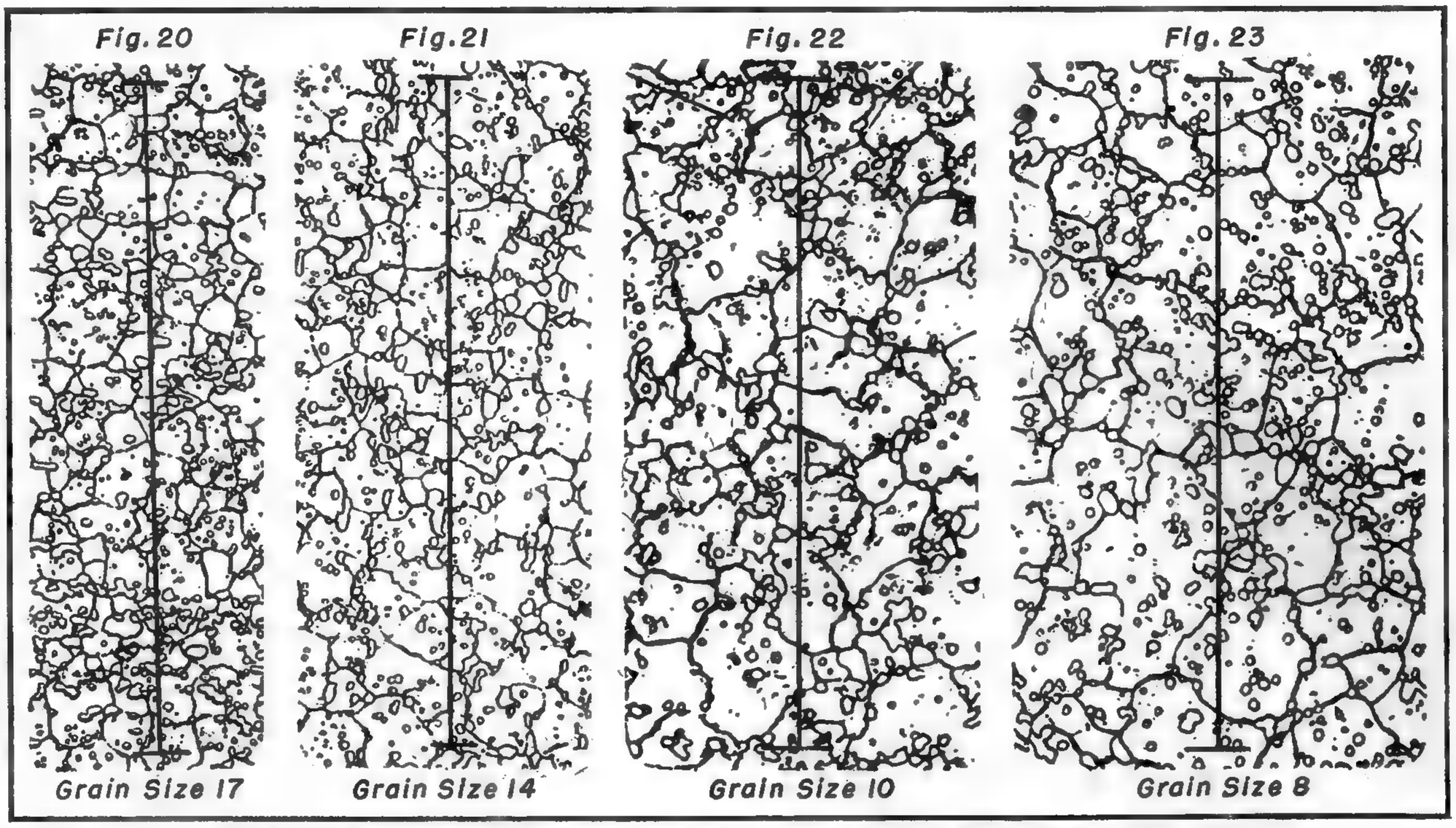


Fig. 20 to 23 Austenitic grain size determined by the intercept method. Specimens were 18-4-1 high speed steel, as quenched. (Original magnification, 750; reduced 20% in reproduction)

used in connection with the inspection of tool steel, the investigation of tool failures, and various research problems.

Cutting, grinding and polishing equipment required for this work is described in the article on page 159. Etching reagents are listed on page 394.

The avoidance of polishing pits and scratches in tool steels is not so difficult as in soft steels. Polishing pits are sometimes mistaken for inclusions and careful polishing is essential for best results. For the etching of tool steel specimens, the use of a solution of 2 to 5% HNO_3 in alcohol is generally applicable. Somewhat stronger solutions may be used for highly alloyed steels.

In the microexamination of tool steel, a microscope with a magnification up to 1000 diam should be satisfactory for all ordinary requirements.

By examination under the microscope, it is possible to determine a number of factors that may affect the quality or performance of tool steel. Among these may be mentioned grain size, effect of heat treatment, structural constituents, size and distribution of carbides, nonmetallic inclusions, and segregations.

Grain Size. (*See* page 415 in this article.)

Effect of Heat Treatment. The most common method of checking the prior heat treatment of tools is by the examination of hardened fractures, but microexamination of hardened structure is more accurate. In instances where steels develop a largely martensitic structure when hardened, the size of the martensitic needles may be considered a measure of the austenitic grain size after a given heat treatment. A structure with enlarged martensitic needles is associated with overheating (*compare* Fig. 24 and 25).

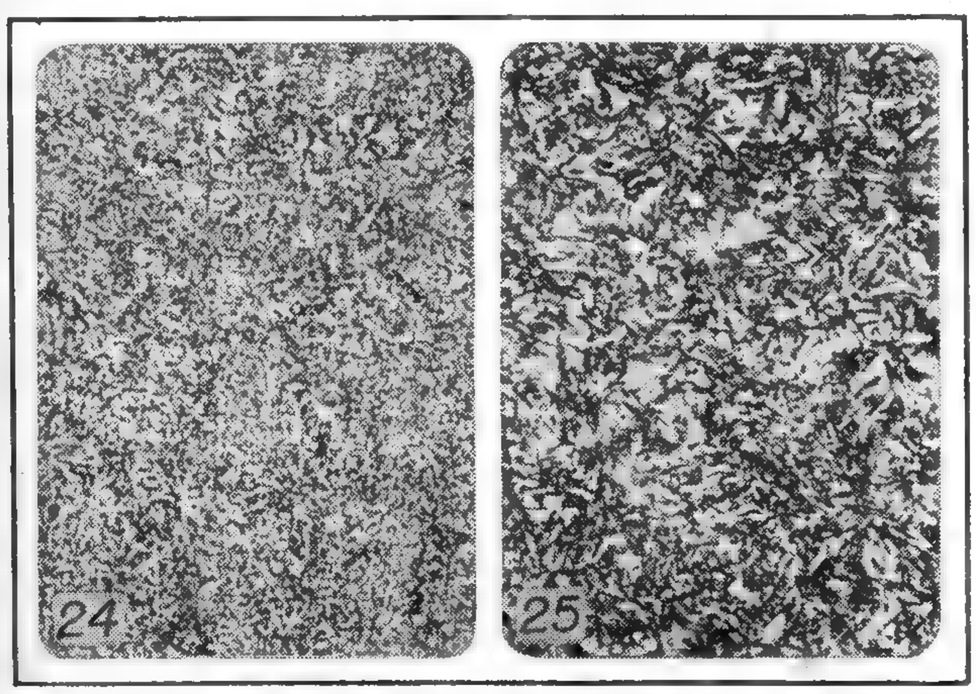


Fig. 24 Manganese oil-hardening steel properly hardened showing a fine martensitic structure. × 500

Fig. 25 Manganese oil-hardening steel, overheated in hardening, showing martensitic structure with enlarged needles. × 500

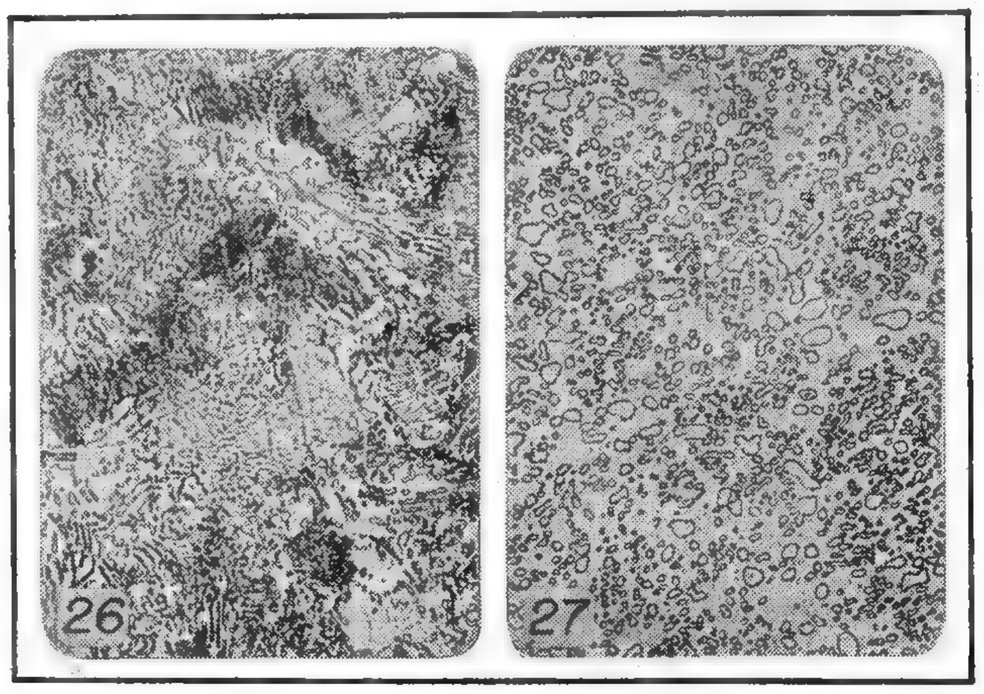


Fig. 26 Carbon tool steel, not fully annealed, with partially lamellar pearlitic structure. × 500

Fig. 27 1.0% carbon tool steel, fully annealed, with carbides spheroidized. × 500

On the other hand, partial or complete absence of martensite, and the presence of numerous small undissolved carbides, may indicate an underheated condition. The relative proportion of austenite, martensite and other constituents sometimes indicates the extent of tempering.

Structural Constituents. A large proportion of tool steels have a comparatively high carbon content and represent eutectoid or hypereutectoid compositions. In such steels, carbide-containing constituents are predominant in the structure. These may be pearlite, cementite, carbide segregate, or other constituents (Fig. 26). Ferrite may exist as a separate constituent in the lower-carbon (hypoeutectoid) tool steels. Also ferrite is the principal constituent of the matrix observed in the examination of the structure of annealed tool steels when the carbides are present in the spheroidal condition (Fig. 27).

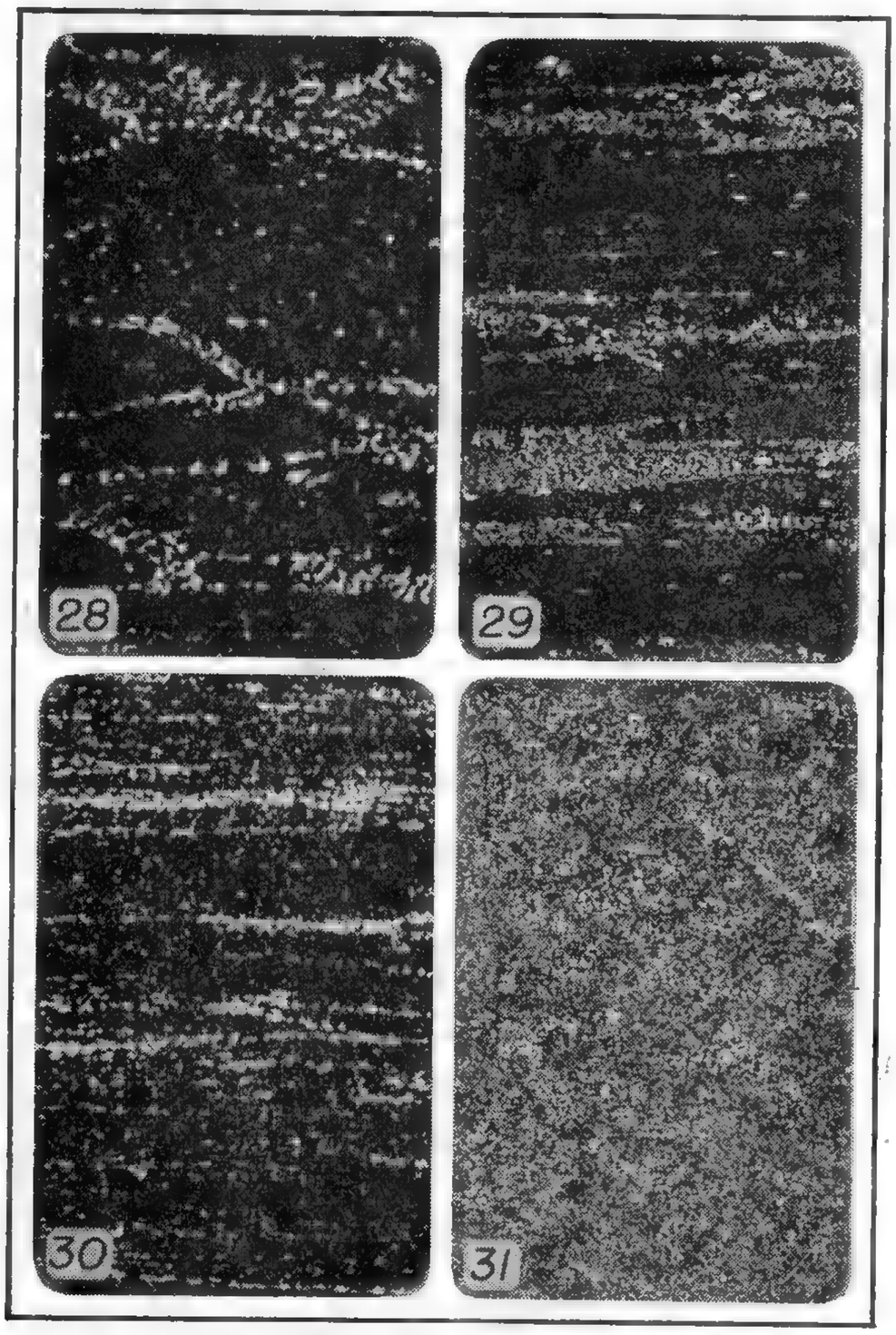


Fig. 28 Section from 6-in. diam bar of 18-4-1 high speed steel showing traces of carbide network. × 100

Fig. 29 Carbide segregation in 3-in. diam bar of 18-4-1 high speed steel. × 100

Fig. 30 Carbide segregation in 1-in. diam bar of 18-4-1 high speed steel. × 100

Fig. 31 18-4-1 high speed steel upset forging, 3-in. diam by 1¾ in. thick, showing uniform carbide distribution. × 125

It may be desired to identify or estimate the proportion of structural constituents of tool steel in the annealed and hardened condition, and sometimes in the hot worked condition. This examination is made on longitudinal or cross sections, usually at 500 diam or more.

Size and Distribution of Carbides. In hypereutectoid carbon tool steels and the more highly alloyed tool steels, such as the high speed and the high-carbon high-chromium types, size and distribution of the carbide segregate affect the quality and may be partly responsible for tool failures. Carbide segregation, the most common kind that may exist in tool steels, is present in varying degrees in the more highly alloyed types, such as high speed and high-carbon high-chromium steels, and less extensively in low-alloy and carbon tool steel. Excessive carbide segregation is objectionable, since it may cause tool failure or difficulty in machining.

The observer must have considerable experience to know what to expect as to uniformity and what is objectionable as to carbide network and segregation in sections of various sizes. Inspection for distribution of carbide is made preferably on longitudinal sections at about 100 diam (Fig. 28 to 31). Size of carbides in low-alloy or carbon tool steels is observed to best advantage at 500 diam or more.

*Nonmetallic Inclusions.** Among the nonmetallic inclusions that may exist in tool steels, are slag or refractory, deoxidation products and various silicates.

Unetched longitudinal sections may be polished and examined for nonmetallic inclusions at 100 diam or more. Steel that tends to pit readily while being polished, should be polished in the hardened condition and examined after the specimens have been etched lightly in nital so that inclusions will show more distinctly (Fig. 32).

Decarburization. The use of the microscope in determining decarburization of tool steels is not recommended because the results obtained are only approximate. More accurate determinations can be made by using a "step-down" test in which successive layers are machined off the surface and are analyzed for carbon content.

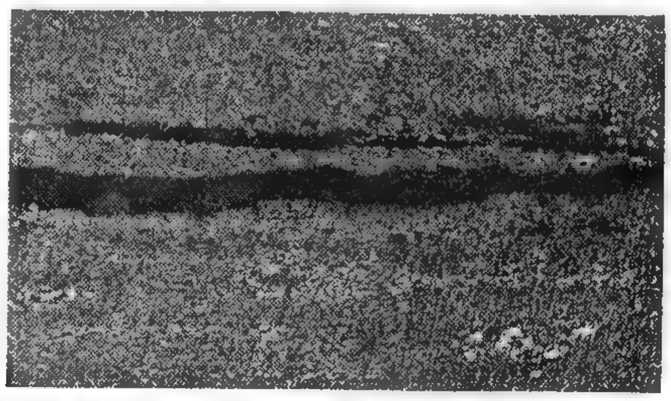


Fig. 32 Large nonmetallic inclusion in high speed steel. × 125

Hardenability Tests. In devising and interpreting tests for the hardening characteristics of tool steel, it is important to consider the type of steel, its application and the method of hardening employed.

Shallow-Hardening and Medium-Hardening Steels. Hardenability is determined by measuring the depth to which a steel will harden during quenching. The carbon and carbon-vanadium steels are typical of shallow-hardening tool steels and the line of demarcation between the hard case and the relatively soft core is quite distinct. Starting with the carbon steel, increasing hardenability can be obtained by the addition of small amounts of such elements as chromium, manganese, silicon and molybdenum. As the hardenability is thus increased, the line of demarcation between the case and the core grows less sharp and, in the extremely deep-hardening steel, is replaced by only a slight decrease in hardness toward the center.

Tests for hardenability are of most value in connection with the shallow-hardening and medium-deep-hardening steels. Because of the wide difference in behavior of these steels, no single test can be adapted to all. Consequently, two types of test—one for shallow-hardening and one for deeper-hardening steels—are suggested here.

For the shallow-hardening steels, a very convenient test is the P-F test (Penetration-Fracture). This consists of hardening in brine four specimens machined to ¾ in. in diam by 3 in. long—one each from 1450, 1500, 1550, and 1600 F—notching each in the middle and fracturing by impact. Then one half of each specimen is examined for the grain size of the case, in comparison with the standard described below. Penetration tests are made on the other half of each sample by grinding the fracture and smoothing it on abrasive No. 0 or finer, etching for 3 min in 1 to 1 HCl at 180 F and measuring the penetration of hardness in sixty-fourths of an inch.

* *See also* the article "Nonmetallic Inclusions in Steel", page 445.

The P-F characteristic is then recorded as numerals. The first four numbers represent the penetration in sixty-fourths, and the last four numbers, the fracture grain size. The first number of each group represents the P-F results for a temperature of 1450 F; the second number of each group represents the P-F for a temperature of 1500 F, and so on. Figure 33 illustrates a typical test; the numbers designate the penetration and fracture values determined for each specimen. This test is especially valuable for measuring the hardening characteristics of a plain carbon steel over a wide range of austenitizing temperatures.

Various precautions must be taken in conducting the P-F test, where results are to be strictly comparable. In the test pieces, the original structure resulting from annealing or pretreatments is important. For general comparisons, since most tools are made and hardened from an annealed bar, it is desirable to make the test on annealed specimens, just as cut from the bar stock. If, however, it is the practice to normalize or in some way to pretreat the tools before final hardening, the P-F tests should be made on specimens that have received these preliminary treatments in order to give an indication of the behavior to be expected from the finished tool.

For accurate results, the time cycle must be controlled carefully, and also the temperature during hardening. Usually the specimens are heated in such a way that the total time in the furnace is 25 min for each temperature. These conditions can be obtained with considerable uniformity by using a relatively large furnace, heating it to the desired final temperature, introducing the specimens, and bringing them up to temperature without allowing the furnace temperature to decrease.

For uniform results, specimens should be placed on a suitable vertical jig and quenched in a flush that contains 10% brine.

Other methods applicable for measuring the hardenability of shallow-hardening and medium-hardening tool steels include (1) the cone tests, described in Trans ASM, **30**, 1202 (1942); (2) the wedge tests, described in Trans ASM, **35**, 584 (1945); (3) the Jominy L-test; and (4) the Shepherd P-V test, described in Trans ASM **38**, 354 (1947). (*See* also "Hardenability Tests", page 489.)

Deep-Hardening Steels. For the determination of hardenability on the deeper-hardening steels, the ¾-in. diam specimen employed in the P-F test cannot be used, since this section would harden all the way through. For such deep-hardening steels, the Jominy end-quench test (*see* article on page 489) has been found much more satisfactory and is generally used. The end-quench test is not applicable to air-hardening steels.

Other Tests Relating to Hardening. *Uniformity of Hardening.* Soft spots are peculiar to tool steels of the shallow-hardening type, because of improper quenching conditions. Misleading information will be developed if standardized methods of quenching are not employed in making a test to determine the uniformity of hardness in these steels.

A hardened sample, tool, or part, may be tested by etching the polished surface with hot 1 to 1 HCl or 10% HNO_3 in alcohol at room temperature. Areas of variable hardness will etch light or dark and may be explored by standard hardness testing methods. Another method is to grit-blast the hardened pieces. This treatment will make the soft spots show up as dark, rough areas.

Susceptibility to Hardening Cracks. A number of tool steels are susceptible to hardening cracks, which result from composition, prior treatment or variables of manufacture. In determining this characteristic in steels of similar composition, it is important that a standardized temperature, time of heating, and quenching cycle be employed. To locate hardening cracks, a properly hardened specimen, tool, or part may be examined magnetically as described under "Magnetic Particle Inspection" on page 145. An alternative method requires the etching of the piece in hot 1 to 1 HCl, 10% HNO_3 in alcohol, or a 10% solution of ammonium persulfate in water, at room temperature.

Sensitivity to Grain Growth. Difference in sensitivity to grain growth may be observed in tool steels when they are heated to different temperatures above the transformation range. This characteristic depends on composition, variables of manufacture, and heat treatment.

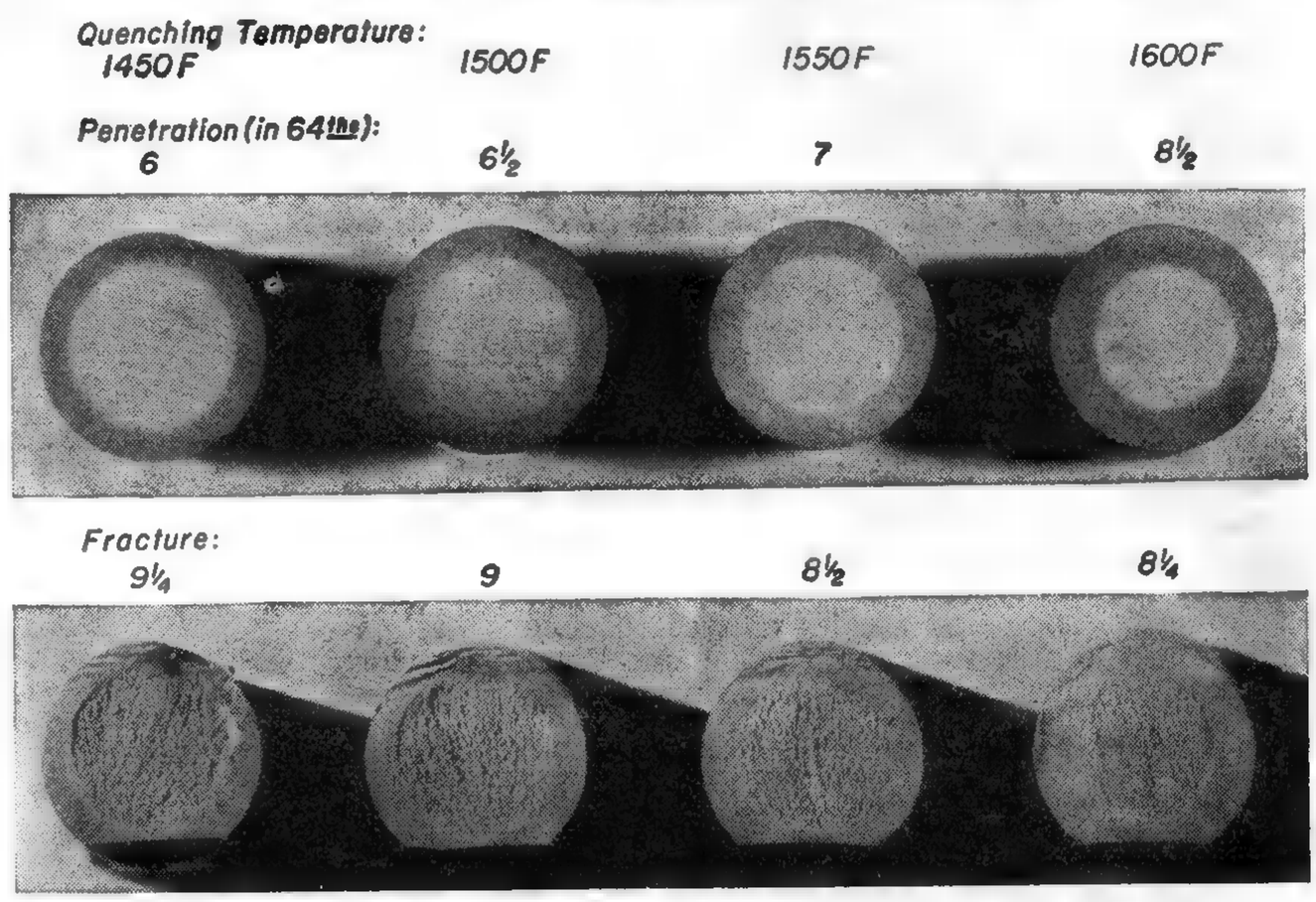


Fig. 33 Etched sections and fractures in P-F test on carbon tool steel

A simple test involves the hardening of test pieces (as described under Hardenability) from various temperatures at and above the customary hardening temperature for a given lot of steel. The pieces are fractured and then compared with a standard or examined microscopically.

Susceptibility to Soft Surface. Several types of tool steel are susceptible to soft surface. Differences between types may be determined by hardening samples of the respective lots from their normal quenching temperatures, after which accurate hardness tests may be made. In testing steels of similar composition, it is important to employ a standardized temperature, correct furnace atmosphere, correct time of heating and suitable quenching procedure. The depth of the soft surface may be measured by a repeated cycle of uniform grinding and hardness testing.

Cutting Tests. The reader may refer to the paper by F. W. Taylor, "On the Art of Cutting Metals", Trans ASME, **28**, 31-279 (1907) and to the recent ASA Standard B 5.19-1946, Life Tests of Single-Point Tools Made of Materials Other than Sintered Carbide.

Machinability. The only practical test for machinability is one based on actual machining operations.

Machinability is not a definable property of tool steel because "machining" may involve a dozen or more different operations, such as turning, tapping, reaming, drilling, broaching, threading, or backing off. Each of these different operations is further complicated by the requirements of the job. For example, milling of the flutes in a tap might require that no burr be thrown up on the teeth, but no such requirement would be imposed for milling the flutes on a reamer. Drilling large holes does not involve the same problem as drilling small holes, and the drilling of gun barrels introduces still other problems. A delicate backing-off operation may dominate all other machining requirements in making certain tools.

Each user must therefore determine which condition in the tool steel produces best machinability for his own particular purpose. Certain tests can be decided on, including chemical analysis, hardness and microstructure, which can reasonably be expected to reproduce the desired machinability. For any given type of tool steel, incoming material can be inspected for machinability by testing the hardness and microstructure and comparing them with standards that have been approved for satisfactory machinability.

Testing of Dimensional Stability. All tool steels change in specific volume during heat treatment. This distortion is affected by the rate of heating, time at the quenching temperature, rate of cooling, tempering time and temperature, design of the part, and characteristics of the steel. Obviously, in any attempt to compare steels for "nondeforming" qualities, all other variables must be controlled.

There should be no difficulty in maintaining uniform rates of heating for test specimens. The holding times and rates of cooling will naturally vary with the type of steel, since some steels must be hardened by quenching in water or brine, others in oil, air blast or still air. The rate of cooling, however, should be uniform when steels of the same type are to be compared.

The hardness resulting from treatment is also important, since a steel hardened to a low hardness will distort less than the same steel hardened to a high hardness. Although uniform rates of heating and cooling should control distortion to some extent, a standard range of hardness for various types of steel should be used.

Numerous sizes and shapes of test specimens are possible, and the observer should select one that most nearly meets his requirements. The following four are suggested:

1 A section of annealed steel may be machined to ¾ in. in diam by 3 to 5 in. long. After machining, the specimen should be stress relieved by heating to a temperature just below the transformation range, and cooling slowly. The specimen should then be ground and measured accurately for length and diameter. A standard uniform heat treatment should be used, with care to avoid scale. The dimensions may be rechecked before and after tempering if desired.
2 A ring 2½ in. OD by 1¼ in. ID by ¾ in. thick may be prepared and handled in the manner of Test 1.
3 Flat specimens at least 6 in. sq by 1½ in. thick are especially valuable as an indication of the distortion that may occur in steels used for large dies. In this test, the specimen may be prepared as described above, but the measurement involves checking the face of the specimen for flatness to determine the extent to which the surface has become convex or concave.
4 Figure 34 illustrates a specimen of nonuniform section sometimes used for tests of distortion. Preparation of this specimen should be similar to that suggested for Test 1. The accuracy of this test is doubtful because slight changes in rates of heating and cooling have a greater effect on the distortion.

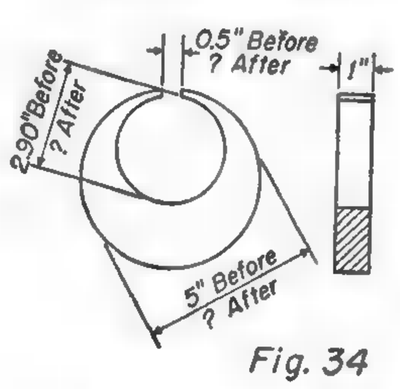


Fig. 34

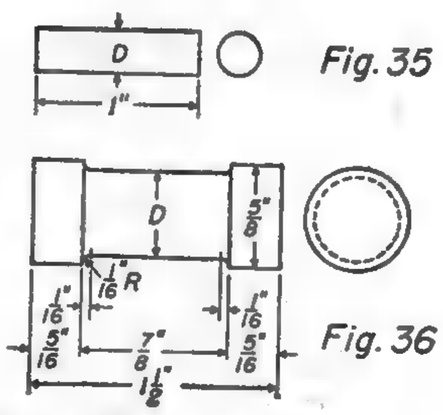


Fig. 35

Fig. 36

Fig. 34 Specimen prescribed by Navy specification for dimensional stability testing

Fig. 35 and 36 Compression-test specimens for tool steel. With both specimens, trim *D* to about 0.020 in. oversize. After hardening, grind *D* to 0.505 ± 0.0005 in. Grind both ends square and parallel with no centers. Use special care in finishing radii of specimen in Fig. 36.

Compression Testing.* Generally the object of compression testing is to determine stress and deformation under load, and the load necessary to produce failure. For tool steel, determination of the load necessary to produce failure is all that is usually required. The test is used mostly in solving problems of tool design, or in comparing one type of steel with another, or one heat treatment with another. The material is tested in the hardened condition.

Figures 35 and 36 show types of specimens that have been used. The form in Fig. 36 is usually preferred. The method of carrying out the test is illustrated by Fig. 37. The following precautions are essential:

1 One bearing block must be provided with a spherical seat.
2 The specimen and bearing blocks must be centered accurately on the table of the machine so that the line of pressure will pass through the axis of the specimen, bearing blocks, and testing machine.
3 The load must be applied at a uniform rate, generally less than 0.02 in. per min.
4 Full protection from flying pieces must be provided.

The drop of the beam or dial pointer is usually taken to indicate ultimate failure. It is recommended that the test be stopped at this point. The load at rupture may be somewhat higher, but is considered to be without significance because of the radical change in shape and dimensions of the test specimen. For more complete particulars the reader may consult references 1, 2 and 3, and the article on page 109 in this Handbook.

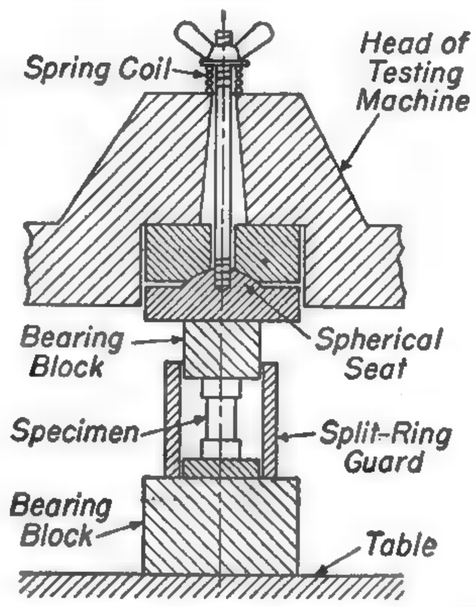


Fig. 37 Method of making compression test

For measuring the resistance of a superficially hardened object to local crushing or sinking under load, two methods have been used. In the first, a plain cylindrical hob is pressed into the object to be tested. After each increase of load is applied, the hob is removed and the piece is examined. The load at which the first signs of permanent sinking occur, is taken as an indication of the local carrying capacity of the surface. In the second method, described by McMullan,[4] special Brinell balls, preferably of the hard carbide variety, are pressed into the surface to be tested under increments of load, and the impressions are measured in the usual manner.

Notched-Bar Impact Tests. The standard impact tests, as described on page 112, are not commercial tests for tool steel except for the shock-resisting types; the values obtained mean little for steel in the annealed condition and when tool steels are tested in the hardened condition, the values are too erratic.

When this type of test is used, the design of the test specimen may be varied according to the characteristics of the steel.

Since the specimens are highly stressed, care is necessary to prevent injury from flying fragments.

With impact test specimens of hardened tool steel, provision should be made for grinding at least 0.005 in. from the surface after heat treating. This grinding will remove surface irregularities that might cause low impact values.

The torsion-impact test is used to measure the torsion-impact strength of tool steels hardened to Rockwell C 60 or higher.

Torsion Tests.* Some of the fundamental properties of hardened tool steel are difficult to determine accurately because exceptionally high strength and low toughness are encountered, as compared with the engineering steels. The tension, transverse bending, and impact tests are limited in usefulness when applied to hardened tool steels, since results are likely to vary and the average is only approximate. The static torsion test has these advantages: the applied stress is less concentrated and it is possible to measure both strength and toughness much more accurately, even when the toughness is very low. With this

* *See also* "Compression Tests", page 109 in this Handbook.

* *See also* "The Torsion Test", page 111.

method of testing, simultaneous observations of both stress and strain are made, and from these results curves can be plotted to illustrate both the elastic and plastic deformation and the approximate location of the yield point.

Method of Making the Torsion Test. Because of the high strength and low toughness of hardened tool steels, a test specimen with a comparatively high ratio of L to D is necessary for best results. (L = length of gage section, D = outside diameter of gage section.) A ratio of 5.78 is used for relatively soft materials, but a ratio of 16 is recommended for hardened tool steels, so that sufficiently high values of strain can be obtained for a given stress. A drawing of the torsion-test specimen for tool steels, a picture of the torsion-testing apparatus, and details regarding the method are given in Proc ASTM, 31, Part 2, 47, 49 (1931). The reader may also consult references 5 and 6.

The principle of the torsion test is that by means of a manually operated turning head, a twisting torque is applied to the torsion specimen, which in turn transmits the torque through a lever system and hydraulic gage to a piston. The gage-reading indicates the applied twisting force or torque in in.-lb, and deformation or angle of twist is measured directly on the twisting head of the machine. The angle through which the specimen twists is recorded for each increment of 25 in.-lb torque until rupture occurs. From these data a stress-strain curve can be plotted that gives information concerning the elasticity, plasticity and ultimate torsional strength of the material being tested.

Tension Tests.* The tensile properties of annealed tool steel are of little commercial value. Tension tests are sometimes used on small sizes of drill rod (for example, less than ⅛ in. in diam) rather than hardness tests because, on such small sizes, the standard methods of testing hardness are rather inaccurate. In heat treated steel, accurate determinations present considerable difficulty and inaccuracy is likely at high hardnesses, such as Rockwell C 55 or more, when the ductility is quite low. A knowledge of tensile properties is useful, chiefly in connection with shock-resisting steels, which are often used when considerably softer than their maximum hardness.

For determining the tensile properties of tool steel, a specially designed test specimen is recommended (Fig. 38).

The specimens are ordinarily heat treated in test-bar size, but about 0.020 in. is left on the diameter to permit removal of decarburized surface and to correct for warpage.

Tension Tests at Elevated Temperature. A joint committee of the ASTM and the ASME has prepared recommended practices* for tension tests of steels at elevated temperatures. These methods are satisfactory for medium-strength or low-strength steels, but it is difficult to obtain accurate results for high-strength steels unless the methods are modified.

The Specimen for Tension Tests at Elevated Temperature. Figure 39 shows a satisfactory form of test specimen. The best practice is to rough turn in the annealed condition, heat treat, and grind as indicated. From high-strength steels with low elongations, best results will be obtained if the ends are tempered for a short time in a liquid bath before grinding.

The diameter of the specimen in the gage-length section may be varied from the dimension shown in Fig. 39 to as small as 0.200 in. with satisfactory results. When a smaller specimen is used, the gage length should equal 4 diam so that the elongation values will be directly comparable with those of the standard specimen. The dimensions of a small specimen are shown in Fig. 40.

Gage marks can be put on the hardened specimens conveniently with the diamond-point hardness tester. The surface is washed with a copper sulfate solution where the gage marks are to be placed; then the 2-in. gage length is scribed with sharp dividers and prick punched or marked with the diamond point. If an extensometer is to be attached to the specimen, it is necessary to put gage marks on opposite sides. This procedure is greatly facilitated by rotating the specimen on centers and using the dividers against a rest while laying off the gage length.

The Testing Equipment. Various forms of shackles may be used to grip the ends of the specimens. A satisfactory

* *See also* "The Tension Test", page 105.
* *See* ASTM Recommended Practices E 21-43 and E 22-41.

Fig. 38

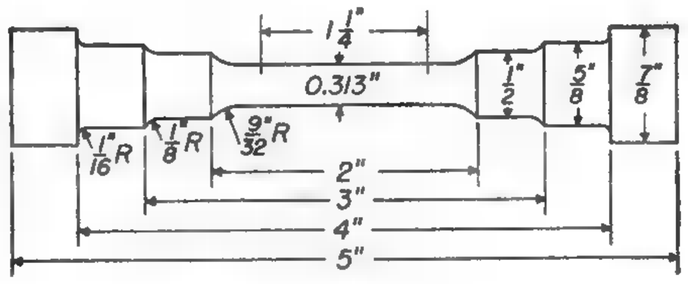


Fig. 39

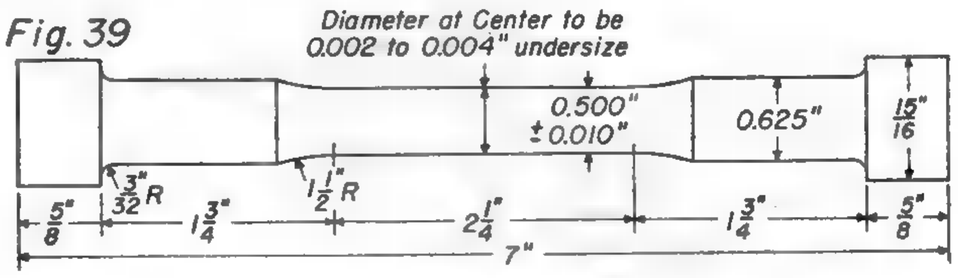


Fig. 40

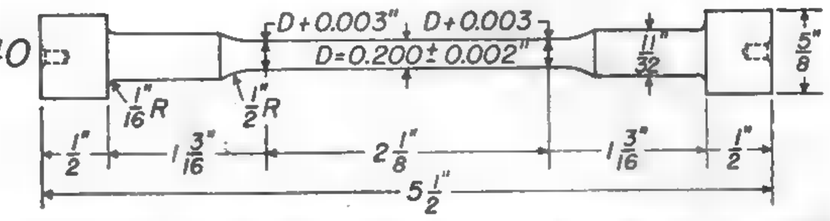
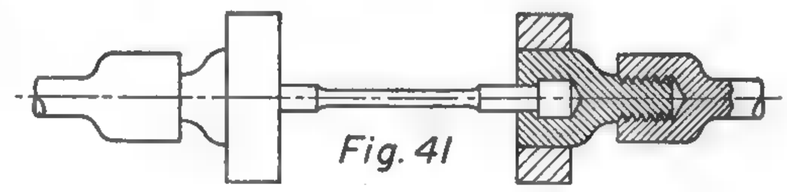


Fig. 38 Special tension-test specimen for tool steel. The ends may be square or ball-shaped.
Fig. 39 Tension-test specimen for tool steel at elevated temperature
Fig. 40 Same as Fig. 39, except smaller

form is shown in Fig. 41. This type is readily adapted to both the threaded-end and the shouldered-end types of specimens. The split adapters that fit the ends of the shouldered-end specimens are strengthened by the solid rings, which have a tapered bore so that they can be wedged on the adapters after the specimen is inserted. Another satisfactory form for shouldered-end specimens is shown in Fig. 42.

The best furnace for making high-temperature tension tests is a differentially wound or gap-wound resistance type of electric furnace. Particular attention should be given to baffling, insulation, and tightness, in order to prevent temperature gradients either in the specimen or in the adjoining shackles. For short-time tension tests at



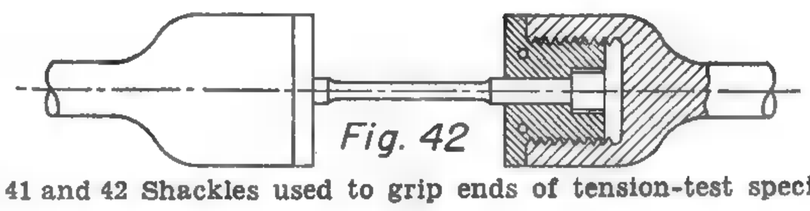


Fig. 41 and 42 Shackles used to grip ends of tension-test specimen

elevated temperature, manual control of the temperature is generally adequate; but for the long-time or creep tests, automatic control is necessary. Under any circumstances, it is essential to know the actual temperature of the specimen and to hold this temperature constant over the part of the specimen that is strained.

The use of the extensometer in high-temperature work makes the maintenance of uniform temperature so difficult that the best results are often obtained by compromises between equipment for heating and apparatus for measuring deformation. When the smaller sizes of specimens are used, uniform temperature can be obtained more easily throughout a specimen.

Self-aligning shackles are essential. The usual method is to provide ball-and-socket joints at the ends of the shackles where they are attached to the heads of the testing machine, as indicated in Fig. 41.

Testing Procedure. It is particularly important, in short-time, high-temperature tension tests, to heat slowly for consistent results. Many of the reported discrepancies are caused by an excessively rapid rate of heating. The elastic properties of tool steels as usually determined—elastic limit, proportional limit, and frequently Young's modulus—are of questionable value because of creep at the

higher temperatures and because of consequent difficulties hindering the accurate determination of such properties. Better results will be obtained by the use of values of yield strength based on some arbitrary value of permanent set or perhaps on two different values of permanent set, such as 0.1% and 0.2%, following the methods given in the Standard Methods of the ASTM (E 8–46). Such values for yield strength need be used only in the absence of a well-defined yield point in the steel, but most tool steels have no well-defined yield point.

Temperatures are best obtained by clamping thermocouples directly on the shoulders adjacent to the gage length of the specimen. To shield the hot junctions from the heat of the furnace walls, asbestos paper should be placed over the junctions before the clamps are applied. Additional thermocouples in the furnace atmosphere may assist in obtaining and controlling the desired temperature, but ordinarily they are not reliable for measuring the temperature of specimens.

In a report of results, the details of the specimen, apparatus and procedure should be given, in addition to the composition and history of the specimen material.

Bend Tests. (*See* the article on page 125.)

Fatigue Tests. The ordinary fatigue tests (*see* page 118) used on soft or medium-hard materials may be applied to annealed tool steels, but seldom are, since tool steels are used largely in the hardened condition. Fatigue tests are not generally used on hardened tool steels, because notches, scratches and residual stresses cause much greater variations in results than are caused by differences in the quality of the steel. The best application of fatigue tests for tool steels would be on specimens that have been hardened and tempered to a hardness of Rockwell C 40 to 50. However, such treatments are seldom used for tools. Information from these tests is most likely to be required in connection with shock-resisting steels.

Fatigue tests on tool steel indicate an endurance limit from ⅓ to ⅔ the static tensile strength, and demonstrate that the resistance to fatigue is increased substantially by changing the direction of final polish of the specimen from circumferential to longitudinal.

In problems of fatigue in tool steels, the main emphasis should be on the design and treatment.

Some manufacturers and users of hollow mining-drill steel have long employed a practical fatigue test to check the quality of various lots of this material. With modifications, this test may be applied to other types of pneumatic tools. It consists of using a representative number of specimens of definite size and length in a jack hammer until failure occurs from fatigue. The time required is compared with standards set up jointly by manufacturer and user.

Nondestructive Testing and Inspection. Magnetic particle inspection, fluorescent penetrant inspection, magnetic testing and radiography are discussed on pages 141 to 158.

A special application of magnetic testing for tool steels has been the use of measurements of magnetic saturation value as a means of following the transformation of austenite during tempering.

Spark Tests. (*See* the article on page 397.)

Determination of Transformation Temperatures. There are three methods of determining the transformation temperatures of tool steels: (1) by plotting the heating and cooling curves on time-temperature co-ordinates (Fig. 43); (2) by dilatometric measurements involving the charting of interruption of progressive expansion or contraction on linear expansion-temperature co-ordinates; and (3) by plotting the change in loss of magnetic intensity during heating.

Thermal Method. In most steels, transformation points are ranges of temperature, since a small temperature range is required to complete the phase transformation.

Inserting a thermocouple into the drilled test specimen and observing and recording on a time-temperature diagram the rate of increase or decrease in temperature, is probably the oldest and simplest method for obtaining transformation points.

A heating and cooling rate from 1 to 2 °F per min is used to determine the transformation points with fair accuracy. Accuracy, of course, depends largely on the quality of the furnace equipment. To eliminate this factor, a neutral or nontransforming metal, such as platinum or an austenitic alloy steel, is heated along with the sample and temperature differences of the two are observed. The "inverse rate" curves, indicated in Fig. 43, give sharp peaks on the curves corresponding to the amount of heat absorbed during heating or evolved during cooling. The inverse rate curves are in general use. Autographic recorders are desirable; in fact, they are almost indispensable where frequent determinations are required.

Dilatometric Method. The dilatometer is a mechanism for determining the expansion or contraction of a sample during heating or cooling. *See* page 168.

Magnetic Method. The magnetic determination of transformation points depends on the loss of ferromagnetism

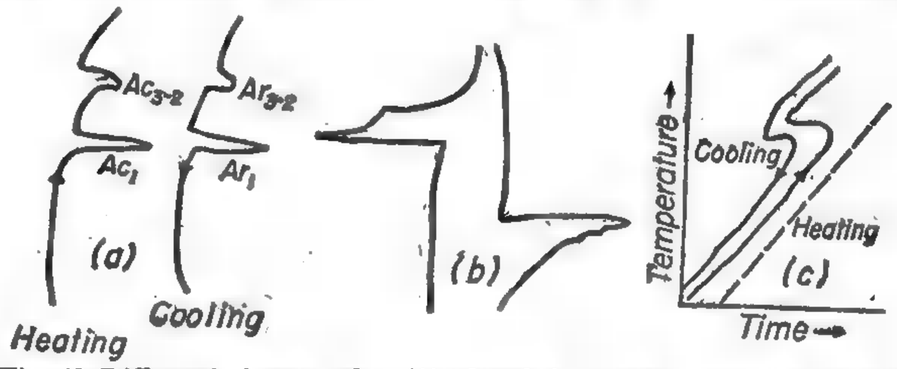


Fig. 43 Different types of critical-point curves. (*a*) Inverse-rate heating and cooling curves for a 0.45% C steel, (*b*) the same for a 1.0% C steel, (c) dilatometric expansion curve for a 0.45% C steel

during heating. These points are established by observing the magnetic transformation and the corresponding temperature. The specimen of tool steel is inserted as an armature in a magnetic circuit, and when the temperature is reached at which magnetic flux ceases to pass through the specimen or when the circuit is disrupted, the loss of ferromagnetism indicates the transformation temperature. A galvanometer in the circuit will then register no deflection and will thus record the transformation temperature.

Abrasion Tests.* Abrasion testing consists in measuring the weight lost from a unit surface area of a tool steel specimen that has been moved over and in contact with a standard hardened and finished machined surface, under a definite pressure, representing service conditions as far as practicable. There is no standard method of testing for resistance to abrasion.

The loss per unit area from the tool steel specimen, compared with the loss per unit area from specimens of different chemical composition, but of identical surface dimensions and tested in this same manner, gives the abrasion value expressed as loss in weight per unit area.

The surfaces may be cylindrical, spherical, or flat, but whether they are curved or straight, maximum and uniform contact and surface finishes are essential.

For an illustration of a wear-testing machine for cylindrical surfaces, the reader may refer to French and Herschman, Wear of Steel, with Particular Reference to Plug Gages, Trans ASST, 10, 692 (1926).

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* *See also* the article "Wear of Metals", page 216.

STRUCTURE AND PROPERTIES OF IRON

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Physical and Mechanical Properties of Iron

By Reid L. Kenyon*

IN SPITE of the difficulties encountered in preparing iron of high purity and in making an accurate chemical analysis of the small amounts of impurities present, the need for accurate information is probably greater today than ever before, because of the demands for greater reliability and for improved or new properties in ferrous metals and alloys.

Determinations of the properties of so-called "pure iron" appear throughout the literature, but the more recent values should be the most reliable since in general they were obtained by using improved methods of preparation, chemical analysis and testing.

The purpose of this article is to give a condensed statement of the physical and mechanical properties of iron, as reported in technical publications.

The data are usually from tests on material prepared by special methods in the laboratory, so in many instances considerable variation in the values of properties must result. An attempt has been made, as far as the data were available, to include the results of tests on commercially available materials such as carbonyl iron, electrolytic iron and ingot iron.*

Because of the variability in composition and treatment of the many different samples of iron used by various investigators, the values given should be considered the best approximations now available for the different properties and should not be used for specification purposes.

Composition. Table I gives the typical composition of several common forms of iron available commercially. Elsewhere in this article are the chemical compositions of a number of individual samples used by various investigators in determining various property values.

Atomic Structure. *Isotopes.* Iron has four isotopes: 54 (6.04%), 56 (91.57%), 57 (2.11%) and 58 (0.28%).

Atomic Number. The atomic number is 26.

Atomic Weight. The atomic weight is 55.85.

Nuclear Structure. The iron nucleus consists of 26 protons and 28, 30, 31 or 32 neutrons (corresponding to the four isotopes). The iron nucleus has considerable stability.

Arrangement of Electrons. In accordance with present concepts of nuclear structure, the 26 outer electrons are distributed on different "shells". Iron is believed to have 2 electrons in the inner K-shell, 8 in the L-shell, 14 in the M-shell, and 2 in the outer N-shell.

Atomic Radius. As reported by Morse, the atomic radius for alpha iron is 1.236×10^{-8} cm, and for gamma iron is 1.284×10^{-8} cm.

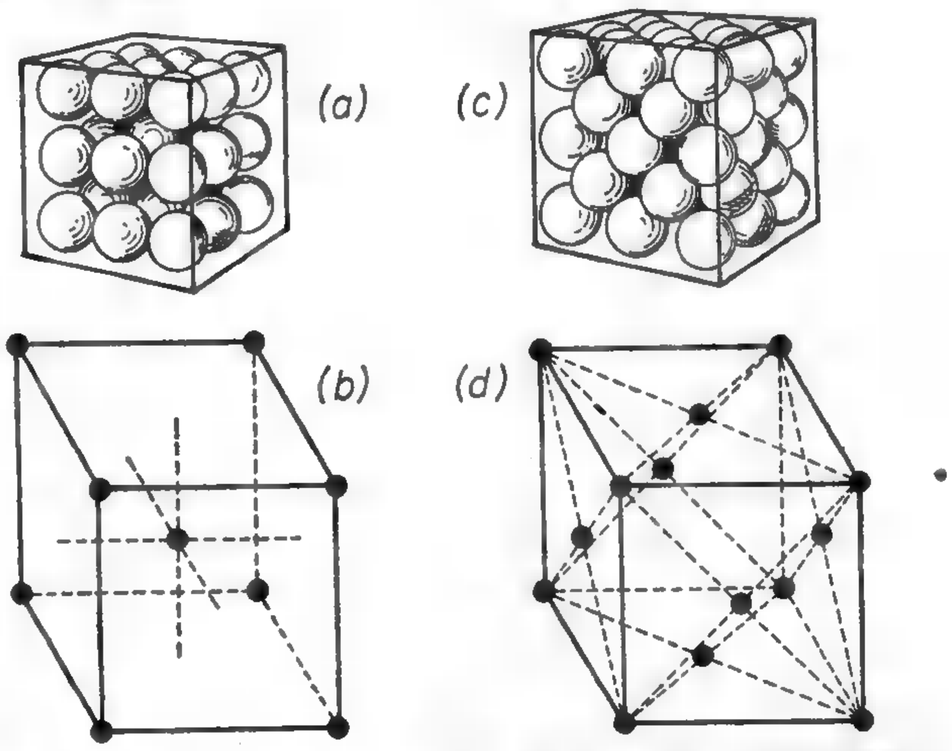

Fig. 1 Crystalline forms of iron: (*a*) body-centered cubic packing, alpha and delta iron; (*b*) alpha and delta iron, body-centered cubic; (*c*) face-centered cubic packing, gamma iron; and (*d*) gamma iron, face-centered cubic

Atomic Volume. This term ordinarily refers to the volume of a gram-molecular weight, and for iron at room temperature this is 7.1 cu cm. The volume of an individual atom can be derived from this by dividing by Avagadro's number which gives 11.7×10^{-24} cu cm for alpha iron at 16 C.

Crystallographic Properties. Iron has two crystallographic forms: body-centered cubic for alpha iron and delta iron, and face-centered cubic for gamma iron (Fig. 1). The dimensions of the unit cube (lattice parameter) vary with temperature, as shown in Fig. 2. The body-

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The data and information for this article have been selected from a number of sources; the preceding edition of this article was taken mainly from the book "The Metal—Iron" by H. E. Cleaves and J. G. Thompson. The author acknowledges the assistance of J. B. Austin (Director of Research, United States Steel Corporation); W. E. Ruder (Metallurgical Engineer, Research Laboratory, General Electric Company); J. G. Thompson (Chief, Division of Metallurgy, National Bureau of Standards); H. E. Cleaves (Metallurgist, National Bureau of Standards); T. D. Yensen (Manager, Magnetic Dept., Research Laboratory, Westinghouse Electric Corporation) in appraising the preceding article critically and making suggestions for its revision.

* In this article "ingot iron" refers to Armco ingot iron.

Table I. Typical Composition of Commercial Irons

Description	C	Mn	P	S	Si	Cu	Ni	O_2	N_2
Armco ingot iron	0.012	0.017	0.005	0.025	trace	....	....	....	....
Electrolytic iron	0.006	....	0.005	0.004	0.005	....	....	....	....
Kahlbaum iron	....	0.001	....	trace	0.015	0.004	0.004	....	....
Hydrogen-purified iron	0.005	0.028	0.004	0.003	0.0012	....	....	0.003	0.0001[a]
Carbonyl iron	0.0007 0.00016	(b)	(b)	(b)	(b)	(b)	(b)	<0.01	....
Bur Standards iron	<0.001	(c)	<0.0005	0.002	0.002	<0.002	(c)	0.003	0.0002

(a) Total reported impurities 0.024%
(b) Unable to identify, also Cr, Co, Mo, and Zn
(c) Unable to identify, also Ag, As, Au, B, Ba, Bi, Ca, Cb, Cd, Ce, Co, Cr, Ga, Ge, Hf, Hg, In, Ir, K, Li, Mg, Mn, Mo, Na, Ni, Os, Pb, Pd, Pt, Rh, Ru, Sb, Sc, Sn, Sr, Ta, Th, Ti, Tl, U, V, W, Y, Zn, Zr, total impurities <0.010%

centered cubic lattice may be considered as two interpenetrating simple cubic lattices of which the co-ordinates are (0, 0, 0) and (½, ½, ½). The face-centered lattice may be considered as four interpenetrating simple cubic lattices and there are, consequently, four atoms in the elementary cell, having the following co-ordinates: (0, 0, 0), (½, 0, ½), (½, ½, 0) and (0, ½, ½).

Density. Determinations of the density of individual specimens may be made with great precision, but the results apply only to the specific small pieces used in the test; therefore, results carried out to several significant figures are of questionable value, at least as a measure of the density of the material as a whole. Three common methods for determining the density of iron are (1) direct measurement, (2) calculation from the lattice constant, as determined by X-ray examination, and (3) extrapolation to

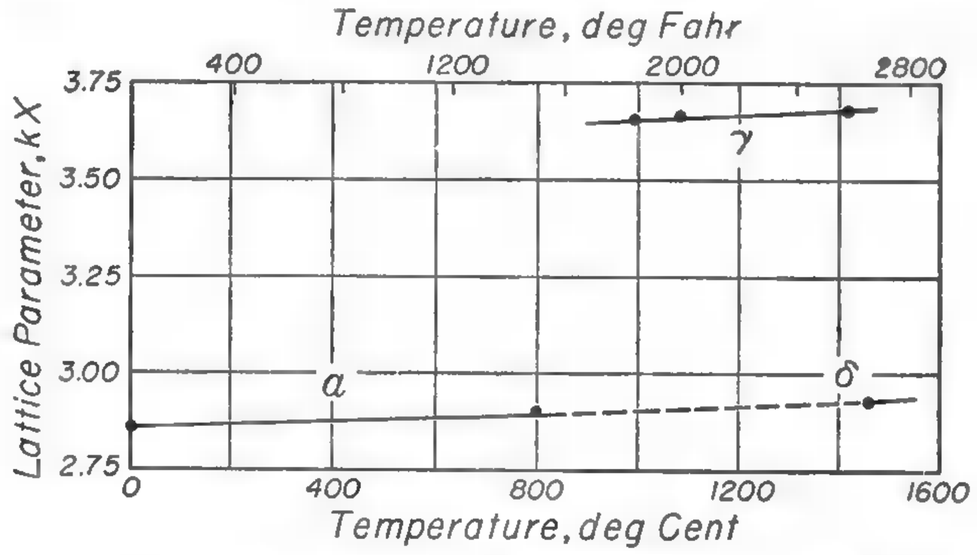


Fig. 2 Effect of temperature on lattice parameter of iron (Sato)

zero content of alloying element of a series of iron alloys. Table II gives average values computed by Cleaves and Thompson from the work of a number of investigators, as well as the value of 7.874 ± 0.001 g per cu cm at 20 C, obtained by Cleaves and Hiegel on iron of high purity prepared at the Bureau of Standards.

Table II. Density of Iron at Room Temperature
(Average Values)

Type of Iron	Density, g per cu cm: Direct Measurement	Calculated from Lattice Constant	Extrapolation
Ingot	7.866	....	....
Carbonyl	7.860	....	....
Electrolytic	7.874	....	....
Variety of 50 samples	....	7.865	....
Avg of 4 investigators	....	....	7.868
Nat Bur Standards Iron	7.874 ±0.001	....	....

Variation of Density With Temperature. At temperatures above room temperature the density is generally determined by calculation from either the coefficient of thermal expansion or the lattice constants. Lack of accurate data on volume changes at the transformation points results in the values for density above the A_3 point being unsatisfactory.

Variation of Density With Cold Working. Cold working lowers the density of iron, as shown by the work of various investigators. Maier's results on rods cold drawn from ingot iron are shown in Fig. 3. Beyond about 87% cold reduction the density increases again but does not attain its initial value corresponding to zero per cent cold work.

Transformation Points. The transformation points are the temperatures at which the various polymorphic changes occur. Because of the wide variation in the methods used for determining these transformation points, considerable

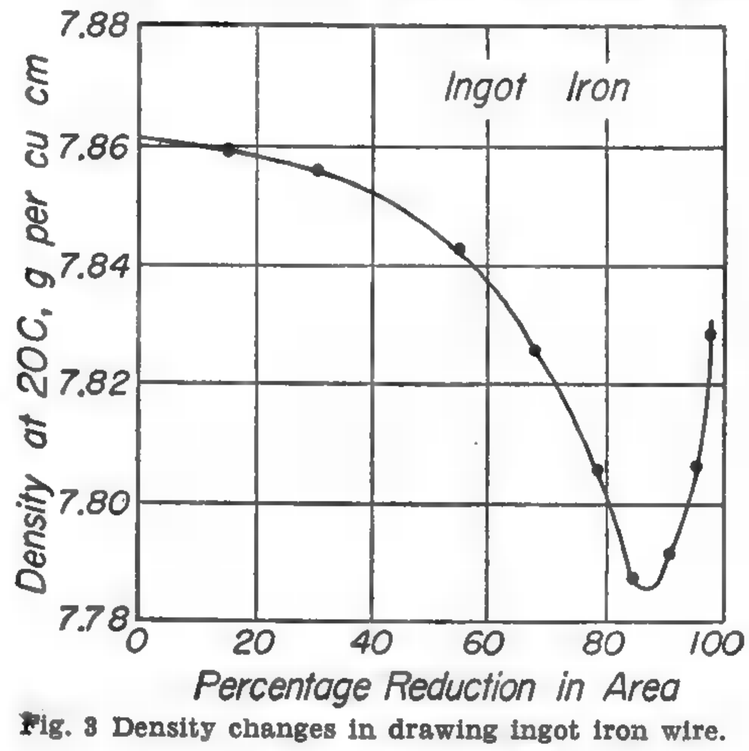


Fig. 3 Density changes in drawing ingot iron wire.

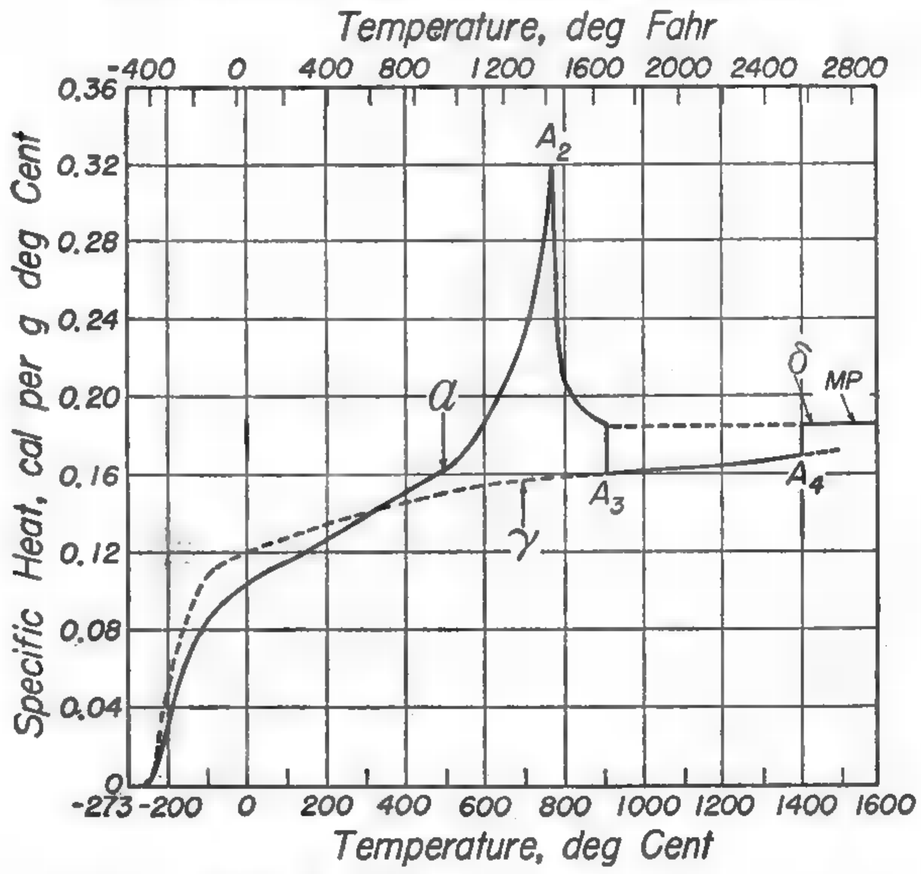


Fig. 4 Specific heat of iron (Austin)

difference in results is to be expected. Some of the methods that have been used are the following: heating and cooling curves and variations of this method, including differential curves; calorimetric measurements; magnetic tests; thermoelectric phenomena; electrical resistance measurements; and dilatation.

A_2 Transformation Range. This is the Curie point of pure iron, below which iron is magnetic and above which it is not. X-ray methods have shown paramagnetic α iron

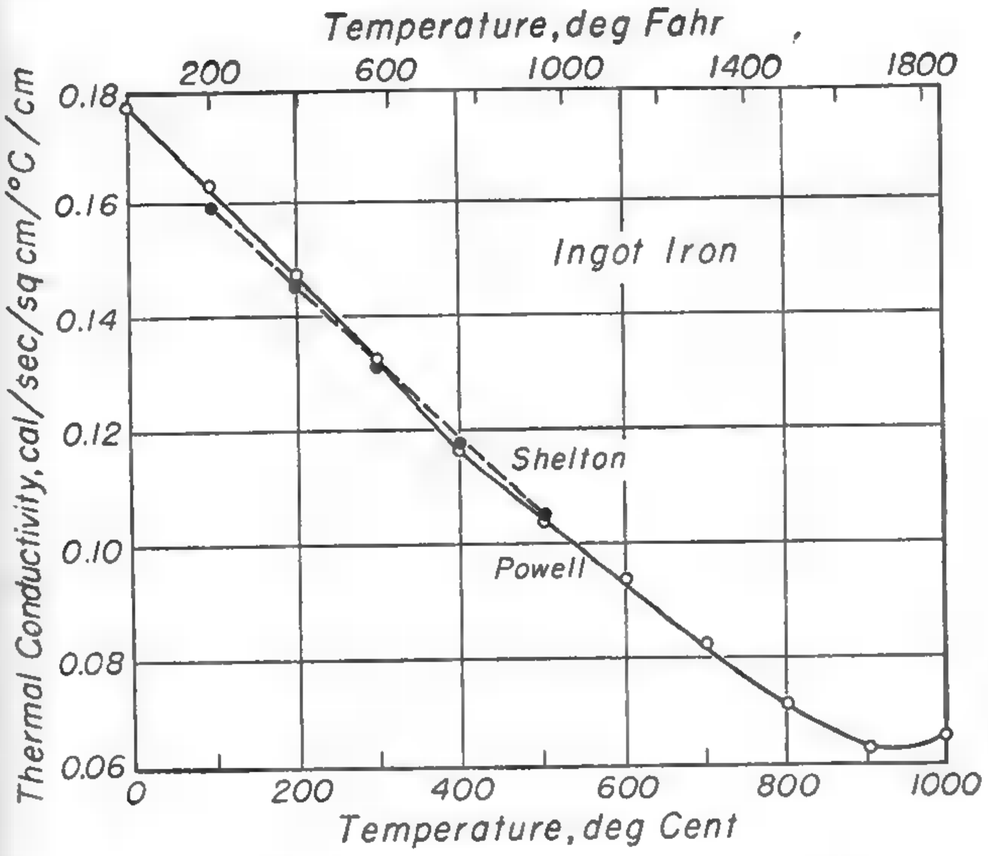


Fig. 5 Effect of temperature on the thermal conductivity of iron

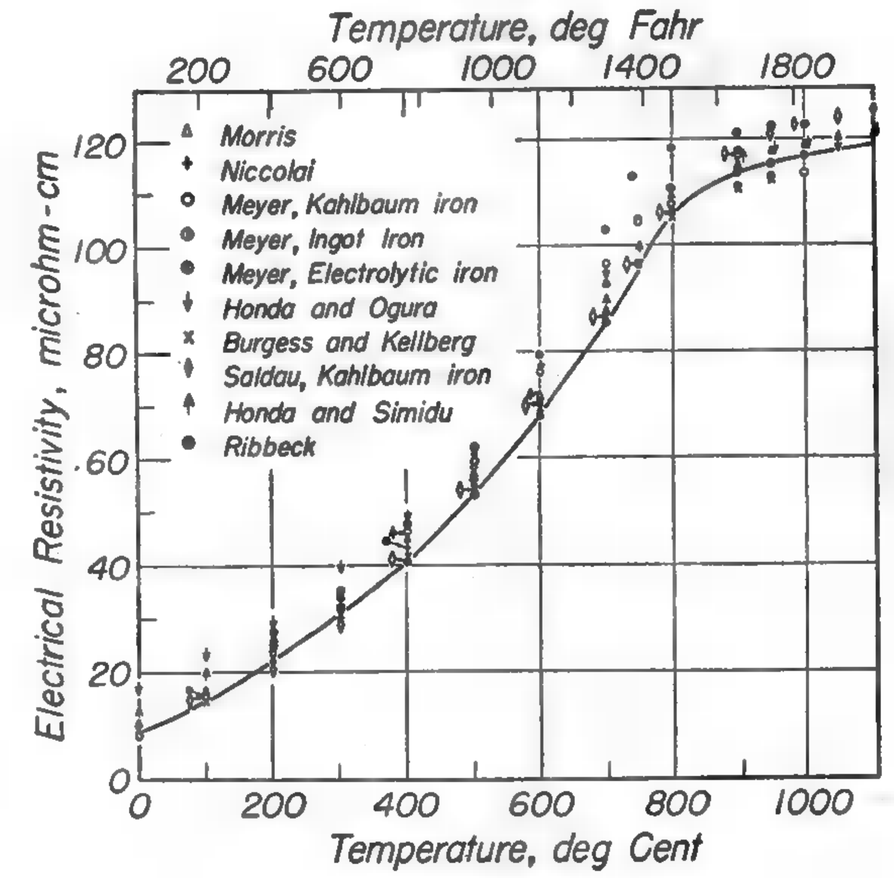
(formerly called β) to be of the same crystal structure as magnetic α iron. The magnetization is not all lost at one point. Most of it is gone after the iron is heated to 768 C, but remaining traces are detectable at temperatures as high as 791 C. This upper temperature depends on the sensitiveness of the instruments used, and on the different conditions of various parts of the specimen. Calorimetric results, which seem to be most consistent, indicate the value 768 C.

Methods that involve heating and cooling curves have yielded fairly consistent results, and several investigators have shown that the greatest thermal effect of the A_2 transition occurs at 768 C. Sauveur found that previous heat treatment has some effect on the determination; successive heatings tend to raise the value gradually to a constant temperature.

A_3 Transformation Temperature. This is the temperature at which pure iron undergoes a crystallographic change from a body-centered cubic to a face-centered cubic lattice. The change is not instantaneous and consequently there is some difference between the transition temperature on heating and that on cooling; also differences accompany variation in heating and cooling rate. Values are given for Ac_3 (heating) and Ar_3 (cooling).

Cleaves and Hiegel[1] report for the iron of high purity prepared at the National Bureau of Standards: "The results obtained by the three (magnetometric, thermal-analysis, and dilatometric) methods are not in perfect agreement—for example, the magnetometric method shows that Ac_3 is completed at constant temperature, whereas the transformation extends over a few degrees in the thermal-analysis experiments and over a greater range in the dilatometric observations. All three methods are in agreement, however, that the Ac_3 transformation in this high-purity iron occurs at 910 to 910.5 C and that the Ar_3 transformation is about ▮ C lower than Ac_3 even with very slow cooling."

A_4 Transformation Temperature. The δ-γ transformation of an iron prepared from ferrous chloride by a chemical



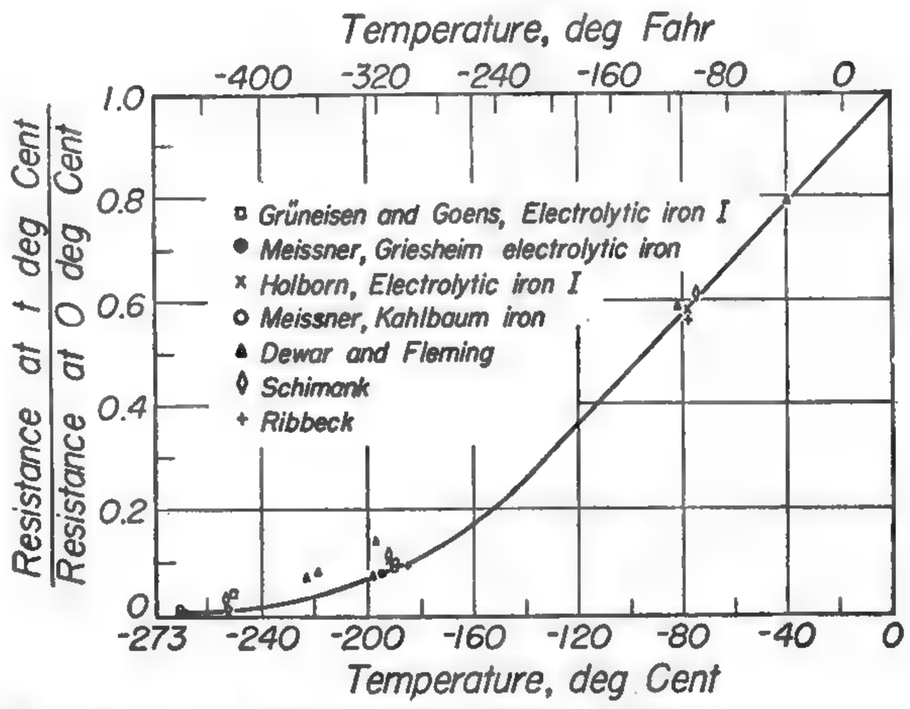


Fig. 7 Electrical resistance of iron at low and elevated temperatures

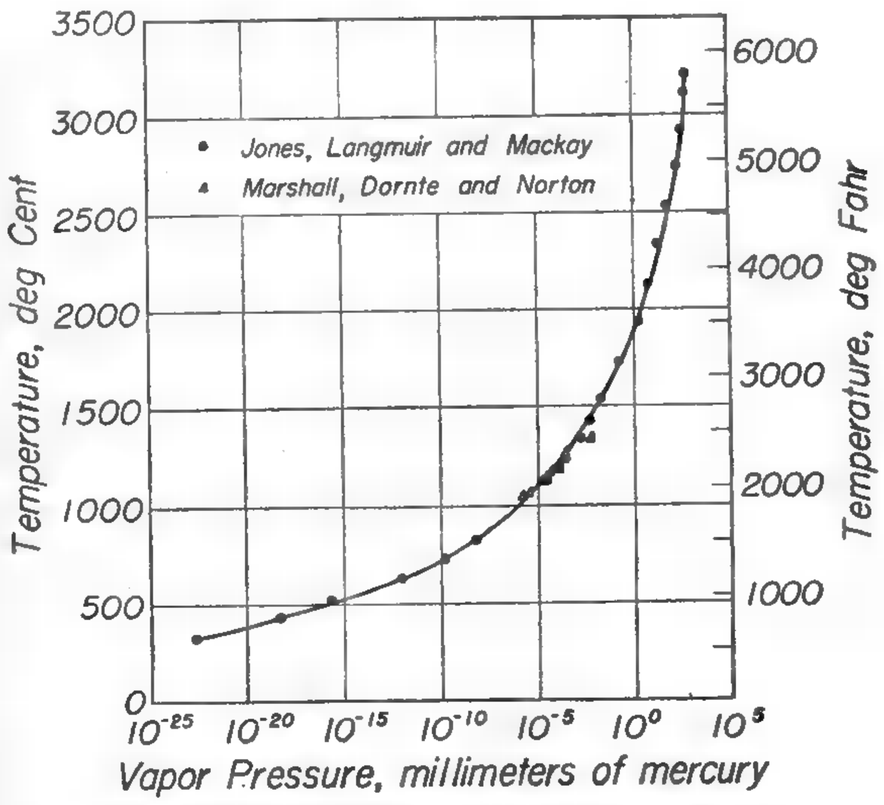


Fig. 6 Effect of temperature on the vapor pressure of iron

process (0.0016% Cu, 0.0006% Si, 0.0024% Ni, 0.0018% Al, 0.0027% S, traces of Mn and Ca) was determined by Adcock,[2] using the thermal-analysis method with Pt-PtRh thermocouples. He found this transformation occurring at 1388 ± 5 C, which is well below the previously accepted value of 1401 to 1403 C.

Heat Capacity, Specific Heat, Entropy. Although considerable data have been published concerning these properties, numerous discrepancies among the data make concise presentation difficult. Both Ralston and Austin have made critical surveys of the available results. Cleaves and Thompson prefer Austin's review, because it is more recent than Ralston's and includes data obtained by improved methods. Thompson considers Austin's results good in spite of recent values given by Jaeger, Rosenbohm and Zuithoff, and by Esser and Baerlecken.

Table III. Specific Heat, Heat Content, Free Energy, and Entropy of Alpha Iron

Temperature °K	Temperature °C	Temperature °F	Specific Heat cal per g °C	Specific Heat cal per g-atom °C	Heat Content (H) Referred to H = O at 0 °K cal per ■	Heat Content (H) Referred to H = O at 0 °K cal per g-atom	Free Energy (F) F = H-TS cal per g-atom	Entropy (S) cal per g-atom °C
0	−273.1	−459.6	0	0	0	0	0	0
20	−253.1	−423.6	....	0.005	....	....	....	....
23	−250.1	−418.2	....	....	....	....	....	....
30	−243.1	−405.6	0.003	0.105	....	....	....	....
40	−233.1	−387.6	0.007	0.367	....	....	....	....
50	−223.1	−369.6	0.013	0.710	0.09	5	−8	0.248
73	−200.1	−328.2	....	....	....	....	....	....
75	−198.1	−324.6	0.032	1.80	....	....	....	....
100	−173.1	−279.6	0.051	2.85	1.88	105	−45	1.40
123	−150.1	−238.2	....	....	....	....	....	....
125	−148.1	−234.6	0.065	3.65	....	....	....	....
150	−123.1	−189.6	0.077	4.33	5.20	290	−134	2.83
173	−100.1	−148.2	....	....	....	....	....	....
175	− 98.1	−144.6	0.086	4.80	....	....	....	....
200	− 73.1	− 99.6	0.092	5.15	9.4	525	−303	4.24
223	− 50.1	− 58.2	....	....	....	....	....	....
225	− 48.1	− 54.6	0.097	5.40	....	....	....	....
250	− 23.1	− 9.6	0.101	5.66	14.5	810	−572	5.53
273.1	0	32.0	0.104	5.84	17.0	950	−715	6.10
283	10	50.0	0.1060	5.919	....	....	....	....
293	20	68.0	0.1075	6.002	....	....	....	....
298	25	77.0	0.108	6.051	19.6	1,096	−871	6.60
303	30	86.0	0.1087	6.070	....	....	....	....
313	40	104.0	0.1097	6.126	....	....	....	....
323	50	122.0	0.1105	6.170	22.4	1,250	−1,014	7.01
333	60	140.0	0.1112	6.209	....	....	....	....
343	70	158.0	0.1119	6.248	....	....	....	....
353	80	176.0	0.1126	6.288	....	....	....	....
363	90	194.0	0.1133	6.322	....	....	....	....
373	100	212.0	0.1141	6.395	28.0	1,566	−1,455	8.10
423	150	302.0	0.121	6.78	33.9	1,894	−1,887	8.94
473	200	392.0	0.128	7.13	40.2	2,246	−2,389	9.80
523	250	482.0	0.134	7.48	46.7	2,610	−2,850	10.44
573	300	572.0	0.140	7.82	53.7	2,998	−3,368	11.11
623	350	662.0	0.146	8.14	60.8	3,394	−3,970	11.82
673	400	752.0	0.151	8.43	68.2	3,814	−4,585	12.48
723	450	842.0	0.157	8.74	76.0	4,244	−5,206	13.07
773	500	932.0	0.163	9.10	84.0	4,689	−5,911	13.72
823	550	1022.0	0.172	9.58	92.4	5,159	−6,581	14.26
873	600	1112.0	0.188	10.54	101.2	5,653	−7,293	14.83
923	650	1202.0	0.208	11.62	111.1	6,204	−8,028	15.42
973	700	1292.0	0.230	12.84	122.0	6,810	−8,894	16.14
1023	750	1382.0	0.276	15.40	133.4	7,451	−9,460	16.53
1033	760	1400.0	0.320	17.89	....	....	....	....
1073	800	1472.0	0.210	11.70	146.0	8,151	−10,573	17.45
1123	850	1562.0	0.194	10.84	156.5	8,737	−11,566	18.08
1173	900	1652.0	0.186	10.39	165.6	9,250	−12,427	18.48
1179	906	1662.0	0.160	9.94	166.4	9,294	−12,500	18.51
1223	950	1742.0	....	....	174.9	9,765	−13,300	18.86
1273	1000	1832.0	....	....	184.1	10,280	−14,251	19.27
1323	1050	1922.0	....	....	193.5	10,795	−15,215	19.66
1373	1100	2012.0	....	....	202.5	11,310	−16,219	20.05
1423	1150	2102.0	....	....	211.8	11,825	−17,233	20.42
1473	1200	2192.0	....	....	221.0	12,340	−18,239	20.76
1523	1250	2282.0	....	....	230.3	12,855	−19,325	21.13
1573	1300	2372.0	....	....	239.4	13,370	−20,339	21.43
1623	1350	2462.0	....	....	248.6	13,885	−21,448	21.77
1673	1400	2552.0	....	....	257.9	14,400	−22,540	22.08
1723	1450	2642.0	....	....	267.1	14,915	−23,645	22.38
1773	1500	2732.0	....	....	276.3	15,430	−24,782	22.68
1808	1535	2795.0	....	....	282.8	15,791	−25,400	22.88

The variation in specific heat with temperature is shown in Fig. 4. In this discussion "specific heat" refers to the rate of change of heat content at a given temperature (sometimes called "true specific heat" in technical literature) and "mean specific heat" refers to the average rate of change through a given temperature range.

Tables III and IV, adapted from Cleaves and Thompson, give values selected by Austin for entropy, heat content, free energy, and specific heat of both alpha and gamma iron throughout the range from absolute zero to the melting point. The specific heat of liquid iron has been reported by various investigators (Wüst, Meuthen, and Dürrer; Umino; Oberhoffer and Grosse) at values varying from 0.142 to 0.222 cal per g. The average of four reported data is 0.177 cal per g.

Heats of Transition. There is no discontinuity in the total heat curve at the A_2 point. Ralston interprets this as indicating only a change in specific heat and not a real heat of transition. Numerous values of heat of transformation are given in the literature for the A_2 point, but these may be the magnetic component of the specific heat integrated over a range of temperature. Ralston states: "The true heat of transition of A_2 is therefore zero, unless we look on the heat accompanying the magnetic changes as a distributed (over a temperature range) latent heat. This latter idea is quite permissible, although not in common acceptance."

Most values for heat of transition at the A_3 point have been determined by measuring the heat content above and below the transition temperature; and since the results are small differences between large numbers, the variations recorded in the literature are not surprising. Since Ralston calculated his value of 4.9 cal per g from an average heat content curve, Klinkhardt and Esser and Bunghardt have made direct determinations of the heat absorbed during the transformation. The average of their results gives 3.63 cal per g or 203 cal per g-atom.

From Umino's data for heat content, Yap computed the heat effect during the alpha-gamma change, when this occurred at various temperatures (Table V).

Although Ralston's value of 1.7 cal per ■ or 94.9 cal per g-atom for the heat effect at the A_4 point, is somewhat lower than Umino's subsequently reported determination of 1.86 cal per g, Cleaves and Thompson state that Austin considered Ralston's value as the most probable one for the heat effect at the A_4 point.

Heat of Fusion. Ralston and Austin agree in their selection of 64.9 cal per ■ as the best value for heat of fusion, and Cleaves and Thompson suggest that this be rounded to 65 cal per g (3630 cal per g-atom) because the reported

Table IV. Specific Heat, Heat Content, Free Energy, and Entropy of Gamma Iron

Temperature °K	Temperature °C	Temperature °F	Specific Heat cal per g °C	Specific Heat cal per g-atom °C	Heat Content (H_1) Based on H_1 = 0 at 0 °K cal per g	Heat Content (H_1) Based on H_1 = 0 at 0 °K cal per g-atom	Heat Content (H_2) H_2 = 960 at 0 °K cal per g	Heat Content (H_2) H_2 = 960 at 0 °K cal per g-atom	Free Energy (F) cal per g-atom	Entropy (S) cal per g-atom °C
0	−273.1	−459.6	0		0	0	17.19	960	960	0
20	−253.1	−423.6	....	0.10	....	....	....	....	....	....
23	−250.1	−418.2	....	...	0.018	1.0	17.21	961	957	0.06
30	−243.1	−405.6	0.004	0.25	....	....	....	....	....	....
40	−233.1	−387.6	0.010	0.53	....	....	....	....	....	....
50	−223.1	−369.6	0.024	1.36	....	....	....	....	....	....
73	−200.1	−328.2	....	...	1.196	66.8	18.37	1,026	939	1.20
75	−198.1	−324.6	0.052	2.90	....	....	....	....	....	....
100	−173.1	−279.6	0.071	3.95	....	....	....	....	....	....
123	−150.1	−238.2	....	...	4.67	261	21.9	1,221	842	3.08
125	−148.1	−234.6	0.089	5.00	....	....	....	....	....	....
150	−123.1	−189.6	0.100	5.60	....	....	....	....	....	....
173	−100.1	−148.2	....	...	9.63	538	26.8	1,498	636	4.98
175	− 98.1	−144.6	0.109	6.10	....	....	....	....	....	....
200	− 73.1	− 99.6	0.114	6.35	....	....	....	....	....	....
223	− 50.1	− 58.2	....	...	15.4	862	32.6	1,822	336	6.66
225	− 48.1	− 54.6	0.116	6.50	....	....	....	....	....	....
250	− 23.1	− 9.6	0.118	6.60	....	....	....	....	....	....
273.1	0	32.0	0.120	6.70	21.2	1,185	38.4	2,145	−12	7.90
283	10	50.0	....	...	....	....	....	....	....	....
293	20	68.0	....	...	....	....	....	....	....	....
298	25	77.0	0.122	6.80	24.3	1,357	41.5	2,317	−228	8.54
303	30	86.0	....	...	....	....	....	....	....	....
313	40	104.0	....	...	....	....	....	....	....	....
323	50	122.0	0.124	6.90	27.5	1,529	44.6	2,489	−420	9.00
333	60	140.0	....	...	....	....	....	....	....	....
343	70	158.0	....	...	....	....	....	....	....	....
353	80	176.0	....	...	....	....	....	....	....	....
363	90	194.0	....	...	....	....	....	....	....	....
373	100	212.0	0.127	7.11	33.7	1,880	50.5	2,840	−867	9.94
423	150	302.0	0.131	7.30	40.2	2,244	57.6	3,214	−1,377	10.83
473	200	392.0	0.134	7.49	46.9	2,617	64.1	3,577	−1,933	11.65
523	250	482.0	0.137	7.67	53.65	2,996	70.8	3,956	−2,550	12.44
573	300	572.0	0.141	7.86	60.6	3,384	77.8	4,344	−3,185	13.14
623	350	662.0	0.143	8.01	67.7	3,781	84.9	4,741	−3,856	13.80
673	400	752.0	0.146	8.18	75.0	4,186	92.2	5,146	−4,545	14.40
723	450	842.0	0.148	8.30	82.4	4,601	99.6	5,561	−5,284	15.00
773	500	932.0	0.151	8.43	89.8	5,016	107.0	5,976	−6,083	15.60
823	550	1022.0	0.153	8.54	97.5	5,442	114.6	6,402	−6,807	16.05
873	600	1112.0	0.155	8.66	105.1	5,872	122.4	6,832	−7,607	16.54
923	650	1202.0	0.156	8.71	112.9	6,307	130.1	7,267	−8,452	17.03
973	700	1292.0	0.157	8.77	120.8	6,744	136.2	7,604	−9,314	17.49
1023	750	1382.0	0.158	8.81	128.7	7,184	145.8	8,144	−10,116	17.85
1033	760	1400.0	....	...	....	....	....	....	....	....
1073	800	1472.0	0.158	8.88	136.5	7,625	153.7	8,585	−11,083	18.33
1123	850	1562.0	0.159	8.91	144.5	8,069	161.7	9,029	−11,971	18.70
1173	900	1652.0	0.160	8.98	152.5	8,515	169.7	9,475	−12,954	19.13
1179	906	1662.0	....	...	153.3	8,552	170.3	9,512	−13,004	19.17
1223	950	1742.0	0.161	8.99	160.5	8,961	177.7	9,921	−13,524	19.50
1273	1000	1832.0	0.162	9.02	168.5	9,411	185.7	10,371	−14,911	19.86
1323	1050	1922.0	0.162	9.05	176.6	9,862	193.8	10,822	−15,916	20.21
1373	1100	2012.0	0.163	9.10	184.8	10,319	202.0	11,279	−16,940	20.55
1423	1150	2102.0	0.164	9.16	192.9	10,774	210.1	11,734	−17,964	20.87
1473	1200	2192.0	0.165	9.21	201.2	11,234	218.1	12,194	−19,020	21.19
1523	1250	2282.0	0.166	9.27	209.4	11,695	226.6	12,655	−20,120	21.52
1573	1300	2372.0	0.167	9.32	217.8	12,160	236.6	13,120	−21,171	21.80
1623	1350	2462.0	0.168	9.38	226.1	12,627	242.8	13,587	−22,265	22.09
1673	1400	2552.0	0.169	9.44	234.6	13,098	251.8	14,058	−23,367	22.37
1723	1450	2642.0	0.170	9.50	243.0	13,571	260.2	14,531	−24,495	22.65
1773	1500	2732.0	0.171	9.56	251.6	14,048	268.8	15,008	−25,630	22.92
1808	1535	2795.0	....	...	....	....	....	....	....	....

data indicate that even the unit figure may be in doubt.

Thermal Conductivity. Most of the published determinations of this property are for impure specimens—a fact which undoubtedly accounts for much of the disagreement among the results of different workers. Grüneisen and Goens found that impurities had a much greater effect at low temperatures than at room temperature. The results of Powell and of Shelton are shown in Fig. 5; Powell's results contain an extension of previous investigations, including determinations at 900 and 1000 C. It is indicated that the thermal conductivity of γ iron increases with an increase in temperature.

Coefficient of Thermal Expansion. The coefficient of linear thermal expansion is the increase in length per unit length for an increase of one degree in temperature, and is sometimes referred to as the "true coefficient of expansion". The average expansion through a range of temperature is the "mean coefficient of expansion" through that range.

The thermal expansion data of Hidnert (on National Bureau of Standards high-purity iron) are given in Table VI. Both Austin and Pierce, and Cleaves and Hiegel report difficulties in determining the coefficient of thermal expansion above 600 C. Cleaves and Hiegel state: "The expansivity of the iron at high temperature is not satisfactorily established by the data available."

Table V. Temperature Variation of Heat Effect at A_3 Point

Temp of Transformation, °C	Heat Effect, cal per g	Temp of Transformation, °C	Heat Effect, cal per g
200	22.4	1000	3.2
400	22.6	1100	1.2
600	18.4	1200	−0.3
800	8.5	1300	−1.5
900	5.6	1400	−1.9

Table VI. Coefficient of Linear Expansion of Alpha Iron

Temperature, deg Cent	Coefficient of Linear Expansion, millionths per deg Cent: Austin and Pierce	Hidnert
−100	...	9.1
− 50	...	10.5
0	...	11.5
20	...	11.7
100	12.6	12.7
200	13.8	13.9
300	14.6	15.0
400	16.6	15.9
500	16.8	16.2
600	16.0	16.0

Melting Point. Many determinations of the melting point of iron are recorded in technical literature, but it is generally conceded that the latest and best value is that reported by Cleaves and Hiegel[3] for the value of 1539 ± 1 C determined by Roeser and Wensel for the National Bureau of Standards high-purity iron.

Boiling Point and Vapor Pressure. Table VII gives the results of determinations of vapor pressure reported by Jones, Langmuir and Mackay and by Marshall, Dornte and Norton. Cleaves and Thompson suggested that a rounded value of 3000 C be used for the boiling point. The data of Table VII are plotted in Fig. 6.

Electrical Properties. The electrical resistance of iron is greatly influenced by impurities and by the previous thermal and mechanical treatment, so reported values are often discordant. Cleaves and Hiegel report the electrical resistivity of the National Bureau of Standards high-purity iron, as determined by Thomas and Cooter, to be 9.71 microhm-cm at 20 C. They also give the fundamental temperature coefficient (through the range from 0 to 100 C) as 0.00651 ohm per °C per ohm at 0 C. These are believed to be the best available values for pure iron.

Table VII. Vapor Pressure of Iron
Temperatures, °C, as given by different observers

Vapor Pressure, mm Hg	Jones Langmuir Mackay	Marshall Dornte, Norton
1.86×10^{-23}	327	....
7.58×10^{-19}	427	....
2.06×10^{-16}	527	....
9.52×10^{-13}	627	....
1.32×10^{-10}	727	....
7.11×10^{-9}	827	....
1.94×10^{-7}	927	....
2.52×10^{-6}	....	1044
3.22×10^{-6}	1027	....
5.15×10^{-6}	....	1068
1.57×10^{-5}	1108	....
3.47×10^{-5}	....	1127
1.14×10^{-4}	....	1186
2.46×10^{-4}	....	1229
2.70×10^{-4}	1227	....
2.77×10^{-4}	....	1241
3.79×10^{-4}	....	1254
4.25×10^{-4}	....	1252
7.34×10^{-4}	....	1280
1.00×10^{-3}	1327	....
9.27×10^{-3}	....	1306
0.0076	1427	....
0.023	1527	....
0.220	1727	....
1.2	1927	....
7.5	2127	....
26.2	2327	....
82.5	2527	....
165	2727	....
345	2927	....
631	3127	....
760[a]	3202	....

(a) This vapor pressure corresponds to the boiling point under "standard conditions".

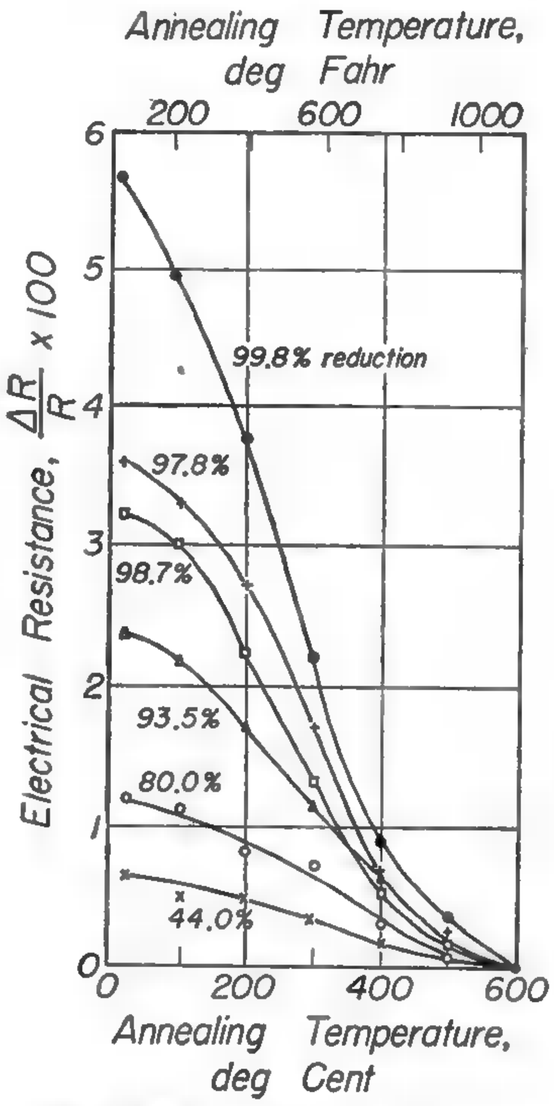


Fig. 8 Effect of annealing on the electrical resistance of cold worked iron. Reduction in area of 97.8% obtained by rolling; other reductions obtained by cold drawing.

The variation in resistivity with temperature shown in Fig. 7, is probably only relative since the resistivity seems to be affected by the prior thermal history of the specimens, and grain growth above 600 C may influence the results from some specimens.

Effect of Mechanical and Thermal Treatment. Cold working increases the resistivity, but reannealing of cold worked iron lowers the resistivity to its initial value. Bardenheuer and Schmidt found virtually no change in resistivity of electrolytic iron cold drawn various amounts as high as 95% reduction in area, but Tammann and Moritz obtained a maximum increase in resistivity of about 5.7% by cold working 99.8%. Annealing at 600 C (1110 F) restored the iron to its original resistivity. Figure 8 is taken from the work of Tammann and Moritz.

Effect of Hydrostatic Pressure. Beckman found the pressure coefficient of electrical resistivity for Swedish iron of low purity (fundamental coefficient of 0.0048) to be 27.4×10^{-7} per atmosphere between 425 and 2097 atmospheres at 0 C ($a = 1/R \times dR/dP$). Bridgman measured

Table VIII. Thermoelectric Properties of Iron Against Other Metals ("Cold End" at 0 °C)
(Values are in millivolts and are positive when current flows from the iron to the other metal at the junction that is at 0° C.)

Temperature		Thermal emf, millivolts					
°C	°F	Aluminum (Dannecker)	Constantan (I.C.T.)	Copper[a]	Lead[b]	Nickel (Dannecker)	Tin (Smits and Spuyman)
−250	−418	....	....	....	−3.5	....	.....
−225	−373	....	....	....	−3.35	....	.....
−200	−328	....	....	....	−3.2	−5	.....
−175	−283	....	....	....	−2.9	....	.....
−150	−238	−1.75	....	....	−2.5	....	.....
−125	−193	....	....	....	−2.2	....	.....
−100	−148	−1.25	....	....	−1.75	−3	.....
− 75	−103	....	....	....	−1.3	....	.....
− 50	− 58	−0.6	....	....	−0.9	....	.....
− 25	− 13	....	....	....	−0.5	....	+1.30 (140 C)
0	32	0	0	....	0	0	+1.31 (150 C)
25	77	....	....	....	+0.4	....	+1.34 (160 C)
50	122	....	....	....	+0.75	....	+1.38 (170 C)
75	167	5.3	+0.95	....	+1.2	....	+1.43 (180 C)
100	212	+1.25	10.8	....	+1.4	+3	+1.53 (190 C)
200	392	2.25	16.3	1.656	....	+6	+1.7 (200 C)
300	572	2.8	21.8	1.869	....	9	+1.76 (210 C)
400	752	3	27.6	1.583	....	10.5	.....
500	932	2.85	33.1	0.870	....	11.8	.....
600	1112	....	39.2	−0.119	....	13.5	.....
700	1292	....	45.4	....	....	15.5	.....
800	1472	....	51.7	−1.797	....	18	.....
900	1652	....	57.9	−2.378	....	20	.....
1000	1832	....	....	....	....	22.5	.....
1100	2102	....	+0.7	....	....	25	.....

(a) Jaeger, Rosenbohm and Zuithoff. (b) I. C. T. and Dewar, and Fleming and Wietzel

the pressure coefficient on basic open hearth iron (fundamental coefficient = 0.0062) and obtained 24.9×10^{-7} per atmosphere at 0 C and zero pressure, and 21.9×10^{-7} per atmosphere at 0 C and 12,400 atmospheres.

Thermoelectrical Properties. Table VIII gives the thermal electromotive force produced by bimetallic couples of iron and other metals. The values are in millivolts and are considered positive if the current flows from the iron to the other metal at the junction which is at 0 C. The data were obtained in some instances on samples of unknown purity and would not be duplicated exactly on other specimens, but are given as an indication of the magnitude of the thermoelectromotive forces produced.

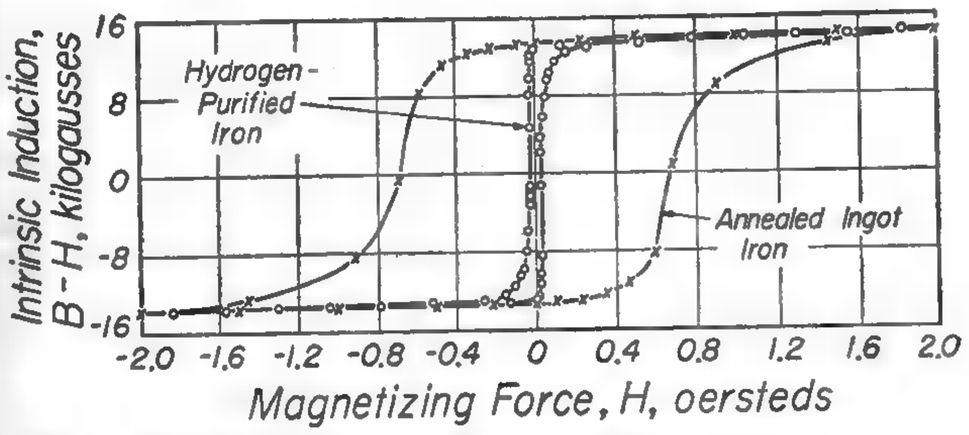


Fig. 9. Hysteresis loops for ingot iron and hydrogen-purified iron.

Electrochemical Equivalent. This constant is computed from the atomic weight and the valence; consequently there are two values for iron: 0.1929×10^{-3} g sec^{-1} amp^{-1} for trivalent iron, and 0.2893×10^{-3} g sec^{-1} amp^{-1} for bivalent iron.

Magnetic Properties.* The magnetic properties, like the electrical, are quite sensitive to small changes in treatment and amount of impurities. Samples of high-purity iron prepared by long-time hydrogen annealing just below the melting point, have furnished new and interesting values for the magnetic properties of iron, but the

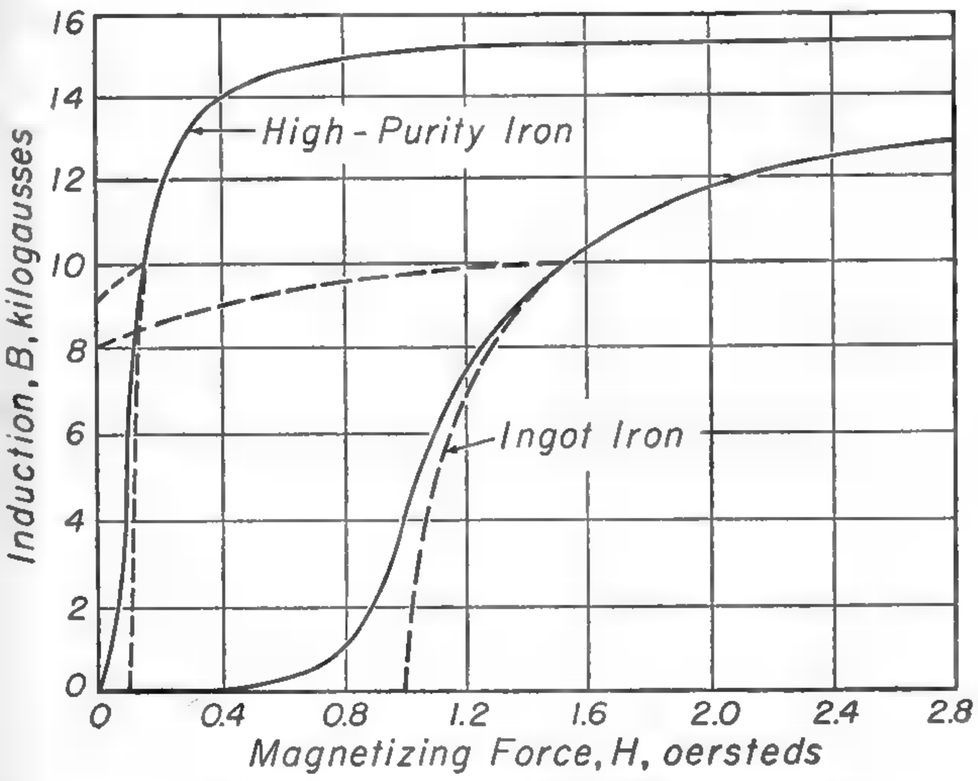


Fig. 10 Magnetization curves for ingot iron and iron of high purity (Yensen)

concomitant effect of large grain size is undoubtedly present also, and the results are included here with the reminder that grain size may have increasing influence on the magnetic properties as the purity increases.

Figure 9 shows hysteresis loops of ingot iron and hydrogen-purified iron as determined by Cioffi. Figure 10 shows hysteresis loops and magnetization curves for ingot iron in comparison with those for iron of high purity prepared at Westinghouse Research Laboratories, where high-vacuum melting was used for eliminating carbon and oxygen. The iron was subsequently annealed in a vacuum to produce large grains. The permeability of the hydrogen-purified iron (0.005% C, 0.028% Mn, 0.004% P, 0.003% S, 0.0012% Si, 0.003% O_2, 0.0001% N_2) is far greater at low inductions than the permeability of irons of commercial purity; but the difference fades out at higher inductions, as shown in Fig. 10 and 11.

A typical hysteresis curve for commercially annealed "magnetic ingot iron"* is shown in Fig. 12. For other magnetic characteristics of this iron, see Fig. 13, 14 and 15.

The magnetic saturation induction for this material is 21.6 kilogausses, which checks the value of 21.578 reported by Cleaves and Hiegel for the high-purity iron prepared at the National Bureau of Standards.

Effect of Temperature. In studying the effect of temperature on permeability of Burgess' electrolytic iron, Terry found that this effect depends on the field strength as

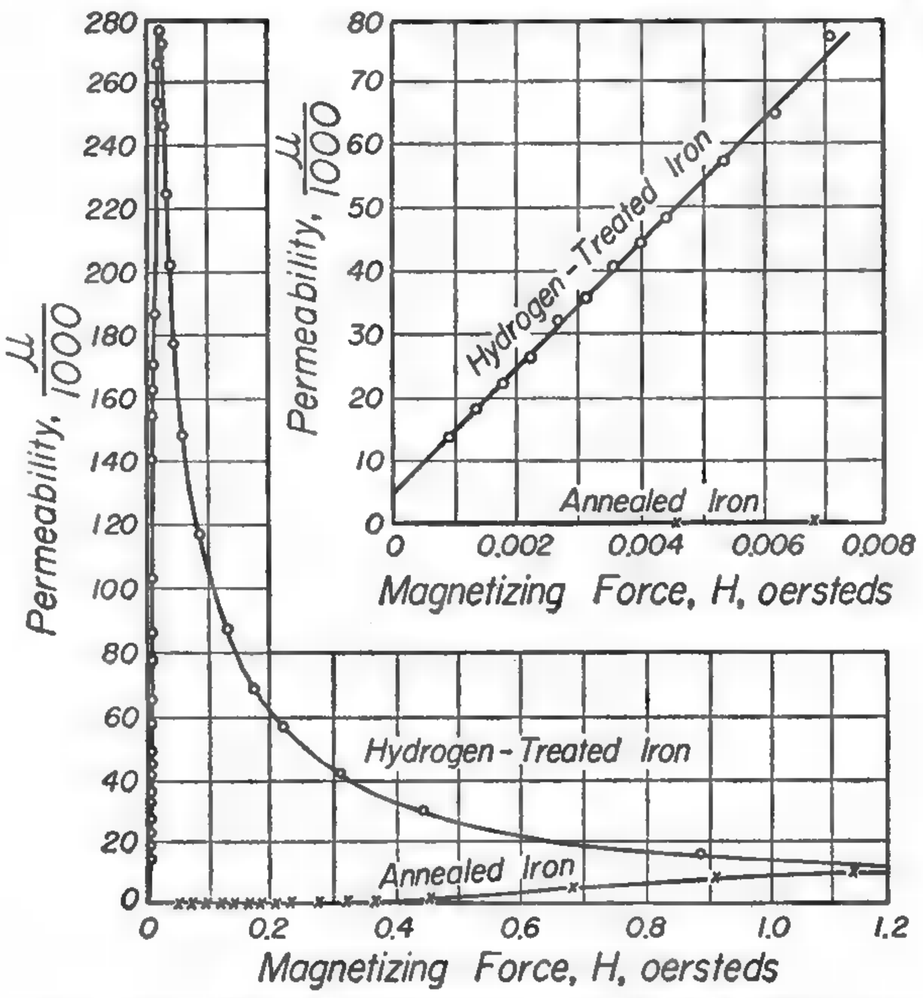


Fig. 11 The effect of hydrogen treatment on the permeability of annealed iron (Cioffi, according to Ellis and Schumacher)

shown in Fig. 16. His results concerning the effect of temperature on the hysteresis constants are given in Fig. 17.

Effect of Grain Size. The work of Sizoo on electrolytic iron (0.024% C, 0.012% S, 0.014% Si) is shown in Fig. 18, while that of Yensen and Ziegler is given in the following equations:

Coercive force = H_c, oersteds
Hysteresis loss = W, ergs per cu cm per cycle
Minimum reluctivity = $\rho_{min} = \frac{1}{\mu_{max}}$

For less than 0.002% C	$\rho_{min} = 0.34 \times 10^{-5} N$; $H_c = 0.0018 N$; $W = 56 N$
For 0.002 to 0.004% C	$\rho_{min} = 0.21 \times 10^{-5} N$; $H_c = 0.00114 N$; $W = 34.4 N$
For 0.004 to 0.008% C	$\rho_{min} = 0.46 \times 10^{-5} N$; $H_c = 0.0025 N$; $W = 75 N$

where N is the number of grains per square millimeter.

The effect of orientation is present, no doubt, in specimens that have larger grain size, but this effect seems not to have been considered by the investigators quoted.

Effect of Cold Work. Cold working has a deleterious effect on the magnetic properties of iron. The effect of various amounts of cold reduction on the hysteresis loop of electrolytic iron (polycrystalline), as determined by

* "Magnetic ingot iron" refers to a commercial product known as "Armco Magnetic Ingot Iron", which is a special grade of ingot iron made particularly for electrical and magnetic applications. This material is selected to have the best composition, and is given the best processing—especially heat treatment—to produce desirable magnetic properties.

* *See also* "Magnetically Soft Materials", page 587.

Gries and Esser, is shown in Fig. 19. Cleaves and Thompson state that cold working decreases permeability and increases residual induction, coercive force and hysteresis loss, leaving only the saturation intensity unaffected.

Optical Properties. *Emissivity.* Determinations of emissivity are rarely made on high-purity iron, and even when

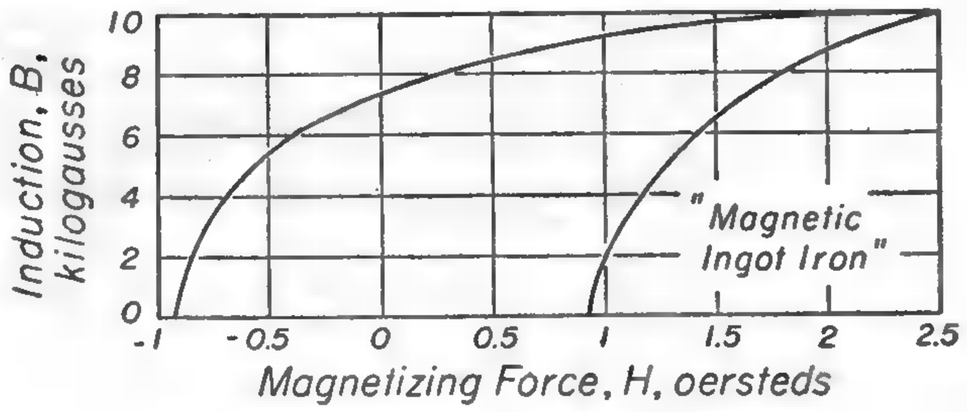


Fig. 12 Typical hysteresis curve for commercially annealed ring sample of "magnetic ingot iron"

specimens of such material have been used, the experimental procedure has often affected the purity; for example, when the source of heat was an arc between carbon electrodes. The best accepted values are those of Burgess

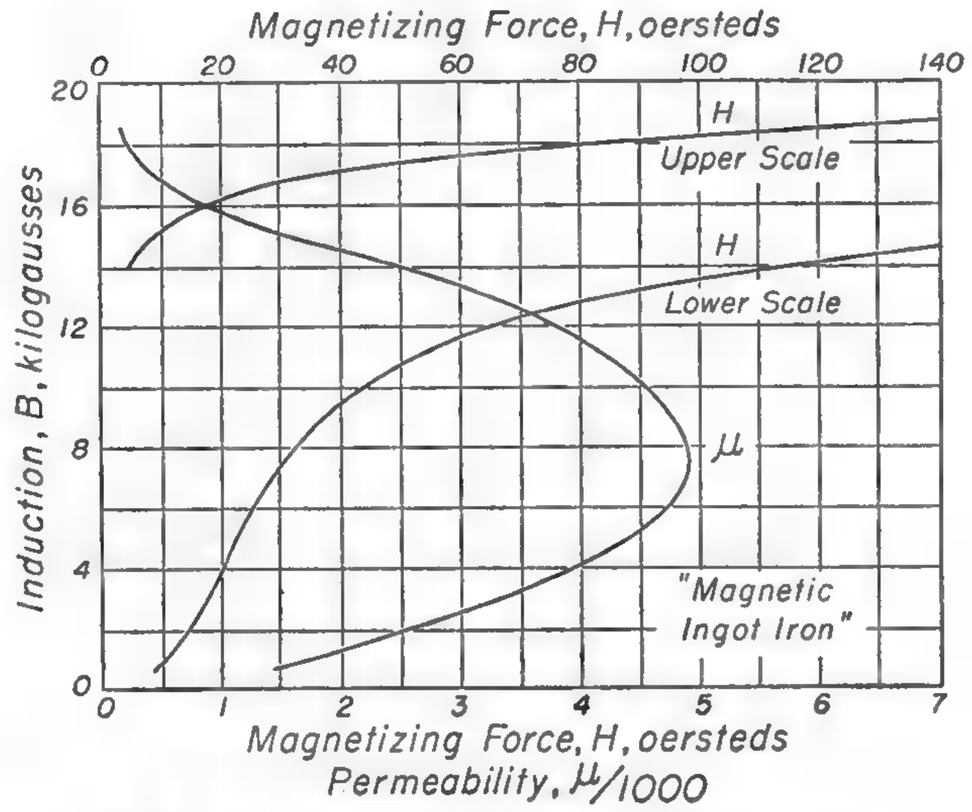


Fig. 13 Typical medium and low induction values for annealed "magnetic ingot iron" tested in ring form

and Waltenberg in Table IX, determined with a micropyrometer.

The above values are all for $\lambda = 0.65\ \mu$ and the average should probably be rounded to 37%.

Emissivity values for iron and steel, as measured in various industrial operations, may differ from this because of oxide on heated surfaces of solid metal, and floating slag on liquid metal. Cleaves and Thompson state that

Table IX. Emissivity of Iron at Various Temperatures

State	Temp, °C	Emissivity, %
Liquid	1050	37.9
	1350	37.2
	1450	36.3
	1530	36.0
Solid	1535	36.5
	Average	36.8

values have been reported between 40 and 45% for liquid metal or for solid metal with a bright surface, and as high as 90% for solid metal with an oxidized surface. In the International Critical Tables, volume 5, page 244, the total emissivity for oxidized surfaces of steel is quoted as 79% at 200 C, 78.8% at 400 C, and 78.7% at 600 C.

The *reflectivity* determinations in technical literature are chiefly for iron of unknown composition. Moreover, the effect of impurities on reflectivity seems not to have been the subject of investigation. Figure 20 presents the combined results of several workers.

Mechanical Properties. *Elastic Constants.* Abram found that ingot iron and mild steel have a slightly higher

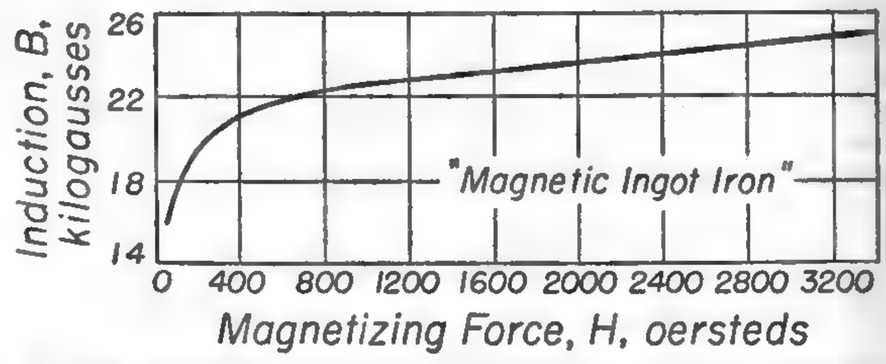


Fig. 14 High induction values for "magnetic ingot iron" annealed bar

Young's modulus than medium-carbon and high-carbon steel. They reported 30.1×10^6 psi for ingot iron and considered that for pure iron in the annealed condition, the value would be about 30.2×10^6 psi. Goens and Schmid determined Young's modulus for different directions in a single crystal of ingot iron and found that it was more than twice as great in the [111] direction as in the [100] direction.

E [100] = 19,000,000 psi (13,500 kg per sq mm)
E [111] = 41,000,000 psi (29,000 kg per sq mm)

Kimura and Ohno have reported the values in Table X for the elastic constants for single crystals of iron.

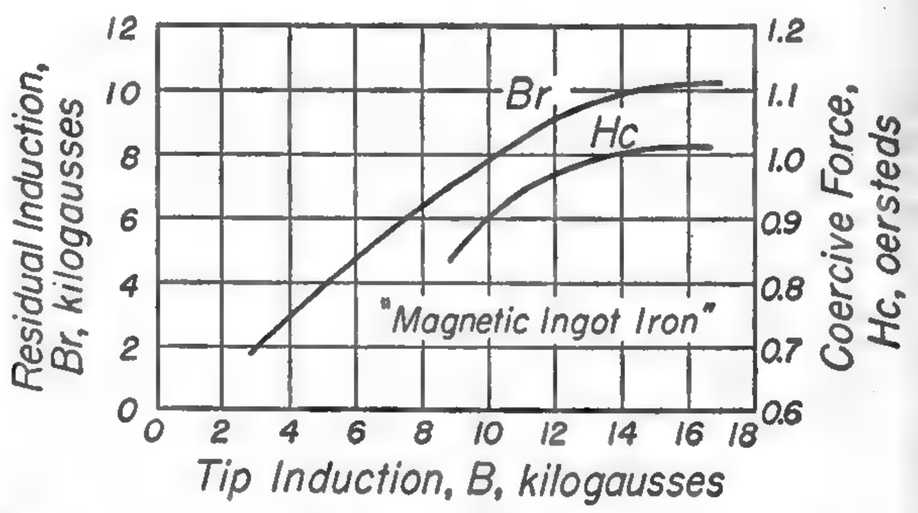


Fig. 15 Residual induction and coercive force versus tip induction for annealed "magnetic ingot iron" ring sample

Other values reported for polycrystalline irons are 29,300,000 psi for ingot iron as determined by Kenyon; 29,600,000 and 30,600,000 psi for electrolytic iron as reported in the International Critical Tables and by Grüneisen, respectively; 29,400,000 psi for carbonyl iron as given by Duftschmid, Schlecht and Schubardt; and 27,200,000 to

Table X. Elastic Constants for Iron (Single Crystals)

	[100]	[110]	[111]
Young's modulus, psi	18.9×10^6	31.3×10^6	40×10^6
Modulus of torsion, psi	16.1×10^6	9.6×10^6	8.5×10^6
Bulk or Voight's modulus, psi	$S_{11} = 10.9 \times 10^6$	$S_{12} = -4.7 \times 10^6$	$S_{44} = 14.7 \times 10^6$
Elastic constants, psi	$C_{11} = 39.4 \times 10^6$	$C_{12} = 24 \times 10^6$	$C_{44} = 18.2 \times 10^6$

30,000,000 psi as found by Cleaves and Hiegel for the National Bureau of Standards high-purity iron.

Values for the modulus in torsion or the shear modulus of polycrystalline irons are as follows:

Ingot iron	11.77×10^6 psi
Ingot iron	11.78×10^6 psi
Electrolytic	11.45×10^6 psi
Electrolytic	11.81×10^6 psi
Electrolytic	11.66×10^6 psi

Poisson's Ratio is generally considered to lie between

0.25 and 0.33 for most metals and is given for iron as 0.28 in various handbooks.

Compressibility. The compressibility of iron has been studied by various investigators, but the outstanding work in this field is that of Bridgman, who determined the compressibility of ingot iron. Cleaves and Thompson have summarized his findings and state that at 30 C the mean

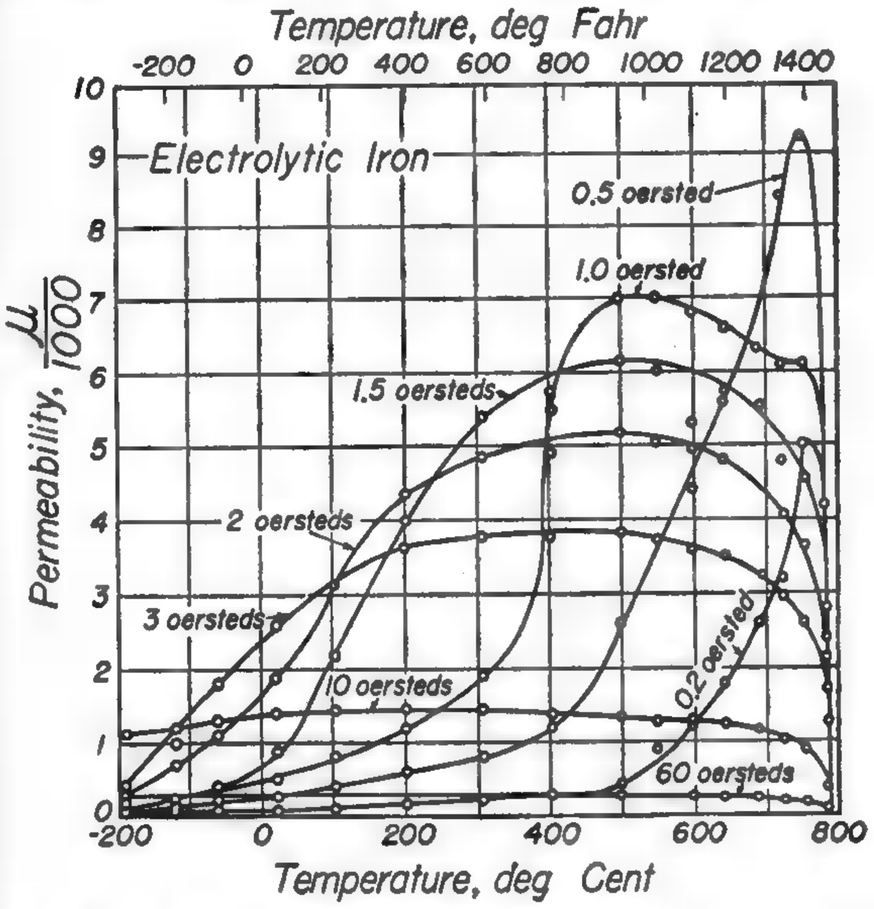


Fig. 16 Variation of the magnetic permeability of annealed electrolytic iron with temperature (Terry)

compressibility between 0 and 10,000 kg per sq cm was 0.566×10^{-6} kg per sq cm, and at 75 C it was 0.572×10^{-6} kg per sq cm over the same range of pressure. The pressure coefficient for this range of pressure was 7.0×10^{-6} per kg per sq cm and the temperature coefficient was 2.3×10^{-4} per degree Centigrade over the range from 30 to 75 C.

Adams found that the compressibility of a specimen of Yensen's high-purity iron agreed with that of Bessemer

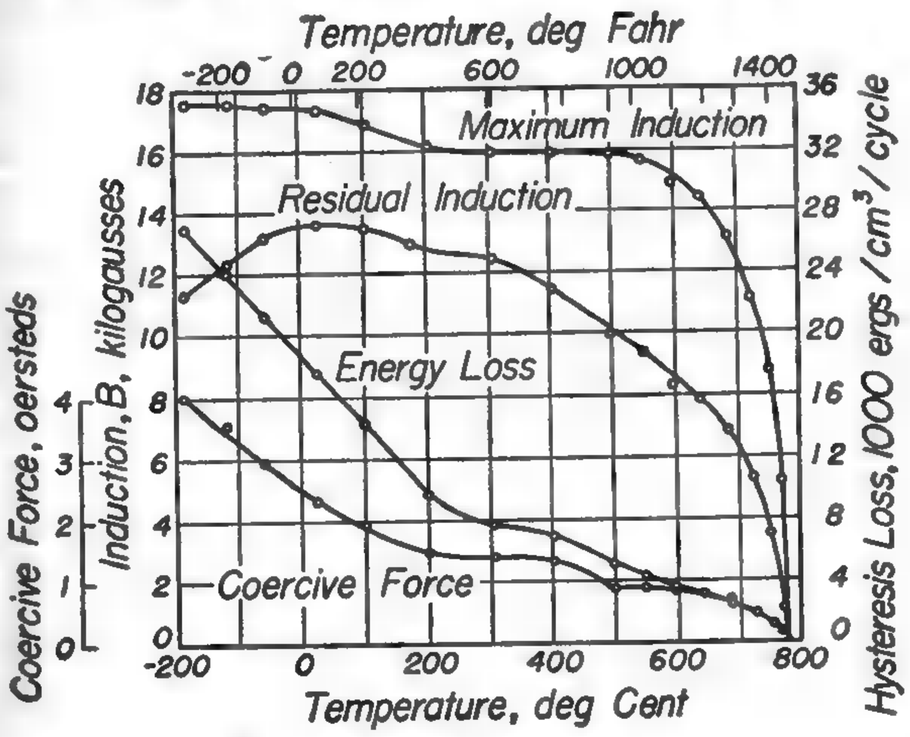


Fig. 17 Variation of the hysteresis constants with temperature in annealed electrolytic iron (Terry)

steel within one part in 500 over a range from 0 to 7000 kg per sq cm pressure.

Compression, Tensile, Torsion, Fatigue, Hardness and Impact Values. These values for polycrystalline irons at room temperature are given in Table XI. The data presented are necessarily only a summary of selected values.

Effect of Temperature on Mechanical Properties. Although variations in testing technique affect the results at room temperature, they have an even greater effect at high and low temperature. Speed of testing, shape of specimen, method of gripping, uniformity of temperature and accuracy of temperature measurement are important factors, which unfortunately are frequently not mentioned in reports of tests found in technical publications.

Results obtained at elevated temperature may be divided into two groups—"short time" and "creep". Tapsell and Clenshaw give the results shown in Table XII for ingot iron when a Martens extensometer was used for determining the modulus at elevated temperatures. The loading

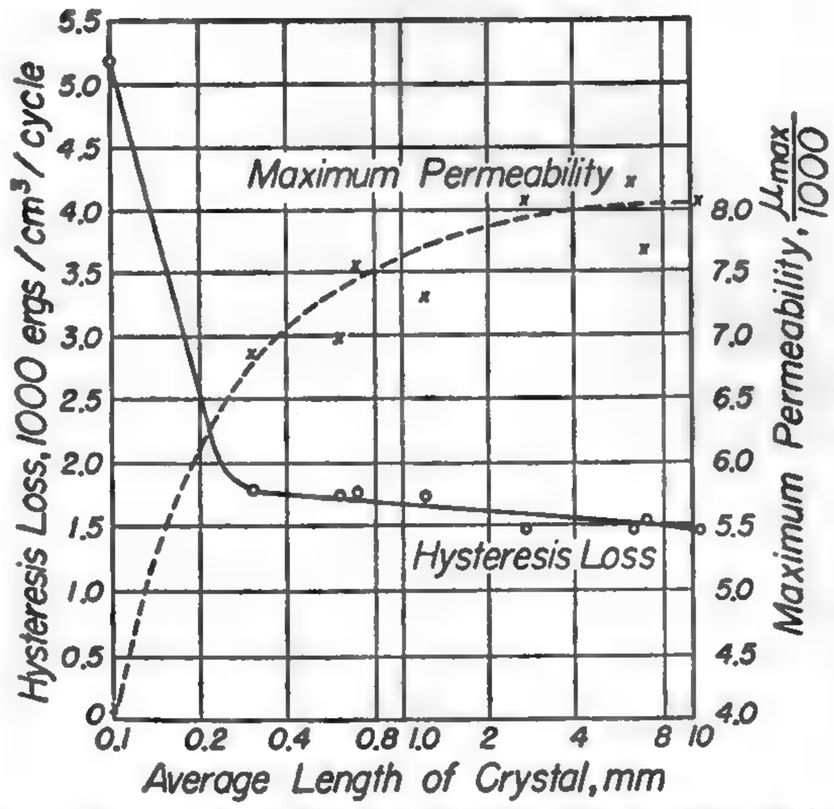


Fig. 18 Effect of grain size of electrolytic iron on hysteresis loss and maximum permeability (Sizoo)

was applied in steps. Total time to proportional limit was about 20 min. Normalized bars 2 in. in gage length and ½ in. in diam were used.

The work of Lea covered the temperature range of minus 40 to 1000 C. In general his tensile values are lower than those of Tapsell and Clenshaw, and above the "blue brittle" range the elongation is greater. These results are shown in Fig. 21.

The maximum in tensile strength at approximately 200

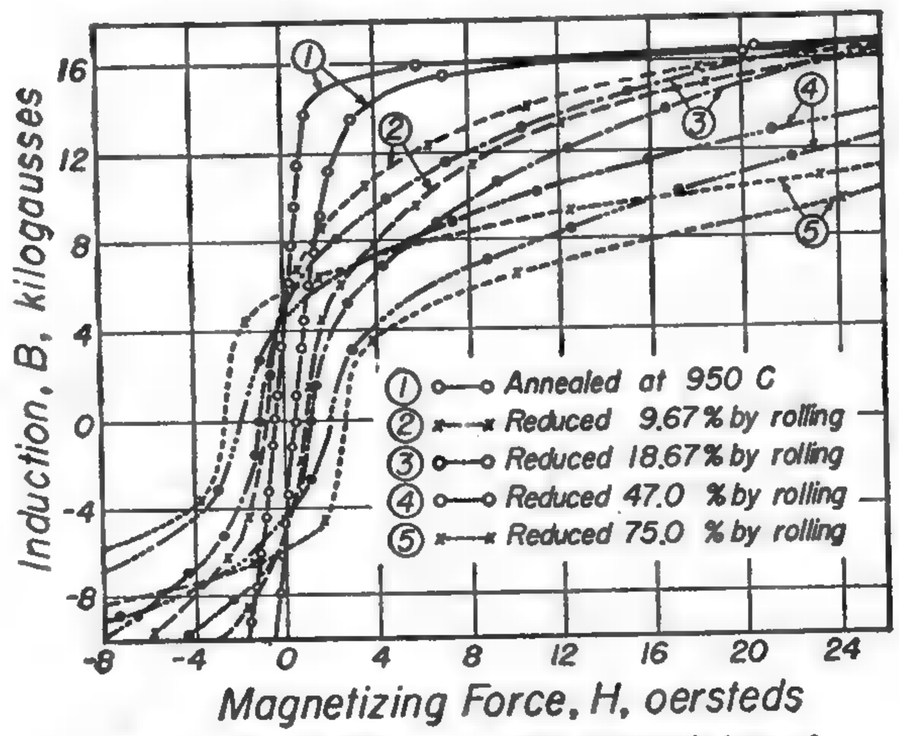


Fig. 19 Effect of cold work on the hysteresis loop of polycrystalline electrolytic iron (Gries and Esser)

C is generally ascribed to the so-called "blue brittle" phenomenon. The temperature at which this maximum tensile strength occurs, depends on testing speed; for slower speeds the maximum is at lower temperatures, and if the test is made slowly enough (two months) at room temperature, a strength is obtained approximately equal to the strength at ordinary rates of testing in the "blue brittle" range.

The "creep" strength is considerably lower than the tensile strength determined in the short-time test. The

Table XI. Compressive, Tensile, Torsion, Fatigue, Hardness, and Impact Values of Ingot Iron

Property	Hot Rolled Rods or Plates	Annealed Rods or Plates	Normalized	Dead Soft	Cold Worked (approx max)	Finished Cold	Finished Hot	Finished Hot, Annealed (a)	Finished Hot, Water Quenched, 1725 F
Compression									
Elastic limit	.....	19,400	.....	.....	.....	.....	.....	.....	.....
Proportional limit	.....	19,200	.....	.....	.....	.....	.....	.....	.....
Yield strength	.....	20,600	.....	.....	.....	.....	.....	.....	.....
Tensile									
Yield strength	26,000 to 32,000	.....	.....	19,000	(b)	26,900	19,100	18,300	30,300
Tensile strength	42,000 to 48,000	.....	.....	38,500	100,000	43,800	42,200	41,000	47,000
% elongation	22 to 28	.....	.....	43 to 48	.....	41.8	44.7	47.0	36.2
Gage length, in.	8	.....	.....	■	.....	2	2	2	2
% reduction of area	65 to 78	.....	.....	70 to 77	65 to 70	75.6	77.3	70.6	70.0
Torsion									
Proportional limit	12,000 to 15,000	.....	.....	.....	.....	.....	.....	.....	.....
Yield strength	14,000 to 23,000	.....	.....	.....	.....	.....	.....	.....	.....
Hardness									
Brinell Hardness No.	82 to 100	.....	.....	67	220	101	90	82	110
Rockwell B	39 to 55	.....	.....	.....	.....	.....	.....	.....	.....
Fatigue									
Reversed bend	.....	26,000(c)	.....	.....	.....	.....	.....	.....	.....
Reversed torsion	.....	12,800	.....	.....	.....	.....	.....	.....	.....
Axial stress	.....	26,700	.....	.....	.....	.....	.....	.....	.....
Impact									
Charpy, kg-m	0.9(d)	.....	2.66(d)	.....	.....	.....	.....	.....	.....
Izod, ft-lb	.....	.....	90.0 Longitudinal	.....	.....	.....	.....	.....	.....
	.....	.....	56.3 Transverse	.....	.....	.....	.....	.....	.....

	Electrolytic Iron: As Deposited	Electrolytic Iron: Fused and Annealed	Hydrogenized Iron	Carbonyl Iron	National Bur Stds Iron
Tensile					
Yield strength	.....	10,000 to 20,000	7,000	15,000 to 24,000	6,000 to 8,000
Tensile strength	55,000 to 113,500	35,000 to 40,000	14,000	28,000 to 40,000	28,000 to 30,000
% elongation	25 to 3	40 to 60	.....	30 to 40	36 to 46
Gage length, in.	2	1.5	.....	$L = 10d$	2
% reduction of area	.....	70 to 90	.....	70 to 80	>90
Hardness					
Brinell Hardness Number	140	45	.....	.....	49 ± 3
Rockwell B	350	90	.....	.....	.....
Scleroscope	.....	.....	B −10 to +10	.....	.....
Impact	.....	.....	.....	56 to 80	.....
Charpy, kg-m	.....	21.2(e)	.....	.....	.....

(a) 25 hr at 1650 F, slow cool
(b) Cold worked iron has no sharp yield point. The stress corresponding to the arbitrarily chosen strain of 0.5% on a 2-in. gage length, can be distinguished up to about 15% cold reduction, beyond which this value coincides with the tensile strength.
(c) 33,000 psi, after water quench from 1500 F
(d) Hot rolled ingot iron, tested at 20 C. Test specimen 60 by 10 by 10 mm
(e) Annealed electrolytic iron, tested at 20 C. Type of specimen probably large Charpy

value obtained depends on the chosen rate of creep. Tapsell and Clenshaw have determined the strength of ingot iron at various rates of creep, as shown in Fig. 22. The rate of creep used for curve 1 is less than 1×10^{-4} in. per day.

Mechanical Properties of Single Crystals. Osmond and Frémont determined the yield strength in compression to

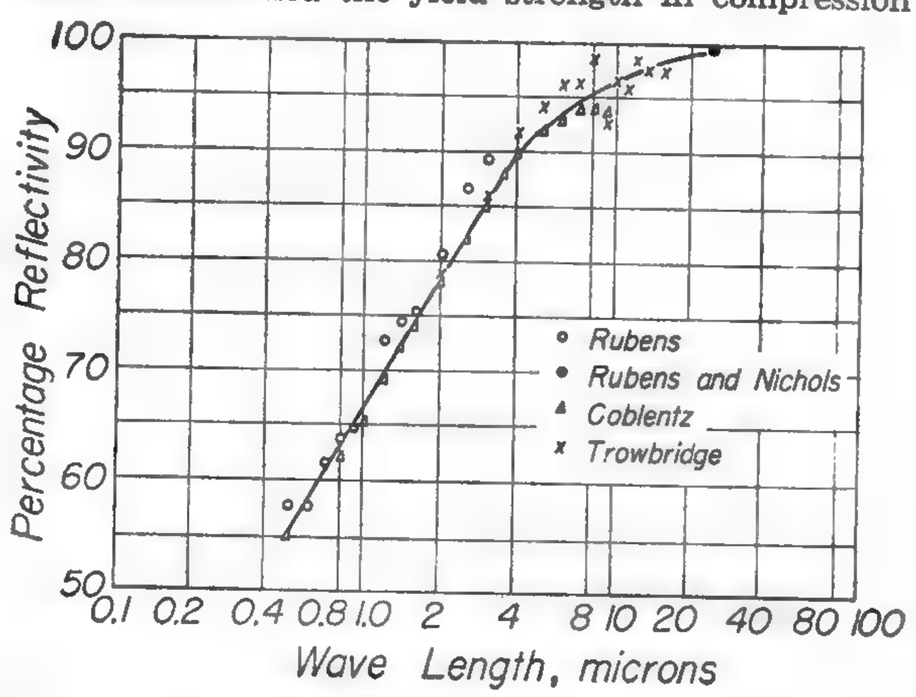


Fig. 20 Reflectivity of iron

be 19,800 psi on cube faces and 24,200 psi on octahedral faces of single crystals prepared from a decarburized steel rail (0.06% C, 0.30% Mn, 0.116% P, 0.02% S, 0.051% Si). This same material had a tensile strength of 39,500 psi and a yield strength of 23,500 psi perpendicular to a cube face, and a reduction of area of 85%.

Edwards and Pfeil prepared single crystals from mild steel and found tensile strength values from 21,000 to 34,500 psi for ten different crystals (orientations not determined); yield strength 4300 to 5600 psi; elongation in 2 in., 30 to 54%; and Young's modulus 22.4 to 29.8 $\times 10^6$ psi.

The results reported by Osmond and Frémont for Brinell hardness of the specimen mentioned above, after annealing at 550 C, were 75 on cube face, 79 on dodecahedral face, and 81 on octahedral face. After the specimen had been annealed at 800 C, the corresponding values were 66, 69 and 76. On his single crystals Pfeil found a Brinell hardness of 80, which was the same in different directions of the crystal, within the limit of accuracy of the test.

Table XII. Tensile Properties of Ingot Iron at Elevated Temperatures (Short-Time Tests)

Temp, deg Cent	Tensile Strength, psi	% Elongation Including Fracture $L = 4\sqrt{\text{Area}}$	% Reduction of Area	Modulus E
16	49,500	45	69	29,800,000
100	57,800	27	61.5	29,250,000
150	59,800	26.5	60	28,400,000
200	65,600	26.5	54	27,800,000
250	64,700	30.0	54	27,200,000
300	62,500	38.5	56	26,500,000
350	56,700	44.5	61	25,800,000
400	44,800	51	67.5	25,000,000
450	37,000	51	67.5	24,000,000
500	27,100	49	63.5	.....
600	15,200	34	49.5	.....
700	9,200	53.5	55.5	.....

Effect of Grain Size on Mechanical Properties. Table XIII gives the variation in tensile properties with grain size as determined by Edwards and Pfeil. Pomp found the

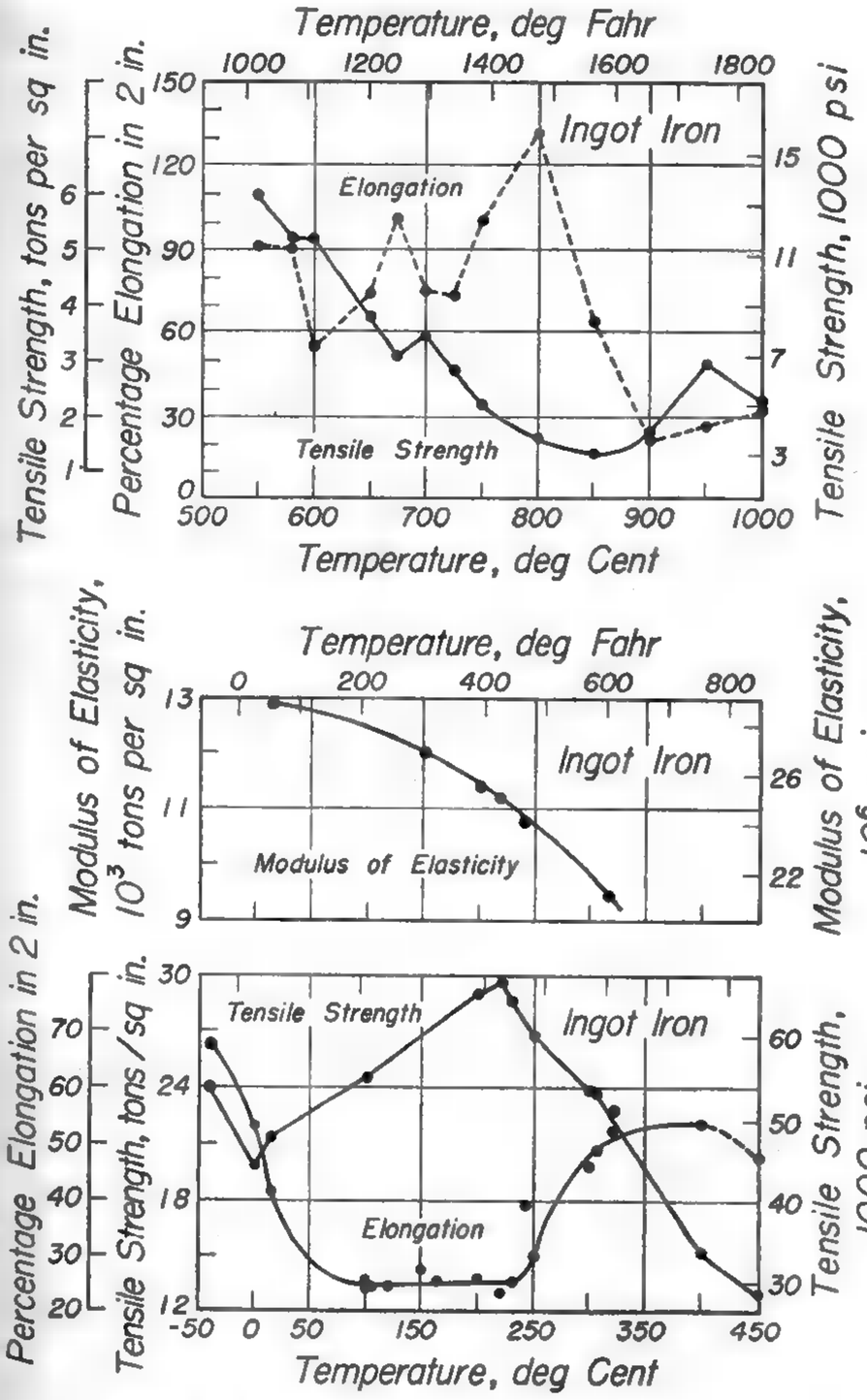


Fig. 21 Tensile properties of ingot iron at various temperatures (Lea)

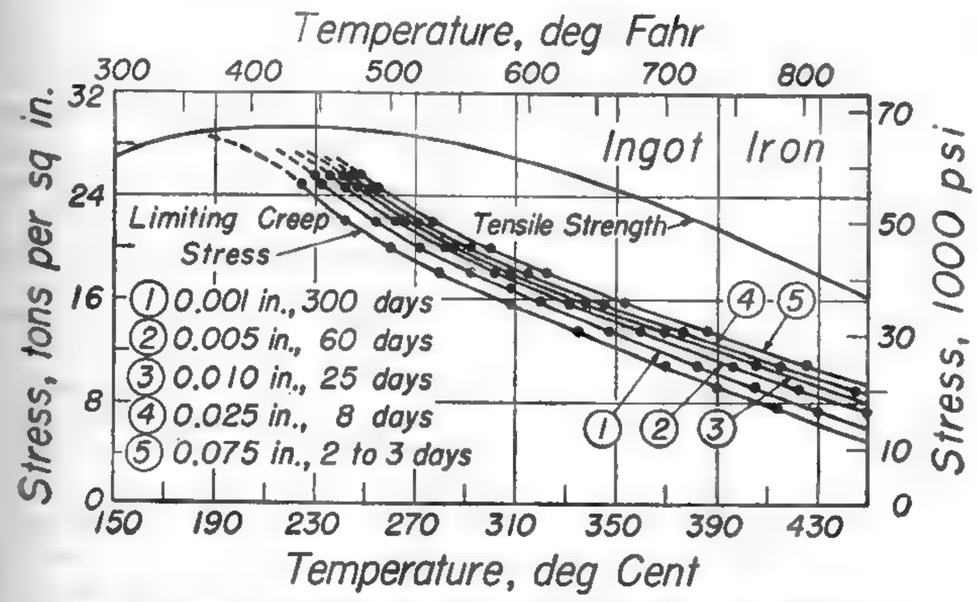


Fig. 22 Creep strength of ingot iron (Tapsell and Clenshaw)

Brinell hardness only slightly affected by grain size and reported the following: Brinell hardness 83 for 68 grains per sq mm; 87 for 827; 89 for 1350; 96 for 2310; and 95 for 3970 grains per sq mm.

Torsion Tests at Elevated Temperatures. Tapsell and Clenshaw determined the torsional strength of ingot iron at elevated temperatures by means of short-time tests of a duration of about 20 min up to the proportional limit and 20 min from the proportional limit to fracture. The results are given in Table XIV.

Hardness at Elevated Temperatures. Both dynamic and static hardness tests have been made on ingot iron by Tapsell and Clenshaw, as shown in Fig. 23. O'Neill determined at various temperatures the scratch hardness of a carbon-free iron made by decarburizing a mild steel in hydrogen. These results are shown in Fig. 24. The hardness values are taken as the resistance to the production of a scratch 0.1 mm wide at various temperatures.

Table XIII. Effect of Grain Size on Tensile Properties of Iron[a]

Specimen No.	Grain Size, Grains per sq mm	Tensile Strength, psi	Yield Strength,[b] psi	Elongation in 2 in., %
		Series 1		
1	9.7[c]	23,900	5,900	28.8
2	7 [c]	26,200	5,600	30.5
3	2.5[c]	30,600	6,400	39.5
4	6.3	33,700	6,500	35.3
5	15.3	36,600	6,200	47
6	35.6	38,200	8,300	48.8
7	48.8	38,300	9,400	50.7
8	51	38,900	10,000	44.8
9	75.5	42,000	20,100	47
10	77.5	41,600	20,200	48.3
11	91.6	40,000	16,600	50.3
12	92	40,300	16,800	50
13	120	41,200	16,700	42.5
14	130	41,600	15,700	41.3
15	194	41,900	15,400	47.5
		Series 2		
1	27	38,500	8,400	41.3
2	34	39,300	10,500	41.3
3	53	38,600	7,700	46.3
4	57	38,000	10,700	38.8
5	78	38,500	11,300	33.5
6	84	39,600	12,100	51.3
7	98	42,300	14,700	46
8	98	43,100	15,500	46.5
9	102	42,600	16,300	44.8
10	108	44,400	15,800	46.3
11	109	42,800	15,100	42.8
12	113	42,200	14,500	47.8
13	118	43,100	18,000	48.5
14	127	43,200	19,500	44
15	135	43,300	22,200	45.3
16	157	44,200	22,600	45.3
17	168	38,100	15,700	45
18	203	38,200	14,200	44.8
19	230	37,700	13,800	48
20	245	37,300	14,000	45.5
21	307	39,100	13,800	48.3

(a) Edwards and Pfeil
(b) Reported as proportional limit
(c) Diameter of average crystal in mm

Table XIV. Torsional Properties of Ingot Iron at Elevated Temperatures

°C	Modulus of Rupture	Modulus of Rigidity	Angle of Twist per in. at Fracture, degrees
16	63,200	11,600,000	778
100	66,100	11,500,000	632
150	70,300	11,400,000	628
200	68,300	11,200,000	479
250	68,300	11,100,000	447
300	69,000	11,000,000	406
350	65,900	10,700,000	297
400	51,700	10,500,000	335
450	41,000	10,300,000	326
500	25,100	.....	249
600	15,000	.....	285

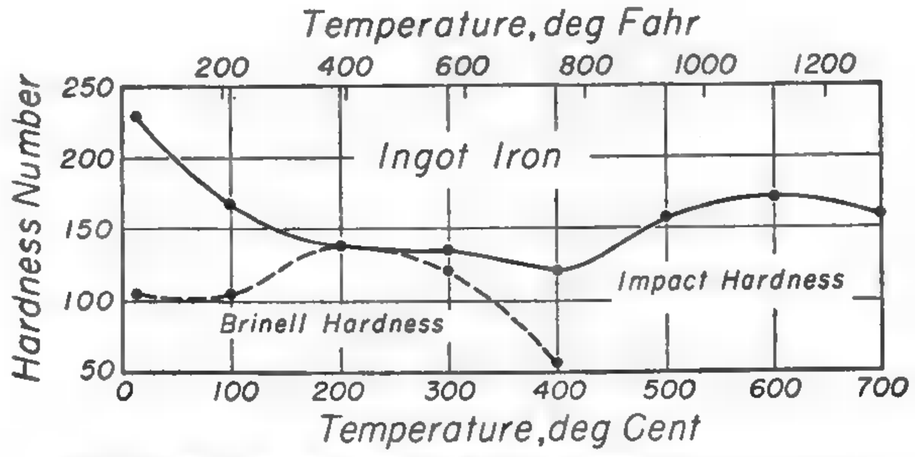


Fig. 23 Hardness tests on ingot iron (Tapsell and Clenshaw)

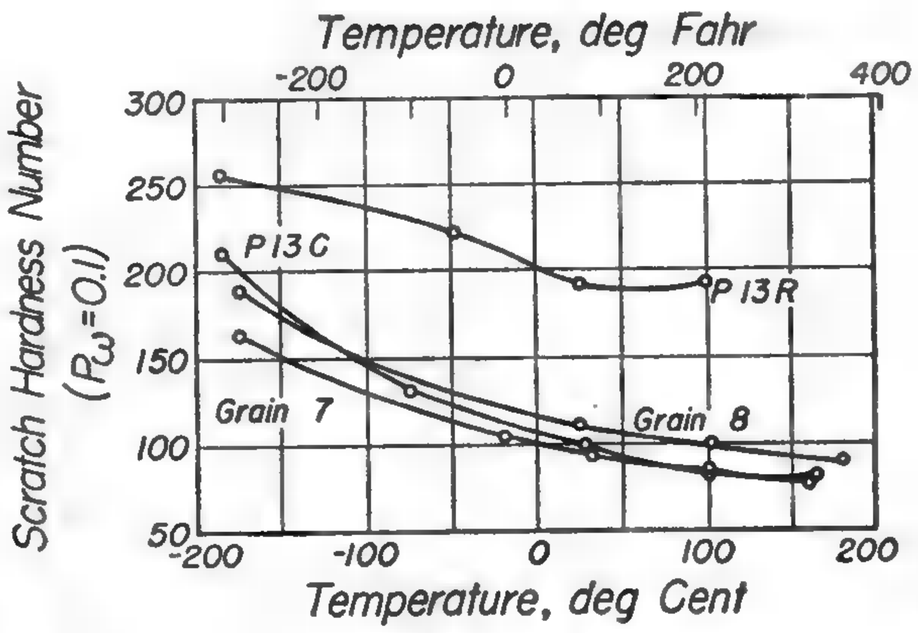


Fig. 24 Change in scratch hardness with temperature. P13R, a cold rolled polycrystalline carbon-free iron, 0.44% Mn, 0.02% Si, 0.028% S, and 0.020% P. P13C same as P13R, but annealed. Grain 8 and Grain 7, two single-crystal grains. The scratch on No. 8 was in the [110] direction on a (100) face.

and 232 at minus 253 C, while Guillet and Cournot found the hardness of electrolytic iron to be 80 at plus 20 C, 77 at minus 20 C, 77 at minus 80 C, 95 at minus 110 C and 269 at minus 182 C.

Alternating Stress Tests at Elevated Temperatures. Alternating stress tests on a Haigh alternating stress machine at 2400 cycles per minute with equal plus and minus stress on a basis of 10^7 reversals gave the following results:

Temperature, deg Cent....	16	100	200	300	400	500
Fatigue stress, psi..... (estimated limiting range)	26,700	24,000	25,500	33,400	28,900	12,300

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The Plastic Deformation of Iron

By C. H. Mathewson*

IRON as well as other metals accommodates itself to plastic deformation by the gliding of crystal blocks or lamellae on one another. This process ordinarily becomes one of pure translation, in which the orientation of the crystal changes only as the gliding along planes cutting across the axis of stress application sets up a bending moment around an axis in the slip plane at right angles to the direction of slip. It is this bending or twisting of crystals and parts of crystals that produces the preferred orientations or textures found in wrought metal. Such effects are important, because the physical properties of the metal are determined largely by the orientation of its particles. The state of purity has a remarkable effect on the force necessary to start translation or keep it in action, and in general on the dynamics of the process. As a guiding principle, it may be said that translation starts when the shear stress on a competent slip plane in a possible slip direction rises to a critical value, but as the simple slipping process brings about change of orientation, the resolved shear stresses change, and slip on one family of planes may soon be accompanied by slip on another family. In single crystals, the normal outcome of the process may be fairly well predicted; but in ordinary polycrystalline metal the mutual interference among the grains leads to complications, and there is no clearly accepted method of rationalizing the textures formed in such material by the translation process.

X-ray studies have revealed the general characteristics of textures[1,2] formed during the different industrial processes of working iron (and other metals), as indicated in a later paragraph, but it must be realized that data of this character give merely a rough indication of the preferred orientations of the crystals, since considerable deviation from any stated orientation always occurs, and the texture changes from one point to another in the object; for example, from surface to center in a drawn wire. It is this variability that renders the study of textures important as a method of controlling the conditions of plastic deformation in the development of desirable directional properties in wrought metal for any particular purpose.

The gliding process may also become one of mechanical twinning, which requires that each slip plane shall move the exact fraction of the distance between atoms on the adjacent slip (twinning) plane that will set up anew the crystal lattice pattern in a changed or twin orientation. In iron, this process does not appear to be of great importance, since twin lamellae, or so-called Neumann bands are produced only under certain limiting conditions and do not usually represent the major effect of the plastic deformation. A general understanding of the elements and the simple mechanism of block movements defining the processes of translation or twinning may be obtained from the following outline. More detailed information on this general subject may be obtained conveniently by reference to the recent volume "Structure of Metals", by Barrett.[3]

Significant Directions and Planes. At temperatures above 2550 and below 1670 F, crystals of pure iron have their atoms arranged according to the simple body-centered cubic pattern as illustrated in Fig. 1 of the article in this Handbook entitled "Physical and Mechanical Properties of Iron", page 423.

For the purpose of considering displacements of atoms and planes by plastic deformation of the iron crystal, it is best to orient the body-centered cubic unit of structure (Fig. 1) so that one of the body diagonals, *ab*, passing through two corner atoms and the central atom, is in a vertical position. This and the other three body diagonals are lines or directions through the crystal along which the atoms make the closest possible approach to one another. When the crystal is forced to change its shape by the action of an external force, the atoms resist separation in these close-packed strings, and shearing occurs by some form of block movement in one or another of these four significant directions <111>. If other unit cells are grouped around the first in Fig. 1, it is clear that the atom at each corner of the original cell belongs to a close-packed string, including the central atom of a neighboring cell. Similarly, the outlying corner atoms of these new cells belong to close-packed groups derived from more distant cells. Using the central string of atoms as an axis, a vertical plane may be rotated into various positions, such as *a c′ b d′*, which is designated as a plane of form {110}; the other shaded position is designated {112}. Each plane furnishes some characteristic spacing of these close-packed strings of atoms and some characteristic geometrical relationship between the atoms in this plane and those in a parallel plane passing through adjacent strings of atoms. These details can be studied in some form of projection such as the one given in Fig. 2, in which all atoms are projected vertically into a plane of the form {111} at right angles to the close-packed string, *ab* (body diagonal), of Fig. 1.

It is evident in Fig. 1 that the atoms of the three different strings originating at *a*, *c* and *d* do not match one another in horizontal planes, while those originating at *c*, *c′* and *c″* or at *d*, *d′* and *d″* meet this condition perfectly. These differences in level are indicated in the projection

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of Fig. 2 by using circles of different sizes, with letters indicating the proper relationship to Fig. 1. A projection of this sort is competent to represent an indefinitely large number of unit cells piled on and around one another according to the plan of orientation selected. Planes of particular significance or interest may be selected for boundaries and in this projection (Fig. 2) dodecahedral planes {110} of Fig. 1 are chosen for right-hand and left-hand boundaries and trapezohedral planes {112} of Fig. 1 for the upper and lower boundaries.

Within the figure it would be possible to draw many sets of parallel lines, bringing the projected strings of atoms into planes of various kinds. Thus a set of lines parallel to the vertical boundaries would represent the closest possible grouping of the strings into dodecahedral planes and inspection of the figure shows that there are two other sets of planes inclined 60 deg to the first set and having these same characteristics.

Slip Planes and Directions. Plastic deformation of a crystal commonly occurs in the direction of a line of closest packing of atoms by block movement along planes of the densest atom-packing on which the stress intensity

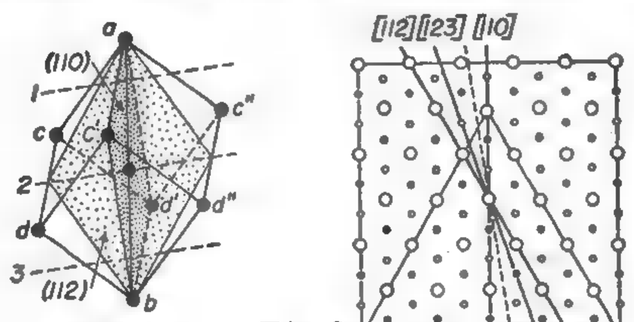

Fig. 1

Fig. 2

Fig. 1 Body-centered arrangement of atoms with a cube diagonal in vertical position. *1, 2, 3.* Body-centered atoms from adjacent cells occur at each of these levels.

Fig. 2 Projection of atoms of body-centered cubic lattice in a plane perpendicular to close-packed strings of atoms (an octahedral plane). Atoms in the plane of the projection and 4th and 7th planes above are shown by large circles; in the 2nd, 5th and 8th planes these atoms are represented by smallest circles; and in the 3rd, 6th and 9th, by circles of intermediate size.

has reached the highest value. In the case of a polished iron crystal, oriented to correspond with Fig. 2, and loaded with maximum stress intensity in the direction of the atom strings (that is, perpendicular to the plane of the projection), this condition would cause one or more sets of slip bands to appear, parallel to the most severely stressed dodecahedral planes. Actually, the slip bands observed in iron are of a more complex character, often irregular, forked or wavy, and apparently unrelated to any principal plane of the crystal. O'Neill[3] and Pfeil[4] have observed bands parallel to planes of the form {112} (horizontal boundaries in Fig. 2). Taylor and Elam[5] emphasize the importance of the close-packed atom strings in guiding the *direction* of slip, but these investigators consider the block movement to occur not along planes of simple indices but in rodlike bundles of atom strings having boundaries that are determined by stress considerations alone. In an elaborate analysis of the deformation of a single crystal of iron stressed in torsion, Gough[6] concludes that slip may occur in the direction of the close-packed atom strings on a variety of planes containing these gliding elements, that is, planes of the form {110}, {112} or {123}. Some of the projections of these planes are shown by the lines drawn in Fig. 2. If the shear stress resolved in the direction of the close-packed atom string is greater on one of the designated crystallographic planes than on any other conceivable plane, slip is likely to occur on the planes of this set without further complication. However, if the maximum shear stress occurs on some intermediate plane corresponding to the dotted line of Fig. 2, slip will occur on particular planes of the above designated forms located on both sides of the plane of maximum resolved shear stress {110} and {123}, in Fig. 2. Under these conditions the slip bands will be of a duplex type with an average slope corresponding to the dotted line of Fig. 2. Fahrenhorst and Schmid,[7] however, considered {123} the most probable planes of slip and Sauerwald and Sossinka[8] found only the traces of these as slip planes after compression at room temperature.

Barrett, Ansel and Mehl[18] have verified Gough's general conclusions, but find that in silicon ferrite, either a low temperature or a high silicon content causes slip to be confined wholly to planes of the form {110}.

Severe Deformation. As the slipping proceeds in any crystal, the process becomes more complicated because of a rotation that accompanies the block movement and consequent increase of stress in other eligible slipping directions. Large amounts of deformation therefore bring many different slip planes into play, and in ordinary polycrystalline material the process is further complicated by inhomogeneity of the force field at the grain boundaries or within the grains themselves. This may result in deformation bands exhibiting characteristic differences of orientation.[19] Hardening accompanies cold deformation, perhaps because of an increased resistance to slip through the minute blocks of crystalline material, which, in moving past one another, have developed slight differences of orientation (nonuniform curvature, lineal nonregistry at boundaries, or other forms of lattice distortion).

Preferred Orientation Under Various Forms of Stress. In spite of the complex mechanism of the slipping process, the crystalline particles of metal, worked into a given form by continued application of stress in some prescribed manner, finally become forced into positions closely approximating a definite and characteristic *preferred orientation*.[2,9] Simple stretching brings a cube-face diagonal <110> into the axis of the rod, with a radial disposition of a corresponding set of cube edges <001> in the different crystals. In cold drawn wires <110> also occurs as the fiber axis. Under compression[5] a body diagonal <111> and to a lesser extent a cube edge occur in the direction of compression, with a cube-face diagonal in the radial position. In torsion, the cube-face diagonal and to some extent the <112> direction become the fiber axis with the body diagonal tangential. Cold rolling brings a face diagonal into the direction of rolling and a cube face into the plane of rolling. For data concerning preferred orientations in iron and other metals, see page 32.

Twinning. Planes of trapezohedral form {112}, parallel to the sides of the triangle outlined in Fig. 2, have the atoms of their close-packed strings at the same level in a given horizontal section. In passing from one to another of these adjacent parallel planes, the strings shift laterally into positions half-way between their former positions and vertically, so as to bring the atoms either one-third or two-thirds of a full atomic distance above the atoms in the first plane, depending on the direction of progression. Beginning with a certain plane (for example, the one projected as the base of the triangle in Fig. 2), if the atoms in the next plane towards the bottom of the figure are brought one-third instead of the normal two-thirds of an atom distance above the atoms in the first plane, and the atoms in the third plane are brought two-thirds instead of the normal one-third above, the altered region is said to be twinned with respect to the rest of the crystal. This change has been effected in the lower rectangular area, which therefore is the projection of a twin band.

Twinning by Pure Shear. The mechanical action of pure shear, in which the distance traversed by any particle in the direction of shear is proportional to its distance from the plane of shear, would produce this result, assuming the first plane (base of the triangle) to be the plane of shear and the shearing movement on the next plane to be exactly one-third of the distance between atoms in the close-packed string. This is believed to be the mechanism of mechanical twinning in iron.[10,11]

Close observation of Fig. 2 will make it clear that this same structural change may be obtained by shearing along any one of the three families of planes of the form {112}, represented by the sides of the triangle, and that no other twin configuration is possible in this projection. However, since there are three additional body diagonals representing close-packed strings of atoms in the iron lattice, three other projections are possible, each competent to illustrate the formation of a new twin configuration by shear, along any one of three additional planes of the form {112}.

Infrequency of Twinning in Iron. So many planes are

available for deformation by the ordinary process of slip that the much more restricted or specialized form of slip necessary for twinning would be expected to occur only exceptionally in pure iron. Stiffening of the lattice by alloying favors the occurrence of twinning. Somewhat brittle coarse-grained ferrite containing silicon or phosphorus twins readily when deformed by impact. Coarse-grained ingot iron also twins readily by impact at room temperature. It is reported[8,12] that pure ferrite twins readily, even by slow deformation at the temperature of liquid air. Barrett, Ansel and Mehl, in their recent investigation[18] of the plastic deformation of iron, have demonstrated that twinning, which could be produced in pure iron by slow deformation (torsion) at minus 200 C, occurs at higher temperatures with increasing silicon content, until, with approximately 5%, it is the favored mechanism of deformation close to room temperature. It is followed in this relatively brittle alloy by cleavage, and then slip on planes of form {110} as the temperature is further increased. Even under the most favorable conditions, only thin sections of a crystal can be stressed in the exact manner necessary to produce the twin structure. Twinning in iron is therefore observed only in the form of thin lamellae usually called *Neumann bands.*

Deformation of Face-Centered Cubic Iron. When ordinary grades of iron are heated above 1670 F but not above 2550 F, or when exceptionally pure iron, containing only minute traces of oxide, nitride or carbide, is heated within the same range, the atoms are arranged according to the face-centered cubic pattern illustrated in Fig. 1*d* of the article "Physical and Mechanical Properties of Iron", on page 423 in this Handbook. Thus far no detailed study appears to have been made of the slip planes and directions brought into play by hot working pure iron in this range of temperature; yet there is little doubt that the mechanics of deformation are analogous to those observed in aluminum,[14] copper,[15] and other face-centered cubic metals.

In wrought and annealed austenitic steels in which iron has been alloyed so as to preserve the face-centered cubic arrangement of atoms, the microstructure is strikingly similar to that of the common face-centered cubic alloy, alpha brass, even exhibiting the familiar twin bands that are seen in both metals after recrystallization following plastic deformation. This resemblance points to a similarity of the deformational process in both metals, and the analogy in all probability may be extended to include the behavior of pure iron at elevated temperatures.

Planes and Directions of Slip in the Face-Centered Cubic Lattice. In the face-centered cubic metals only the planes of closest atom-packing, the octahedral planes {111}, function as slip planes and the slip occurs in the direction of one of the three cube-face diagonals representing close-packed rows of atoms on the given plane. Four families of octahedral planes are available for slip.

In single crystals under tension stress, slip starts on the set of octahedral planes for which the computed shear stress is a maximum, and continues on these planes until rotation of the lamellae brings an equal load on another set of octahedral planes. After a short period of extension by slipping on both sets of planes, the crystal usually breaks with a wedge-shaped fracture.

Pursuing the analogy with face-centered cubic metals still further, hot rolling of iron above 1670 F might be expected to develop preferred orientation of the crystalline particles[9,16] with the normal to a trapezohedral plane {112} approximately parallel to the direction of rolling and a dodecahedral plane {110} parallel to the plane of rolling. Subsequent cooling below the A_3 point would produce some form of reorientation, depending on the relationship between the two sets of crystal axes established during the transformation. No accurate details of this process are yet available.[17]

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The Effects of Cold Work on the Properties of Iron

By Reid L. Kenyon* and Robert F. Mehl*

THE physical and mechanical properties of pure iron are given in another article in this Handbook.[1] The present article deals only with the effect of plastic deformation on these properties. Critical examination of the literature reveals that many of the published data on "pure iron" are actually on low-carbon steel, sometimes with as much as 0.10% C and 0.50% Mn, besides other impurities. Because few if any of the properties of *pure* iron can be extrapolated from such data, they are omitted from this article. Although ingot iron and electrolytic iron are not pure iron, they have been taken as pure for the purpose of this tabulation. Since the few published results are from isolated tests, it is impossible to discriminate and select "best values". The data given here should be considered only provisional—an indication of the need for further experimental work on the properties of plastically deformed pure iron.

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The Effect of Cold Working. The previous mechanical and thermal history of the material, such as residual strain and grain size, has been found to have a marked effect on the response to cold working. Gries and Esser[2] give the results of Brinell tests on polycrystalline and monocrystalline iron after various degrees of cold rolling. Their values are reproduced in Fig. 1. The method of cold working also affects the results. Wire drawing produces a greater change than rolling for the same amount of reduction. Jeffries and Archer[3] have given tensile strength values for cold drawn ingot iron wire, which are compared in Fig. ■ with cold rolled materials. Greulich[5] also reports the effect of cold rolling on the tensile properties of ingot iron, but shows it to be considerably greater than normal,

probably because of a different previous treatment.

Various attempts have been made to express the properties of cold worked metals as functions of the percentage reduction. Greulich[5] finds these relationships between reduction in thickness and hardness, yield point and tensile strength to be logarithmic up to a limiting amount of reduction, but Templin[6] shows that the tensile strength versus percentage reduction of area is a straight line. He gives the following equation for the tensile strength of ingot iron: Tensile strength $= 37{,}500\ (1 + 1.64\,R)$, where R is the fractional reduction of thickness. Greulich[5] gives the equation: Tensile strength $= 46{,}000 + 7510 \log_e \phi$, where ϕ is the percentage reduction of thickness.

Templin's formula is believed to be in better agreement with most test data, although it should be remembered that all such particular relationships should be expected to apply only to material in the same initial condition. Their general application to pure iron in all conditions is doubtful.

A work hardening coefficient may be derived from Meyer's equation relating load and diameter of impression in the Brinell hardness test.[7] In this equation, $p = a\ d^n$; the exponent n may be taken as a measure of the capacity

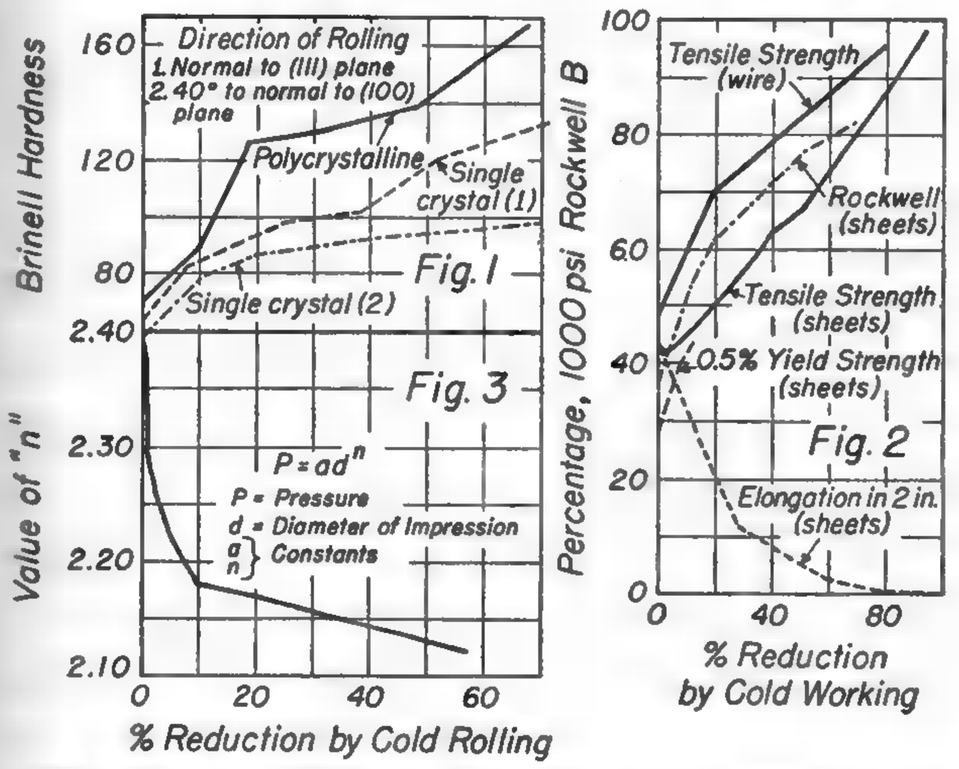

Fig. 1 Effect of grain size and orientation on increase of hardness with cold rolling (Gries and Esser[2]).

Fig. 2 Effect of cold working on the properties of ingot iron (tests on wire by Jeffries and Archer[3] and on sheet by Kenyon and Burns[4]).

Fig. 3 Variation of Meyer's constant n with cold rolling.

of a material to work harden. Figure 3 shows a series of such values of n for ingot iron* cold rolled up to 57% reduction in thickness. It will be seen that n decreases with cold work as expected. The slope of the true stress tensile curve is much used in Germany as a measure of rate of work hardening,[8,9] but doubt has been expressed[4] concerning its usefulness, because this slope is often a constantly changing quantity. (*See* Stead[10] and O'Neill and Greenwood[11] for additional studies on true stress curves.)

The effect of cold working on the shape of the curve of tensile stress versus strain for ingot iron is shown in Fig. 4. The disappearance of the yield point, increase of the tensile strength, and loss of ductility are the most noticeable effects. The curves in Fig. 4 are for specimens tested immediately after cold rolling; aging at room temperature or at slightly elevated temperatures alters these curves profoundly.[15]

The effect of cold work on the density is given elsewhere.[1] The electrical conductivity and magnetic properties are affected adversely, but no data have been found for iron of high purity.

Structure. The first visible effect of cold plastic deformation on the microstructure of iron is the production of slip bands on a polished surface. If the deformation is carried to a sufficient extent, the grains become distorted and elongated, and this appearance, unlike slip bands, is not changed by repolishing and re-etching.

* Unpublished work, Research Laboratories, American Rolling Mill Co.

Sudden or impact deformation produces the so-called "impact twins" or "Neumann bands". These twins differ from twins in face-centered cubic metal in that they frequently exhibit irregular or serrated outlines. Apparently iron forms no strain-anneal twins.

The mechanical properties of plastically deformed iron change with time after cold deformation when the material is held at room temperature, and at a more rapid rate at slightly elevated temperatures. This is called "aging" and is discussed in the next article in this Handbook.

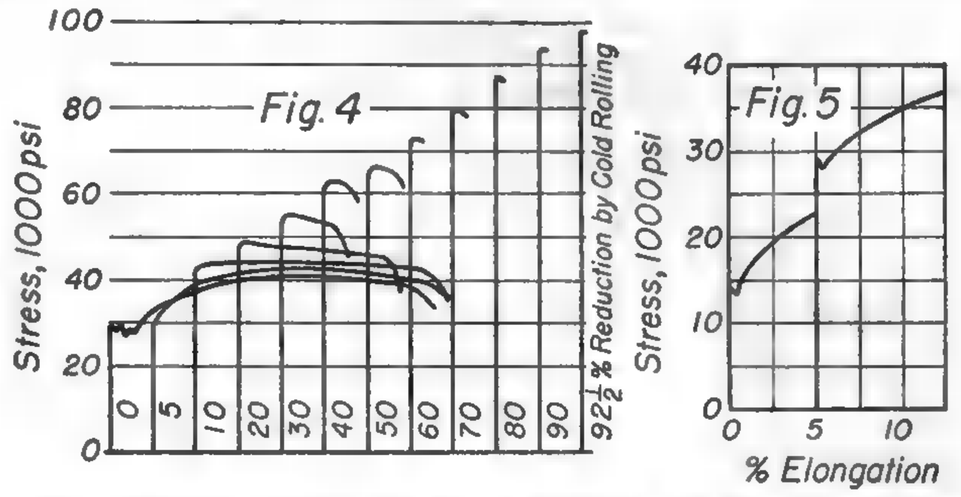

Fig. 4 Effect of cold rolling on the shape of the stress-strain curve of ingot iron (Kenyon and Burns[4]).

Fig. 5 Effect on the yield point of aging electrolytic iron (Ludwik and Scheu[17]).

Sufficient plastic deformation eliminates the sharp yield point from the tension stress-strain curve when the test is performed immediately, but this yield point is made to reappear by allowing the metal to age long enough at the particular temperature. This is shown for electrolytic iron in Fig. 5. Köckritz[15] showed the increase in tensile strength and yield point of ingot iron in comparison with other materials. (Fig. 6)

The behavior of iron plastically deformed at room temperature and aged at temperatures in the blue brittle range, is duplicated in kind, though in somewhat different degree, by simple plastic deformation in the same range. Since at this temperature the rate of aging is very great,

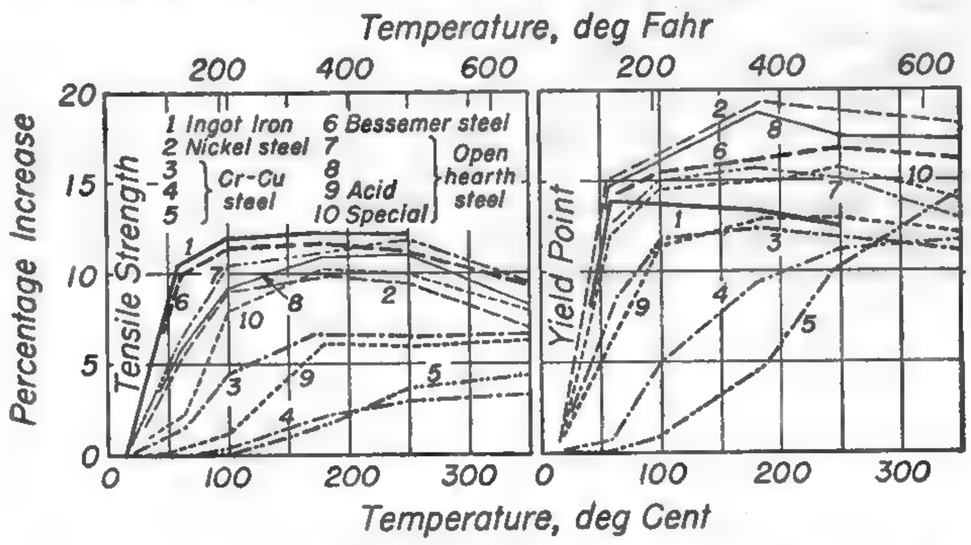

Fig. 6 Increase in yield point and tensile strength of various steels as a result of cold stretching 5% and heating for one hour at the indicated temperature (Köckritz[15]).

the resulting increase in strength and decrease in ductility manifest themselves during a tension test on previously unstrained material. This has been shown by Jeffries and Archer[18] and also by Kenyon[19] for ingot iron. Figure 7 is reproduced from Kenyon's article.[19]

When plastically deformed iron is heated to various temperatures, the properties are altered. The amount of the change depends on the amount of cold deformation, the original condition (such as grain size) and the temperature and duration of heating after cold working. These changes do not all take place at one temperature but are progressively greater as the temperature is raised, although there is a minimum temperature below which the changes are relatively small. The magnitude of these changes is increased if recrystallization occurs.[20] According to Sato[21] the increased energy introduced during cold deformation is released at approximately 570 C. Tammann[22] shows a

gradual decrease in electrical resistivity and thermoelectric force with increasing temperature of annealing, whereas the magnetic susceptibility remains unchanged at temperatures as high as approximately 750 C, at which temperature it suddenly increases.

Annealing of cold worked iron has a pronounced effect on the mechanical properties as determined at room temperature. Published data are almost exclusively for steels; the only results found for pure iron are those for Brinell hardness as reported by Tammann.[22] With suitable conditions of grain size, amount of deformation, and annealing time and temperature, these changes in mechanical properties are accompanied by a profound change in grain size. The metal undergoes *recrystallization*. It is possible, however, to soften cold worked iron without causing recrystallization.[25] The recrystallization of iron is represented conveniently, though inadequately, by a three-dimensional diagram relating to degree of cold work, temperature of heating and resultant grain size. Figure 8, taken from Oberhoffer and Oertel,[23] represents the general relationships, although it is believed that there is a critical temperature range that leads to the extreme grain growth, varying with the amount of deformation. The curve on the basal plane shows the amount of strain required to cause recrystallization at a given temperature and indicates that this may occur as low as 400 C. McAdam[24] showed that ingot iron will recrystallize at 485 C under certain conditions. Factors not represented in Fig. 7 are known to affect recrystallization. Thus, the initial grain size is an important factor; to initiate recrystallization, small grains require less overstrain than large grains as measured by changes in dimensions. The duration of heating is also important, as well as rate of heating if slow.

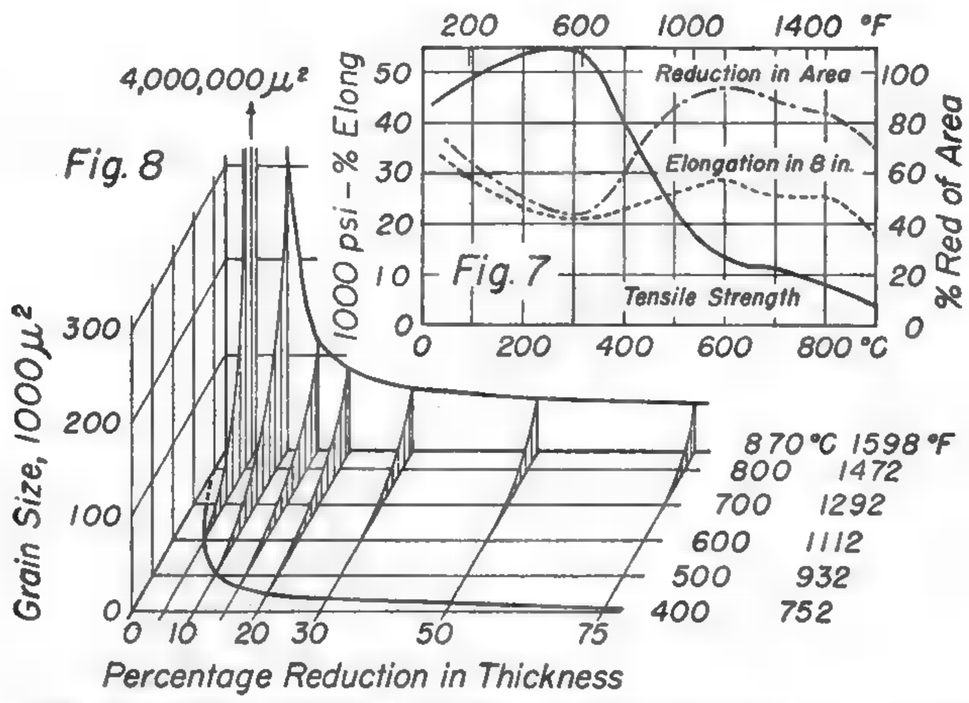

Fig. 7 Tensile properties of ingot iron at elevated temperatures (Kenyon[19]). **Fig. 8** Recrystallization of iron.

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NOTE. The following list of references is not complete and all the papers are not referred to in the preceding article.

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Aging of Iron and Steel

BY SAMUEL EPSTEIN*

AGING is a change that occurs in the properties of iron or steel at atmospheric temperature or at a moderately elevated temperature, after rapid cooling or after cold working. "Quench-aging" is the term used to denote the changes that take place in steel after a final operation consisting of fairly rapid cooling from an elevated temperature. "Strain-aging" is the term applied to the changes that take place when the final operation consists of cold working. Aging may result in an increase in hardness and strength; a loss in ductility and impact resistance; the reappearance, after cold working or after quenching, of a sharply defined yield point in the stress-strain curve of a tension test; an increase in coercive force; and similar changes in other properties.

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The aging changes proceed relatively slowly at room temperature, but at an accelerated rate as the aging temperature is raised. This indicates that aging is a manifestation of a trend toward equilibrium and away from some unstable condition set up by rapid cooling or cold deformation, the most recent operation performed on the steel. Aging is generally assumed to be caused by the decomposition of a supersaturated solid solution.

Since carbon has a much higher solubility in austenite than in ferrite, the transformation of austenite to ferrite leads to a precipitation of carbide and to hardening. Indeed, such precipitation may contribute to the high hardness of quenched high-carbon steel. However, the term "aging" is generally used only with reference to precipitation phenomena in ferrite itself, below the A_1 transformation temperature. Such aging occurs in several alloys of iron—for example, the iron-copper alloys. Precipitation phenomena may account, in part, for the high creep-strength of some of the alloy steels used at elevated tem-

peratures. However, this article will deal only with aging effects in ordinary iron and steel and not in special ferrous alloys.

Interest in aging increased when it became apparent that the "blue heat phenomena" in iron and steel are associated with aging,[1] and when it was found that so-called "nonaging" steels can be produced by additions of aluminum, titanium[2] and other elements. Such aluminum-treated steel shows virtually no strain-aging, but nevertheless still exhibits a considerable degree of quench-aging. It also has a distinct yield point in the as-annealed condition. A recent investigation shows that steel treated with rather large amounts of titanium (about five times the carbon content) exhibits neither strain-aging nor quench-aging; neither does such steel show a yield point in the as-annealed condition.[3] It has also been found that heating low-carbon steel in moist purified hydrogen at about 1325 F (approximately 3 hr for 20-gage sheet) likewise produces a steel that shows no strain-aging, no quench-aging, and no yield point in the as-annealed condition.[4]

Elements That May Cause Aging Effects. The following elements are found in ordinary iron and steel: carbon, manganese, silicon, phosphorus, sulfur, oxygen and nitrogen. Of these, carbon and nitrogen have an appreciable solubility in ferrite directly below the A_1 temperature, and much lower solubility at room temperature. Thus, if the solubility at room temperature is less than the amount of the element present, precipitation and aging phenomena can occur. Figure 1 presents curves of this type, showing to what extent temperature will change the solubility of carbon, oxygen and nitrogen. All these solubility curves may be of uncertain accuracy and should therefore be regarded merely as approximations.

Silicon and phosphorus have solubility curves similar to those shown in Fig. 1. However, the solubility of each of these elements in ferrite at room temperature is much higher than the amount that is ordinarily present in iron and steel. Therefore silicon and phosphorus do not cause precipitation effects, although they may influence the aging phenomena by causing carbon, oxygen and nitrogen to precipitate more readily. Manganese also has a higher solubility in ferrite than the amount of manganese ordinarily present, so it should not give precipitation effects. Sulfur is present mainly as manganese sulfide inclusions and is not considered responsible for precipitation effects. However, it is known that manganese sulfide has a slight solubility in ferrite and it may therefore influence aging.

Carbon and nitrogen have been shown definitely to give rise to precipitation or aging effects when present in amounts ordinarily found in low-carbon iron and steel.[5,6] It will be observed in Fig. 1 that the solubility of nitrogen in ferrite at room temperature is not more than 0.001%, so precipitation effects caused by nitrogen may occur in steel containing more than this amount. Open hearth steel generally contains about 0.003 to 0.006% N, while Bessemer steel usually contains about 0.015% N and may contain more than 0.020%. The precipitated nitrogen in such steels may, under certain conditions, be observed under the microscope as nitride needles.

At one time oxygen was considered a main cause of aging in steel.[7] Magnetic aging effects, apparently caused by oxygen, have been reported in very pure iron, virtually free from carbon and nitrogen.[8] Oxygen has been reported as the main cause of strain-aging also.[5] On the other hand, several investigators have concluded that in iron or steel containing oxygen in amounts ordinarily present in such materials (for example, up to 0.035%), the oxygen does not cause quench-aging in the absence of carbon and nitrogen, although it may cause some strain-aging.[5,9–12] The most recent work has indicated that oxygen itself does not cause aging, although it may have a secondary influence on the amounts of carbon or nitrogen required to cause aging.[4]

This seems to contradict the well-known fact that strongly deoxidized steel is not susceptible to strain-aging. The probable explanation is that the strong deoxidizers, in combining with or "fixing" the oxygen (so that the oxygen can no longer give rise to precipitation-aging effects by going in and out of solution), fix the nitrogen in the same way. The strong deoxidizers are also very strong nitride formers. Strain-aging is thus obviated not because the oxygen is fixed, but mainly because at the same time the nitrogen is also fixed. It has been found that adding about 1 lb of vanadium per ton to rimming steel produces a nonaging steel. Previously all nonaging steel was killed steel.[13]

With reference again to the titanium-treated nonaging steel that does not strain-age, quench-age, or show a yield point in the as-annealed condition, the titanium undoubtedly fixes the carbon as well as the nitrogen. The experiments in which nonaging steel was produced by annealing in purified moist hydrogen indicate that the unfixed carbon and nitrogen must each be brought below 0.001% to

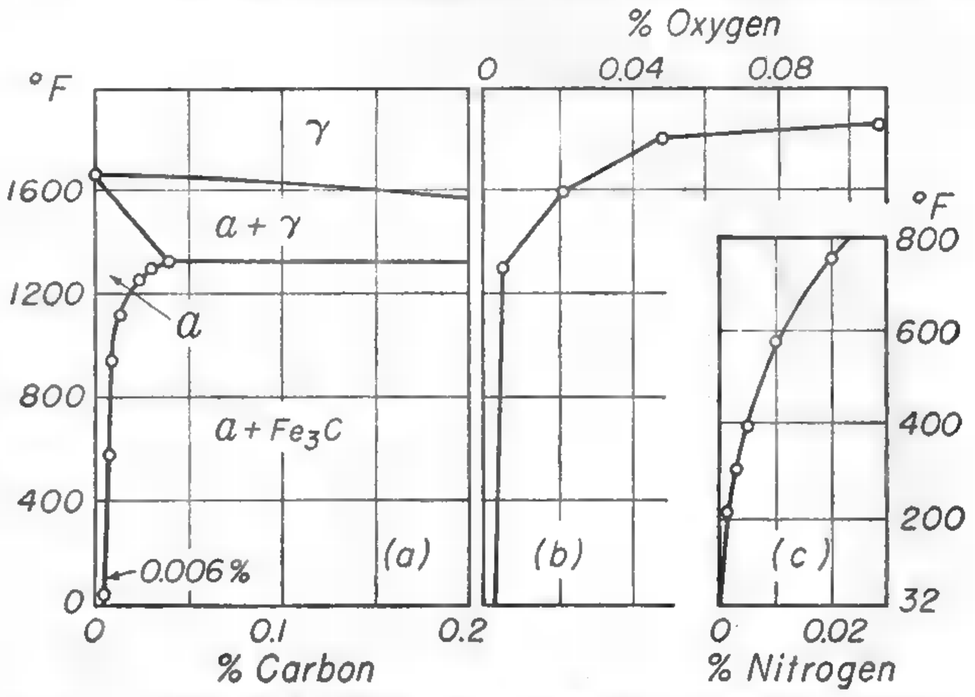

Fig. 1 Change in solubility with temperature of carbon, oxygen and nitrogen in fairly pure ferrite[16,8,6]

obviate strain-aging, quench-aging, and the presence of the yield point in the as-annealed condition.[4] The exact mechanism that produces the yield point in steel is still uncertain but precipitation-aging phenomena appear to be involved. The presence of as little as 0.001% of either carbon or nitrogen, in the unfixed condition, appears to be sufficient to cause the yield point to appear.[4] As a rough approximation based on present knowledge, the chief causes of the described aging effects appear to be as follows: nitrogen is the main cause of strain-aging; carbon is the main cause of quench-aging; carbon and nitrogen,

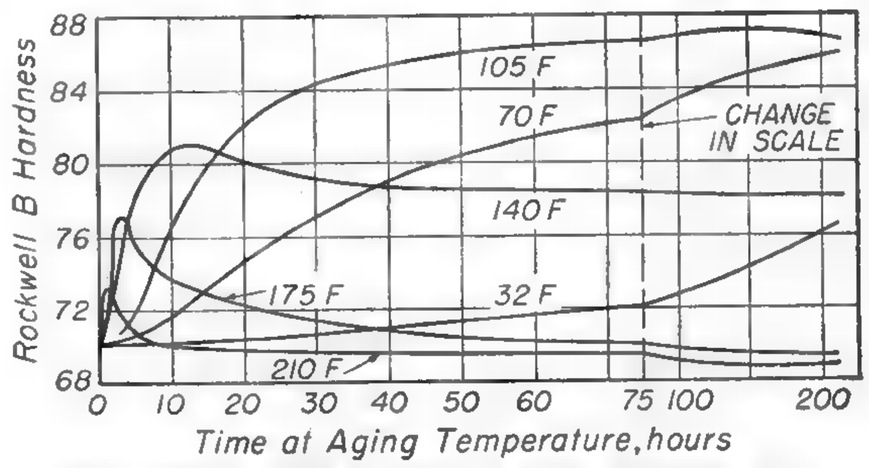

Fig. 2 Quench-aging of 0.06% C steel. Hardness after quenching from 1325 F and aging at indicated temperatures[5]

separately or together, cause the yield point; oxygen plays a relatively minor and indirect part in aging. In explanation of the effect of strong deoxidation in appreciably decreasing quench-aging,[14] it may be considered that although oxygen itself does not give rise to aging effects, it may cause carbon to do so. That is, oxygen may so greatly reduce the solubility of carbon in ferrite at room temperature that the carbon will precipitate and cause aging. When the oxygen is removed or fixed by a strong deoxidizer like aluminum, the room-temperature solubility of carbon may become greater; consequently the carbon is less likely to precipitate and cause aging.

Quench-Aging. In quench-aging above room temperature, the hardness increases more rapidly than in aging at room temperature, but the maximum hardness attained is lower. After the maximum hardness has been reached, further aging at elevated temperature causes a decrease in hardness (Fig. 2). This is sometimes called "overaging".

Table I. Quench-Aging of Low-Carbon Alloys

Composition, percentage				Brinell Hardness Number	
C	Mn	P	Si	Immediately after Quenching from 1300 F	After Aging 44 hr at 125 F Following Quenching
0.028	0.39	0.025	0.003	102	163
0.044	0.44	0.036	0.005	128	185

The magnitude of the quench-aging effects that may occur in low-carbon alloys is illustrated by Table I.[15]

In a series of iron-carbon alloys made from electrolytic iron without manganese and with 0.02 to 0.03% P, 0.007 to 0.008% Si, and less than 0.001% S, the results in Table II were obtained.[15]

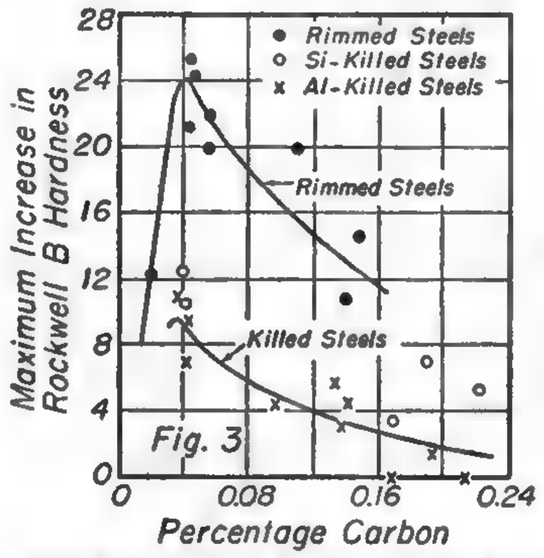

Fig. 3 Reduction in the aging effect as a result of strong deoxidation.[14] The silicon-killed steel contained about 0.15% Si and the aluminum-killed steel contained an equal amount of silicon with about 0.04% Al. The maximum aging effect occurred at about 0.05% C.

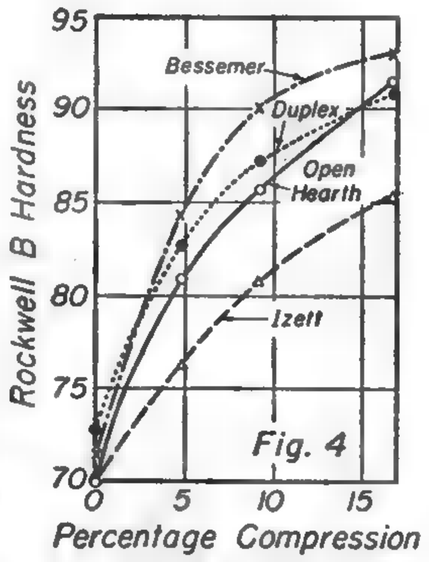

Fig. 4 Increase in hardness with cold work of Bessemer, duplex, open hearth and Izett steel.[17] The first three are aging steels and the last is an aluminum-killed nonaging steel. Hardness increased less rapidly with cold work in the nonaging steel. Compositions of steels:

Steel	Percentage C	Mn	S	P	Si	Al
Bessemer	0.08	0.47	0.035	0.102	...	...
Duplex	0.22	0.54	0.030	0.017	...	...
Open hearth	0.21	0.40	0.035	0.010	...	...
Izett	0.13	0.58	....	....	0.04	0.05

No appreciable age hardening occurred in alloys containing less than about 0.035% C. The age hardening effect reached a maximum in the 0.063% C specimen.

The extent of quench-aging is reduced appreciably by strongly deoxidizing the steel, particularly by killing with aluminum, as indicated in Fig. 3.

Strain-Aging. Here strain means "overstrain", that is, permanent deformation by straining beyond the elastic limit. In strain-aging, precipitation occurs presumably because overstraining causes local supersaturation along slip planes. Straining may result in two effects: (1) the increase in hardness that accompanies cold working in even the purest single-phase metal, and (2) the increase in hardness caused by the precipitation or dispersion of another phase induced by the straining. Strain-aging is usually determined by measuring the change in hardness or impact resistance with time after straining. During this time, the specimen is held either at room temperature or at a somewhat elevated temperature. Some precipitation may also occur during the straining. This is presumed to be the reason why cold working produces a greater increase in hardness in aging than in nonaging steels, as shown in Fig. 4. However, during cold working at room temperature, a very small increase in hardness results from aging during the straining itself. The differences in the increase of hardness for similar amounts of cold working, among the various steels shown in Fig. 4, probably occurred mainly as a result of aging between the time the samples were strained and the time they were tested for hardness after straining. In Fig. 4, no tests were made between 0 and 5% compression. Between 0 and 2% deformation, it is frequently observed that no hardening, but instead a slight softening, actually takes place. This phenomenon appears to be analogous to a slight softening sometimes observed in the early stage of quench-aging, designated as the "incubation period".

Table II. Quench-Aging of Iron-Carbon Alloys

	Percentage Carbon					
	0.019	0.033	0.043	0.063	0.087	0.166
	Brinell Hardness Number					
Immediately after quenching from 1300 F	85	79	89	123	127	136
After aging 8 days at 125 F following quenching	92	80	101	207	170	194
Increase in Brinell hardness	7	1	■	84	43	58

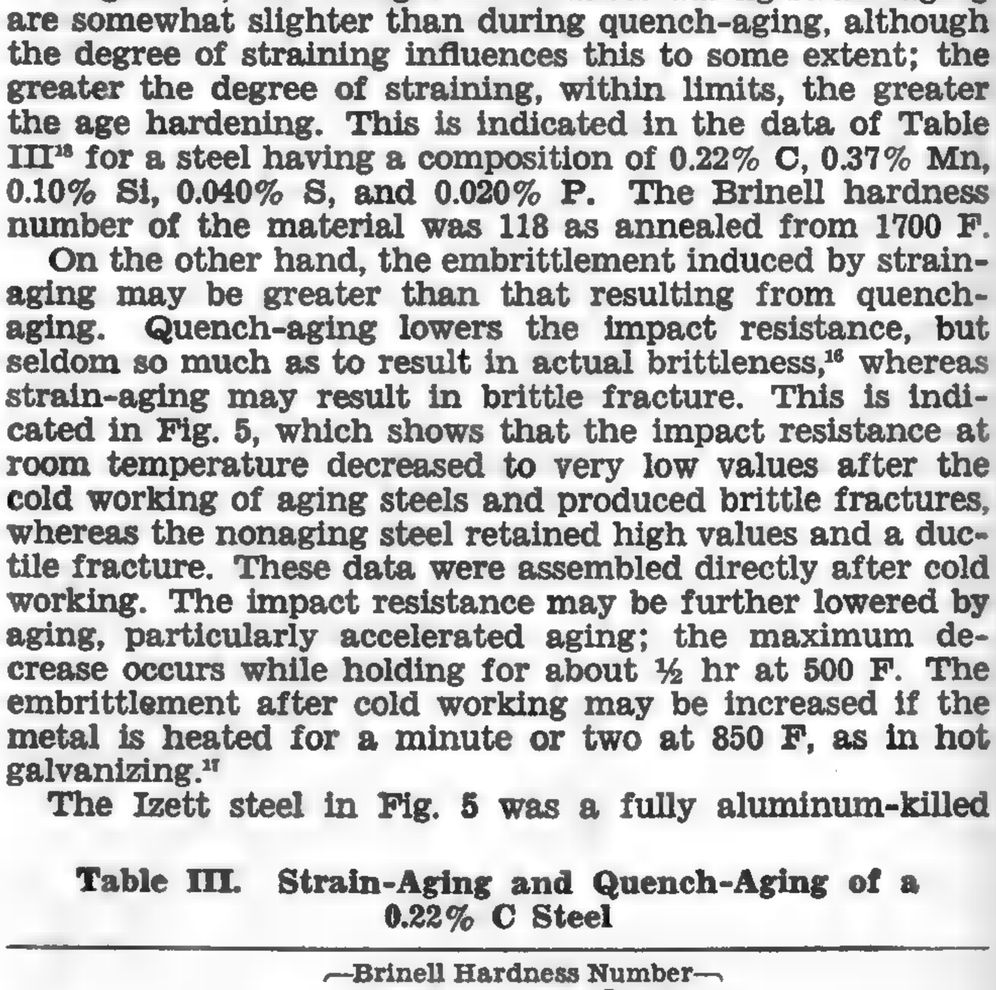

Fig. 5 Effect of cold work on impact resistance of aging and nonaging steels.[17] Charpy specimens with keyhole notches. Armco iron, duplex, open hearth, and Bessemer steel are aging; Izett is nonaging.

In general, the changes in hardness during strain-aging are somewhat slighter than during quench-aging, although the degree of straining influences this to some extent; the greater the degree of straining, within limits, the greater the age hardening. This is indicated in the data of Table III[18] for a steel having a composition of 0.22% C, 0.37% Mn, 0.10% Si, 0.040% S, and 0.020% P. The Brinell hardness number of the material was 118 as annealed from 1700 F.

On the other hand, the embrittlement induced by strain-aging may be greater than that resulting from quench-aging. Quench-aging lowers the impact resistance, but seldom so much as to result in actual brittleness,[16] whereas strain-aging may result in brittle fracture. This is indicated in Fig. 5, which shows that the impact resistance at room temperature decreased to very low values after the cold working of aging steels and produced brittle fractures, whereas the nonaging steel retained high values and a ductile fracture. These data were assembled directly after cold working. The impact resistance may be further lowered by aging, particularly accelerated aging; the maximum decrease occurs while holding for about ½ hr at 500 F. The embrittlement after cold working may be increased if the metal is heated for a minute or two at 850 F, as in hot galvanizing.[17]

The Izett steel in Fig. 5 was a fully aluminum-killed

Table III. Strain-Aging and Quench-Aging of a 0.22% C Steel

Treatment	Brinell Hardness Number: As-Quenched or Rolled or Both	Aged 2 Months	Increase of Hardness Because of Aging	Type of Aging
Quenched in water from 1250 F	151	181	30	Quench-aging
Cold rolled 10%	155	166	11	Strain-aging
Quenched in water from 1250 F and then cold rolled 10%	183	221	38	Quench-aging and strain-aging

mild structural steel normalized after rolling. It was thus a finer-grained steel than the other steels of Fig. 5, which were ordinary semikilled structural steels in the as-rolled condition. The slighter tendency to embrittlement of the Izett steel should probably be attributed not only to its nonaging quality but also to its fine grain size. The results of hardness tests have indicated that coarse-grained steels age more than fine-grained steels[14] both after quenching and aging and after deformation and aging. As measured by impact tests, the results were somewhat ambiguous, but there is no doubt that coarse-grained steels are more susceptible than fine-grained steels to embrittlement (brittle fracture) after straining and aging.

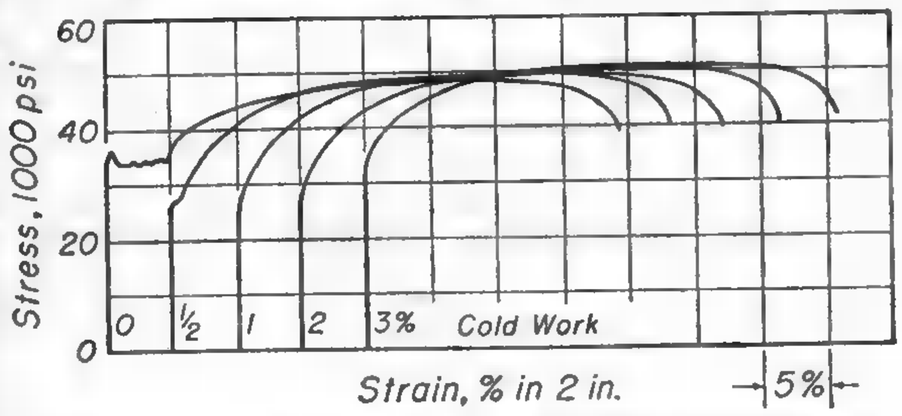

Fig. 6 Jogged stress-strain curve in annealed mild steel sheet.[19]

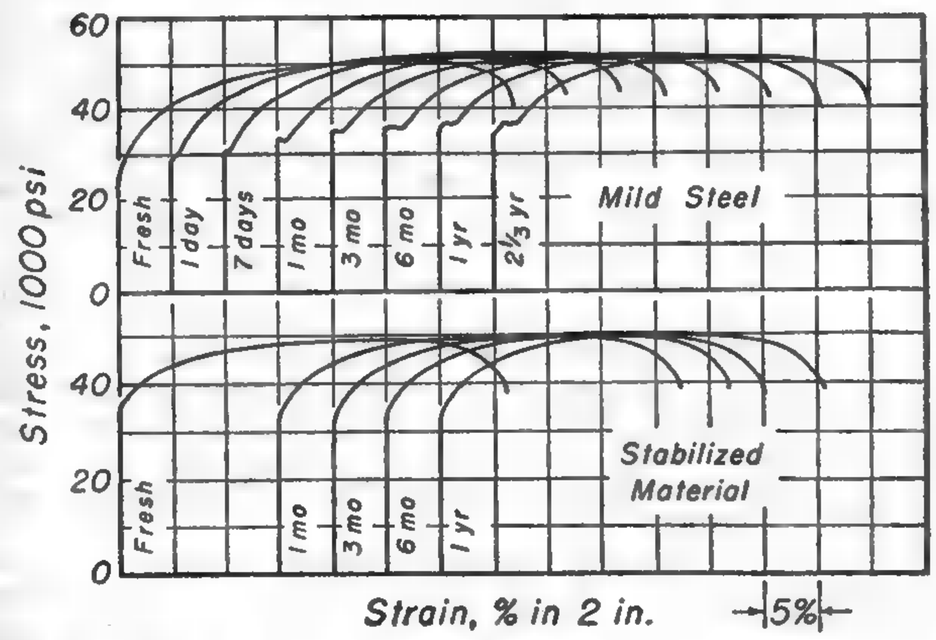

Fig. 7 Return of jogged stress-strain curve in ordinary mild steel during aging after straining. Retention of smooth rounded curve after aging in nonaging material.[21] Both materials were rolled 1% before aging. Typical percentage compositions of nonaging material treated with aluminum and titanium:

C	Mn	P	S	Si	Ti	Al
0.05	0.03	0.005	0.019	....	0.067	0.042
0.042	0.47	0.011	0.014	0.073	0.058	0.037

It should be emphasized here that to maintain high resistance to impact after cold working, steel should not merely be fully aluminum-killed, but should also be normalized after rolling, in order to become fine-grained (as in the Izett specimen shown in Fig. 5). The impact resistance of aging steel, such as ordinary rimming steel, can also be increased by normalizing after rolling. The sharp decrease in impact resistance of ferritic steels as the temperature is lowered, takes place at lower temperatures in nonaging fine-grained steels than in aging coarse-grained steels. This is indicated in Fig. 5.

A convenient method for determining the embrittlement, after various amounts of cold work, is the work-sensitivity or work-brittleness test,[38] which consists in drawing a tapered specimen through a die, notching it at points representing various increments of cold work, and breaking it through these notches in an Izod impact machine. The resultant work-embrittlement curve is characteristic of the steel. After the various increments of cold work, the impact resistance decreases less rapidly in the nonaging, fine-grained steels than in the aging, coarse-grained steels.

The behavior of iron and mild steel at the yield point, that is, the jog in the stress-strain curve that causes the drop in the beam in a tension test, is an interesting phenomenon and one not fully understood. Cold deformation causes the yield point to disappear and a rounded stress-strain curve is obtained instead, with no sharply defined proportional limit (Fig. 6). The disappearance of the jog and the rounding of the stress-strain curve have usually been attributed to loss of elasticity caused by the setting up of residual stresses.[20] Cold working before tension testing may bring the material to a condition where the rate of work hardening during the tension test is high enough to prevent any decrease in load, while the specimen is deformed beyond its elastic limit.[21]

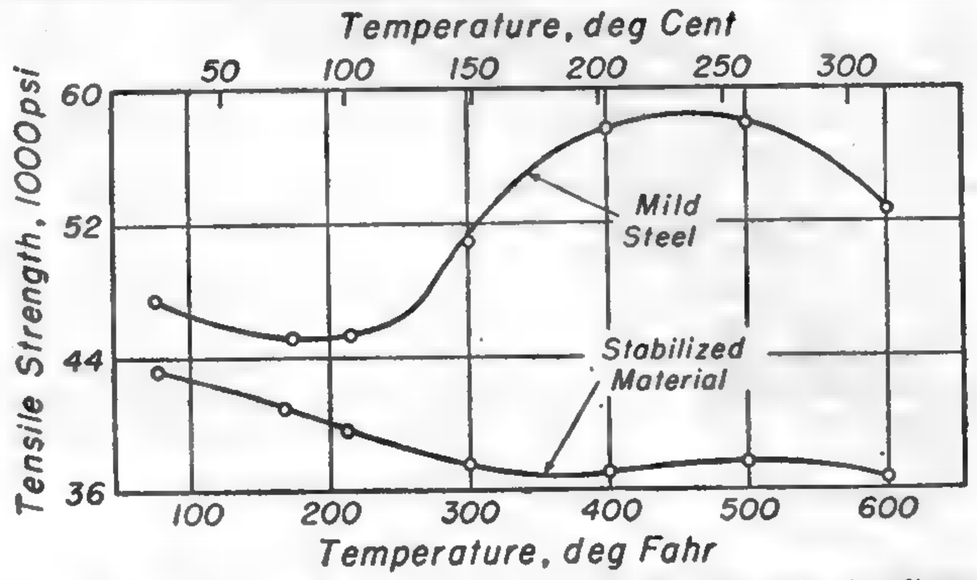

Fig. 8 Effect of testing temperature on tensile strength of ordinary mild steel and of nonaging steel.[22] The nonaging steel gives almost no indication of the "blue heat" phenomenon. The ductility in a tension test of the nonaging steel in the "blue heat" region is considerably higher than the ductility of ordinary aging mild steel sheet.

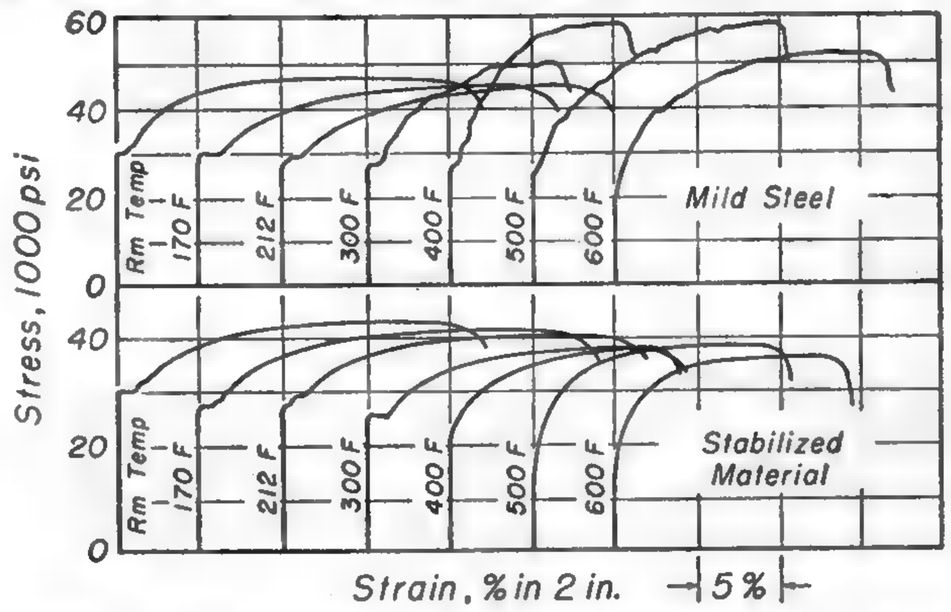

Fig. 9 Stress-strain curves of ordinary mild steel sheet and nonaging sheet tested at various temperatures.[22] The higher tensile strength and the "stepped" or "saw-toothed" stress-strain curve of the ordinary sheet in the "blue heat" region are characteristic. These features are absent in the nonaging sheet.

The jogged type of stress-strain curve is again obtained in ordinary mild steel, such as sheet, during aging after cold working. In nonaging steel, however, a rounded curve is still obtained after aging (Fig. 7).

It was early suggested that aging causes the increase in tensile strength observed in the vicinity of 400 F, the "blue heat" region. The suggested explanation was that at these elevated temperatures, precipitation and aging are so rapid that the test specimen increases in hardness from aging after cold work. (The cold work is the deformation that takes place in the tension-test specimen during testing.[1]) This hypothesis received striking confirmation in tension tests of nonaging structural and sheet steel.[21,22] Neither of these nonaging materials exhibited the pronounced increase in strength shown by aging steel, in the "blue heat" region. Thus the "blue heat phenomenon" is obviously an aging effect. Such results from tension tests on aging and nonaging sheet are shown in Fig. 8 and 9.[22] A tension test in the "blue heat" region is one of the simplest ways to distinguish aging from nonaging material.

The "blue heat" region is frequently referred to as the "blue brittle" region. This term is accurate in implying that the ductility in a tension test at these temperatures is appreciably lower. After deformation at temperatures in the "blue brittle" region, or after deformation at room tem-

perature followed by heating at "blue brittle" temperatures, a marked decrease is observed in impact resistance at room temperature. But there is no brittleness in notched-bar impact tests if the samples are tested while they are at the "blue heat" temperature, for example at 400 F. As a matter of fact, the impact resistance is nearly at a maximum during testing in the "blue heat" temperature (Fig. 5).

At temperatures considerably above the "blue heat" region, a minimum occurs in the curve of impact resistance versus temperature (Fig. 10). The minimum is assumed to result from an aging effect; that is, it is generally maintained that at the high speed of fracture in a dynamic impact test, any aging (hardening) during the instant of fracturing can occur only at the higher temperature, at which this reaction takes place rapidly. At lower temperatures, precipitation during a dynamic impact test cannot occur rapidly enough to cause hardening; consequently, there is no lowering of the impact resistance. It is not known whether nonaging steel shows a less pronounced minimum than aging steel in the curve of impact resistance versus temperature above the "blue heat" region.

Oddly enough, at approximately the same temperature as the minimum in the curve of impact resistance versus temperature, a minimum occurs also in the ductility during

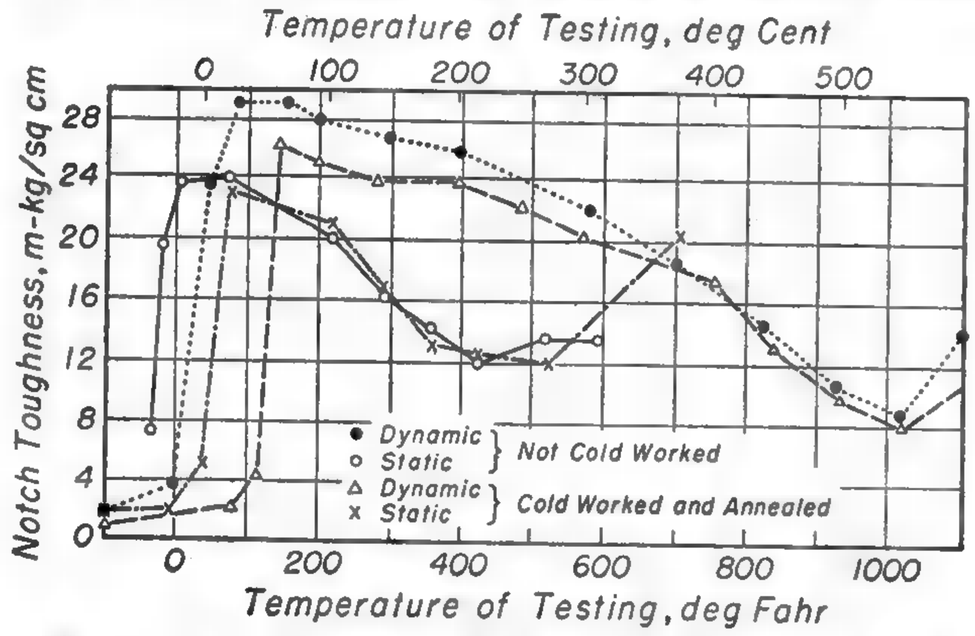

Fig. 10 Static and dynamic notched-bar tests at various temperatures with annealed and with cold worked and aged mild steel.[37] During slow bending, the energy absorption is at a minimum in the "blue heat" region, but in the impact test the minimum in energy absorption occurs at a considerably higher temperature. In both the impact and slow bend tests, the specimens were of the following dimensions: 160 by 30 by 16 mm; keyhole notch with circle 4 mm in diam, 15 mm deep.

a tension test. This has been termed the "secondary low-ductility range".[24] The degree of the secondary low ductility, which varies greatly in different steels, appears to be more severe in fully aluminum-killed steel. However, it seems rather doubtful that secondary low ductility is mainly a precipitation or aging effect. It has been suggested that the condition may be connected with the rate of recrystallization at this temperature, during and after deformation.[25] The rate of recrystallization may differ according to the degree of deoxidation, grain size, and rate of cooling of the steel.

Practical Aspects. In practice, the effects of strain-aging are possibly of greater importance than those of quench-aging. This is particularly true in the manufacture of low-carbon sheet and strip steel for stamping and deep drawing. The final mill operation on this product is frequently a light "skin pass" or temper-rolling that leaves the steel in an ideal condition for strain-aging. Unless the material is fabricated promptly, the increase in hardness, and loss in ductility by aging may cause failure in deep drawing.

The jog in the stress-strain curve at the yield point in a tension test, shows itself as "stretcher strains", during the drawing and stamping of sheet, and causes an undesirable roughening of the surface.[26] The jog is a characteristic of iron and steel in the soft condition, as after normalizing or annealing. This jog can be eliminated by slight deformation, as in the final "skin rolling" that is given the annealed sheet both for this purpose and for straightening. In aging material, the jog may return with time, so that, after leaving the steel mill and being stored in the customer's plant, the sheet may regain the tendency to stretcher-strain, accompanied by an increase in hardness. It has been reported that these aging effects do not occur in aluminum-killed, nonaging sheet[21] or in vanadium-treated, rimmed nonaging sheet[13] and that both of these types of sheet have good deep-drawing properties.

It has been reported also that very slow cooling, as in box annealing, further decreases the strain-aging tendency. The preferred heat treatment for the least amount of aging was reported to consist in heating above the transformation range, cooling at a relatively rapid rate, then reheating below A_1 and finally cooling very slowly.[21]

Cold deformation of structural steel, particularly when followed by reheating, as in galvanizing or welding, may lead to decided embrittlement. For example, a punched rivet hole in a thick structural member provides a severe notch condition (attributable in large measure to the cold working around the punched hole), which may cause brittle fracture.[17] A practical precaution is to ream out the cold worked steel after punching. However, the tendency to fracture in a brittle manner around a punched hole or in the presence of any other notch condition, is much less marked in aluminum-killed nonaging steel. This increased resistance to embrittlement is also maintained at lower temperatures and in the presence of cold work, whether followed by reheating or not. The benefits of the aluminum-killed steel in decreasing the chances of occurrence of embrittlement, are not fully realized in the as-rolled condition, but only after normalizing. Evidently the grain refinement that results from normalizing the fine-grained type of aluminum-killed steel, has an important influence in the avoidance of embrittlement. Ordinarily, fully aluminum-killed Bessemer steel exhibits as great resistance to embrittlement as the similarly killed open hearth steel of the same tensile strength.[39]

Bessemer steel makes screw stock that cuts more freely than open hearth steel. One probable reason is that the higher content of nitrogen in the Bessemer steel promotes aging.[27] At the elevated temperature reached during machining, aging steel becomes more embrittled by cold work than nonaging steel. Thus, in the aging steel, the chips become more brittle under the action of the cutting tool and break off more readily.

Nonaging steels have greater damping capacity. It has been suggested that for this reason they are less sensitive to notch effects in fatigue tests below the endurance limit.[28] It has also been suggested that since nonaging steels do not harden further after cold work, they are better able to withstand occasional overstresses considerably above the endurance limit, without embrittlement and fatigue failure;[29] in other words, that nonaging steels can withstand considerable cold work and plastic action without cracking —a property termed "crackless plasticity".[30] There is considerable uncertainty about the whole subject.

Two probable instances of quench-aging in which straining plays no part are temper brittleness, and the galvanizing embrittlement of malleable iron.

Temper brittleness is a decrease that occurs in impact resistance when hardened medium-carbon structural steel is held within, or is cooled slowly through, a certain range of temperature below the transformation range. This effect was first noticed in nickel-chromium steel, but has been observed also in carbon steel.[31] Temper brittleness is undoubtedly a precipitation or aging effect, and as with other aging phenomena, it appears to be less pronounced in strongly deoxidized steel.[32,33] Temper brittleness appears to be more pronounced in steel that contains higher percentages of manganese and chromium, while molybdenum is known to reduce this effect. The influence of molybdenum may be to reduce the rate of precipitation of the embrittling component, so that when enough molybdenum is present, embrittlement does not occur even during slow cooling from the tempering temperature.

Malleable iron may be decidedly embrittled by heating to 850 F, as in galvanizing. It has been shown that such embrittlement may be overcome by heating the castings to 1200 F, and quenching in water before galvanizing.[34] Although the mechanism of this immunizing treatment is by no means understood,[35] galvanizing embrittlement of malleable iron may possibly be an aging effect. The chemical composition of the iron, particularly the phosphorus and

Table IV. Effect of Cooling Rate From 1650 F Before Quenching From 1250 F on Quench-Aging (Harrison[18])

Heat Treatment Before Quenching in Water from 1250 F	Brinell Hardness Number: Tested Immediately After Quenching	Brinell Hardness Number: Tested After Aging 2 Months	Brinell Hardness Number: Change	Izod Impact Values, ft-lb: Tested Immediately After Quenching from 1250 F	Izod Impact Values, ft-lb: Tested After Aging 2 Months	Izod Impact Values, ft-lb: Change
Water-quenched from 1650 F	132	140	+ 8	108	97	− 11
Air-cooled from 1650 F	130	190	+ 60	100	34	− 66
Slowly cooled in furnace from 1650 F	124	192	+ 68	94	6	− 88

silicon content, is an important factor in galvanizing embrittlement.[36]

The prolonged annealing and slow cooling of malleable iron may possibly make it more susceptible to subsequent embrittlement by galvanizing. The data in Table IV point to an apparently analogous effect in steel; the more slowly cooled specimen is more susceptible to subsequent embrittlement in quench-aging than the more rapidly cooled specimen.[18] Somewhat similarly, concerning temper brittleness in steel, it has been found that if the steel is held for a long time at the tempering temperature, embrittlement occurs even during rapid quenching after tempering.[31]

The galvanizing embrittlement in malleable iron differs from that in the other examples mentioned, in that the fracture is intercrystalline.[36] Possibly the dispersion effects occur in the grain boundaries as in carbide precipitation in 18 Cr–8 Ni stainless steel. Usually, in quench-aging and strain-aging of mild steel, the dispersion effects take place throughout the grain and on slip planes. Fracture is mainly transcrystalline.

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The Corrosion of Iron and Steel

By T. S. Fuller*

In 1903 Whitney[1] announced the results of experiments that led to the electrolytic theory of corrosion. Distilled water was boiled in test tubes to expel all the air and CO_2; polished samples of iron were added and the tubes were sealed while the water was boiling. The tubes stood in this manner for weeks without the slightest appearance of rust on the surface of the iron or any appearance of a corrosion product on the glass or in the solution. At the end of several weeks the tubes were opened and a small amount of air was admitted. A precipitate of ferric hydrate quickly settled out. A generally accepted interpretation of the results follows:

Iron goes into solution in pure liquid water until the water becomes saturated with iron ions and a state of equilibrium is established. The iron ions replace hydrogen ions and hydrogen is "plated out" on the surface of the iron. The film of hydrogen on iron, in the absence of oxygen, hinders further corrosion by insulating the iron from the water and by its own tendency to go back into solution in the water. This is called "polarization". Oxygen reacts with the hydrogen film, removes it from the iron surface by the formation of water, and also reacts with the dissolved iron to form a precipitate of ferric hydroxide. Both reactions are involved in the corrosion process; the removal of the hydrogen film allows the solution to contact the iron and the precipitation of ferric hydroxide reduces the amount of dissolved iron, thus encouraging further solution. The conclusion is reached

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that iron goes into solution in liquid water in the absence of both an acid radical and oxygen and that corrosion is, therefore, essentially an electrolytic phenomenon. When the iron is dissolved by the water it first forms ferrous hydroxide, $Fe(OH)_2$; yet because of its solubility, the ferrous hydroxide is not noticeable until a further reaction with oxygen has taken place.

$$2Fe(OH)_2 + H_2O + O = 2Fe(OH)_3$$

The ferric hydroxide, $Fe(OH)_3$, settles out of the solution as a reddish-brown precipitate which, when exposed to air, gradually passes to ferric oxide, Fe_2O_3, commonly known as rust.

These reactions will not take place in dry air or in water free from oxygen but, since ordinary water always contains some dissolved oxygen, corrosion will always take place when iron or steel is exposed to moist air.

Experiments of Whitney, which led to the electrolytic theory, gave considerable impetus to the study of corrosion. Later Cushman and Walker developed a reagent, known as ferroxyl indicator, that demonstrates quite clearly the nature of ferrous corrosion.

The indicator has been described in detail by Cushman.[2] Briefly, it may be prepared by mixing dilute water solutions of phenolphthalein and potassium ferricyanide. If a more or less permanent record is desired, the solution is thickened with gelatin or agar. The action of the ferroxyl indicator is this: a solution containing phenolphthalein becomes pink in the presence of an excess of hydroxyl ions; potassium ferricyanide in the presence of ferrous ions gives a dark blue precipitate. Therefore, when the indicator is in contact with an iron surface, the positive areas—that is, points where iron is going into solution in the ferrous condition—are colored blue, and the negative areas, where there is ■ predominance of hydroxyl ions, are colored pink by these ions.

Rate of Corrosion. The rate of corrosion of every piece of iron or steel depends on the individual conditions existing in the particular locality in which the metal is in use, as well as on the precautions that have been taken to prevent corrosion.

The two substances besides iron necessary for ferrous corrosion are liquid water and oxygen. Corrosion phenomena are of many types. Iron samples that are wholly immersed corrode faster if the water is moving rapidly than if it is in a state of rest. The rate of corrosion of iron tanks or pipes holding water is much slower if they are kept full than if they are alternately wet and dry. Atmospheric corrosion proceeds much more rapidly in districts where the atmosphere is chemically polluted by sulfur vapors and the like than it does in districts where the atmosphere is free from contamination. The corrosion of iron or steel is accelerated or retarded by contact with other metallic elements, depending on whether the elements are electropositive or electronegative with respect to iron. The corrosion rate increases with rising temperature.

The rate of corrosion depends also on the character of the steel as determined by its chemical composition and heat treatment. Stainless steels with large amounts of chromium, and the various alloys of nickel, chromium, silicon and iron are highly resistant to corrosion. The addition of 0.25% Cu improves the resistance of steels to atmospheric corrosion but not to underwater corrosion.

The chemical and structural compositions of iron and steel vary throughout the mass and, because the several constituents have different electrical potentials, corrosion may be either accelerated or retarded thereby. The different electrical potential thus developed is usually comparatively great in badly segregated iron and steel or in metal containing impurities, all of which accelerate the corrosion.

The work of U. R. Evans emphasizes the influence of protective films on the corrosion rate.

Stainless Steels. Because of their high resistance to corrosion, considerable quantities of alloy steels containing large amounts of chromium, or chromium and nickel have come into general use. The most common of these are one containing about 12% Cr, and another containing 18% Cr and 8% Ni. The 12% Cr alloy can be heat treated to give excellent mechanical properties, varying over a wide range. The 18 Cr–8 Ni steel is austenitic in structure and therefore cannot be heat treated to give specific properties; those properties are imparted only by the hot and cold working processes. For maximum resistance to corrosion it is necessary that both alloys be heated and cooled in such a manner as to leave the carbides in solution. For information on the resistance of stainless steel to corrosion, see the article on page 557 in this Handbook.

Stainless steels are rendered somewhat more resistant to corrosion by a surface treatment called "passivation". (*See* "Cleaning, Pickling and Passivating of Stainless Steel", on page 584 of this Handbook.) This treatment does not ordinarily affect the appearance of a polished or machined surface and does not alter dimensions. It should be used after all machining, grinding, and polishing operations, since it removes any particles of the cutting or grinding tools that might be embedded in the metal.

Protective Coatings. Protective coatings for iron and steel form an important section of metal technology and may be grouped as paints, metallic coatings, chemical coatings, and greases.

1 *Paints.* Various specially prepared paints are used for protecting the surface of iron and steel from dampness such as sea water, from oxidizing gases, and from smoke. Therefore no one paint is suitable for all purposes and before a paint is applied, the nature of the corrosive influence present must be determined.

Some paints protect the surface merely by the formation of an impervious film, such as asphaltum and tar. Other paints exert a chemical protective action; such are the ones containing linseed oil as the vehicle and red lead as the pigment. The linseed oil absorbs oxygen from the atmosphere, thus forming a thick elastic covering. This reaction is hastened by boiling the linseed oil before using, and by adding salts of manganese or lead which are called "driers".

A few of the pigments used in paints are red lead, oxides of iron, lead sulfate, zinc sulfate, graphite, aluminum and hydrocarbons. The driers, vehicle and pigments used must be inert to the steel; otherwise corrosion will be hastened instead of prevented.

2 *Metallic Coatings.* The metallic coatings include hot galvanizing, sherardizing, hot tin dip, and electrolytic plates of tin, nickel, copper, chromium, cadmium and zinc. These are discussed in the METALLIC COATINGS SECTION.

3 *Chemical Coatings.* The chemical coatings include phosphate and black oxide coatings.

Phosphate Coatings. These are coatings produced by converting the surface of iron or steel parts to an insoluble phosphate, such as iron phosphate or zinc-iron phosphate. For further information, see page 732.

Black Oxide Coatings. This type of coating is produced by converting the surface of iron or steel to black iron oxide (Fe_3O_4) with a thickness of less than 0.0001 in.

The process consists in immersing the cleaned iron or steel parts in a highly concentrated solution of salts, sold on the market under many trade names. The solution is strongly caustic and must be maintained at a temperature of 290 to 300 F to provide suitable coatings. The time of treatment is approximately 15 min.

This coating affords very limited corrosion protection, perhaps 2 to 5 hr in the standard salt spray test, but it does produce a pleasing black color and provides a good base for the application of rust-inhibiting oils. Its applications are limited to indoor exposure where corrosive conditions are not severe.

4 *Greases.* Greases and oils of various grades are used to protect the surface of iron and steel by applying a thin film over the surface. This method is especially useful for parts of machines, tools, and steels which are to be put in storage or are to be shipped. For details of this method, see the article entitled "Rust-Preventive Compounds", page 734.

Deactivation. Much has been said and written lately about the deactivation of water. In general, the method consists of passing the water to be used in a closed system over scrap iron to remove the dissolved oxygen. Once the oxygen has been removed, theoretically the water may go on circulating indefinitely in the system without cor-

rosive action. Such installations have proved successful.

Dissolved gas can be removed from water by passing the water over an electrically heated, heat-resisting ribbon, allowing the gas liberated thereby to escape.

Iron may become immune to corrosion by being made cathode, that is, the negative pole in a cell, with a potential just sufficient to balance the solution pressure of the metal. This method is not used much because it is costly.

Mechanical De-aeration. Speller[3] in his book has given a very complete summary of the principles involved and the methods used in mechanical de-aeration. Dissolved gases can be removed from water, if the temperature and pressure conditions are so regulated that the gases become insoluble, and if a sufficient amount of time is allowed for their complete mechanical separation from the water. Most types of mechanical de-aerators function by agitating water exposed to favorable conditions of pressure and temperature. Many types and designs of mechanical de-aerators are in use.

Corrosion Tests. Several tests are made on iron and steel to determine their deterioration resulting from corrosion. The tests usually made are salt spray, total immersion, alternate immersion, accelerated electrolytic, subjection to atmospheric conditions and subjection to gases.

The test specimens are of various designs; often the finished object is subject to the test. The deteriorating effect of the immersion tests is determined by the loss in weight and physical properties as well as by the depth of pits and the appearance of the surface. The size of the specimens and the condition of the surfaces should be alike if possible, in order to obtain a satisfactory comparison.

The solutions used may be natural water, such as sea water, city water or mine water, or may be specially prepared solutions containing salts and acid. When preparing special solutions it is advisable to use distilled water; otherwise the impurities might increase corrosion.

The interpretation of results in all tests should be based on the relationship of the results to practical service conditions. Many factors make it difficult to obtain quantitative results and before drawing conclusions the following should be considered: the temperature and degree of aeration of the solution, the machined surface of the specimen before testing, the length of time during which the specimen was subjected to the test, the apparatus employed, and the care used in cleaning and drying the specimen before weighing.

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Nonmetallic Inclusions in Steel

BY THE SUBCOMMITTEE ON NONMETALLIC INCLUSIONS IN STEEL*

ANY specimen of steel when examined closely enough will reveal the presence of particles of material incongruent with the metal lattice and demonstrating either definite nonmetallic or quasi-metallic properties.* Some of these are obviously of foreign origin and are entrained particles of refractory, slag and the like, that have been entrapped by the freezing steel. These are called exogenous, adventitious, or accidental inclusions. Others just as evidently have been precipitated from the liquid or solid metal as a result of chemical reactions or of solubility changes caused by varying temperature. Such inclusions are known as indigenous, natural, or native inclusions and must be considered an integral part of the heterogeneous and complex material known as steel. They are as much a part of steel as seeds are part of a fruit. Much erroneous thinking has resulted from considering all nonmetallic inclusions as something foreign and apart from steel—something not present if steel has been made properly.

Although the title of this section specifies only nonmetallic inclusions, it is difficult to make a clean-cut distinction between the inclusions that are purely nonmetallic and those of a quasi-metallic nature. The question of recognition or identification also arises, and what is even more important is the difficulty of differentiating the effects of inclusions on the properties of steel on the basis of chemical definition. The present article is expanded, therefore, to include some discussion of most of the obvious inclusions to be observed in a highly polished but unetched section of steel—carbides, nitrides, and even graphite.

The presence of inclusions in steel is not regarded as good or bad in itself but as a fact. In certain steels, correlations with service behavior may be accepted as evidence of the effects of inclusions; some of these instances are discussed below. It must be recognized, however, that in regard either to identification or to effects, situations not conforming to the majority pattern are to be expected, but these, in general, are outside the scope of this article.

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* This is not peculiar to steel but is common to most metals and alloys that have been molten.

As far as possible, a clear-cut distinction is made between the natural, precipitated inclusions and those of extraneous origin. This distinction is regarded as desirable because of the widely different sources, because ordinarily they are readily distinguished, and because of important differences in effects of the two types of inclusion.

Origin of Inclusions

Of the two kinds of nonmetallic inclusions that are usually recognized, exogenous inclusions are entrapped inadvertently in the steel, while indigenous inclusions separate from it because of a change in composition or temperature of the steel. Exogenous inclusions originate almost exclusively from particles of nonmetallic matter that are occluded in the steel while it is in the molten state. Indigenous inclusions may be produced in either molten or solid steel by the precipitation of nonmetallic substances in the form of droplets or particles, when these substances are produced in such amounts (by reactions or temperature changes) that their solubility in the steel is exceeded. In most instances, both exogenous and indigenous inclusions are composed of oxides, sulfides and nitrides, or various combinations of these.

The precipitation of indigenous inclusions from either liquid or solid steel follows the laws of heterogeneous equilibrium. The process of formation of an inclusion involves the separation of a second phase, known as the "inclusion", from the phase already present, known as the "metal". This happens when such changes occur in composition or temperature of the steel that the metal phase becomes unstable, but equilibrium may be approached by the precipitation of the inclusion phase. During the manufacture of steel new conditions, with which the steel tends to come to equilibrium, are being established continually. When the metal is in the liquid state, additions to the furnace or ladle will change the composition. In the solid state, changes in composition may be caused by reaction of the steel with furnace gases or other materials with which the steel comes in contact while hot. The composition and temperature of the steel and its surroundings determine the equilibriums involved. Depending on these factors, the inclusions may be solid or liquid and, in either instance,

may be a solution or a substance of fixed composition. Occasionally two or more phases are required in the inclusion for equilibrium with the steel.

Liquid iron at a given temperature may hold in solution a certain quantity of oxygen. If this amount of oxygen is present in the metal and the temperature is lowered, the solubility of oxygen in the metal is decreased, but equilibrium can be re-established by the separation of an oxide phase. The oxide forms droplets. If these are trapped by freezing of the metal before they rise to the surface, they are called inclusions. The addition of manganese, silicon and aluminum, or any other element that can combine with oxygen in the metal, will alter the amount of oxygen that can remain in solution in the metal without the precipitation of an oxide phase. The inclusions that may precipitate as the result of these conditions will be composed of that oxide which has exceeded its solubility in the metal. For example, the addition of manganese may produce (Mn, Fe)O inclusions. The addition of silicon may cause the precipitation of SiO_2 or liquid FeO-SiO_2 solutions. With the addition of aluminum, possible oxide phases are $FeO.Al_2O_3$ and Al_2O_3.

The change in the solubility of each oxide phase with change in temperature is important. With such deoxidizers as aluminum, the oxides included in steel have very small solubilities that change little with alteration in temperature. Therefore, once the deoxidation reaction is completed, virtually no more inclusions precipitate from the steel during teeming and solidification of the ingots. However, the solubilities of the oxides of manganese and silicon may change considerably with temperature. Thus, one may find inclusions that precipitated after the steel was teemed, as droplets of liquid FeO-MnO-SiO_2 solution. Although oxide inclusions have been used as examples, the same principles apply in the formation of sulfides, nitrides and other indigenous inclusions.

When equilibrium has been maintained between the inclusion and the steel, the phase or phases in the inclusion will be the ones that can exist in the presence of the metallic phase. Usually the lower oxides, sulfides and nitrides are found in such inclusions, but not always. For example, Fe_3O_4 rather than FeO is the stable phase below about 580 C. However, at the temperature at which iron oxide is formed in steel, FeO is the stable phase, and apparently it does not alter on cooling, except that crystals of Fe_3O_4 are occasionally found within FeO inclusions. The more common state may be exemplified by a rimming steel, wherein inclusions of (Mn, Fe)O precipitate from the metal on cooling. The higher oxides of manganese and iron do not occur. Similarly, the common sulfide inclusions that precipitate from steel on cooling have the composition (Mn, Fe)S. Sulfides containing a higher proportion of sulfur in relation to their iron and manganese contents, have not been observed. The same conditions prevail in the formation of a subscale by the reaction of elements in the steel with elements derived from the furnace gases, which diffuse into the solid steel. For example, when nitralloy is being heated in dissociated ammonia gas, nitrogen dissolves into the steel and reacts with the aluminum there. As a result, a subscale containing crystals of AlN forms just below the surface of the specimen. Graphite almost never forms as a primary phase in steels of ordinary composition, but sometimes does form by solution of metastable cementite and precipitation of graphite as small nodules during continued heating in temperature regions in which graphite is stable in the presence of iron.

Inclusions that have melting points above the temperature at which they precipitate from the steel will usually form idiomorphic crystals—that is, crystals with well-developed faces. Chromite and titanium cyanonitride inclusions are of this type. Ordinarily such inclusions do not elongate when steel is rolled or forged. When inclusions are liquid at the temperature of precipitation, they usually assume a droplet shape. Many of the siliceous inclusions are of this nature. Such inclusions often, although not always, deform during hot working of the steel. Sometimes inclusions may be a single phase at the time of formation in the steel, but during cooling, they may separate into two phases. A common example of this is the silicate-sulfide inclusions, which are a single phase at high temperatures but which, during cooling, separate into (Fe, Mn)S and a siliceous liquid. Sometimes metal-inclusion eutectic structures are observed. A common example of this type is the metal-(Mn, Fe)S eutectic structure observed in steels that have been treated with an appropriate amount of aluminum.

The distinction between exogenous and inherent inclusions is not always sharp. A nonmetallic particle in equilibrium with its surroundings in the furnace may suddenly become out of equilibrium with the metal in the ladle because of rapid alteration in the metal composition as a result of ladle additions and change in temperature during tapping. Such inclusions must seek equilibrium with the steel in the ladle, and again in the mold if carried there, where the temperature is lowered even further. Under these conditions, and when extraneous nonmetallic matter is inadvertently entrapped in the steel, equilibrium may be established prior to solidification, but more often the reactions are arrested by the effect of chilling. Exogenous inclusions may be of wide variety; for example grains of sand adherent to sandcast ferro-alloys, inclusions in ferro-alloys, and siliceous material eroded from ladle lining, well, stopper-head, or nozzle. In a steel containing residual aluminum, the aluminum may react with exogenous siliceous inclusions. The Al_2O_3 formed thereby will become a part of the inclusion, while a stoichiometric amount of FeO, MnO, or SiO_2 in the inclusion will be reduced to iron, manganese or silicon, respectively, and will dissolve in the steel. Complete reduction of such an inclusion by aluminum results in an alumina inclusion, which may be indistinguishable from alumina formed by other steelmaking reactions. The reaction of alloying elements in the steel with exogenous inclusions can occur only by diffusion of the reactants to the interface between the inclusion and the steel and by diffusion of the products away from the interface. Therefore, the size of the inclusion is determined by the size of the original occlusion and the stage at which the reaction is arrested by chilling of the steel. If equilibrium has not been attained during the solidification of the ingot, there is the possibility of considerable change in the character of such inclusions when the solid steel is being heated for rolling or is being heat treated.

Identification of Inclusions

Selection and Preparation of Specimens. 1 *Macroscopic Examination.* For a successful study and evaluation of nonmetallic inclusions in steel, consideration must be given to their location and general distribution. Steel ingots are heterogeneous and the ultimate bar or piece of steel reflects, in cross section, the heterogeneity existing in that portion of the ingot which it represents. This condition is revealed by suitable macroscopic examination. In general, the purpose of the investigation and the shape and condition of the material will determine the location from which specimens should be cut. The location should be selected so as to be truly representative of the parent metal, since any random sampling may fail to appraise the steel as a whole or to detect the specific condition that is to be uncovered. When rolled or forged materials are involved, transverse and longitudinal sections should be examined.

Deep-Etch Test. A deep-etch test in 1 to 1 hydrochloric acid (cp) is most commonly employed for macroscopic examination. The preparation of the sample and the details of the test are described in another section of the Handbook (*see* page 389). In the examination of the etched surface for nonmetallic inclusions, some experience is necessary for recognition of the appearance and type of such inclusions. Pits resulting from oxides and other nonmetallic inclusions should not be confused with pits occurring from the etching out of metallic aggregates. When nonmetallic inclusions are suspected in highly alloyed steels that may contain metallic aggregates, a comparison should be made of an annealed specimen and a hardened specimen etched alike. If the etching pits are the result of nonmetallic inclusions, they will appear to be similar in the annealed and the hardened specimen; if they are the result of metallic segregate, they will differ. It must be emphasized, however, that not every pit developed indicates the occurrence

of an inclusion, since pitting may also occur as a result of acid attack around carbide particles. Frequently, it may be helpful to examine the surface in the finely ground and only lightly etched condition under good binoculars prior to deep etching. Specimen and lighting should then be arranged so that the metal background looks white.

Fracture Test. Sometimes a fracture test is employed for the purpose of detecting internal defects or macroscopic nonmetallic inclusions in steel. This test is carried out by nicking preferentially on one side suitable sections of a billet or bar in the hardened condition, and striking the end close to the nicks with a sledge hammer. The fractured surface should be parallel to the rolling direction.

Sulfur Printing. The distribution of the sulfide inclusions can be brought out by sulfur printing. Sulfides containing chromium, titanium, zirconium, and vanadium, which offer a higher resistance to etching by acids, are not likely to respond to this method.

Magnetic Particle Inspection. Larger inclusions may be detected by the magnetic powder method of inspection, a continuity test based on the abrupt change made in a magnetic field by flaws or metallic discontinuities. Subsurface metallic discontinuities may be located by this method, depending on their size, location, depth beneath the surface, condition of the material and the procedure used. This method is described in an article on page 145.

Supersonic Inspection. Recently in a new method, supersonic waves have been used for detecting inclusion segregations, laminations and other flaws in steel. (*See* page 157).

2 *Selection and Preparation of Sample for Microscopic Examination.* Whenever possible, nonmetallic inclusions should be studied in the as-cast condition of the metal, since the deformation of the steel in the solid or plastic state alters the shape of the inclusions and tends to make their original appearance and distribution unrecognizable. Samples of forged or rolled materials should, therefore, be taken parallel to the direction of rolling. The success of the microscopic examination is determined largely by the proper preparation of the sample. In general, any method of polishing will be suitable that will produce a flat metal surface, free from scratches, flowed surface layers and films, and will keep the inclusions clearly outlined, leaving a satisfactory polish on their surface. Detailed instructions for metallographic polishing are given on page 159 of this Handbook. With the exception of alumina inclusions, which are hard and brittle and have a marked tendency to "wipe", most of the inclusions can be polished with little difficulty. Sometimes, it may be advantageous to harden the specimen in order to facilitate polishing, keeping in mind, however, that the thermal treatment involved may produce structural changes in certain types of inclusions. A previously deep-etched surface is not suitable for the preparation of specimens for microscopic examination unless the whole acid-affected surface layer, which may extend to a depth of ¼ inch or more, has first been removed by mechanical means. It is also not recommended to use graphite in conjunction with the dry-polishing papers, since graphite particles may be embedded in the surface of the metal and, after final polishing, may be mistaken for inclusions. Great care should be taken in cleaning and drying the prepared surface. Dried water spots, particles of the polishing mediums or dirt on the surface of the specimen may lead to erroneous conclusions. It is not advisable to etch the specimen before micro-examination with polarized light, because the surface roughness produced by etching causes scattering reflections. Heat-tinted specimens should not be used since such treatment may cause oxide films on the surface of the inclusions.

General Characteristics. Nonmetallic inclusions in steel differ from metallic substances by their lower mechanical strength, by their relative brittleness, especially at low temperatures, by their lower density and inferior electrical conductivity, and by their lower coefficient of reflection. According to their nature and mode of formation, they are either crystalline or vitreous, refractory or fusible, plastic or brittle, of lower or higher hardness, opaque or translucent or transparent, colored or colorless, of higher or lower reflectivity and refractivity, resistant to chemical reagents or easily attacked by them. Their nature, constitution, and morphological characteristics are controlled to a considerable degree by the manner and extent of the deoxidation and by the conditions of cooling. A study of the thermal equilibrium diagrams of the various systems of compounds of which nonmetallic inclusions consist is very helpful for their identification. These diagrams show the phases resulting from their mutual combinations, their respective compositions, constitutions and melting relationships.

Certain types of inclusions are characteristic of the deoxidation practice employed. For example, in rimmed steel to which only enough deoxidizers are added to maintain the FeO and MnO content within certain limits, the oxide (Fe, Mn)O and the sulfides FeS, (*Fe,* Mn)S and (*Mn,* Fe)S occur, as well as complex compositions consisting of the single phases associated with eutectic mixtures. Silicates and alumina inclusions tend to be absent in this type of steel. In silicon-killed steel to which no aluminum or other similarly strong deoxidizers have been added, iron-manganese silicates or manganese silicates of varying silica contents are observed. If deoxidation by silicon is followed by a large enough aluminum addition to result in a noticeable amount of residual aluminum, the deoxidation products consist mainly of hard and brittle alumina inclusions. Alloying elements are responsible for inclusions derived from the special element added. Thus, in steels deoxidized with Zr-FeSi, zirconium ferrous silicate, zirconium nitride and zirconium nitride-carbide solid solution crystals may be encountered. In steels treated with FeCr, chromium-bearing silicates, chromite ($Cr_2O_3 \cdot FeO$) and chromium oxide (Cr_2O_3) or complex chromite-oxide inclusions may be found. Steels deoxidized by titanium may contain TiO_2FeO (ilmenite) if the residual titanium is low. If the residual titanium is high, TiO_2 (rutile) is likely to occur. Titanium steels are also likely to contain TiN and titanium nitride-carbide solid solution crystals. Alloying elements usually participate also to some extent in the formation of sulfides. However, because of their solubility in the generally predominant (Mn, Fe)S, these alloyed sulfides seldom appear as separate, distinguishable constituents, but ordinarily occur as solid solutions or complex sulfide inclusions.

Examination in Reflected White Light. After proper preparation of the polished surface (*see* page 159) the specimen is usually examined in reflected white light as the first step in the identification of nonmetallic inclusions. For this examination a background of experience is very helpful; the experienced metallographer can identify readily, at sight, the majority of inclusions to be found in steel, recognizing them by characteristic color, shape, size and distribution.

For example, MnS is characterized by a dove-gray color, a tendency to form in globules (except when they form as part of a eutectic) located in primary grain boundaries, and plasticity during hot rolling. FeS, on the other hand, is likely to be canary yellow and tends to form in thin continuous films in the grain boundaries. Silicates may be opaque, translucent or transparent, but usually occur as globules in cast steel and are nearly always plastic during hot rolling. Inclusions of alumina occur as clusters of fine crystals that are very hard and tend to pull out and scratch during polishing. Zirconium or titanium nitrides are yellow cubic crystals. Data given in Table I show the common properties of many inclusion-forming materials

Knowledge of the composition and finishing practice of the steel under examination is always a great help in identifying inclusions. As was pointed out in the previous section, inclusions are characteristic of the steels in which they occur. In fact, if the inclusions do not correlate accordingly, there is room for suspicion that the steel is not as represented.

Accidental or adventitious inclusions do not, of course, follow any such pattern, and if occasional noncharacteristic inclusions are found, it is proper, as a first assumption, to regard them as exogenous. Other ways in which many exogenous inclusions may be recognized are by unusually large size, irregular shapes and heterogeneous structure.

Visual examination, however, is neither infallible nor always adequate, and there are occasions when more searching means of identification are desirable. Some such methods are described below. A word of caution is needed: Polishing for identification of inclusions requires

care and skill. All too often particles of dust or polishing grit, stains and holes are mistaken for inclusions. No attempt at identification should be made until the inclusions are clean and clearly resolved.

Examination by Reflected Plane-Polarized Light. As a further aid in the identification of the inclusions, the unetched specimen may be examined with reflected plane-polarized light. The usual metallurgical microscope is satisfactory for such examination if accessory equipment is added, with which to obtain and analyze the plane-polarized light. Certain precautions are necessary in utilizing this equipment and in interpreting the results. The microscopist should have a thorough knowledge of the petrographic microscope and the theory of polarized light. Limitation of space prevents an adequate discussion here; however needed information can be found in the literature on the subject (*see* references following this article).

Examination under crossed nicols may enable the investigator to distinguish between the isotropic (vitreous and cubic-system inclusions) and those having anisotropic properties. These characteristics, together with color reflected through the inclusion from the inclusion-metal interface, may be advantageous in identification.

The method of identification by reflected polarized light contains tables of properties of substances that may be encountered as nonmetallic inclusions. It should be noted that inclusions in iron and steel rarely consist of a single pure component; therefore, their properties are not likely to correspond precisely to the pure mineral. The minerals described, however, will help to identify inclusions, if the optical characteristics can be determined.

Table I

Distinctions to Be Observed for the Identification of Inclusions in Steels and Irons with Reflected Polarized Light

System Used Below for Property Designation

1 Name and Formula
- *a* Crystal system
- *b* Melting point
- *c* Hardness (Mohs' scale)
- *d* Color by reflected white light
- *e* Color by transmitted white light (plane-polarized light, crossed nicols)
- *f* Index of refraction
- *g* Common occurrence
- *h* Remarks

Inclusion Minerals That Always Remain Dark During 360-deg Rotation

1 Ferrous oxide, FeO
- *a* Isometric
- *b* 1360 C (2480 F)
- *c* 5.5 to 6.5
- *d* Medium gray
- *e* Opaque
- *g* In scale, and as more or less rounded single-phase globules in rimming and similar steels low in silicon and manganese.
- *h* Somewhat malleable at steel rolling temperatures.

2 Magnetite, $FeO.Fe_2O_3$
- *a* Isometric
- *b* 1327 to 80 C (2421 to 2516 F)
- *c* 5.5 to 6.5
- *d* Light gray
- *e* Opaque
- *g* In scale
- *h* Not malleable at steel rolling temperatures

3 Titanium nitride, TiN
- *a* Isometric
- *c* 9 to 10
- *d* Yellow
- *e* Opaque
- *g* In steels and irons treated with ferrotitanium
- *h* Not malleable at steel rolling temperatures. May contain TiC in solid solution. Color in reflected white light varies from yellow to pink to violet with increasing carbon content. Pink sometimes called cyanonitride. The inclusions are strongly angular and easily pitted in polishing.

4 Zirconium nitride, ZrN
- *a* Isometric
- *b* 2950 C (5342 F)
- *d* Yellow
- *e* Green
- *g* In steels and irons treated with ferrozirconium
- *h* Not malleable at steel rolling temperatures. May contain ZrC in solid solution, which produces varying colors by reflected white light—orange, brown, violet, blue. The inclusions are strongly angular and they may be distinguished from TiN by etching tests. They are softer and easier to polish than TiN.

Translucent Isotropic Inclusion Minerals

1 Manganous oxide, manganosite, MnO
- *a* Isometric
- *b* 1700 C (3092 F)
- *c* 5 to 6
- *d* Very dark gray
- *e* Green
- *f* N = 2.16 (Li)
- *g* In steels and irons high in manganese which have not been deoxidized with other more effective deoxidizers, for example, aluminum and silicon.
- *h* Somewhat malleable at steel rolling temperatures. Usually contains more or less FeO in solid solution. Color by reflected white light changes from dark gray to medium gray with increase in FeO. Color by transmitted light changes from green to red or brownish red to opaque with increase in FeO.

2 Manganous sulfide, alabandite, MnS
- *a* Isometric
- *b* 1620 C (2948 F)
- *c* 3.5 to 4
- *d* Medium gray
- *e* Green
- *f* N = 2.70 (Li)
- *g* Steels and irons except those with very low manganese content
- *h* Very slightly malleable at steel rolling temperatures, malleability increases with increase in FeO in solid solution. Usually contains FeS in solid solution. In stainless steels probably also contains Cr in solid solution. Color by reflected white light changes from medium gray to grayish white, with pearly luster, with increase in FeS. Color by transmitted white light changes from green to greenish yellow or brown to opaque with increase in FeS.

3 Iron aluminate, hercynite, $FeO.Al_2O_3$
- *a* Isometric
- *b* Above 1700 C (3092 F)
- *c* 7.5 to 8
- *d* Medium to dark gray
- *e* Colorless, green, yellow brown, reddish brown, opaque when rich in iron oxides.
- *f* N = 1.80
- *g* In steels and irons treated with aluminum and in some inclusions derived from refractories.
- *h* Not malleable at steel rolling temperatures. Change in color and translucence due to solid solution. Opaque varieties are lighter gray by reflected white light. Frequently occurs as equiaxed euhedral crystals. Not so difficult to polish as inclusions rich in Al_2O_3.

4 Chromite, $FeO.Cr_2O_3$
- *a* Isometric
- *b* Above 1780 C (3235F)
- *c* 5.5
- *d* Medium gray
- *e* Red, reddish brown, yellowish brown, or opaque, depending on the thickness.
- *f* N = 2.07 to 2.16
- *g* In chromium produced by the aluminothermic process and in any steel containing residual aluminum and appreciable amounts of nitrogen.
- *h* Not malleable at steel rolling temperatures. Usually found as very fine network in primary austenite grain boundaries in the form of euhedral crystals. Has limited solubility in high-temperature austenite.

5 Silica glasses
- *a* Noncrystalline
- *b* Variable
- *c* Approximately 7
- *d* Light to very dark gray, sometimes with bright internal reflections.
- *e* Colorless or all colors, depending on contamination with other oxides.
- *f* Variable
- *g* In steels and irons that contain silicon and that have not been thoroughly deoxidized with other more effective deoxidizers, for example, aluminum; and in some inclusions from refractories.
- *h* Varying degrees of malleability at steel rolling temperatures. May be more or less milky because of precipitation of other minerals in finely divided state within the glass on cooling. In cast or weld metals transparent spherical glassy silicates exhibit the dark optical cross by transmitted white polarized light.

Opaque Minerals Showing Anisotropic Behavior

1 Ferrous sulfide, troilite, FeS
- *a* Hexagonal
- *b* 1180 to 1190 C (2156 to 2174 F)
- *c* 3 to 4
- *d* Light tan or yellow
- *e* Opaque
- *g* In steels and irons very low in manganese
- *h* Malleable at steel rolling temperatures. Under reflected plane-polarized light with nicols crossed, properly oriented grains show four extinctions in 360 deg.

2 Graphite, C
- *a* Hexagonal
- *c* 1 to 2
- *d* Light to dark gray
- *e* Opaque but shows strong anisotropic reactions
- *g* One of the principal constituents of cast iron and malleable cast iron. Also found in graphitic steels. May be found in still tubes, steam lines, die and tool steels after prolonged exposure to elevated temperatures.
- *h* Graphite is somewhat pleochroic and the plane glass vertical illuminator polarizes light sufficiently to cause graphite to appear light or dark, depending on its crystallographic orientation. Graphite in steels will go into solution if heated well above the transformation temperature.

Translucent Anisotropic Minerals with Weak Birefringence

1 Alumina, corundum, Al_2O_3
- *a* Hexagonal
- *b* 2050 C (3722 F)
- *c* 9
- *d* Medium gray
- *e* Colorless
- *f* No = 1.77 Ne = 1.76 (Na)
- *g* In steels and irons treated with aluminum, and in some inclusions derived from refractories.
- *h* Not malleable at steel rolling temperatures. Color by transmitted light changed variously by impurities in solid solution. Occurs as equiaxed or elongated grains with irregular surfaces, or euhedral crystals. These have a tendency to group together in clumps or small clouds of particles. During rolling or forging these groups are formed into irregular rows of particles in the direction of working. These inclusions are rarely pure and may contain FeO

and SiO_2. The inclusions rich in Al_2O_3 are difficult to polish and frequently their anisotropic behavior is masked by reason of their transparency and highly reflecting metal inclusion interface, or by rounding the edge of the cavities left by their removal.

2 Mullite, $3Al_2O_3.2SiO_2$
a Orthorhombic
b 1816 C (3301 F)
c 7.5
d Medium to dark gray
e Colorless, pink
f Ng = 1.654, Nm = 1.644, Np = 1.642
h Frequently occurs as long euhedral crystals in glass inclusions.

3 Quartz, SiO_2
a Hexagonal
b 1600 to 1750 C (2912 to 3182 F)
c 7
d Medium to dark gray
e Colorless
f Ne = 1.55, No = 1.54

4 Cristobalite, SiO_2
a Pseudo-isometric (tetragonal?)
b 1696 C (3085 F)
c 6-7
d Medium to dark gray
e Colorless
f No = 1.487, Ne = 1.484
h Usually associated with glass

Translucent Anisotropic Minerals with Strong Birefringence

1 Fayalite, $2FeO.SiO_2$
a Orthorhombic
b 1205 C (2201 F)
c 6.5
d Medium to dark gray
e Colorless, light green, yellowish green, yellowish brown
f Ng = 1.886, Nm = 1.887, Np = 1.835
h Frequently contains $2MnO.SiO_2$ in solid solution

2 Ferric oxide, hematite, Fe_2O_3
a Hexagonal
c 5
d Medium to light gray
f No = 3.22, Ne = 2.94 (Na)
g Frequently occurs as outer layer of scale

3 Chromic oxide, Cr_2O_3
a Hexagonal
b 1900 C (3452 F)
d Medium to light gray
e Green, depending on the thickness
f N = 2.5±
g In stainless steels and other high-chromium materials
h Not malleable at steel rolling temperatures. These inclusions are harder than chromite.

4 Aluminum nitride, AlN
a Hexagonal
b 2150 to 2200 C (3902 to 3992 F)
d Dark to very dark gray
f Birefringence high (indices not available). Often shows brilliant polarization colors.
g In chromium produced by the aluminothermic process and in chromium steels containing aluminum.
h Frequently occurs as euhedral crystals.

Examination in Reflected Unpolarized Light After Etching. As indicated in the preceding section, much information can be derived from shape of inclusions and their color and optical activity in transmitted light. When this method of approach has been exhausted and the nature of inclusion material is still in doubt, etching is recommended. If the microscope used is not equipped for studies with polarized light, then etching is the only method available. In this situation it should be understood that the identification will not be so reliable as when both methods are employed.

The effect of certain etching reagents on inclusion material is shown in Table II. In using this table, it must be remembered that the effect of the etchants shown applies only to the inclusions described, and that there is no way of predicting the effect on inclusion types not shown. Similarly, if one of the two sequences of etching shown is used, then the other sequence should not be used without complete regrinding and repolishing.

Identification by Extraction. When visual and surface etching methods leave something wanting, nonmetallic inclusions may be extracted for more detailed study.

If the inclusions in question are of sufficient size, they may be extracted mechanically with the aid of a jeweler's screw driver containing a sharpened phonograph needle. The technique is simply the process of forcing the needle into the metal almost adjacent to the inclusion, which will then be displaced, usually in fragments.

Another method that may be used is to dissolve away the steel with dilute mineral acids or with alcoholic iodine solution. However, such chemical methods should be used with considerable discretion because many of the inclusions are also attacked. Generally speaking, chemical extraction should be used only on killed steels.

Electrolytic extraction, in which the specimen is made the anode in an electrolytic cell, has been very successfully used. When the electrolyte is properly buffered, sulfides and even carbides can sometimes be retained intact while the metal is dissolved.

Table II. Scheme for Etching Identification Tests

Appearance with Reflected White Light (× 200, × 500, × 1000)

Gray or Black Inclusions

Etch 10 sec in 10% alcoholic nitric acid

More contrast	Unattacked
(*a*) FeO in FeO.FeS eutectic darkened	Etch 5 min in 10% chromic acid in water
Attacked	**Unattacked**
(*a*) Removes FeS.MnS, rich in MnS (*b*) Darkens FeO.MnO	Etch 5 min in boiling alkaline sodium picrate
Attacked	**Unattacked**
(*a*) Removes FeS.MnS, rich in MnS (*b*) Removes FeO.MnO	Etch 5 min in 5% alcoholic hydrochloric acid
Attacked	**Unattacked**
(*a*) Removes FeO.FeS (*b*) Removes FeO (*c*) Removes remaining FeO.MnO (*d*) Removes $MnO.SiO_2$	Etch 10 min in a 20% aqueous solution of hydrofluoric acid
Attacked	**Unattacked**
(*a*) Removes $FeO.SiO_2$ (*b*) Removes $CaO.SiO_2$ (*c*) Removes some siliceous alumina	(*a*) Al_2O_3, $FeO.Al_2O_3$ and (FeO, MnO) Al_2O_3 (*b*) Chromite ($FeO.Cr_2O_3$). Etch 5 min in boiling 10% H_2SO_4 and 1% $KMnO_4$ and lightly repolish
Attacked	**Unattacked**
(*a*) Chromite ($FeO.Cr_2O_3$) isotropic: red to brown by transmitted light	(*a*) Chromic oxide (Cr_2O_3) anisotropic: purplish gray by reflected light, bright green by transmitted light (*b*) Ferrous aluminate ($FeO.Al_2O_3$) opaque isotropic: light gray

Yellow, Tan or Pink Inclusions

Etch 10 min in boiling alkaline sodium picrate solution

Attacked	Unattacked
(*a*) Removes FeS (pale yellow)	Etch 10 min in a 20% aqueous solution of hydrofluoric acid
Attacked	**Unattacked**
(*a*) Removes zirconium nitride (yellow cubes) (*b*) Removes zirconium sulfide (tan crystals)	(*a*) Titanium nitride (yellow cubes) (*b*) Titanium cyanonitride (violet) strongly angular, easily pitted in polishing (*c*) Titanium carbonitride (blue cubes)

After extraction, the inclusions may be examined by standard petrographic techniques,[16] they may be subjected to ordinary chemical analysis or examined for mineral constituents by X-ray diffraction.

A different approach developed by Baeyertz involves preparing a thin section for examining inclusions by transmitted light, according to petrographic procedures.

Effects of Inclusions

One of the criteria by which steel quality and fitness for some particular uses are judged is the content and character of nonmetallic inclusions. The fact that they are nonmetallic and, therefore, incongruent with the metal lattice has often been considered sufficient evidence of undesirability. It is a fact, however, that the true import of inclusions in regard to steel properties has never been satisfactorily clarified, and opinions vary widely. Nevertheless, as was mentioned earlier, certain correlations noted be-

tween observed inclusions and service behavior of steel may be taken as evidence of their effects. It is apparent, however, that total contents are not sufficient data on which to evaluate all effects.

An analogy might be drawn between inclusions in steel and certain low organisms such as bacteria. Because some of the latter have been found to be responsible for many distressing and fatal diseases, anathema has been cast on the whole breed. Yet it is true that the vast majority of such organisms are either benign or beneficial, and it is probably true that the higher animals could not exist without them to dispose of waste, fix nitrogen and prepare soil. Similarly, although it is known that some inclusions have harmful effects, it may well be that some of the properties that are considered characteristic and useful in steel would not exist were it not for a very fine precipitation of inclusions. Precipitation hardening, for example, is attributed to the critical dispersion of precipitated particles.

Indigenous and exogenous inclusions are discussed separately for two principal reasons. In the first place, indigenous inclusions have a fairly homogeneous macrodistribution and any effect will be common throughout the steel, whereas the sporadic occurrence of exogenous inclusions limits effects to their locality. In the second place, exogenous inclusions are generally much larger and are often imperfectly "wetted" by the steel, both of which factors tend to intensify their effects.

Effects of Indigenous Inclusions. *Machinability.* The machinability or free-cutting quality of most steels is markedly enhanced by an increase in the sulfur content. Such an increase naturally produces more numerous or larger sulfide inclusions. Just how far this improvement will continue with increasing sulfur has not been determined, but apparently it continues up to the point where sulfur content makes the steel all but unrollable. Although other factors in the addition of sulfur may also affect machinability, it is believed that the actual presence of the sulfide inclusions has the greatest effect.

This effect has been explained by some on the basis of the embrittling effect of sulfides, and by others on the basis of internal lubrication. Selenium, which forms selenides with the general appearance and characteristics of sulfides, has much the same effect as sulfur on machinability. The metallic inclusions of lead in leaded steels are outstanding in their ability to improve machinability.

Refractory oxide inclusions, such as silicates or alumina, have been designated as distinctly harmful to machinability because of abrasive action, although the case against them is largely circumstantial evidence. On the other hand, some chromium oxides have been credited with improving the machinability of austenitic stainless steels.

Grain Size. The inhibition to grain growth in "fine-grained" steels below their grain-coarsening temperature has been ascribed to a mechanical barrier in the grain boundaries, which prevents diffusion across them. Although this barrier is apparently too fine to be observed and identified with the ordinary microscope, strong circumstantial evidence predicates its presence, and it is thought to be of the nature of nonmetallic inclusions.

Because of the known behavior of fine-grained steels, it has been postulated that the grain-boundary inclusion substance (still unknown) has an appreciable solubility in alpha iron at high temperatures but precipitates in the boundaries of the newly formed austenite grain during transformation while heating. There the inclusion substance effectively prevents grain growth until it is redissolved in austenite at the grain-coarsening temperature.

Alumina has been mentioned widely as one of the growth-inhibiting materials, because of the generally fine-grained nature of aluminum deoxidized steels. There are reasons, however, to believe that aluminum nitride is a more likely agent. The nitride seems to be an improbable factor in the steels deoxidized with titanium or zirconium, because the nitrides of these elements are very insoluble. The sulfides or suboxides of these elements and of vanadium appear to be possible factors in grain-growth inhibition, whereas the carbides have less potentiality because of generally higher solubility in gamma than in alpha iron.

Ductility and Notched-Bar Impact Properties. The mechanical properties of steel, as measured by the ordinary tensile and notched-bar impact tests, are affected directly by the quantity of inclusions present but even more strongly by the size and distribution of the inclusions.

These effects are best shown with sulfide inclusions, because they are more readily controlled in quantity and type. The quantity, of course, will vary directly with the sulfur content, while the type and distribution can be controlled by the deoxidation practice. The effects are much more evident in cast steel, which has almost no directional properties, but can also be shown in wrought steel if specimens are taken both longitudinal and transverse to the direction of rolling.

When sulfides are precipitated as relatively large globules and far apart, as in silicon-deoxidized steels, they have the minimum effect for a given quantity. However, when aluminum or some other strong deoxidizer is used in an amount that will cause the sulfides to precipitate as part of a eutectic, in which form they constitute a nearly continuous chain or film envelope around the primary grains, the sulfides have the maximum effect on ductility. In a cast steel, the ductility and notched-bar impact values may be reduced by 50% with the eutectic sulfides, as compared with the globular type. In rolled steel, the effect is usually not noted if the specimen is taken in the direction of rolling, but it may be exaggerated in the transverse direction.

The effect of quantity alone, when other factors are equal, has been noted even in steels with very low sulfur contents. For instance, in a Ni-Cr-Mo steel,[19] an increase in sulfur content from 0.007 to 0.013% caused a consistent drop in the notched-bar impact value from 30 to 26 ft-lb in longitudinal tests and 19 to 14 ft-lb in transverse tests.

In a medium-carbon silicon-killed cast steel,[10] an increase in sulfur from 0.02 to 0.06% (tripling the sulfide content) caused a decrease in elongation from 34.0 to 29.5%, in reduction of area from 61.5 to 46%, and in Izod value from 51.5 to 27 ft-lb.

In rolled steels, a comparison of a C1019 and a B1112 steel will suffice. These steels have the following approximate compositions:

	Percentage			
	C	Mn	S	P
C 1019	0.19	0.85	0.05 max	0.045 max
B 1112	0.10	0.75	0.20	0.10

Tested in the hot rolled condition, they showed average properties as listed in Table III.*

Because of variations in content of elements other than sulfur, all differences in properties cannot be ascribed to sulfur. Higher phosphorus in the B 1112 undoubtedly affects the Charpy value, for example. However, it will be observed that whereas the values for longitudinal ductility are not greatly reduced by the higher sulfur content, the transverse ductility is affected to a much greater extent. No similar data seem to be available in regard to the effect of the quantity of oxide inclusions, and it is only presumed that they would act in a similar manner.

Brittle Fracture. From time to time in the examination of cast or forged steels, extremely brittle conditions are encountered in which the fractures are characterized by smooth, undulating, or coarsely crystalline surfaces. These have sometimes been called "rock candy" fractures but are probably more accurately termed "intergranular" fractures in which the primary grain boundaries are involved. The condition may occur at any time after the steel is cast, even after it is fully heat treated.

Although it seems that the cause of brittle fracture may sometimes be ascribed to a ferrite network,[20] or to massive carbide precipitation in the primary grain boundaries of raw steel, or even to hot tears, the majority of such fractures appear to be caused by a precipitation of inclusions in the primary grain boundaries, either during freezing or during slow cooling from ■ high temperature used in heat treating or forming. Aluminum nitride and manganese sulfide inclusions have been identified as two substances that behave in this manner. Both of these materials have an appreciable solubility in gamma iron—a solubility that

*Unpublished work at Battelle Memorial Institute

Table III. Mechanical Properties of Two Hot Rolled Steels

Steel	Tensile Strength, psi		Yield Strength, psi		Elongation in 0.75 in.		Reduction in Area, per cent		V-Notch Charpy, ft-lb	
	Long	Trans	Long	Trans	Long	Trans	Long	Trans	Long	Trans
C 1019	64,000	61,800	36,300	32,700	43.5	36.0	66.5	53.7	88.5	35.0
B 1112	66,900	62,500	39,900	35,900	37.5	22.6	60.5	24.5	18.0	9.0

varies with temperature. Other substances may be involved in individual instances and any material that will form a fairly continuous network, however thin, in the steel will have the same effect.

Hot Shortness. Iron sulfide, which precipitates as films in the primary grain boundaries, has an effect on hot shortness that has been widely expounded. Manganese sulfide also, when it precipitates in eutectic form, has much the same effect, although to a lesser degree. Such sulfides have been blamed for excessive hot tears (in steel castings, for example) but there seems to be no clear-cut evidence that they have been responsible for rolling difficulties.

Fatigue. A deleterious influence of nonmetallic inclusions on the fatigue endurance properties of steel is probably one of the most widely expected effects, and yet experimental evidence does not support belief in any important detriment to endurance values from indigenous inclusions in their ordinary range of occurrence. Throughout a wide range of steels, endurance values for polished bars bear a significantly constant relation to tensile strength.

Any such general statement has limitations; for example, in a certain ingot, it was found that the butt cut had an oxide inclusion content about 50 times as great as the upper cuts.* Specimens from the upper cuts showed endurance values of 55% of the tensile strength; no definite value could be determined for the butt cut because of the erratic behavior of the specimens, one of which broke at a fiber stress as low as 47% of the tensile strength at ▮ million cycles.

Fatigue testing is naturally a study of notch propagation, and the reason why indigenous inclusions have so little effect on endurance values is thought to be that they do not produce internal notches in steel. In other words, there is no cavity around an indigenous inclusion; it is wetted by the steel, and there is a bond between steel and inclusion. Thus, the inclusions support some of the stress, even though the modulus of elasticity may be different. There is no apparent reason why an oxide or sulfide inclusion should have any more effect than carbides on endurance.

It should be emphasized that this discussion concerns only the small, naturally precipitated inclusions. Inclusions are thought to harm endurance values more in very hard steels, such as ball or roller bearings. A study of many references to fatigue failures caused by inclusions indicates that the inclusions in question were probably adventitious in origin. Reference to these is made in the next section.

Corrosion. In stainless steel, the effect of inclusions on corrosion resistance has been termed definitely harmful, and sulfide inclusions on polished surfaces are sometimes thought to tend to localize corrosive attack. Localized corrosion, however, is usually an electrolytic phenomenon and most inclusions are too insoluble in water or are too nonconductive to make an electrolytic couple in either atmospheric or submerged corrosion. On the whole, normal variations in the corrosive environment have far more influence than the variations in inclusions.

Weldability. Normal amounts of oxides, sulfides, and nitrides are not harmful to most welding processes. Sulfides are considered to have the most deleterious effect on weldments, because of the characteristic of hot shortness imposed on the zone of fusion during solidification and cooling through the range of hot shortness, when stresses can produce separation of the metal.

Rolled plate, forgings and castings of steel are successfully joined to each other by many processes, such as metal-arc welding, submerged-arc welding, flash butt welding, gas welding and resistance welding.

Experience teaches that certain qualities are desirable in the steel for each particular process of welding.[21] This acknowledges that size and distribution of inclusions may affect the capacity of steels to be fabricated by welding into structures adequate for the service requirements. In metallic arc welding, 0.05% S in the parent metal may have no deleterious effect on the weld metal. When segregated MnS inclusions occur in the parent metal, as is possible in semikilled steels or between the core and case of rimmed steel, these inclusions react with explosive violence during welding and create gas pockets at the fusion line. It is not uncommon to find in highly segregated steel that the inclusion material will be melted out of a ghost band beyond the junction line of the weld and parent metal. High-quality welds are difficult to obtain with high-sulfur free-machining steels. The presence of 0.15 to 0.30% S in the parent metal causes porosity and cracking in the weld metal deposited with mild steel electrodes. Satisfactory welds have been made with the new all-mineral electrode of low hydrogen content. The lime-silica ratio of the coating apparently fixes the sulfur in a harmless form and is important to the soundness of the weld metal. The low hydrogen content of this electrode helps to hold back underbead cracking. When sulfur segregations are suspected in steel for welding and a sulfur print, exposed for one minute, shows concentrations exceeding ⅛ in. in diam and more than 2 per sq in., the steel is considered detrimental for arc welding. The amount of sulfur in root beads and fillet weld metal for heavy plate welding should not exceed 0.04%; otherwise there will be a strong tendency to crack. The tendency for welds to crack as a result of sulfur inclusions, can be controlled by the selection of electrodes and preheat schedules.

The welds of stainless alloys, nickel or monel, on carbon steel are more sensitive to sulfide inclusions than they would be with mild steel electrodes. The high-nickel alloys are especially susceptible to cracking in the presence of small amounts of segregated MnS. Opinions vary as to the amount of sulfur that can be present and still produce crack-free deposits, but this is placed between 0.025 and 0.05% S.

Submerged-arc welding presents a greater problem from the difficulty with sulfides in the parent metal than multi-pass arc welding, because more parent metal is fused. Because of this manner of solidification in thick, single-bead, submerged-arc weld deposits, the sulfur dissolved from segregated areas of the parent metal can cause cracking along the coarse columnar grains, which may not be observed readily by X-ray inspection. Cracking at the weld stock junction may also be overlooked because of porosity. Killed steels are preferred to rimmed or semikilled steels because they are less segregated.

In summarizing the effect of inclusions on metal-arc welding, it may be stated that sulfides are always undesirable, that oxides are less undesirable and that silicates are least harmful.

In spot welding, 0.05% S has no deleterious effect on the welding of steel. The sulfur content of mild steel when spot welded to stainless steel should be lower than 0.05% to avoid cracking of the stainless steel. Resistance welding of free-machining SAE 1112 steel containing 0.16 to 0.23% S resulted in a brittle condition at the weld, by reason of a nearly continuous line of inclusions (derived from the manganese and iron sulfides in the parent metal) which appeared at the weld line.

Inclusions in steel have a detrimental effect on flash welding. This effect varies with the number, size and distribution of the inclusions. Two weaknesses inherent in flash welding contribute to the detrimental effect of the inclusions. Numerous inclusions may allow sufficient slag to remain on the flashing edges immediately before upsetting to form a discontinuity in the weld line. All stringer-type inclusions necessarily follow the upsetting pattern of

*Unpublished work at Battelle Memorial Institute

the metal and form an end-grain effect in the flow lines on either side of the weld areas. Stringer inclusions of oxides, sulfides and silicates extruded with the upset metal can reduce the ductility of the weld area and produce poor performance in bend and fatigue tests.

To minimize the effects of coarse inclusions, some importance is attached to the direction of rolling and the location of the edge to be flashed, with respect to its location in the ingot. Depending on the size and shape of the inclusions, a higher quality weld will result if the weld is made normal to the direction of rolling than if made parallel to it. Under some conditions, it is economical to locate the welding edge to some area of the metal that is fairly clean. Using the rimmed portion of a rimming steel is an example.

High-sulfur free-machining steels are not considered weldable by flash welding. Concentrations of the sulfide inclusions produce a very uneven burn-off, creating uneven spacing along the edges during the flashing period. This condition is conducive to cold welding and insufficient extrusion at final bump, resulting in weld weakness. It is believed, however, that steel containing as much as 0.08% S uniformly distributed can be successfully flash welded.

The effect of inclusions on atomic hydrogen weldability is not well understood. In the welding of SAE 4335 steel, it has been recognized that welding metal containing 0.008% S is freer from objectionable porosity than metal containing 0.012% S. Some authorities place the limit for sulfur at 0.015%. The amount of aluminum used for deoxidation of the steel is apparently important so as not to produce eutectic sulfides. In some instances, sulfides of the eutectic type appearing in the parent metal have been thought responsible for poor atomic hydrogen weldability, an inferiority made evident by a deep boiling and scumming action during the welding process, with resulting undercutting, porosity and cracks. On the other hand, a small residual aluminum content suppresses porosity in the presence of sulfur. It is apparent that hydrogen is very reactive with sulfide inclusion material and cleanliness is felt to be essential to high-quality welds.

In oxyacetylene welding, metal that contains less than 0.05% S causes no trouble. The probability of cracking increases as the sulfur content is increased. Sulfur segregations, such as cause difficulty in arc welding, would be expected to cause deleterious results in oxyacetylene welds.

Effect of Exogenous Inclusions. *Surface Appearance.* Owing to their larger size, exogenous inclusions are more likely to have a detrimental effect on certain properties of steel than the microscopic natural inclusions. However, nonmetallic inclusions are often blamed for apparent defects in steel, when their origin is actually traceable to other causes. Thus, pitting, which is encountered occasionally in the polishing of stainless steel surfaces, is not infrequently ascribed to nonmetallic inclusions, whereas a closer examination may reveal that improper polishing technique or lack of cleanliness is the real culprit. It cannot be denied, however, that large adventitious inclusions, particularly when agglomerated or drawn out into rows, may produce imperfections or blemishes on the surface of polished stainless steel that impair its usefulness, although such occurrences are generally rare.

Service Failures. Occasionally, stringers of adventitious inclusions may lead to ruptures and seams on the inside surface of tubes in piercing, but as a rule even the large accidental inclusions do not constitute a problem in fabrication processes.

The large adventitious inclusions may have a more serious effect on the performance of steel parts in service. Experience has shown that little trouble is to be expected from such inclusions in statically stressed ductile materials. However, their occurrence in highly cold worked steel or in higher-carbon or alloy steels, particularly when the latter are in the quenched and only slightly tempered condition (for instance, in spring steel), may lead to failures under impact or repeated stresses if the inclusions are located in critical regions and if their orientation is unfavorable in relation to the existing stresses. Any nonmetallic inclusion of macroscopic size, situated in a critical zone in or near the surface of a dynamically stressed part, may be compared to a notch with a triaxially stressed condition at the root, which causes a great strength reduction of the metal under repeated stress. Examination of the fracture surfaces of failed ball or roller bearings often discloses patches of green or brown slaglike material from which the cracks appear to have started. However, it should be well understood that even macroscopic inclusions may have no detrimental effect whatever if they are located away from the critically stressed zone. The presence of large adventitious inclusions in critical regions of dynamically stressed material undoubtedly constitutes a threat to the life of the part, but experience has also shown that fatigue failures, resulting from poor fillets, tool marks, keyways, stamped numbers, accidental scratches, and similar imposed stress-raisers, greatly outnumber failures resulting from nonmetallic inclusions. *See also* the article on page 243.

Weldability. Refractory and slag inclusions that appear at the welding surfaces of steel for arc welding, and are large enough to view visually with the unaided eye or with a 5 × hand lens, are objectionable because they contribute to sidewall defects during welding, with consequent lowering of strength and impairment of X-ray quality. Upon detection such defects should be chipped out and the surface weld should be repaired before attempting the welding of heavy sections. Laminations or near-laminations caused when refractory or slag material is rolled out, can be a source of trouble in arc welding, by forming gases with the filler material. In general, exogenous refractory inclusions consisting of alumina and silicates have given little difficulty in arc welding except when the inclusions are large.

Any slag inclusions or laminations at the welding edge for flash welding are very injurious, because they result in a notch effect along the outbent fiber and weaken the weld area. Inclusions that tend to laminate plates or forgings are objectionable for pressure welding processes because the heat and pressure open the cavity around the filling.

Exogenous inclusions in sheet or plate for spot welding, when these occur close to the surface to be welded, are harmful because of their effect on the electrical resistance of the steel, an effect that results in overheating and flashing with consequent weakness of spot welds.

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ALLOYING ELEMENTS IN STEEL

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Functions of the Alloying Elements in Steel

BY J. M. HODGE* AND E. C. BAIN*

ALLOYING elements are added to steel to enhance the properties. Some elements may be used in high percentage to obtain increased resistance to corrosion, as in the stainless or heat-resisting alloys. This function is discussed in detail in the articles on pages 549 to 580, concerning these types of alloy steels. Alloying elements may be added sparingly to impart greater strength and corrosion resistance to low-carbon as-rolled steels for use in welded structures, as described in the article concerning high-strength low-alloy steels, on page 534. Alloying elements may be used to impart resistance to abrasion, as in tool steels (page 658), or to enhance electrical or magnetic characteristics (pages 587 to 599). In a sense, these are specialized functions, utilized in specialized and somewhat limited applications of alloy steels, and since they are discussed in detail in other sections of this Handbook such functions will not be discussed further in this article. Many of these specific functions are discussed also in the various articles about individual alloying elements.

By far the largest tonnage of alloy steels is of the types containing generally 0.25 to 0.55% C, or less if for carburized parts—widely used in automotive and aircraft machinery and almost always quenched and tempered for high strength and toughness. This article will deal primarily with the functions of the alloying elements in this high-tonnage class of alloy steels.

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Prepared for the Subcommittee on Alloying Elements in Steel

Manganese, silicon, nickel, chromium, molybdenum, vanadium, aluminum and boron are commonly incorporated in these steels to enhance the properties obtainable after quench-hardening and tempering. Alloy steels of these types were utilized in large tonnages before the mechanisms were understood by which the alloying elements accomplished the improvements.

These alloy steels are ordinarily quench-hardened and tempered to the level of strength desired for the application. Even though the strength level at which the steel is used may be as low or lower than that which could be achieved by the microstructure (fine pearlite or upper bainite) developed by a simple cooling from forging or normalizing temperature, quench-hardening and tempering are performed, indirectly reflecting the engineering and economic basis of the demand for this type of steel. The microstructure (tempered martensite or bainite) produced by quenching and tempering these properly designed alloy steels is characterized by a greater toughness or capacity to deform without rupture at any strength level. Similarly, under the adverse state of stress below a notch in bending, the tempered martensite may flow considerably at a testing temperature far below that at which a pearlitic steel of equal strength would break in a brittle manner; the Charpy or Izod values are thus improved. The basic phenomenon of developing this favorable microstructure by heat treatment is manifest in plain carbon steels, but only in small sections; thus the most important effect of the alloying

elements in these steels is to permit the attainment of this microstructure, and the accompanying superior toughness, in larger sections.

Alloying Elements Dissolved in Austenite. The general effect of elements dissolved in austenite is to decrease the rates of transformation of the austenite at subcritical temperatures. This mechanism is described in the article concerning isothermal transformation, on page 607. The only one among the common alloying elements to behave exceptionally in this regard is cobalt. Since the desirable products of transformation in these steels are martensite and lower bainite, formed at low temperatures, this decreased transformation rate is essential; it means that pieces can be cooled more slowly, or larger pieces can be quenched in a given medium, without transformation of austenite to the undesirable high-temperature products, pearlite or upper bainite. This function of decreasing the rates of transformation, and thereby facilitating hardening to martensite or lower bainite, is known as *hardenability* and is the most important effect of the alloying elements in these steels. Thus, by increasing hardenability, the alloying elements greatly extend the scope of enhanced properties in hardened and tempered steel to the larger sections involved in most applications.

The several elements commonly dissolved in austenite prior to quenching, increase hardenability in approximately the following ascending order: nickel, silicon, manganese, chromium, molybdenum, vanadium and boron. The effect of aluminum on hardenability has not been accurately evaluated, but at 1% Al, as used in "nitralloy" steels, the

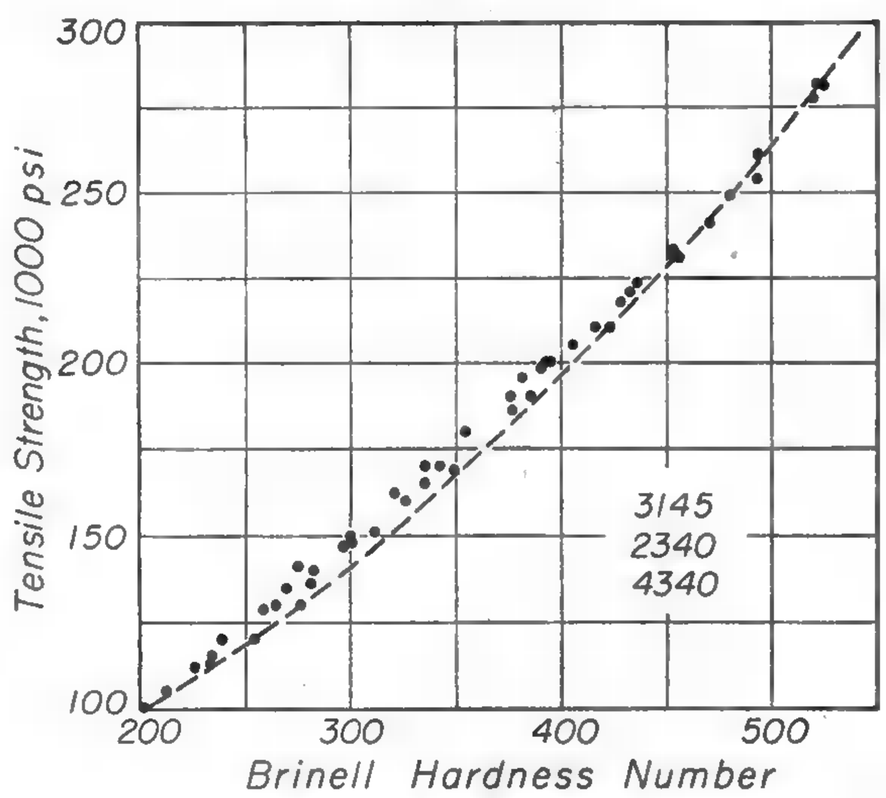

Fig. 1 Relationship between hardness and tensile strength for three quenched and tempered alloy steels

effect on hardenability seems to be relatively small. Multiplying factors that express the hardenability effects of these elements will be found in the article concerning the calculation of hardenability, page 494. Further, it has been found that the addition of several alloying elements in small amounts is more effective in increasing hardenability than the addition of much larger amounts of one or two.

In order to increase hardenability effectively, it is essential that the alloying elements be in solution in the austenite, and the steels containing the carbide-forming elements—chromium, molybdenum and vanadium—require special consideration in this respect. These elements are present predominantly in the carbide phase of annealed steels, and such carbides dissolve only at higher temperatures and more slowly than iron carbide. Hence, for effectiveness, heating schedules should be set up in such a way as to dissolve an adequate proportion of these elements. It is uneconomical to heat at such low temperatures that the carbide-forming elements are largely undissolved.

Since the basic function of the alloying elements in these steels is to increase hardenability, the selection of a steel and the choice of suitable austenitizing conditions should be based primarily on the assurance of adequate hardenability. More than adequate hardenability is rarely a disadvantage, except in economy.

Alloying Elements in Quenching. Since the sections treated are often relatively large, and since the alloying elements have the general effect of lowering the temperature range at which martensite is formed, the thermal and transformational stresses set up during quenching tend to be greater in these alloy steel parts than those involved in quenching the necessarily smaller sections of plain carbon steels. In general, this means greater distortion and risk of cracking.

The alloying elements, however, have two functions that tend to offset these disadvantages. The first and probably the most important of these functions is that of permitting the use of a lower carbon content for a given application. The decrease in hardenability accompanying the decrease in carbon content may be offset very readily by the hardenability effect of the added alloying elements, and the lower-carbon steel will exhibit a much lower susceptibility to quench cracking. This lower susceptibility results from the greater plasticity of the low-carbon martensite and from the generally higher temperature range at which martensite is formed in the lower carbon materials. It has been found that quench cracking is seldom encountered in materials containing 0.25% C or less, and that the susceptibility to cracking increases progressively with increasing carbon content.

The second function of the alloying elements in quenching is to permit slower rates of cooling for a given section, because of increased hardenability, and thereby generally to decrease the thermal gradient and, in turn, the cooling stress. It should be noted, however, that this is not altogether advantageous, since the direction as well as the magnitude of the stress existing after the quench, is important in relation to cracking. In order to prevent cracking, the surface stresses after quenching should be either compressive or at a relatively low tensile level and, under certain circumstances, lowering the cooling rate may lead to increased tensile stresses at the surface, thus increasing

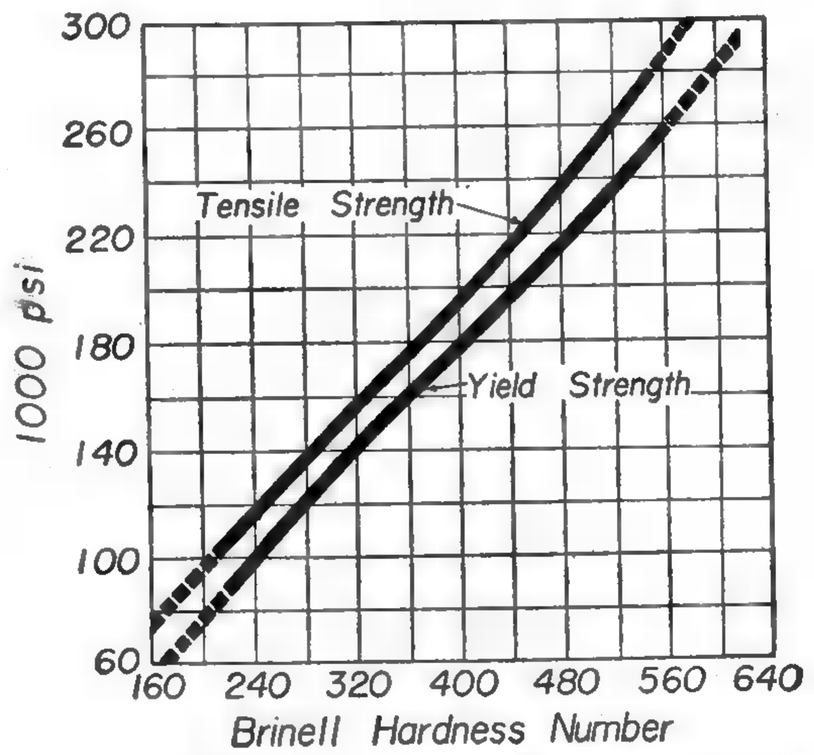

Fig. 2 Statistical mean of the relationships among Brinell hardness, tensile strength and yield strength in quenched and tempered alloy steels

the tendency to crack. In general, though, unless a study of the particular piece being quenched indicates that it falls within this category of increased susceptibility with decreased quenching rates, the use of a less drastic quench suited to the hardenability of the material, will result in lower distortion and greater freedom from cracking.

Furthermore, the increased hardenability of these alloy steels may permit heat treatment by "austempering" or "martempering", and thereby the level of adverse residual stress before tempering may be held to a minimum. In "austempering", the work piece is cooled rapidly to a temperature in the lower bainite region and is allowed thereafter to transform completely at some chosen temperature. Since this transformation occurs at a relatively high temperature and proceeds rather slowly, the stress level after

transformation is quite low and distortion is held to a minimum. In "martempering", the piece (1) is cooled rapidly at the surface to a temperature that permits very little martensite to form, if any, (2) is equalized at this temperature, and (3) is then cooled slowly so that transformation throughout the whole section occurs more or less simultaneously, thereby holding transformational stresses at a very low level and minimizing distortion and danger of cracking.

Alloying Elements in Tempering. Hardened steels are softened by reheating, but this effect is not the one actually sought in tempering. The real need is for increasing the capacity of the piece to flow moderately without fracture, and this is inevitably accompanied by a loss of strength. Since the tensile strength is very closely related to hardness in this class of steels as heat treated, it is satisfactory to follow the effects of tempering by measuring the Brinell or Rockwell hardness. The results of a careful study of this relationship for three steels is shown in Fig 1.

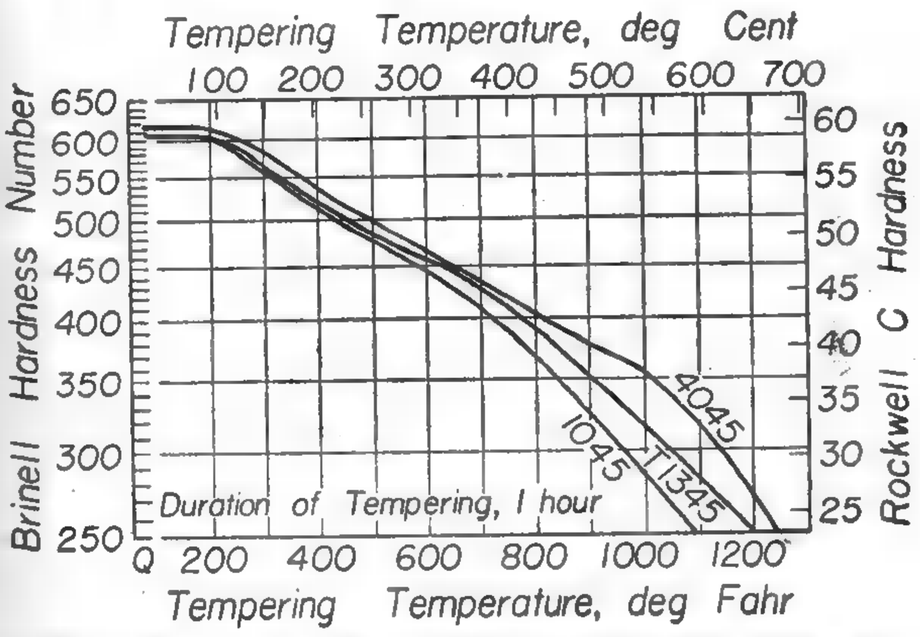

Fig. 3 The softening of 1045, T1345 and 4045 steels at various temperatures (one-hour tempering)

The dotted line in this plot represents the commonly used relationship of Scott and Gray. Probably the stress at the limit of the elastic range correlates well also with hardness, but since the elastic limit is a property difficult to measure and confused by initial stress in the specimen, the data are less well related. The statistical mean of these relationships among Brinell hardness, tensile strength and yield strength, is shown in Fig. 2, drawn from many data.

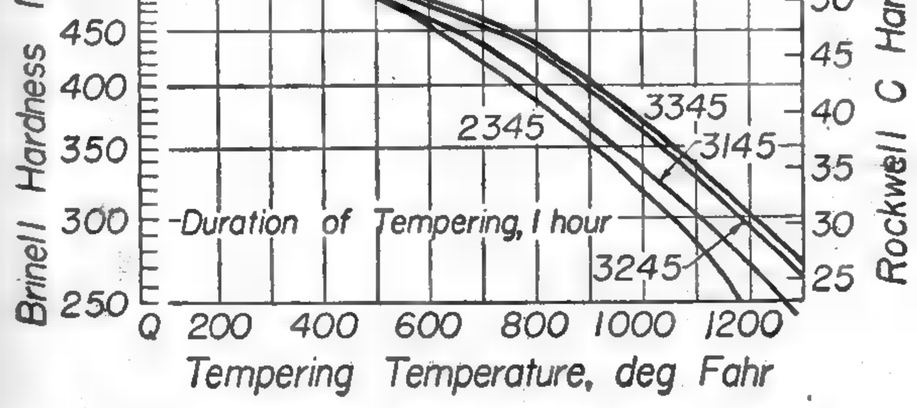

Fig. 4 The softening of 2345, 3145, 3245 and 3345 steels at various temperatures (one-hour tempering)

Figures 3, 4, 5 and 6 show the softening pattern of many familiar 0.45% C steels with increase in the tempering temperature for one hour. Somewhat shorter or longer intervals at temperature would show little difference in hardness values. As a first approximation, the softening pattern of steels similar but differing in carbon content through the range from 0.25 to 0.55% C may be estimated from Fig. 7. This illustrates the general effect of carbon content on this softening pattern in terms of Rockwell C hardness units to be added to or subtracted from the 0.45% C value at different levels of tempering temperature, but accurate data that would permit a strictly quantitative relationship of this type are not available. It will be noted that the effect of carbon content on the hardness of the tempered steels is much greater at the lower tempering

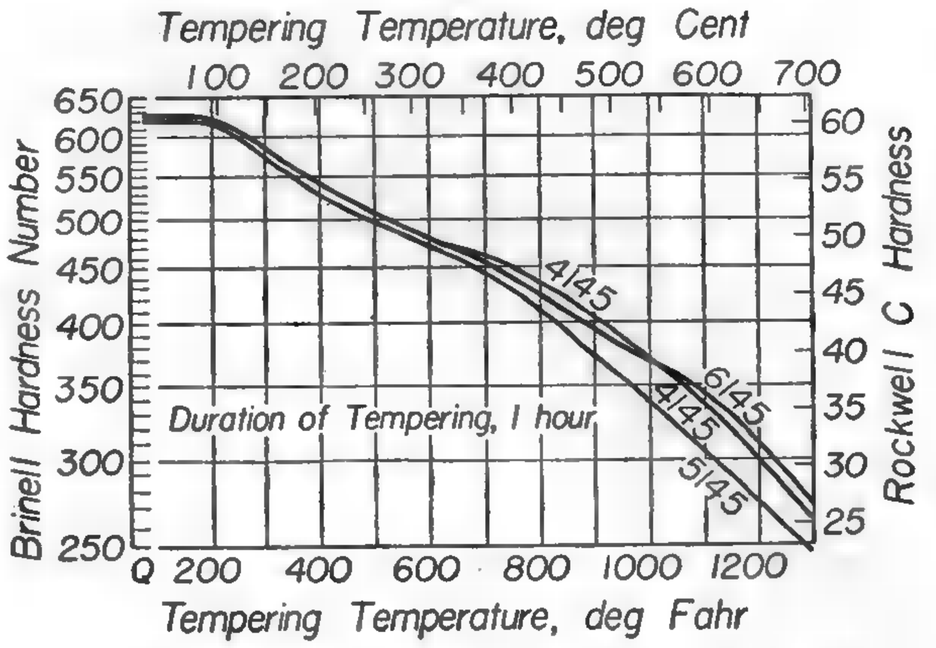

Fig. 5 The softening of 4145, 5145 and 6145 steels at various temperatures (one-hour tempering)

temperatures than at temperatures at 1200 F and higher, and that the effect likewise decreases when there is more than 0.50% C. These charts, used together, make it possible to estimate the strength from a given tempering treatment applied to a given type of steel.

It will be seen that the general effect of the alloying elements is to retard the softening rate, so these alloy steels will require a higher tempering temperature to obtain a given hardness. However, the individual elements show significant differences in the magnitude of their retarding effect. Nickel, silicon, aluminum and, to a large extent,

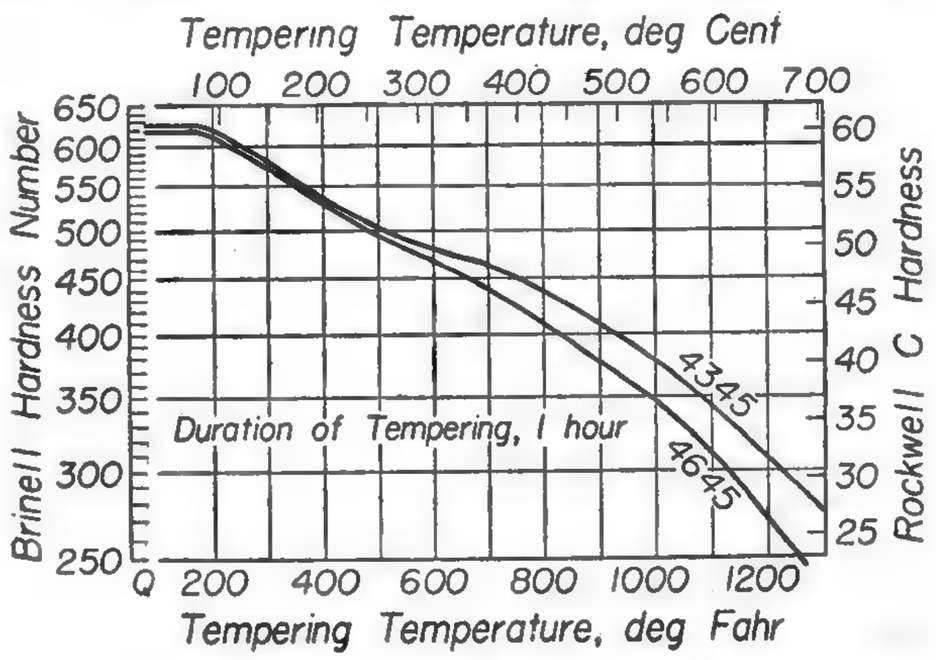

Fig. 6 The softening of 4345 and 4645 steels at various temperatures (one-hour tempering)

manganese, which have little or no tendency to occur in the carbide phase, and merely remain dissolved in ferrite, have only a minor effect on the hardness of the tempered steel—an effect that would be expected from the general pattern of solid solution hardening. Chromium, molybdenum and vanadium, on the other hand, which migrate to the carbide phase when diffusion is possible, bring about a retardation of softening, particularly at the higher tempering temperatures. These elements not only raise the tempering temperature but, when they are present in higher percentages, the rate of softening is no longer a continuous function of the tempering temperature; that is, the softening curves for these steels will show a range of tempering temperature in which the softening is retarded or, with relatively high alloy content, in which the hardness may actually increase with increase in tempering temperature. This characteristic behavior of the alloy steels containing the carbide-forming elements is known as

secondary hardening and results presumably from a delayed precipitation of fine alloy carbides.

As mentioned previously, the primary purpose of tempering is to impart a degree of plasticity or toughness to the steel in contrast with the brittleness of the martensite, and the loss in strength is only incidental to this very important increase in toughness. The increase in toughness after tempering reflects two effects of tempering: (1) the relief of residual stress set up by the quenching operation, and (2) a precipitation, coalescence and spheroidization of iron and alloy carbide, resulting in a microstructure of greater plasticity. In addition to their effects on the microstructure, as discussed above in connection with the softening behavior, the alloying elements have a secondary function. The higher tempering temperatures for a given hardness, which has been seen to be a characteristic of these alloy steels, particularly of the ones containing the carbide-forming elements, will presumably permit greater relaxation of the stress and thereby improve the resulting properties. Furthermore, as discussed in the section on quenching, the hardenability of these steels may permit the use of less drastic quenching practices, so that the stress level before tempering will be lower, thereby permitting the use of these steels at a higher level of hardness, since the higher temperatures are not then required for relief of quenching stresses. It should be noted, however, that this latter is only a secondary function of the alloying elements in tempering; the effect is primarily a reflection of the hardenability function of the alloying elements.

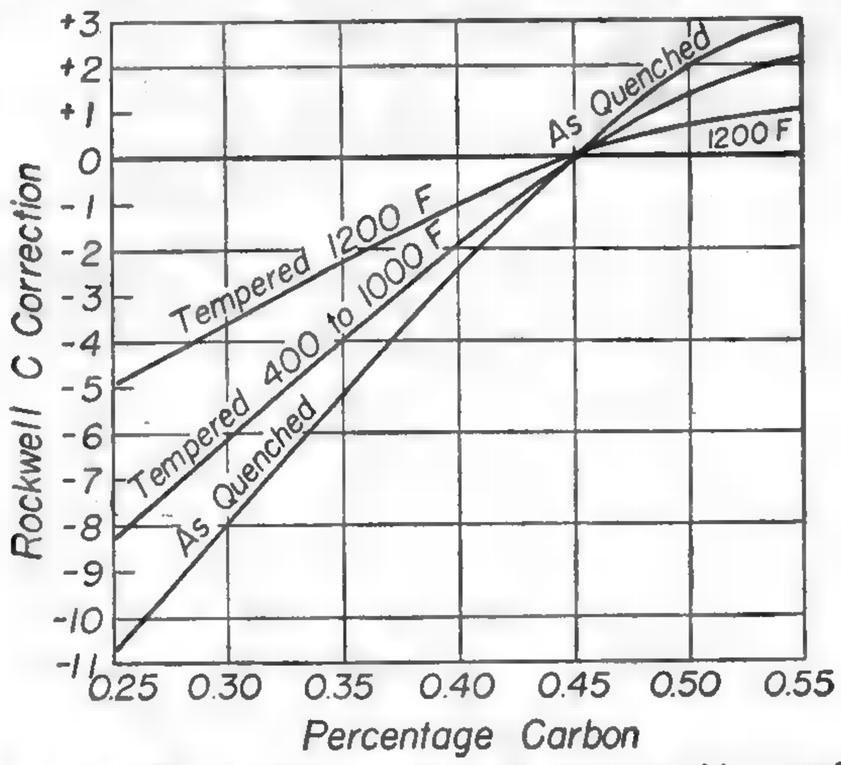

Fig. 7 The effect of carbon content on the hardness of tempered steel

Still another secondary function of the alloying elements in tempering is to permit the use of steels with lower carbon content for a given level of hardness, since adequate tempering may be assured by taking advantage of the retardation of softening brought about by the alloying elements. This results in greater freedom from cracking and generally improved plasticity at the given hardness. Here again, however, the function of the alloying elements in tempering is a secondary function; their primary function is to increase the hardenability sufficiently to offset the effect of the decreased carbon content.

The increase in plasticity on tempering is discontinuous in these alloy steels and their behavior under the stress condition of a notch shows a characteristic irregularity at approximately 500 to 600 F. The quenched martensitic steel gains toughness, as reflected in the notched-bar impact test, by tempering at temperatures as high as 400 F, but after tempering at higher temperatures this type of steel loses toughness until it may be less tough than the untempered martensite. Still higher temperatures for tempering restore greater toughness. The mechanism of this behavior is not fully understood, but it seems to be associated with the first precipitation of carbide particles, and is presumably a grain boundary phenomenon since fractures of steels tempered in this region tend to be intercrystalline. Thus, there is a range of tempering temperatures (about 400 to 700 F) never used for these steels; the tempering temperature is either 400 F (max) or more than 700 F. Although this phenomenon is common to all these alloy steels, the alloying elements have a secondary function in this connection; a combination of carbon and alloy contents of suitable hardenability may be chosen, which would permit tempering to the desired strength at temperatures outside this undesirable range.

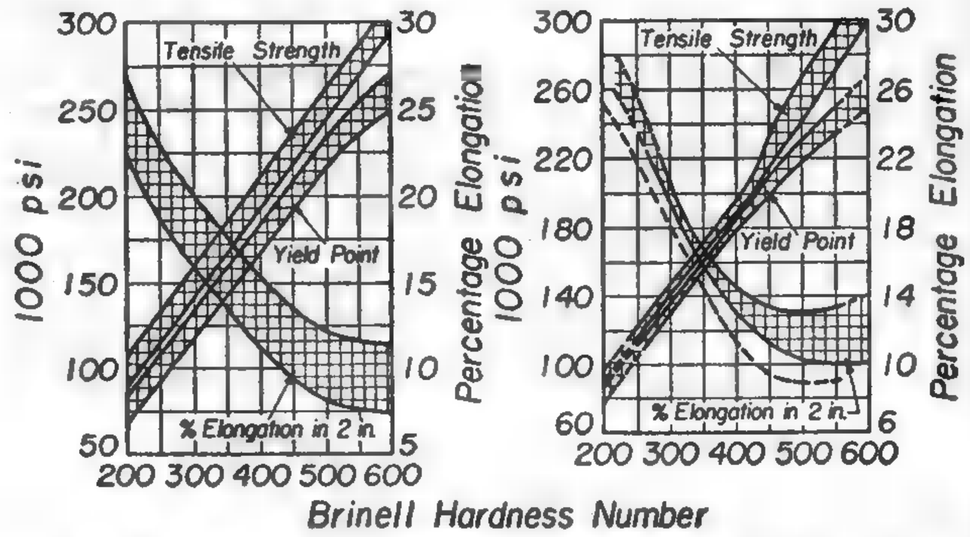

Fig. 8 The range of tensile properties in several quenched and tempered steels as a function of hardness. *Left*, data of Janitzky and Baeyertz. *Right*, more recent Cr-Ni-Mo steels

Temper brittleness is another example of a discontinuous increase in plasticity after tempering steels of these types. This phenomenon is manifested as a loss of toughness observed after slow cooling from tempering temperatures of 1100 F or higher, or after tempering in the temperature range between approximately 850 and 1100 F. Thus, a steel that is susceptible to this type of embrittlement may lose much of its plasticity, as indicated by a notched-bar impact test, during slow cooling from a tempering temperature of 1150 F, although the same steel will be very tough if it is quenched from the same tempering temperature. This expedient of quenching from the tempering temperature is a common practice to insure freedom from loss of toughness. However, in steels that are susceptible to temper brittleness, embrittlement will also be observed after tempering at 850 to 1100 F, particularly if the tempering times are protracted, and under such circumstances quenching from the tempering temperature will never restore the toughness completely. This phenomenon is also not fully understood, although the behavior suggests that something which dissolves at temperatures of 1100 F and above, precipitates in a damaging form at

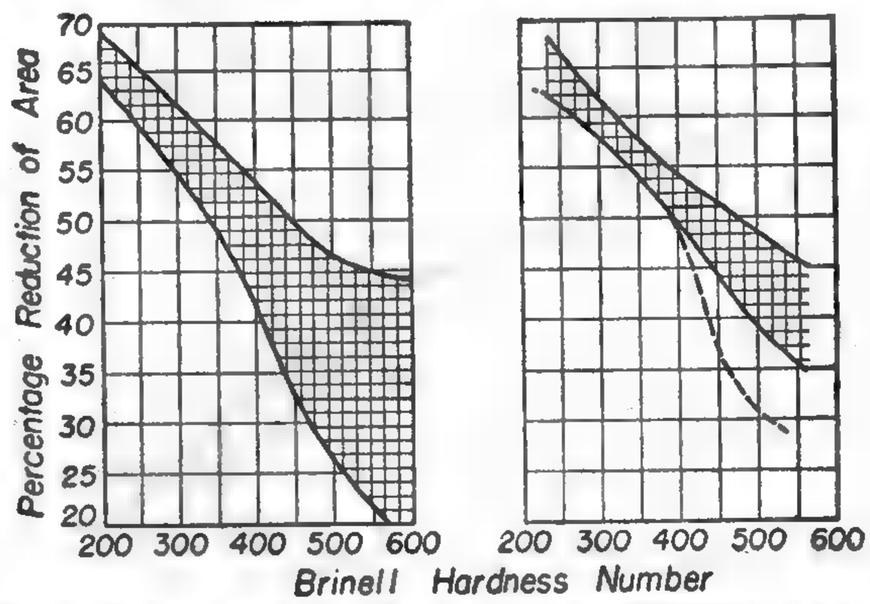

Fig. 9 The range of reduction of area in several quenched and tempered steels as a function of hardness. *Left*, data of Janitzky and Baeyertz. *Right*, more recent Cr-Ni-Mo steels

the lower temperatures, either during slow cooling or during reheating to these temperatures. High manganese, phosphorus and chromium appear to accentuate this behavior; and molybdenum has a definite retarding effect. Here again the carbon and alloying elements may be chosen so that the susceptibility to temper embrittlement is minimized, or the desired strength level may be obtained by tempering either below 850 F or above 1100 F, and then quenching.

Marked Similarities Among the Steels. This article has

emphasized hardenability as the primary function of the alloying elements in alloy steels and it has been found that, if the hardenability and heat treatment are such as to obtain a tempered martensitic microstructure, the mechanical properties of steels are markedly similar regardless of the alloy combination used to obtain the requisite hardenabilities. This similarity among the properties of heat treated steels was noted early by Janitzky and Baeyertz and has since been verified by many investigators. Figures 8 and 9 show these property bands as determined by Janitzky and Baeyertz and also as more recently determined on a wide range of Mn-Ni-Cr-Mo steels. For comparison, the more recent plots include the values for a simple carbon-manganese steel (treated to tempered martensite) which is plotted as a dotted line.

This should not be interpreted as implying that these tempered martensitic steels are alike in every respect, regardless of composition, because the composition is responsible for differences in preservation of strength at elevated temperatures, for differences in abrasion resistance, in resistance to corrosion and even, to a certain extent, in toughness. However, the similarities are sufficiently marked to permit reasonably accurate predictions of the mechanical properties of tempered martensitic steels, regardless of composition, and thereby to justify the emphasis on hardenability as the most important function of the alloying elements.

The most recent and comprehensive study of this nature has been made by Patton. The average values of the mechanical properties of tempered martensite as found in this study are shown in Fig. 10. Although this study represented a compilation of data concerning a very wide variety of alloy steels from a wide range of sources, with inevitable differences in treating and testing, the results still fell within quite narrow bands. Therefore these curves can be used to predict the properties of any of the common alloy

Table I. Specific Effects of Alloying Elements in Steel

Element	Solid Solubility: In Gamma Iron	Solid Solubility: In Alpha Iron	Influence on Ferrite	Influence Exerted Through Carbide: Influence on Austenite (Hardenability)	Influence Exerted Through Carbide: Carbide-Forming Tendency	Influence Exerted Through Carbide: Action During Tempering	Principal Functions
Aluminum .. Al	1.1% (Increased by C)	36%	Hardens considerably by solid solution	Increases hardenability mildly, if dissolved in austenite	Negative (graphitizes)	.....	1 Deoxides efficiently 2 Restricts grain growth (by forming dispersed oxides or nitrides) 3 Alloying element in nitriding steel
Chromium .. Cr	12.8% (20% with 0.5% C)	Unlimited	Hardens slightly; increases corrosion resistance	Increases hardenability moderately	Greater than Mn; less than W	Mildly resists softening	1 Increases resistance to corrosion and oxidation 2 Increases hardenability 3 Adds some strength at high temperatures 4 Resists abrasion and wear (with high carbon)
Cobalt ..... Co	Unlimited	75%	Hardens considerably by solid solution	Decreases hardenability as dissolved	Similar to Fe	Sustains hardness by solid solution	1 Contributes to red hardness by hardening ferrite
Manganese . Mn	Unlimited	3%	Hardens markedly; reduces plasticity somewhat	Increases hardenability moderately	Greater than Fe; less than Cr	Very little, in usual percentages	1 Counteracts brittleness from the sulfur 2 Increases hardenability inexpensively
Molybdenum Mo	3%+ (8% with 0.3% C)	37.5% (Less with lowered temperature)	Provides age-hardening system in high Mo-Fe alloys	Increases hardenability strongly (Mo > Cr)	Strong; greater than Cr	Opposes softening, by secondary hardening	1 Raises grain-coarsening temperature of austenite 2 Deepens hardening 3 Counteracts tendency toward temper brittleness 4 Raises hot and creep strength, red hardness 5 Enhances corrosion resistance in stainless steel 6 Forms abrasion-resisting particles
Nickel ..... Ni	Unlimited	10% (Irrespective of carbon content)	Strengthens and toughens by solid solution	Increases hardenability mildly, but tends to retain austenite with higher carbon	Negative (graphitizes)	Very little in small percentages	1 Strengthens unquenched or annealed steels 2 Toughens pearlitic-ferritic steels (especially at low temperature) 3 Renders high-chromium iron alloys austenitic
Phosphorus. P	0.5%	2.8% (Irrespective of carbon content)	Hardens strongly by solid solution	Increases hardenability	Nil	.....	1 Strengthens low-carbon steel 2 Increases resistance to corrosion 3 Improves machinability in free-cutting steels
Silicon ..... Si	2%+ (9% with 0.35% C)	18.5% (Not much changed by carbon)	Hardens with loss in plasticity (Mn < Si < P)	Increases hardenability moderately	Negative (graphitizes)	Sustains hardness by solid solution	1 Used as general-purpose deoxidizer 2 Alloying element for electrical and magnetic sheet 3 Improves oxidation resistance 4 Increases hardenability of steels carrying nongraphitizing elements 5 Strengthens low-alloy steels
Titanium ... Ti	0.75% (1%+ with 0.20% C)	6%+ (Less with lowered temperature)	Provides age-hardening system in high Ti-Fe alloys	Probably increases hardenability very strongly as dissolved. The carbide effects reduce hardenability	Greatest known (2% Ti renders 0.50% carbon steel unhardenable)	Persistent carbides probably unaffected. Some secondary hardening	1 Fixes carbon in inert particles (a) Reduces martensitic hardness and hardenability in medium-chromium steels (b) Prevents formation of austenite in high-chromium steels (c) Prevents localized depletion of chromium in stainless steel during long heating
Tungsten ... W	6% (11% with 0.25% C)	33% (Less with lowered temperature)	Provides age-hardening system in high W-Fe alloys	Increases hardenability strongly in small amounts	Strong	Opposes softening by secondary hardening	1 Forms hard, abrasion-resistant particles in tool steels 2 Promotes hardness and strength at elevated temperature
Vanadium... V	1% (4% with 0.20% C)	Unlimited	Hardens moderately by solid solution	Increases hardenability very strongly, as dissolved	Very strong (V < Ti or Cb)	Maximum for secondary hardening	1 Elevates coarsening temperature of austenite (promotes fine grain) 2 Increases hardenability (when dissolved) 3 Resists tempering and causes marked secondary hardening

steels within plus or minus 10%, if the hardenability and heat treatment are such as to obtain a microstructure consisting essentially of tempered martensite.

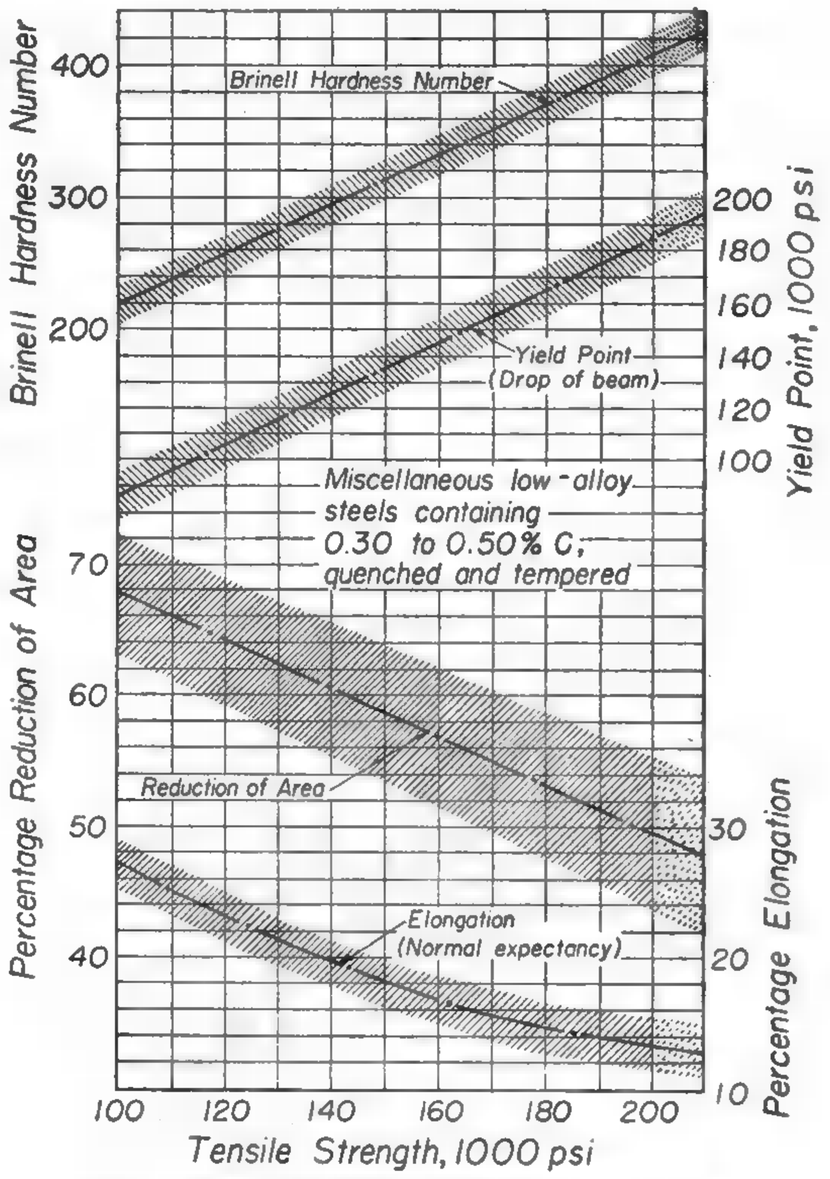

Fig. 10 Most probable mechanical properties of tempered martensite (Patton)

Selection of Steels. Throughout this article emphasis has been placed on the fact that hardenability is the primary consideration in the selection of a steel to obtain certain desired properties or for a specific application. However, in every instance there will be a wide choice among the carbon and alloy combinations that may be used to obtain this hardenability; consequently the final selection will be based on the secondary functions of the alloying elements, or perhaps on economy. The following outline lists the steps to follow in selecting a suitable steel.

1 The question of the need for a heat treated steel should be answered first. If the allowable elastic deflection is exceedingly small, possibly a soft steel in approximately designed section is indicated, since the maximum stress would necessarily be very low.

2 The carbon content selected should be one that will give the desired strength level after tempering at a temperature that will avoid the range from 500 to 600 F and will minimize possible temper embrittlement. If toughness is of paramount importance, or if the section is one that favors quench cracking, the carbon content should be as low as is consistent with the desired strength level. If the application involves wear resistance, as in sliding parts, or the repeated application of heavy loads, as in springs, higher carbon contents are indicated.

3 The total effective alloy content must, first of all, insure the needed hardenability compatible with the section and the quenching practice to be used.

4 When adequate hardenability is assured, most of these steels have ample toughness for parts of good design. Under these conditions, the choice of alloying elements can be based primarily on economy. For the occasional applications in which extraordinary toughness is considered essential, such as ordnance material or critical aircraft parts, full use should be made of the secondary functions of the alloying elements. If these parts are to be of high hardness, the addition of nickel will be useful; while at the lower levels of hardness the higher tempering temperatures, made possible by the addition of the carbide-forming elements, are distinctly advantageous. For applications involving toughness at low temperatures the use of nickel is indicated, together with low carbon contents and an adequate amount of alloying elements to insure tempered martensite. These characteristics can be evaluated approximately and compared by notched-bar tests.

Table I summarizes the specific effects of the alloying elements and may also be helpful in arriving at a choice of an appropriate composition for particular applications.

5 The heating for hardening should be such as to insure effective solution of the alloying elements without permitting excessive grain growth, and the quenching practice should be such as to insure full hardening in the composition chosen, with due regard to the danger of quench cracking and distortion. The tempering temperature can be derived approximately from the charts of Fig. 3, 4, 5, 6 and 7, and should be chosen so as to avoid the range from 500 to 600 F and also the danger of temper embrittlement.

Chromium in Steel

By Walter Crafts*

CHROMIUM is alloyed with iron to form useful steels containing from less than 1% to more than 30% Cr. In low-carbon ranges the steels are ductile, but with higher carbon contents, the steels may be made very hard. Consequently chromium is one of the most versatile and widely used of the alloying elements in both plain chromium and complex steels. Chromium confers outstanding resistance to corrosion, oxidation and wear, and is the essential component of stainless iron and steel. More extended reviews of the characteristics of chromium steels are given in monographs on iron-chromium alloys.[1,2]

Effect of Chromium in Ferrite and Low-Carbon Iron Alloys. In high-purity iron alloys, a chromium content less than 12% permits the formation of austenite and forms the compound FeCr (sigma phase) between 30 and 65% Cr, but through the rest of the iron-chromium system there is a continuous body-centered cubic structure with a gradually changing parameter. As shown by Adcock[3] in Fig. 1, the hardness of the alloy attains a maximum at about 70% Cr. However, iron containing about 3% Cr or less is somewhat softer than unalloyed iron.[4,5] This initial tendency to soften is also evident in some low-chromium, low-carbon steels of the structural type, in which chromium exerts a toughening rather than a hardening influence, at both atmospheric and subzero temperatures.[6, 7, 8]

Chromium increases the hardness or tensile strength of low-carbon or relatively pure iron alloys to a lesser degree than other alloying elements.[9] This fact is reflected in the properties of 0.10% C steels shown by Thum in Fig. 2.[10] The relative softness and resulting malleability of steels that contain as much as 30% Cr has contributed greatly to the successful fabrication and use of stainless irons and steels. The recrystallization or softening temperature of cold worked ferrite is raised to a significant degree by chromium.[11]

The ferritic low-carbon steels containing more than 15% Cr do not form austenite on heating, and tend to be relatively coarse-grained unless submitted to cold working. Grain growth is restrained and the toughness is improved by the addition of nitrogen. Such steels are serviceable without excessive embrittlement at relatively high temperatures. After heating in the range between 750 and 1100 F, low-carbon steels that contain 18 to 30% Cr develop

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Prepared for the Subcommittee on Alloying Elements in Steel

abnormal embrittlement. Steels with more than 30% Cr have useful ductility in the proper condition of heat treatment, but the utility of such alloys may be limited by the formation of sigma phase after heating under certain conditions.

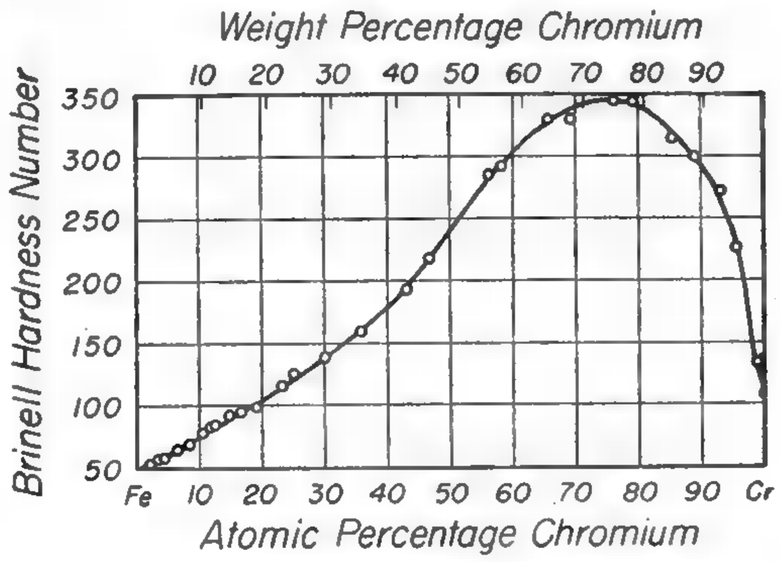

Fig. 1 Brinell hardness of iron-chromium alloys (F. Adcock[3])

Effect of Chromium on Medium-Carbon or High-Carbon Steels in the Pearlitic Condition. Chromium increases the time required for isothermal transformation of austenite, both in the pearlitic range higher than 1000 F, and in the bainitic range at lower temperature. The transformation of austenite to pearlite is retarded to a greater extent in lower-carbon steels. In the medium-carbon and low-carbon steels, the increase of chromium to more than 2 or 3% suppresses the formation of pearlite to such an extent that bainite is formed during continuous cooling at rates slow enough to avoid martensite formation. In normalized medium-carbon steels containing as much as 2 or 3% Cr, the transformation is depressed and the pearlitic structure becomes finer, with corresponding increase in tensile strength, as the content of chromium is increased. In steels that contain higher percentages of chromium, the pearlite produced by isothermal transformation is a confused sublamellar structure which, according to the results of Lyman and Troiano,[12] is formed by initial transformation to cementite and subsequent conversion to more stable Cr_7C_3.

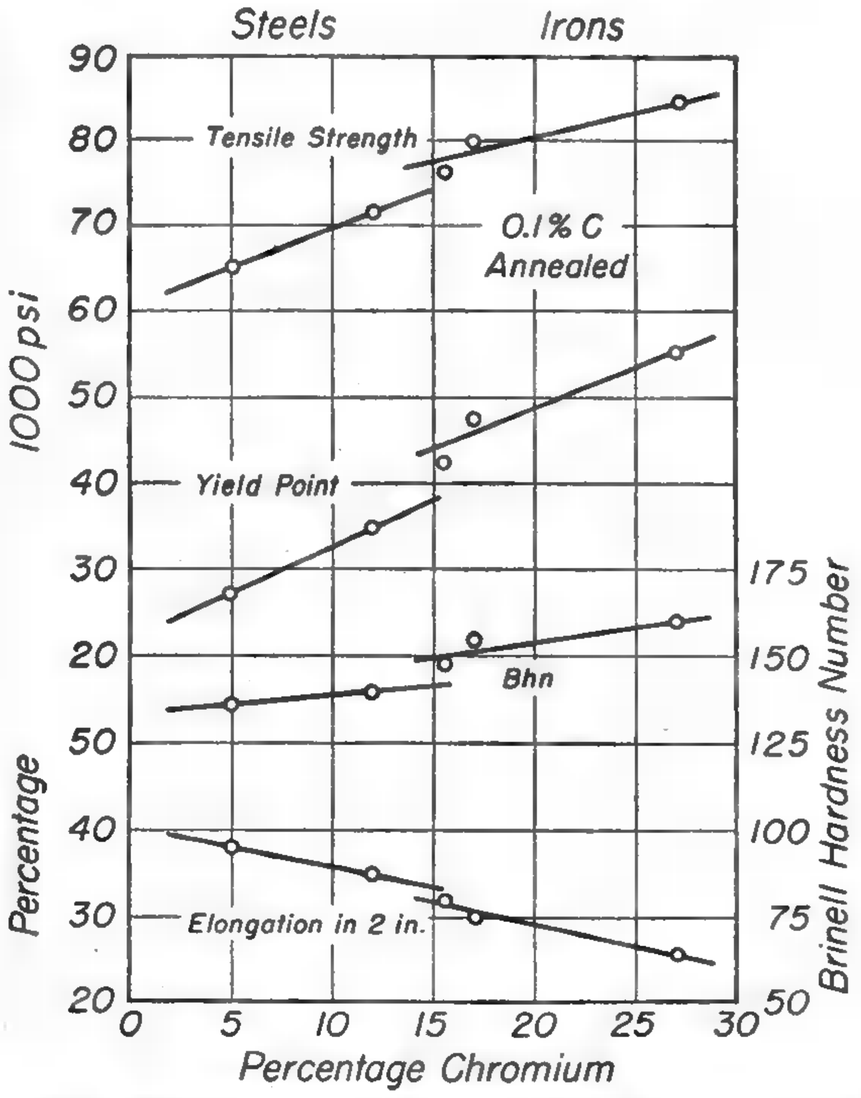

Fig. 2 Mechanical properties of annealed chromium steels containing 0.10% C (Thum[10])

Effect of Chromium on Behavior During Heating for Hardening or for Normalizing. Chromium restricts the range of carbon content and temperature within which austenite may be formed free from ferrite in low-carbon steel, or free from carbide in high-carbon steel. As indicated in Fig. 3,[13] the single-phase austenitic field extends over a range from just more than 12% Cr when the carbon content is zero, to 20% Cr with 0.57% C. The "eutectoid" composition is reduced from about 0.8% C to hardly 0.3% C at 15% Cr. In the range of carbon content of structural

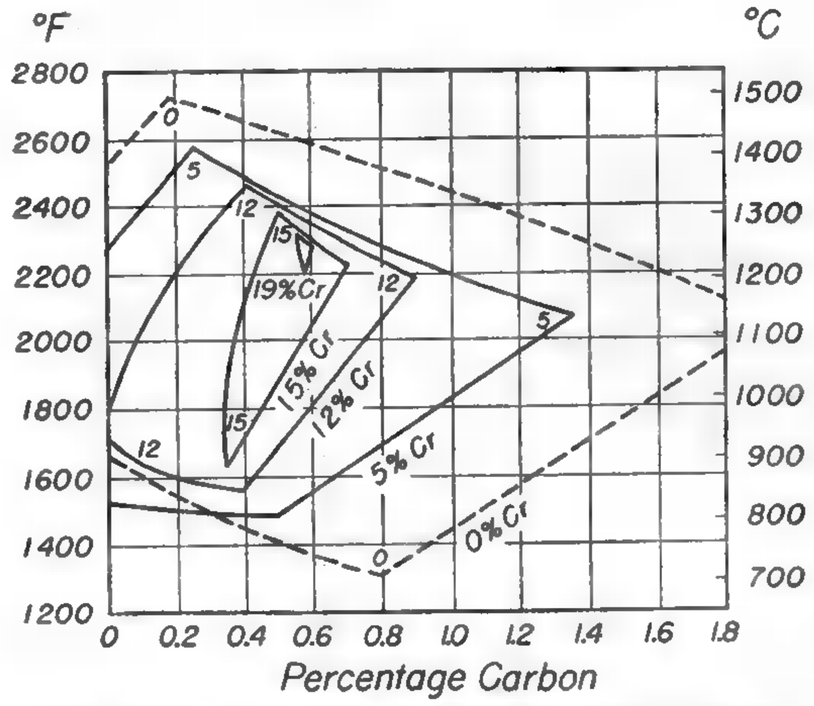

Fig. 3 Range of austenite in chromium steels (Tofaute, Kuttner and Buttinghaus; see Bain.[13])

and heat treating steels that contain less than 12% Cr, it is apparent that the steels may be completely austenitized at the temperatures commonly employed in heat treatment. In steels that contain more than 12% Cr and a low or medium percentage of carbon, some ferrite may be present at all temperatures. The high-carbon, high-chromium steels require high heating temperatures to dissolve all the carbides; these steels can be made completely austenitic at high temperatures only in a limited range of composition. (*See* PHASE DIAGRAM SECTION.)

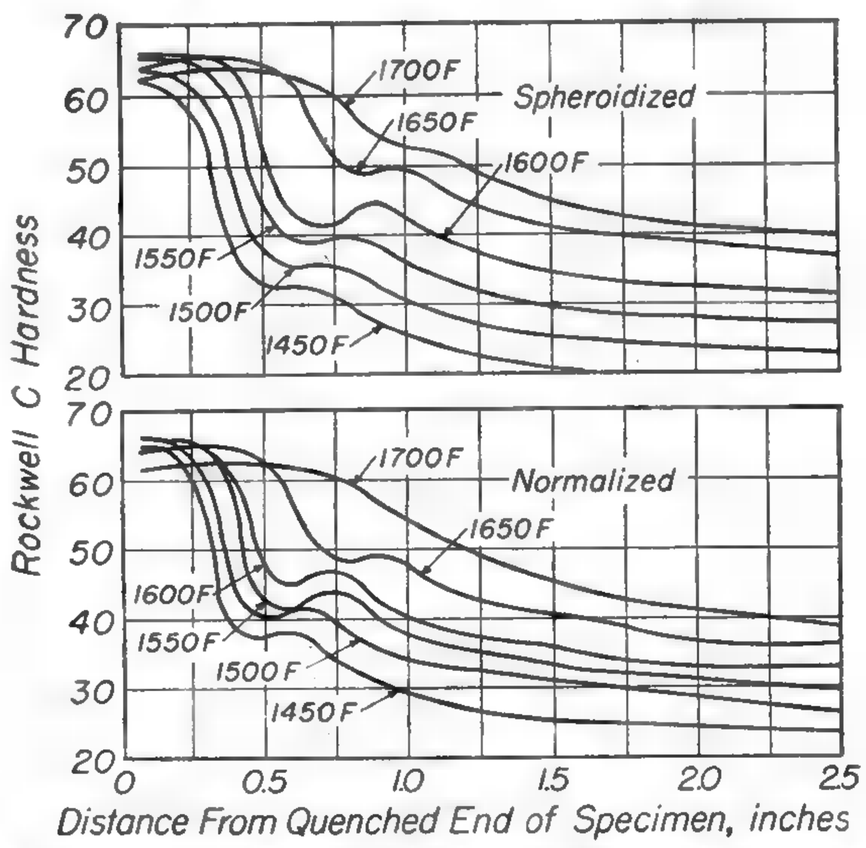

Fig. 4 Effect of quenching temperature and initial condition on hardenability of SAE 52100 steel (Rowland, Welchner and Marshall[14])

In certain steels the presence of carbide or ferrite in the austenite before cooling, is beneficial to the control of grain size, retained austenite, hardenability and related properties, such as toughness and weldability. In SAE 52100 bearing steel (1.0% C, 1.5% Cr), which is usually quenched with carbides in the austenite, it was demonstrated by Rowland, Welchner, and Marshall,[14] as shown

in Fig. 4, that at the usual quenching temperature of 1550 F, only a fraction of the hardenability was realized, but that maximum hardness, fine grain and relatively little retained austenite were produced. Likewise, the carburized case of chromium carburizing steel contains carbides but little retained austenite. One of the specific effects of chromium is to promote "normality" and thereby avoid soft spots in carburized steel, by preventing divorce of ferrite and carbide.

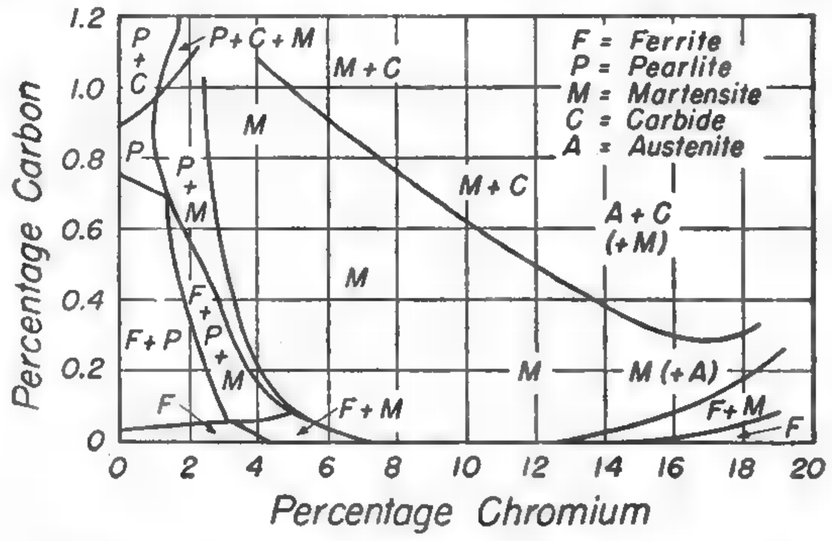

Fig. 5 Constitution of chromium steels normalized in ½-in. cubes (Bain and Grossmann)

Where high chromium contents restrict the solubility for carbides, as in type 440 (12 to 18% Cr cutlery and tool steels), austenitizing temperatures between 1800 and 2100 F are employed in order to dissolve a maximum of carbides in the austenite. Incomplete solution of ferrite is also utilized to avoid excessive hardening during the welding of steels, such as 4 to 6% Cr steel tubing for oil stills, and low-carbon 12% Cr steel.

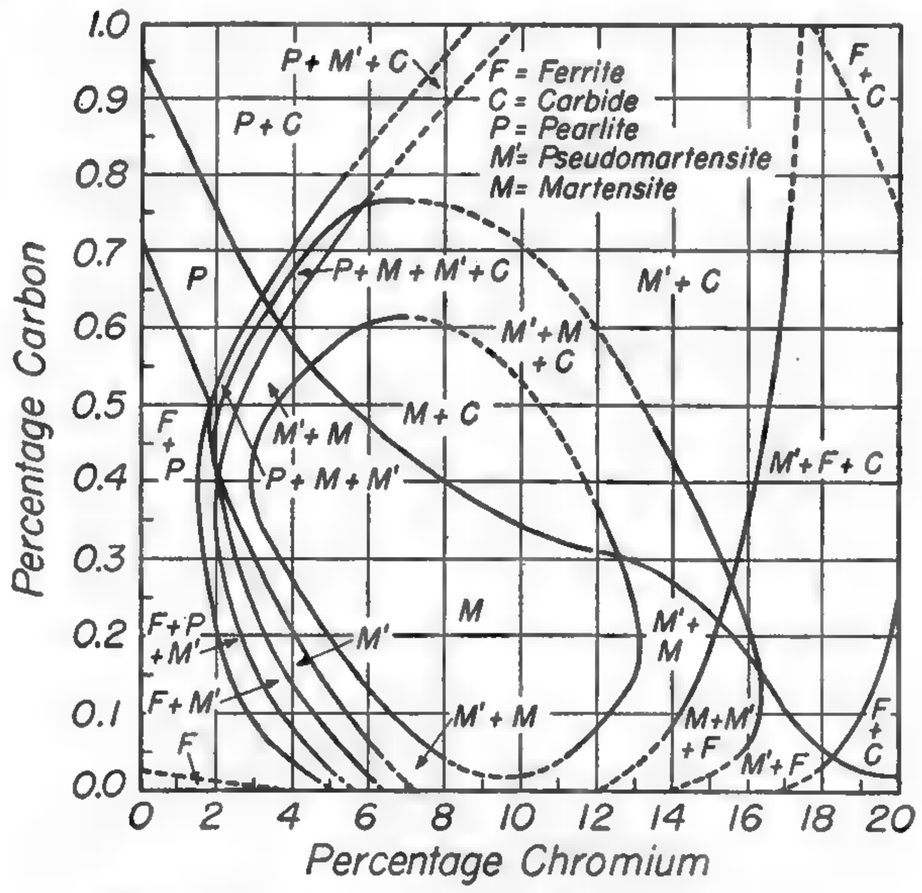

Fig. 6 Constitution of chromium steels normalized in bars 1 in. in diam

Effect of Chromium on Behavior During Cooling from the Austenitic State. During cooling from the austenitizing temperature, the transformation of austenite is retarded by chromium, so that the harder constituents are formed. The structures resulting from normalizing chromium steels in ½-in. cubes are indicated in Fig. 5 and in bars 1 in. in diam, in Fig. 6. It will be noted that there is a field of martensite at medium carbon contents with approximately 8% Cr. This represents the most readily hardenable combination of carbon and chromium. With lower chromium contents the steels transform more readily to ferrite, pearlite and bainite. It will be noted that the martensitic field is larger in the smaller specimens because of the faster cooling rate, and a similar change is produced by higher contents of manganese and other elements that increase hardenability. The steels that contain 2% Cr or less are therefore considered pearlitic; 2 to 5% Cr steels are bainitic; 5 to 18% Cr steels are air-hardening with medium and high carbon contents; and low-carbon steels that contain more than 15% Cr are ferritic.

When, by virtue of high chromium contents or rapid cooling, certain chromium steels do not transform to ferrite, pearlite, or bainite at elevated temperatures, these steels have a relatively slight tendency to retain austenite because of incomplete formation of martensite. As shown by Grange and Stewart,[16] the M_s temperature is lowered only to a moderate degree with higher chromium contents.

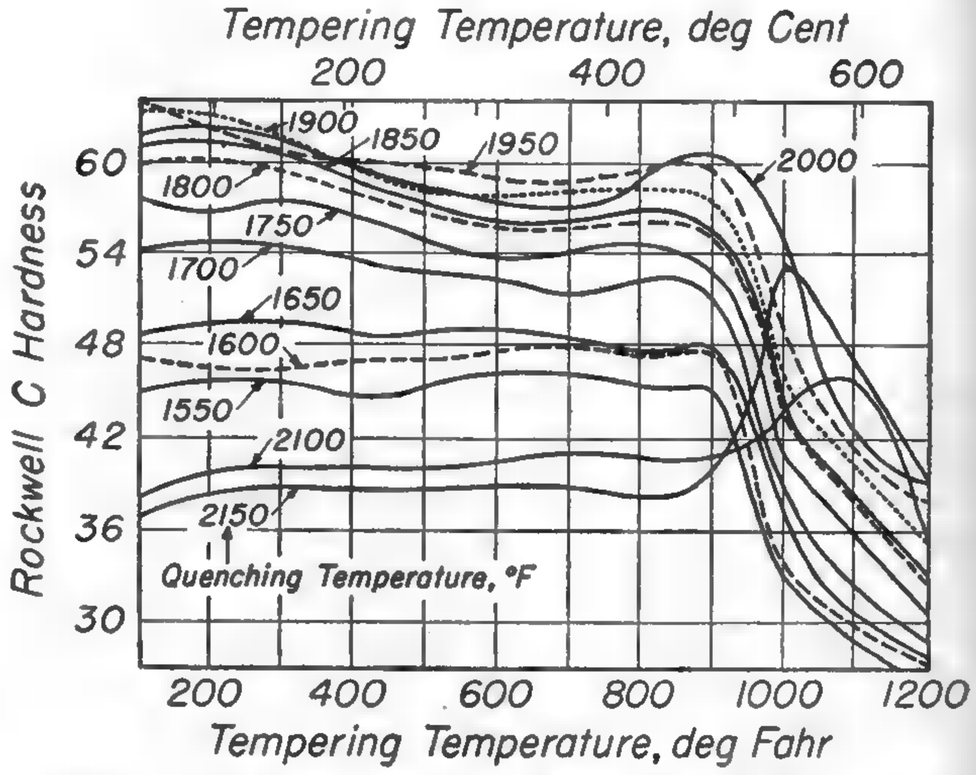

Fig. 7 Effect of tempering on the hardness of 1.6% C, 17% Cr steel quenched from various temperatures (Gill[17])

Effect of Chromium on the Tempering of Quenched Steels. Chromium steels apparently resist softening during tempering, as suggested by Bain,[13] by diffusion and reconcentration of chromium in carbides formed from martensite. Retarded softening becomes more noticeable as the tempering temperature is raised, until a maximum effect is reached at 800 F and higher temperatures. In hardened steels containing 1% Cr, the resistance to softening amounts to about 5 Rockwell C units, and rises to 12 Rockwell C units in steels that contain 3.5% Cr, as compared with comparable chromium-free steels. In high-carbon, high-chromium steels, as shown in Fig. 7 by Gill,[17] strong secondary hardening results from tempering, after austenitizing at a temperature sufficiently high to absorb an effective amount of carbide. It is probable that this secondary hardening is caused both by the formation of martensite (from austenite retained after quenching from the hardening temperature) during cooling from the tempering temperature, and by the tempering of martensite that was formed during quenching from the hardening temperature.

In spite of the strong secondary hardening character of chromium steels, they are readily softened for machining by tempering at high temperatures. The transformation temperature during heating (Ac_1) rises abruptly from about 1350 to 1450 F in steels that contain 3% Cr or more, so that high softening temperatures may be employed. When the chromium content exceeds about 2%, the more stable carbides are the trigonal Cr_7C_3 from 2% to about 9% Cr and the cubic Cr_4C ($Cr_{23}C_6$) at higher chromium contents. Bainite and tempered martensite formed in steels containing as much as about 10% Cr, contain iron carbide, which transforms to a chromium carbide when heated to more than about 900 F, in the composition range shown in Fig. 8.[18] The stability of the carbides in chromium steels is helpful in obtaining a spheroidized structure and avoiding graphitization. In tempering and in service at elevated temperatures, graphitization is inhibited by approximately 1% Cr, or even less. This effect of chromium in avoiding graphitization is utilized also to increase the carbide stability and wear resistance of cast iron.

Tempering brittleness common to martensitic steels tempered in the range from 400 to 700 F is not influenced appreciably by chromium in the small amounts used in steels of the SAE type.[1, 2, 10] In hardenable steels that contain more chromium, the embrittling range is raised to between 750 and 1000 F; for example, in the 12% Cr steels used for turbine blades and cutlery. Chromium steels that have been tempered in the embrittling range have decreased resistance to corrosion, as well as low impact strength. Consequently the steels are used either in the hardened condition (after stress relieving below 700 F) or after tempering at temperatures of 1100 to 1300 F—higher than the temperatures that will cause brittleness. Chromium is not effective in reducing the susceptibility to temper brittleness caused by long holding or slow cooling from tempering temperatures in the range from 1000 to 1200 F.

Special Effects of Chromium in Steel. Chromium is used for improving the mechanical properties in steel and also for increasing the resistance to oxidation, corrosion and wear. Chromium is also used in steels for nitriding and for permanent magnets.

Resistance to Corrosion. Additions of chromium develop the general order of resistance to atmospheric corrosion illustrated in Fig. 9.[19] Although full protection requires 12

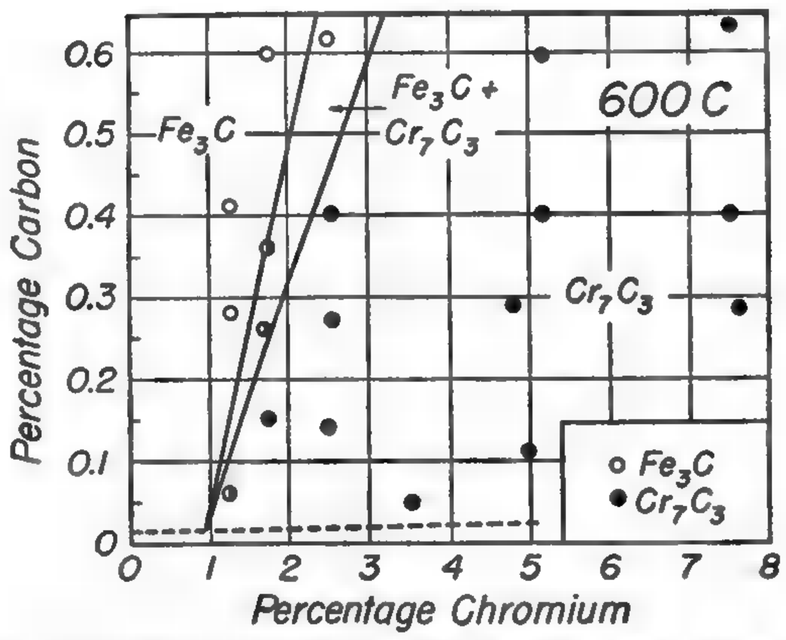

Fig. 8 Carbides in chromium steels quenched and tempered at 600 C (1112 F) (Crafts and Offenhauer[18])

to 18% Cr, 1% Cr is used in conjunction with copper, silicon and phosphorus to improve resistance to corrosion in structural steel and to exercise the specific toughening effect of chromium in phosphorus steel.[7, 20] In steel that contains 3% Cr, the rust becomes tougher and more adherent, so that benefit is derived from the improved resistance to corrosion as well as from better adherence of paint.[8]

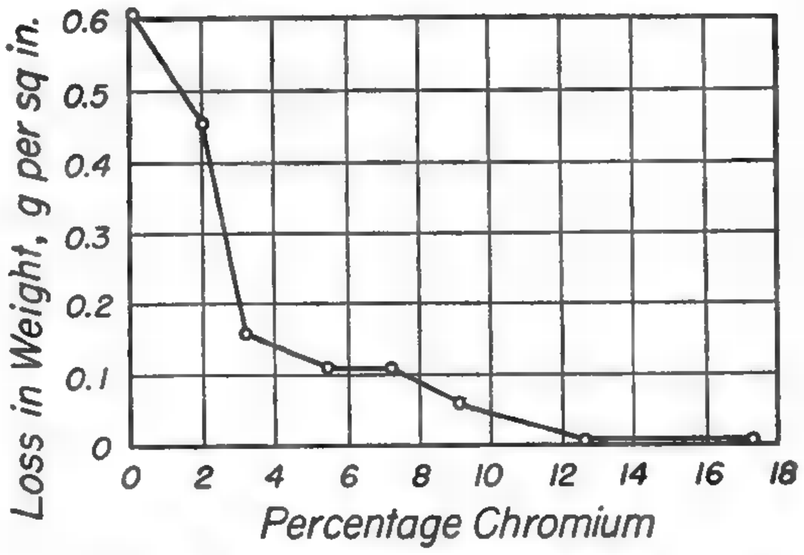

Fig. 9 Corrosion of chromium steels in an industrial atmosphere (Binder and Brown[19])

This steel also has remarkable resistance to sea water.[21] Low-carbon 12 and 18% Cr steels are used in the cold rolled condition for certain types of cutlery and for automotive trim. Because of the blue-white color, such steel matches the color of chromium plate well. The low-carbon plain chromium steels with as much as 30% Cr are resistant to oxidizing acids, such as boiling nitric and dilute aerated sulfuric acid.

The hardenable 12 to 18% Cr steels may contain as much as 2% C, depending on the required hardness. After heat treatment and with cleanly prepared surfaces, these steels are resistant to atmospheric attack and oxidizing and fruit acids. They are frequently modified by nickel, molybdenum, vanadium and the like, to intensify special properties, and are useful for the best grades of cutlery, turbine blading and engineering applications. All the higher-chromium steels, and especially the 12% Cr steel used for steam turbine blading, have a high damping capacity that increases the resistance to vibrational stresses.

The most commonly used stainless steels are of the austenitic chromium-nickel type, which combines ease of forming and welding with high resistance to corrosion. The steels are used for resistance to acid in chemical and food-handling plants, as well as for furnace parts, extremely low-temperature service, architectural trim, and for structural members and surfaces of lightweight equipment such as airplanes and railroad cars. This family of steels contains from 12 to 25% Cr and from 7 to 35% Ni, although the combination most generally used is 18% Cr—8% Ni. These steels are annealed by rapid cooling from 1800 to 2100 F and may contain titanium or columbium to inhibit precipitation of intergranular carbide, molybdenum to increase resistance to less oxidizing acids, and several other elements for special properties. After cold rolling, this type

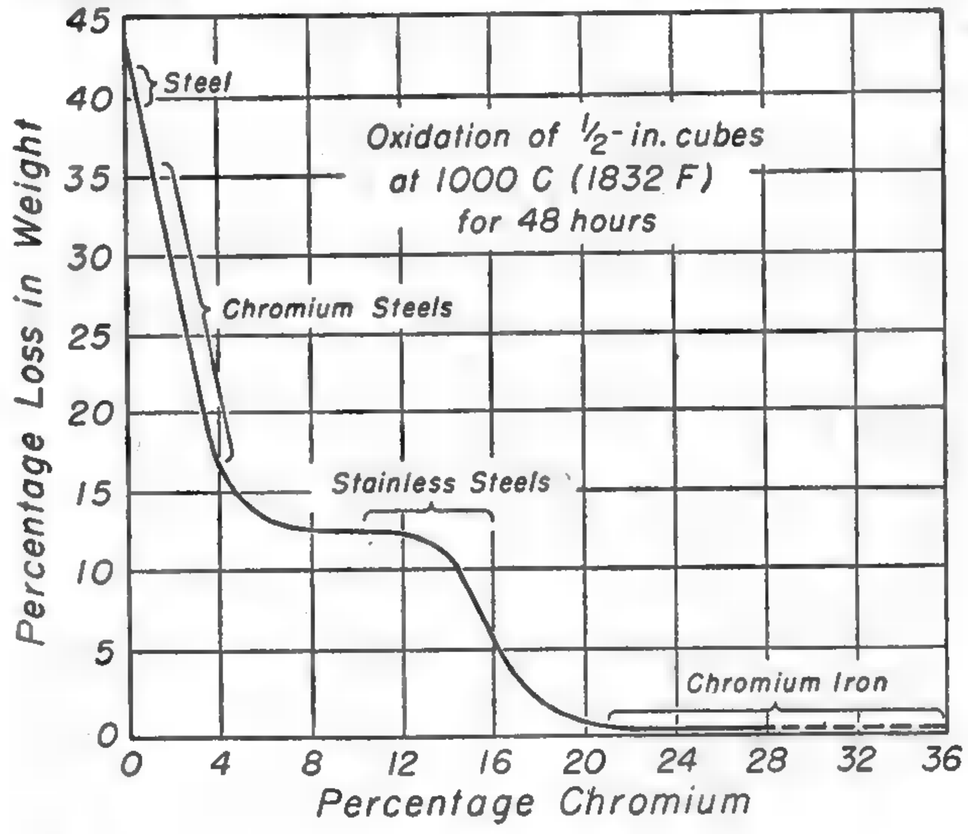

Fig. 10 Oxidation of chromium steels at 1000 C (MacQuigg)

of steel has high load-carrying ability when in the form of thin sheet and strip.

Resistance to Oxidation. Resistance to oxidation at elevated temperatures is increased by chromium in the manner illustrated in Fig. 10.[22] The 4 to 6% Cr level is used for resistance to sour oil in still tubes. Valves for internal-combustion engines are made of 8% Cr silicon steel, 12% Cr steel, and complex steels of higher chromium content. Steels with 12, 18, and as much as 28% Cr are used for resistance to oxidation, depending on the severity of the conditions. The higher chromium steels are sensitive to grain growth and may be given a persistent fine grain size by the presence of about 0.20% N.[23] The austenitic steels, such as 25% Cr—20% Ni steel and modified types, are used for furnace and gas turbine components, because of high creep strength. Manganese-chromium steels have specific resistance to sulfur-bearing atmospheres. A 37% Cr—7½% Al alloy is resistant to oxidation at temperatures approaching 2400 F, and is useful for resistance elements. Normally chromium has little effect on creep strength; the maximum improvement is noted at about 12% Cr.

Resistance to Wear. Wear resistance is an outstanding property of chromium steels because they are capable of developing high hardness, and also resist the surface oxida-

tion that accompanies and aggravates wear. For example, Ellis[15] found that 3, 8, and 15% Cr steel grinding balls wore less in proportion to their chromium contents if air or an oxidizing atmosphere was present; but they were no better than ordinary balls in nonoxidizing atmospheres. High-carbon steel containing 1.5% Cr, high-carbon tool steels containing 12 to 18% Cr, and cast iron with as much as 30% Cr, are usually applied where resistance to wear and abrasion are primary requirements. The chromium hot work steels and piercing-point steels probably owe their special value largely to the type of scale at the surface.

Chromium is a component of nitriding steels to assist in developing a suitable initial microstructure and in forming a hard nitrided case. Although nitriding steels also usually contain aluminum or vanadium, plain chromium steels from 1 to 18% are successfully nitrided. Chromium-vanadium steel is also used for reaction vessels in the synthesis of ammonia and alcohol.

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Copper in Steel

By C. H. Lorig*

THE copper-bearing steel containing about 0.25% Cu is well known and is widely used for structural purposes and sheet because of its resistance to atmospheric corrosion. Copper in quantities as large as about 4% is also used to a limited extent in steels to give increased fluidity to the melt, and to improve tensile and yield strengths with only minor loss in ductility. Copper is being used in one type of stainless steel in amounts as great as 10% to improve resistance against certain corrosive mediums and to increase machinability.

In the solid state, the iron-copper alloys may consist either of homogeneous solid solutions of the one metal in the other, or of heterogeneous mixtures of these solid solutions. The maximum solubility of copper in alpha iron is 1.4%, but it decreases with decreasing temperature, becoming constant below 1200 F at 0.35%. Gamma iron dissolves 4.5% Cu at 1530 F, 8.5% at 2000 F, and possibly about 10% at 2690 F.

Table I. Hardness of Annealed Iron-Copper Alloys

Copper, per cent	0.0	0.5	1.0	2.4	2.7	4.0
Rockwell B hardness	27	58	72	95	94	95

In steel, copper is found only in solid solution (both as iron-rich and as copper-rich solid solution phases). It does not appear in the carbide phase or as intermetallic compounds with iron. Because of the limited solubility of copper in alpha iron, the alloys and most steels containing more than 0.6% Cu can be hardened by precipitation. Lattice changes during precipitation hardening have been correlated with hardness values, and it has been shown that the principal increase in hardness takes place prior to the precipitation of the copper-rich phase.[1]

Because of selective oxidation of the iron, copper tends to concentrate on the surface beneath the scale when copper-bearing steels are heated under oxidizing conditions. This concentration of copper at the surface can lead to surface checking during hot working when the hot working temperature for the steels is near or above the melting point of copper. Surface checking has been observed in steel containing as little as 0.25% Cu. Because nickel raises the hot working temperature at which checking occurs, copper-bearing steels are frequently alloyed intentionally with nickel in proportions of at least one-third the copper content to minimize surface checking.

Table III. Yield Ratios of Copper Steels (0.02% C)

Copper, per cent	Yield Ratio After Normalizing	Yield Ratio After Normalizing and Precipitation Hardening
0	0.78	0.78
0.5	0.80	0.83
1.0	0.80	0.88
1.5	0.89	0.92
2.0	0.91	0.92
2.5	0.91	0.92
3.0	0.91	0.91

The Effect of Copper in Ferrite and Low-Carbon Iron Alloys. Rockwell hardness values of annealed, vacuum-melted iron-copper alloys, made from electrolytic iron and electrolytic copper, are given in Table I.[2]

The tensile properties of annealed iron-copper alloys are given in Table II.[3]

When as much as 2% Cu is present in low-carbon steels, the copper has little influence on ductility, but has a most noticeable influence on yield strength, particularly for normalized steels and for steels hardened by precipitation. The yield ratios of normalized and of normalized and precipitation-hardened copper steel containing 0.02% C, are given in Table III.

Table II. Tensile Properties of Annealed Iron-Copper Alloys

Copper, per cent	0	0.5	1.0	1.5	2.0	3.0	4.0
Tensile strength, psi	52,000	57,000	66,000	66,000	67,500	68,500	69,500
Yield strength, psi	33,000	40,000	45,500	49,500	51,500	52,500	55,000
Elongation, per cent	31	36	32	30	28.5	26	23
Reduction of area, per cent	59	68	67	64	62	57	51

The alloys of copper and iron need not be drastically quenched in order to produce a supersaturated solid solu-

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Prepared for the Subcommittee on Alloying Elements in Steel

tion of copper in iron, which will respond to the precipitation-hardening treatment. Air-cooling suffices to keep the copper in solution in sections as large as several inches in diameter. To obtain the full benefit from precipitation hardening, the air-cooled material needs to be heated only to the precipitation temperature. The maximum hardening effect is produced by reheating, or by interrupting the cooling during air quenching, at 840 to 930 F. On the average, precipitation hardening of low-carbon steels containing from about 1.0 to 1.5% Cu produces an increase of 20,000 psi in tensile strength and

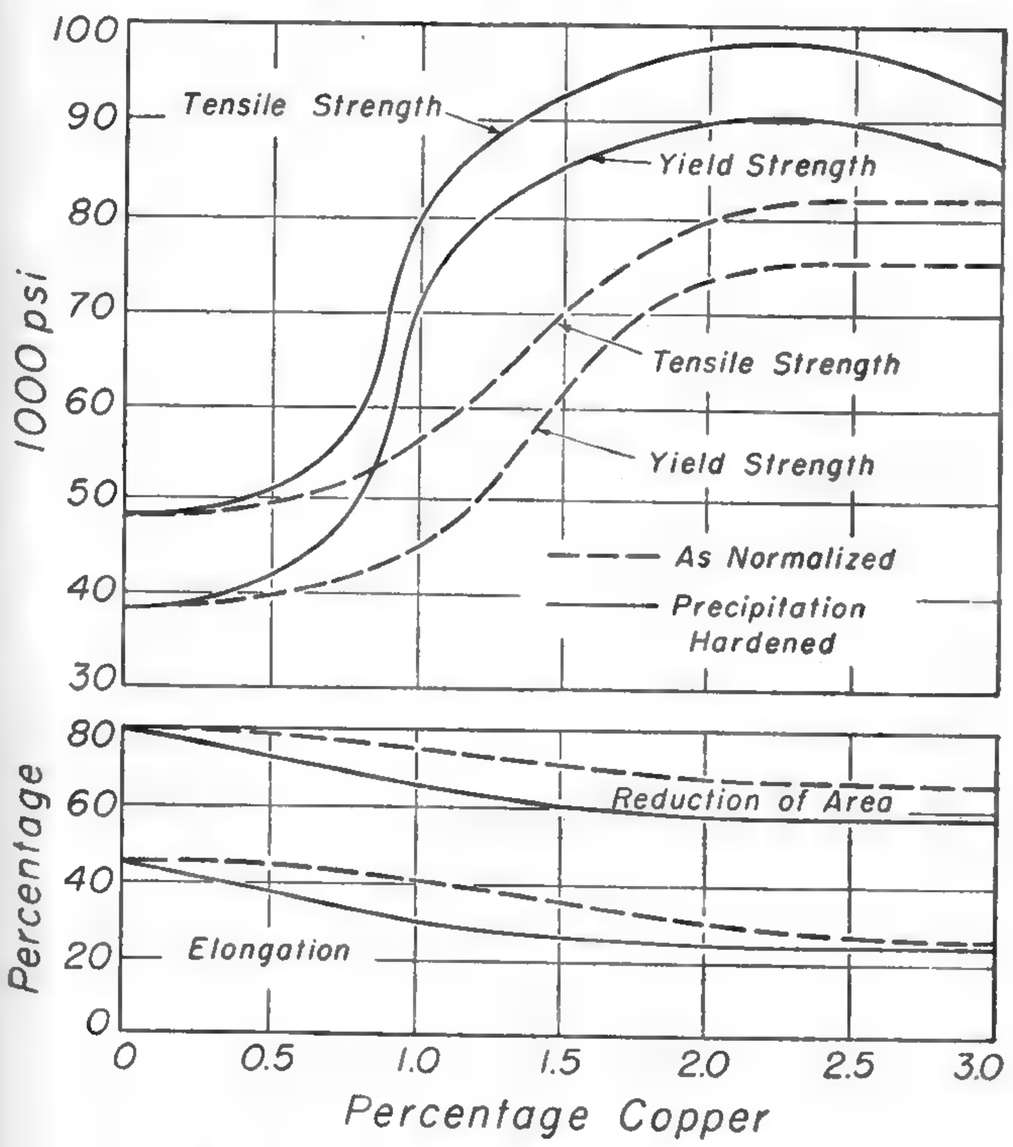

Fig. 1 Effect of copper on tensile properties of normalized and of normalized and precipitation hardened 0.02% C steels

25,000 psi in yield strength over the respective properties of the same steel in the normalized condition. The increase in strength is accompanied by some loss in ductility as determined by elongation, reduction of area, and notched-bar impact values, but the steel is not rendered notably brittle.

Typical curves showing the effect of copper on tensile properties of normalized and of normalized and precipitation-hardened 0.02% C wrought steel are given in Fig.

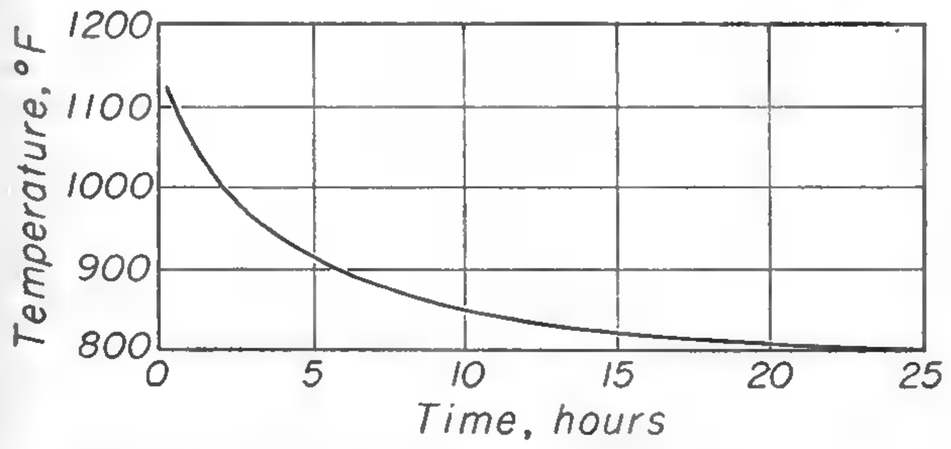

Fig. 2 Time-temperature relation for maximum increase in hardness resulting from precipitation hardening

1. Figures 2 to 4 show the time-temperature relations for maximum increase in hardness during precipitation hardening; Fig. 3[5] shows the influence of carbon content on the maximum increase in strength after precipitation hardening; Fig. 4[5] shows the influence of cooling rate prior to precipitation hardening, on the increase in strength resulting from precipitation hardening.

Other elements added in small amounts to copper steels have little influence on the increase in hardness resulting from precipitation hardening. According to Halley,[6] the precipitation-hardening rate, however, was more than doubled by reducing the silicon content from 0.188 to

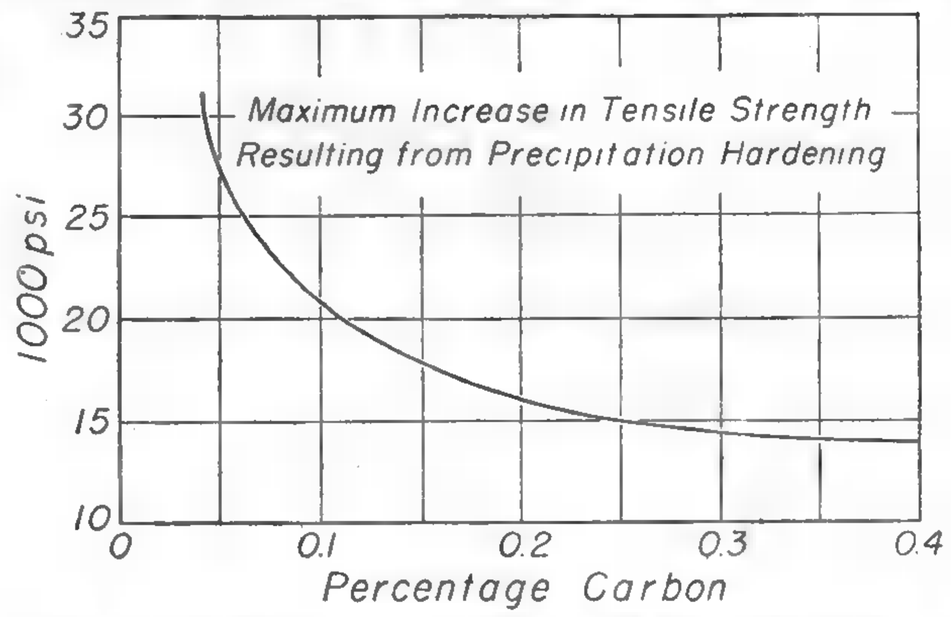

Fig. 3 Influence of carbon content on the maximum increase in tensile strength resulting from precipitation hardening

0.020% in a steel containing approximately 0.10% C, 0.12% P, 1.00% Cu and 0.50% Ni.

Small additions of copper in steel are effective in minimizing atmospheric corrosion. Figure 5 shows the effect

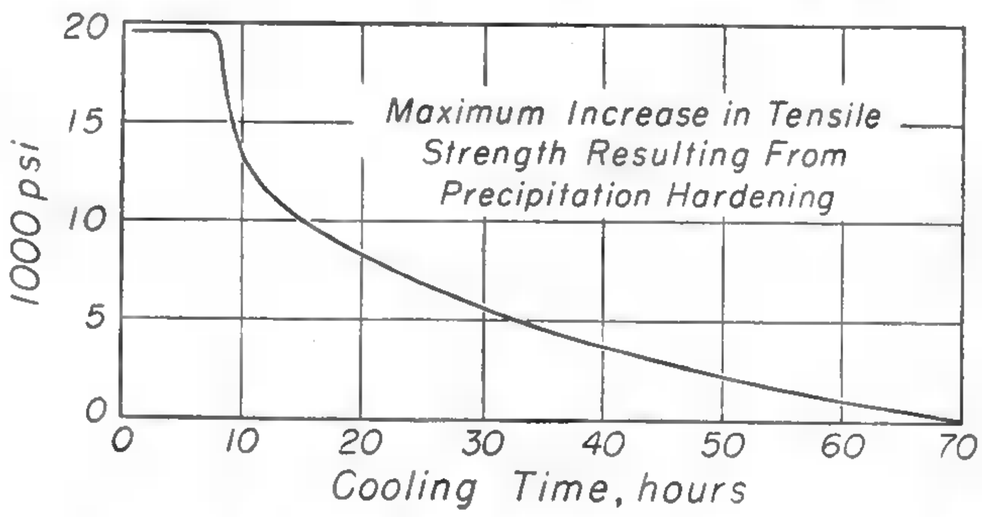

Fig. 4 Influence of cooling time, prior to precipitation hardening, on the increase in strength resulting from precipitation hardening

of copper on corrosion of low-carbon steels exposed to the atmosphere for three years.[7]

In carburizing tests, Smith* observed that copper in amounts less than 3% had very little effect on the depth of carburization of iron, but high-copper specimens, lightly oxidized before carburizing, showed somewhat irregular cases attributed to the protective action of a film of copper formed beneath the thin oxide scale.

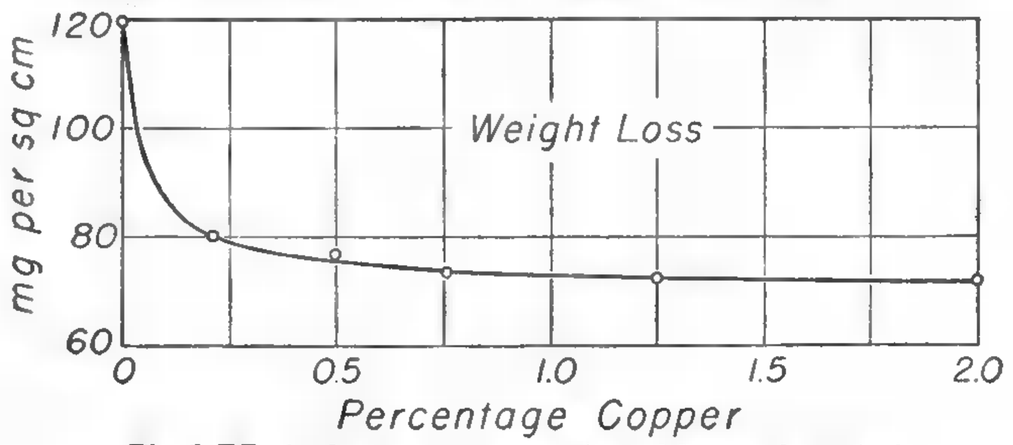

Fig. 5 Effect of copper on corrosion of low-carbon steels exposed to the atmosphere for three years

The Effect of Copper on Medium-Carbon or High-Carbon Steels in the Pearlite Condition. Copper has a very mild effect in retarding the rates of nucleation and growth of pearlite, and in decreasing the interlamellar

* C. S. Smith, American Brass Company, unpublished report.

spacing of pearlite. As the carbon content of copper-containing steel increases, the response to precipitation hardening decreases.

The Effect of Copper on Behavior During Heating for Hardening or for Normalizing. Because copper and cementite apparently do not alloy, the copper content evidently does not affect the rate of solution of cementite in austenite, while a steel is being heated for normalizing or for hardening. The eutectoid carbon content apparently is not changed by copper.

The Effect of Copper on Behavior During Cooling from the Austenitic State. The structures obtained while cooling copper-bearing steels from the austenitic state are substantially the same as those obtained with copper-free steels of the same carbon content. In alloys containing moderate amounts of copper, however, the copper that exceeds the solubility limits separates out as a copper-rich constituent, epsilon, in the form of very small particles not usually distinguishable under the microscope. If more than 8% Cu is present, the excess copper separates out as a distinct phase in the grain boundaries.

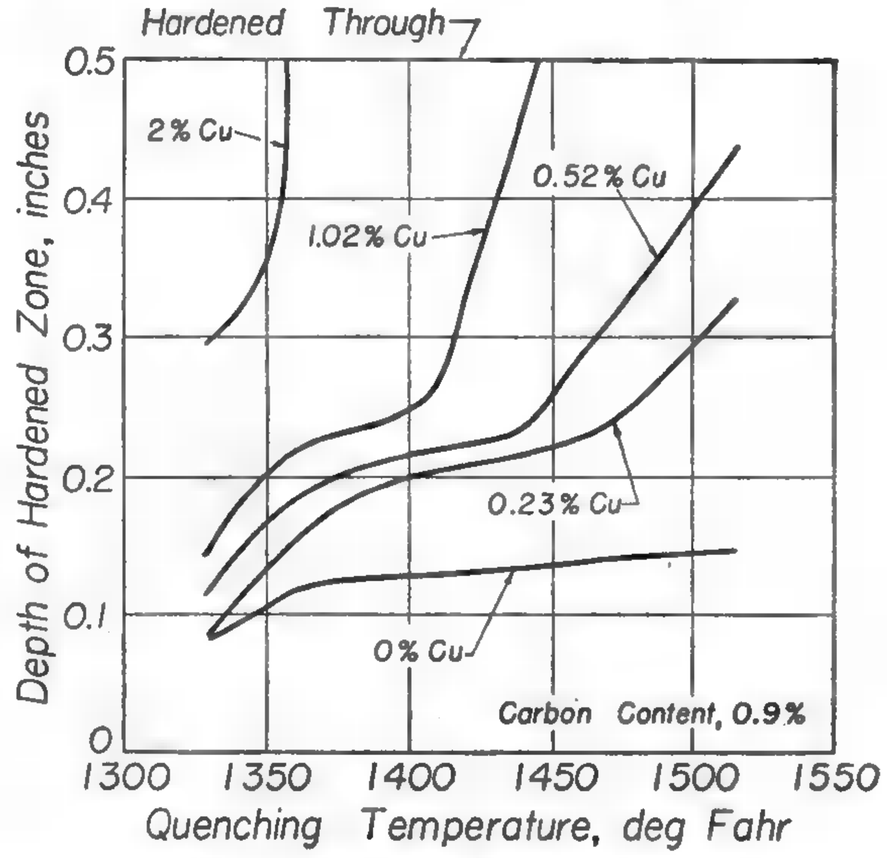

Fig. 6 Effect of copper on the depth of hardening in a quenched 0.9% C steel

The effect of copper on hardenability is similar to that of nickel. Although copper favors deep hardening, its relative effect is much greater in the high-carbon than in lower-carbon steels. The effect of copper on depth of hardening in a quenched 0.9% C steel is shown in Fig. 6.[8]

There is some evidence that copper widens the temperature range throughout which annealing produces spheroidized cementite.[8]

It has been reported[10] that steels containing from 1.11 to 1.27% C and from 3 to 4.85% Cu graphitized rapidly at temperatures above 2010 F. Reed,[11] however, failed to observe graphitization in high-copper, high-carbon steels that had been subjected to long annealing at 1832 F.

The Effect of Copper on the Tempering of Quenched Steels. Copper in amounts from 1 to 5% has little influence on the structure of oil-quenched and tempered steels containing between 0.65 and 1.20% C.[12]

No data are available to show the softening pattern of quench-hardened copper-bearing steels with increasing tempering temperature. For a steel containing 0.25% C and 1.05% Cu, quenched in water from 1500 F (but apparently not fully hardened) and tempered between 600 and 1200 F, data showed that the effects of softening by tempering and hardening by precipitation are superimposed, as illustrated in Fig. 7, when the tempering is at temperatures that cause precipitation hardening.[13]

Special Effects of Copper in Steel. *Properties at Elevated Temperature.* Short-time tensile tests at elevated temperature, on normalized copper-bearing and copper-free steels of the same carbon content, showed that copper has a tendency to reduce ductility but to influence tensile strength only a little. The information available indicates that the creep strength of steel is not improved by copper.[14] Copper appears to render iron somewhat more resistant to oxidation at high temperatures; the greatest effect is attained with copper contents between 0.25 and 0.50%. This improvement in oxidation resistance probably results from the fact that the scale formed on copper steels is slightly more adherent, and hence offers more protection against oxidizing atmospheres.

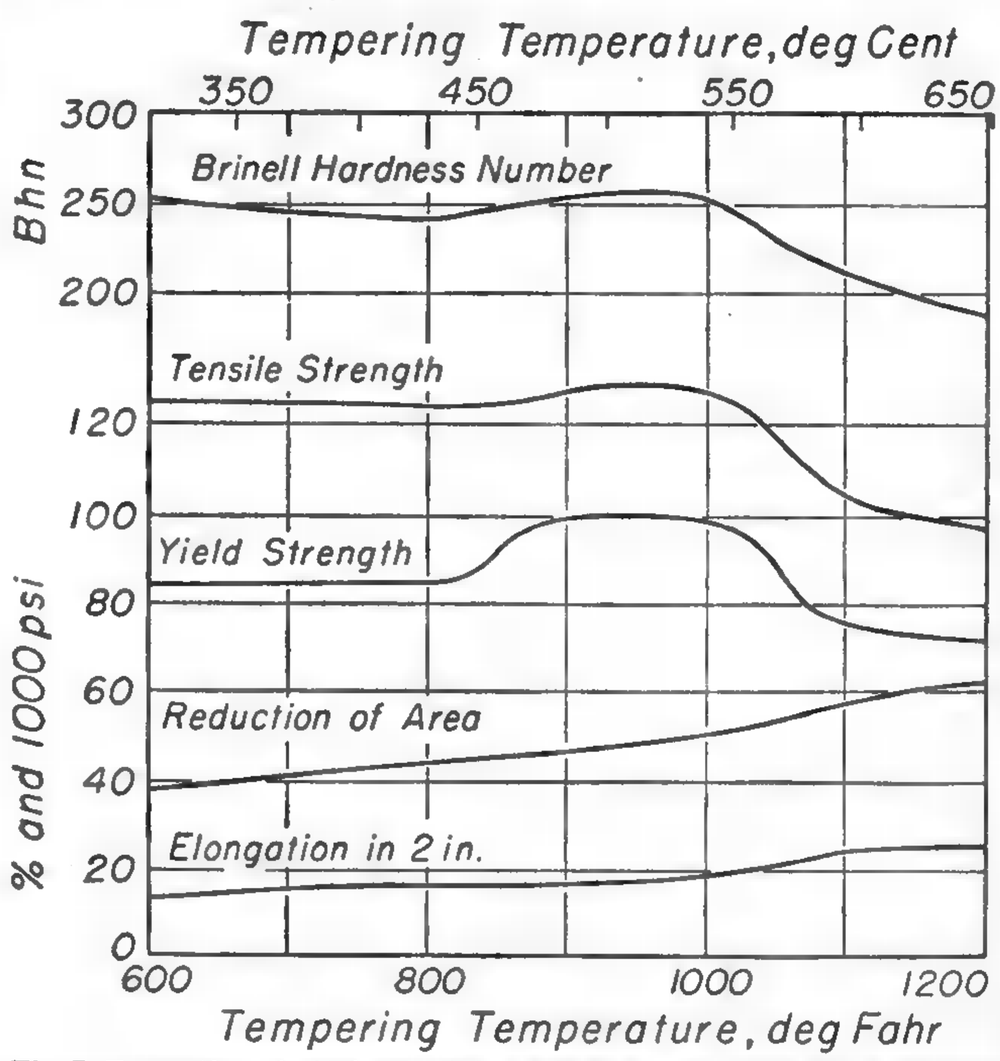

Fig. 7 Properties of steel containing 0.25% C and 1.05% Cu, quenched in water from 1500 F and tempered at various temperatures

Resistance to Corrosion. Field and service tests have demonstrated that the life of iron and steel exposed to the corrosive action of the atmosphere is increased materially by the addition of 0.15 to 0.25% Cu. Higher percentages of copper seem to provide no further benefits.

The results of field tests, under conditions of partial or total immersion in various types of water and under conditions of exposure underground, indicate that the

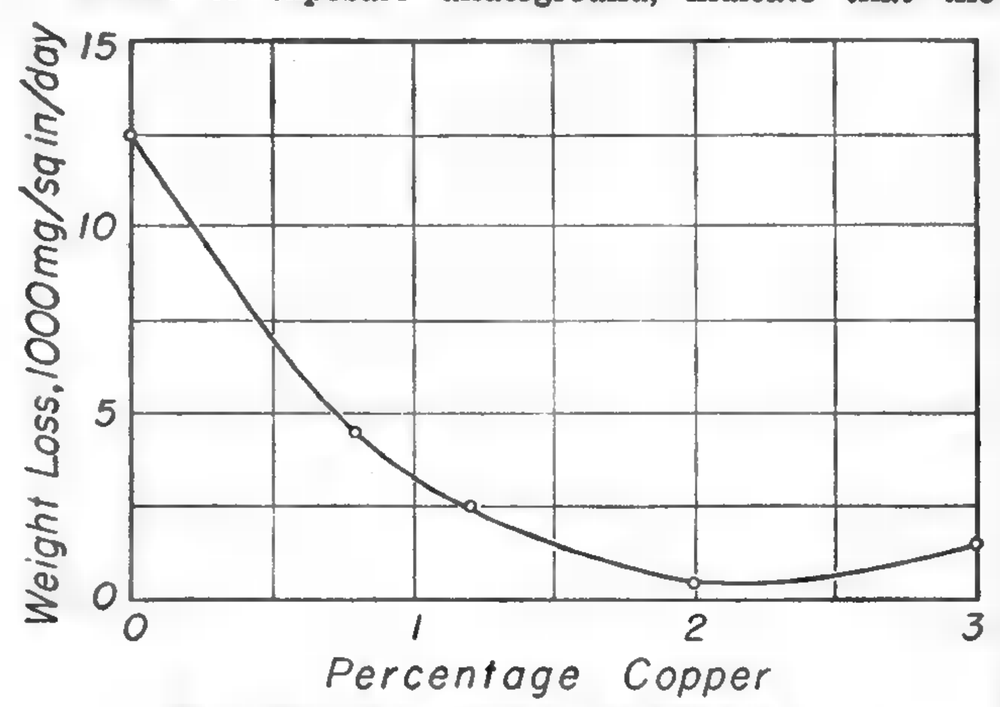

Fig. 8 Effect of copper on loss in weight of 18-8 stainless steel in boiling 10% sulfuric acid

effect of copper on submerged and underground corrosion, if at all noticeable, is not very pronounced.

There is some indication that paint adheres better to copper steel, and that zinc coatings on copper steel are more resistant than those on copper-free steel.

Copper is especially effective in increasing the corrosion resistance of steel in sulfuric acid. From 0.75 to 3.0% Cu in cast stainless steel containing 0.15% C, 18% Cr, and 8% Ni, decreased the corrosion rate in 10% boiling sulfuric acid enormously, as shown in Fig. 8. A copper addition to 18-8 stainless steel appears to have little effect on the corrosion rate in either nitric or acetic acid, nor does it seem to influence intergranular corrosion in any way. From 1 to 2% Cu is frequently added, however, to the highly-alloyed, corrosion-resisting steels of both the ferritic and austenitic types, in order to impart added corrosion resistance to certain mediums.

Low-Alloy, High-Strength Steels. Many low-alloy, high-strength steels have recently been developed to provide a relatively inexpensive structural material with about the same ductility and formability as ordinary structural steel, but with a decidedly higher yield strength. Nearly all these newer steels contain copper. (*See* the article on page 534 of this Handbook.) They are usually steels of complex alloy content, containing two or more alloying additions. Copper is used in almost every one of them to increase resistance to atmospheric corrosion. In some, more than 0.75% Cu is employed to raise the yield ratio and the tensile strength. It does not interfere with weldability. Steels containing 0.5% or more copper usually contain nickel in proportions of at least one-third the copper content, in order to improve rolling characteristics by reducing their tendency to crack, as well as to confer additional strength. For the same reason nickel is frequently used in forging steel containing 0.5% Cu or more.

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Manganese in Steel

By C. E. Sims*

THIS article deals with the effect of manganese in pearlitic steels. The austenitic manganese steels are discussed in the article beginning on page 526.

The phase diagram of the C-Fe-Mn system (*see* pages 1252 and 1253) shows that manganese lowers the transformation temperature range of steel. Dilatometric tests indicate that manganese lowers the Ar_3 point more than the Ac_3 in binary iron-manganese alloys[2] (Fig. 2). The rates of heating and cooling in these tests were 18°F per min. At these heating and cooling rates, the Ac_3 and Ar_3 points occur at nearly the same temperature for pure iron. With a 1.1% Mn alloy, there is an apparent lag of 25 F; and with the 4.4% Mn alloy, the Ar_3 point lags about 450 F behind the Ac_3.

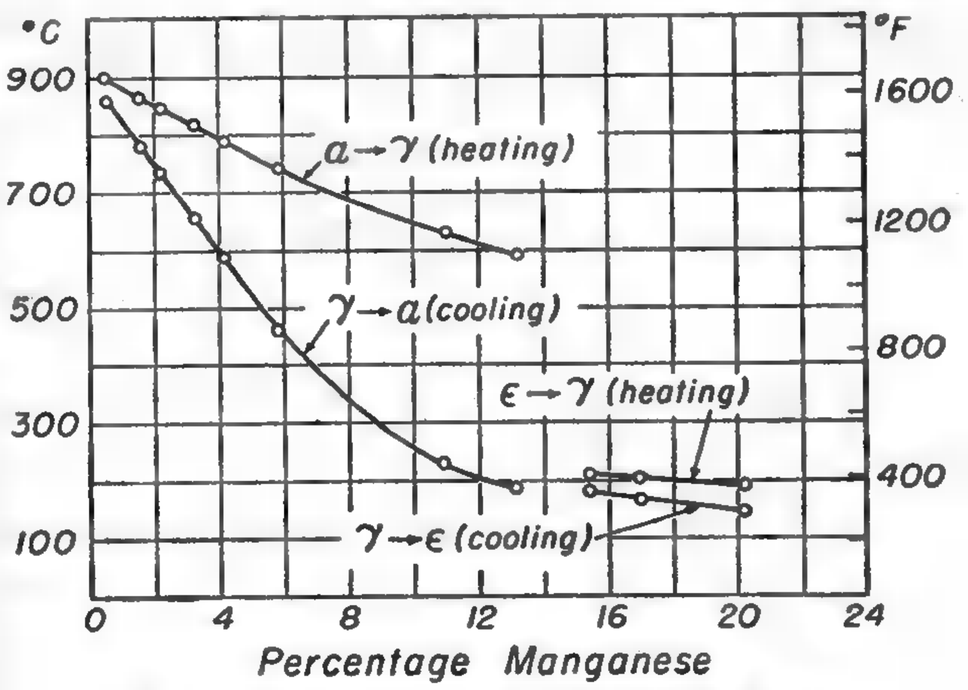

Fig. 1 Initial transformation temperatures for the gamma ⇄ alpha and gamma ⇄ epsilon transformations[1]

A summary of published results obtained in studies of pearlitic manganese steels[3] shows that the Ac_1 point is lowered approximately 11 F for each percentage of manganese; the Ac_3 point is lowered 116 F by the addition of 1% Mn, but further increase in manganese content has a much slighter effect. The Ar_3 point is lowered 125 F, and the Ar_1 point about 90 F for each 1% Mn in pearlitic steels.

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Prepared for the Subcommittee on Alloying Elements in Steel

Effect of Manganese in Ferrite and Low-Carbon Iron Alloys. The effect of manganese as an alloying element in carbonless iron has been found to be very slight. Figure 4 shows the influence of manganese on carbonless iron alloys, containing as much as 1.4% Mn.[5] A straight-line relationship is indicated between the mechanical properties of the alloys and their manganese content in this range. The Brinell hardness number was raised from 70 for pure iron to 95 for a 1.4% Mn alloy. Tensile strength was increased from 42,000 to 54,000 psi, while the elongation and reduction of area remained unchanged. The influence of manganese on mechanical properties of carbonless

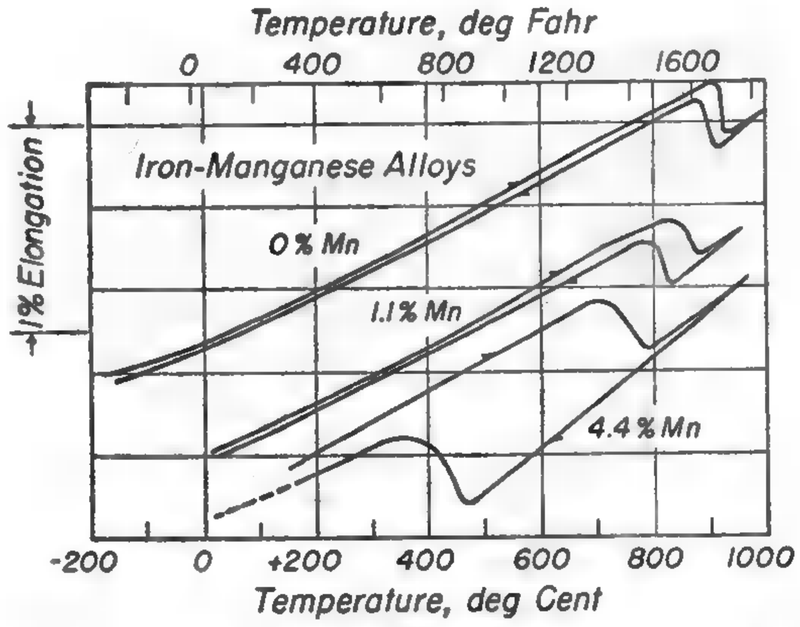

Fig. 2 Dilatometric tests on binary iron-manganese alloys[2]

and low-carbon iron in the higher range of manganese contents has not been investigated thoroughly. Bain has determined the most probable hardness values for carbon-free as well as for 0.1% C alloys,[6] (Fig. 5); the results are in agreement with values determined on the low-manganese alloys.[5] All data shown in Fig. 4 and 5 were obtained on annealed material.

Effect of Manganese on Medium-Carbon or High-Carbon Steels in the Pearlitic Condition. In pearlitic medium-carbon steels, manganese has a twofold function. It has a solution-hardening effect on the ferrite, and it influences the fineness of pearlite. Bain[6] shows the isolated solid-solution effect of manganese on a series of 0.55% C steels annealed to a uniform, lamellar structure in Fig. 6. In the

range from 0 to 7% Mn, the graph indicates an increase in strength, with a progressive loss in ductility. When the steels are compared on the basis of constant cooling rate, instead of on the basis of uniform structure, the properties are vastly more affected by manganese, because of the

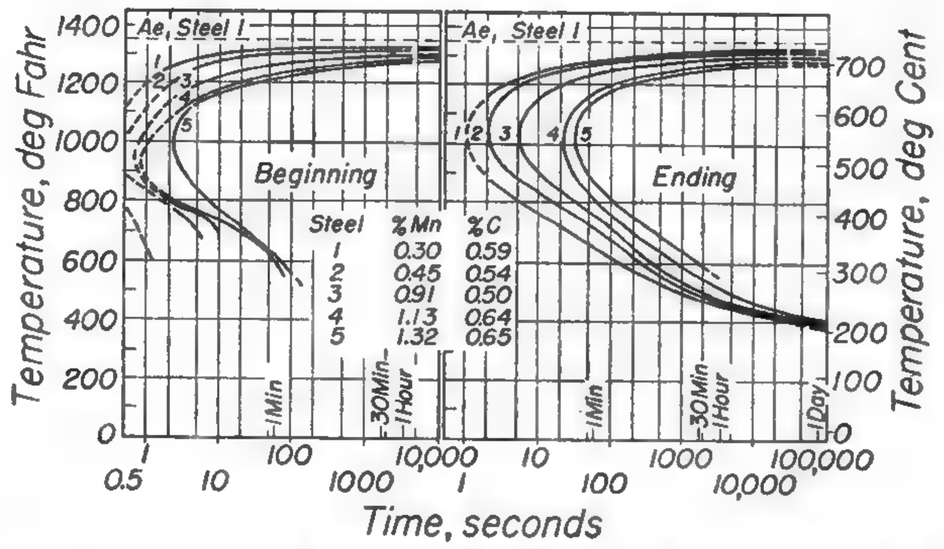

Fig. 3 Comparison chart showing influence of manganese on the isothermal transformation curve. *Left*, beginning; *right*, ending.[4]

refining influence on pearlite. This effect is shown in Fig. 7 taken from the same source.[6]

In the as-rolled condition, the mechanical properties of pearlitic manganese steels are determined largely by the fineness of the lamellar structure; and, as a general rule, a higher manganese content requires a correspondingly lower carbon content in order to provide the desired tensile

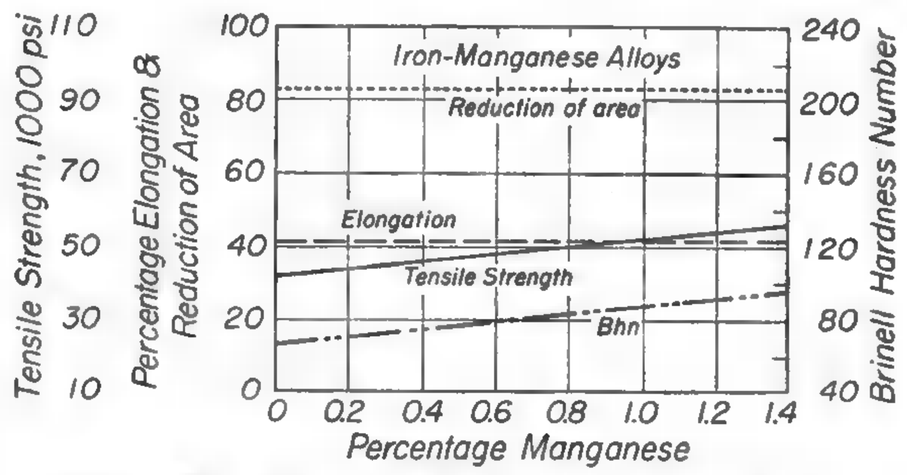

Fig. 4 Effect of manganese on mechanical properties of carbon-free iron-manganese alloy[5]

strength. Because it permits a lower carbon content for a required tensile strength, manganese is often employed as the principal alloying element in the manufacture of low-alloy, high-strength structural steels. With the use of manganese as an alloying element, either higher strength with equal ductility and impact properties, or better ductility and

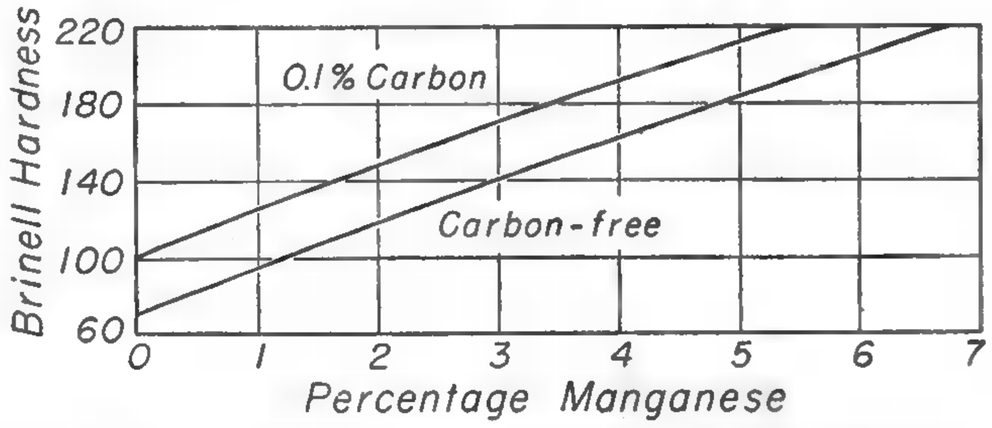

Fig. 5 Effect of manganese on hardness of carbon-free and low-carbon iron-manganese alloys[6]

impact properties with equal strength can be obtained than by the use of plain carbon steel.

Effect of Manganese on Behavior During Heating for Hardening or for Normalizing. Although manganese has generally been regarded as a carbide-forming element, because of its thermodynamic properties, no manganese carbide has been identified in steel, although such carbides have been observed in Mn-Fe-C alloys containing more than 50% Mn.[7] Manganese does occur in cementite of manganese steels. The rate of solution of cementite in the austenite of manganese steels during heating for hardening and for normalizing is similar to that in plain carbon steels. It is to be noted, however, that the minimum temperature for complete austenite formation shifts to lower

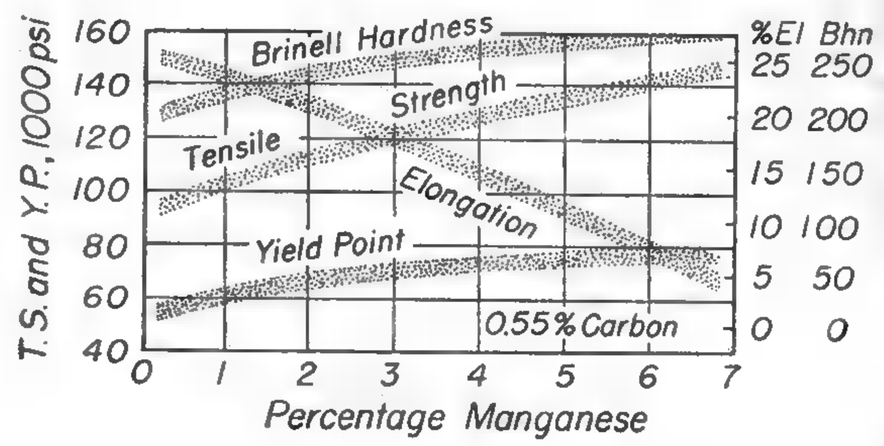

Fig. 6 Effect of manganese on mechanical properties of medium-carbon steel, heat treated to a uniform lamellar structure[6]

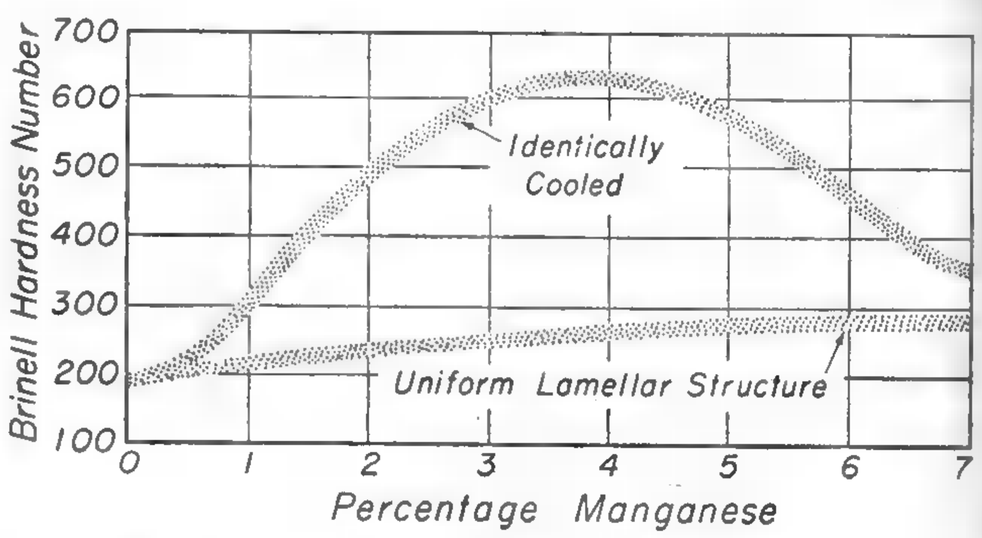

Fig. 7 Effect of manganese on hardness of medium-carbon steels[6]

temperatures, and that the eutectoid carbon content is appreciably lowered, with an increasing manganese content in the steel.[6] This condition is shown graphically in Fig. 8.

Effect of Manganese on Behavior During Cooling from the Austenitic State. As indicated by the transformation curves (Fig. 1 and 3), manganese retards transformation of

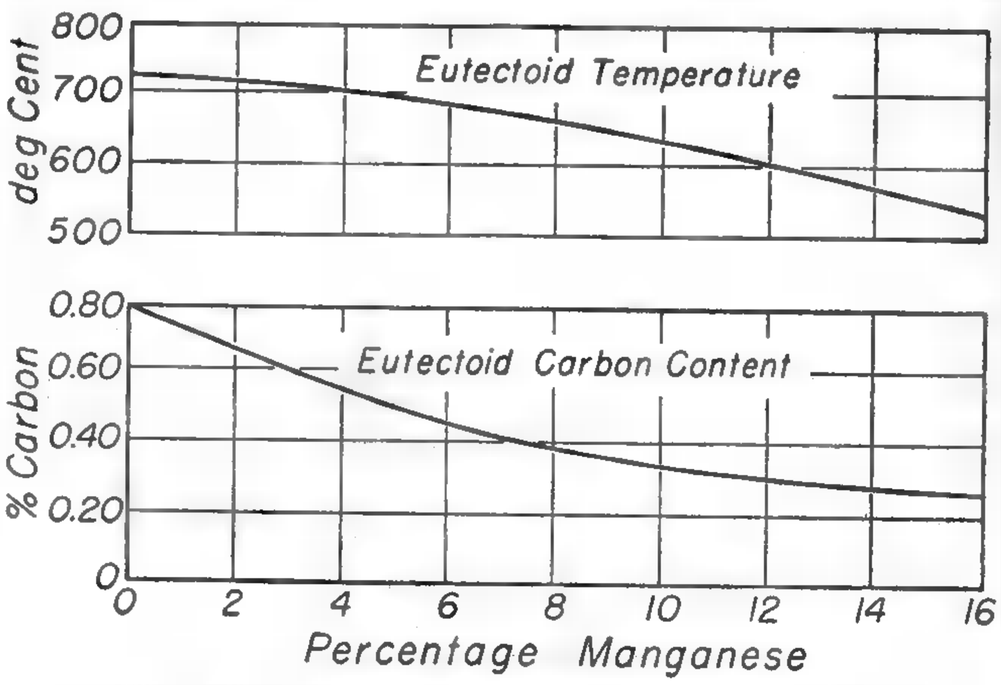

Fig. 8 Effect of manganese on eutectoid carbon content and eutectoid temperature of manganese steels[6]

austenite during cooling. The net result is a marked refinement of pearlite during air cooling, or a lower critical cooling rate for transformation into acicular products during quenching. The effect of manganese on the structures formed during cooling from the austenitic state is shown in Fig. 9 and 10. These structures were obtained by quenching thin specimens ½ in. sq in water from 1740 F (Fig. 9) and by cooling similar specimens in air from the same temperature (Fig. 10).

Of considerable importance in the industrial application of manganese steels is the fact that manganese decreases the rate of austenite transformation at subcritical temperatures[4] (Fig. 3). The familiar S-curve of isothermal transformation shifts to the right as the manganese content of the steel is increased.

The retarding effect of manganese on the rate of austenite transformation at subcritical temperatures is an important hardenability factor, because it reduces the cooling rate necessary to prevent transformation at the higher temperatures, where the products of transformation would be fine pearlite rather than martensite. Manganese is one of the most potent elements influencing hardenability, of those

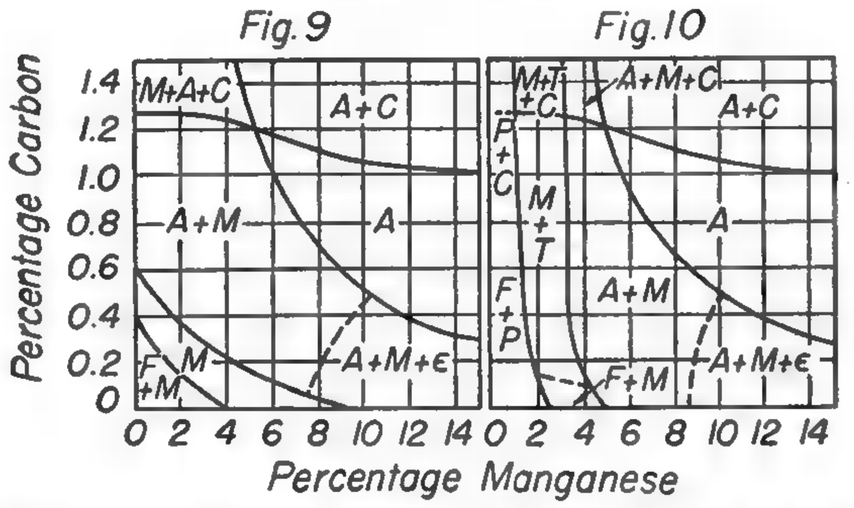

Fig. 9 Structural diagram showing the effect of manganese on structures of steel during water quenching from 1740 F[6]

Fig. 10 Structural diagram showing the effect of manganese on structures of steel during air cooling from 1740 F[6]

commonly employed in steelmaking.[8,9] The effect of manganese on hardenability is relatively greater above 1% than below 1%.[10]

With the exception of carbon, manganese lowers the martensite transformation temperatures more than any of the other alloying elements in steel. This is illustrated in

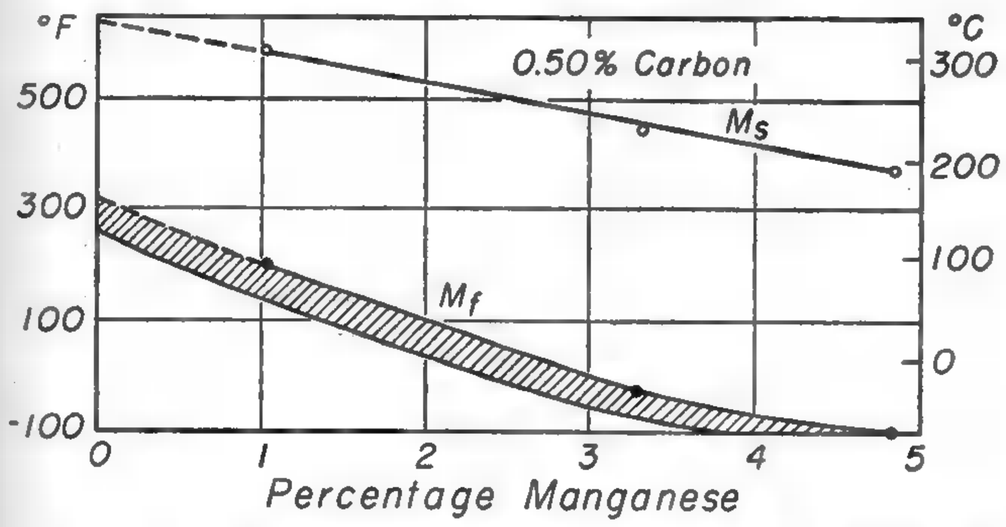

Fig. 11 Effect of manganese on the martensite transformation temperatures of a 0.50% C steel. Ms, starting point; M_f, finishing point[12]

Fig. 3 and 11. In high-carbon steels, manganese favors retention of austenite after quenching.[6]

Effect of Manganese on the Tempering of Quenched Steels. A comparison of the behavior during tempering of plain carbon and manganese steels is shown in Fig. 12, as given by Bain.[6] It is evident that, although the manganese steel had a higher level of hardness through the entire tempering temperature range, the two steels reacted similarly. For the same time and temperature of the tempering treatment, manganese steels show the same relative drop in hardness as do unalloyed carbon steels.

In high-carbon steels containing more than 1% Mn, appreciable quantities of austenite may be retained after oil quenching. However, no perceptible "secondary hardening" effects have been observed in manganese steels.[6]

Manganese steels show a pronounced tendency to temper-brittleness, often exhibiting a 50% loss in notch toughness after slow cooling from a temperature of 1100 F or higher. Quenching after tempering above 1100 F is, therefore, a recommended practice for these steels, particularly when the heat treated part has a fairly large cross section.

Characteristics of spheroidization and graphitization in manganese steels have not been satisfactorily evaluated, but circumstantial evidence points to the conclusion that manganese has a mild negative effect on both properties.

Special Effects of Manganese in Steel. *Effects of Manganese on Hot Shortness.* Among all the alloying elements employed in the manufacture of steel, manganese occupies a unique position. It is an indispensable ingredient in all commercial steels, and all efforts to make manganese-free steels have been in the nature of laboratory experiments.

Manganese reduces the "hot shortness" ("red shortness") resulting from the presence of sulfur, thereby enabling the metal to be hot worked. When manganese is absent, or very low, the predominant sulfide is FeS, which forms a eutectic with iron and has a tendency to form thin continuous films around the primary crystals during solidification of the steel. These films are liquid at the rolling temperature of steel and produce a condition of hot shortness. Manganese is outstanding in its power to combine with sulfur, and manganese sulfide has a much higher

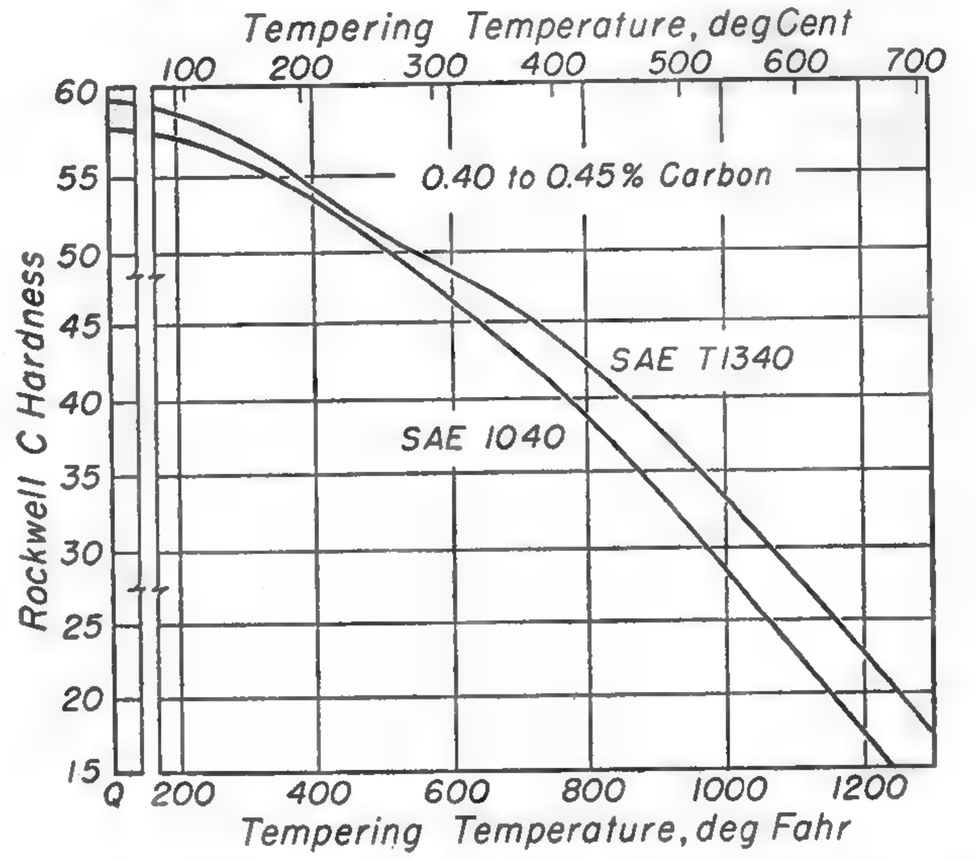

Fig. 12 Apparent effect of manganese on the behavior of steel during tempering.[6] Manganese content of SAE 1040 is 0.60 to 0.90%; that of SAE T1340 is 1.60 to 1.90%

melting point than the iron sulfide eutectic. It generally forms as separate globules, which remain solid at rolling temperature and have a less adverse effect on the hot working properties of steel. No other element seems to approach manganese in this property of preventing hot shortness. As a deoxidizer, manganese has an additive beneficial effect on the hot working characteristics of steel.

Effectiveness as an Alloying Element. Since manganese is present in all steels, there is no sharp dividing line between plain carbon steels and the so-called pearlitic manganese steels. Some authorities place the dividing line at 0.60% Mn, others at 0.80%, or even higher. Regardless of the arbitrary level at which manganese may be classified as an alloying element, it begins to function as an alloying element when present in amounts greater than about 0.60%, unless the sulfur content of the steel is unusually high.

Effect on Properties at Low Temperature. The transition zone from ductile to brittle fractures, as measured by notched-bar tests, is usually shifted to appreciably lower temperatures in both normalized, and quenched and tempered steels when the manganese content exceeds about 1%.[12] This is undoubtedly a secondary effect, stemming from the effect of manganese on the response to heat treatment.

Effect on Weldability. In common with most alloying elements which lower M_s and M_f temperatures, manganese increases the crack sensitivity of welded joints, particularly when this sensitivity is associated with higher carbon contents.*

* Unpublished results, Battelle Memorial Institute

Miscellaneous Effects. In pearlitic manganese steels, manganese does not appear to affect the resistance to oxidation, corrosion or abrasion one way or the other, nor does it appear to influence creep significantly at high temperatures.

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Molybdenum in Steel

By A. J. Herzig*

THE principal contributions made by molybdenum when it serves as an alloying element in steel, may be summarized in a discussion of the effects of molybdenum on the hardening reaction, on the extent of temper brittleness and related phenomena, and on the properties of steel at elevated temperatures. Research into the fundamental processes by which molybdenum influences the properties of steel has led to studies of the effect of molybdenum on the lattice parameter of alpha iron,[1] the sharing of molybdenum by the solid solution and the carbide phases,[2,12] the role of molybdenum in the hardening of eutectoid steel,[3] the effect of molybdenum on the diffusion rate of carbon in steel,[4] and the rate at which molybdenum diffuses in austenite and in ferrite.[5]

These studies indicate that molybdenum is present in steel in the solid solution phase and in the carbide phase. In alpha solid solution, molybdenum expands the ferrite lattice. In the carbide phase, it may be dissolved in iron carbide, or it may enter a complex iron-molybdenum-carbon compound. The diffusion rate of molybdenum is exceedingly slow as compared with the diffusion rate of carbon.

Table I. Effect of Molybdenum Content on the Hardness of Annealed, Low-Carbon Steels

Carbon, per cent	Molybdenum, per cent	VPN, 10-kg load
0.02	0.004	67
0.03	0.11	76.5
0.03	0.54	92.5
0.04	1.50	99.5

Molybdenum slightly accelerates the rate of diffusion of carbon in austenite at temperatures higher than 2000 F, and slightly retards diffusion at temperatures lower than 2000 F. The slight effect of molybdenum on the rate at which carbon diffuses in austenite at subcritical temperatures can account for only a small part of the pronounced effect of molybdenum on the transformation of austenite. In an unpublished thesis,[6] there is evidence that 2% Mo raises the lowest temperature of recrystallization of iron by about 360 F.

Table II. Effect of Molybdenum Content on the Hardness and Tensile Properties of Annealed, Low-Carbon Steels

Carbon, per cent	0.08	0.08	0.09	0.10	0.09	0.08
Manganese, per cent	0.25	0.28	0.22	0.30	0.22	0.26
Silicon, per cent	0.10	0.10	0.06	0.06	0.05	0.03
Molybdenum, per cent	0.48	1.05	1.49	1.99	3.02	4.97
Tensile strength, psi	53,350	57,860	59,510	70,070	66,880	58,520
Yield strength, psi	25,300	26,125	28,140	35,750	32,100	24,750
Elongation, per cent in 2 in.	38.8	37.0	33.0	29.3	31.5	39.0
Reduction of area, per cent	65.0	63.8	64.0	60.8	62.8	79.4
Brinell hardness number	97	105	109	134	124	112

It may be concluded that the contributions of molybdenum to steel are derived both from the effect of the element in solid solution in ferrite, and the effect on the composition, mode of formation, and distribution of the carbide.

The Effect of Molybdenum in Ferrite and Low-Carbon Iron Alloys. The solid-solution hardening effect of molybdenum in annealed, low-carbon iron-molybdenum alloys, as reported by Austin,[7] is given in Table I.

The hardness and tensile properties of annealed, low-carbon molybdenum steels are given in Table II.*

Table III. Hardness of Quenched Iron-Molybdenum Alloys

Molybdenum, per cent	*Hardness As-Quenched from 2597 F* Brinell	Rockwell C
0	60	..
3	100	..
5	110	..
10	146	7
15	173	10
20	200	23
22	225	26

Iron-molybdenum alloys of more than 6% Mo contain the intermetallic compound Fe_3Mo_2 (epsilon phase), if equilibrium is attained at room temperature. Because of the presence of Fe_3Mo_2, the hardness of an annealed iron-molybdenum alloy that contains more than 6% Mo, is somewhat higher than the hardness of the alloy when it is a true solid solution. However, it is possible to retain as much as 22 to 30% Mo in solid solution in alpha iron, by quenching from temperatures of the order of 2550 F. The hardness of quenched iron-molybdenum alloys determined by Sykes[9] is given in Table III.

Table IV. Hardness of Quenched Fe-C-Mo Alloys

Molybdenum, per cent	Quenching Temperature, deg Fahr	*Hardness — VPN 10-kg load* As-Quenched	Reheated 25 hr at 1150 F
7.33	1900	186	189
10.33	2000	199	285
12.67	2000	210	360
17.55	2200	267	541
21.61	2350	338	812

The hardness of quenched Fe-C-Mo alloys containing 0.07 to 0.08% C, 0.27 to 0.31% Mn, and 0.05 to 0.07% Si, is given in Table IV.* In the as-quenched condition, the alloy consists of a solid solution of molybdenum in alpha iron and small quantities of iron-molybdenum carbide.

* Climax Molybdenum Company, Detroit
Prepared for the Subcommittee on Alloying Elements in Steel

* Climax Molybdenum Company, Laboratory Records

Age Hardening Alloys. Iron-molybdenum alloys that contain 6 to 30% Mo can be age hardened. Some of the hardness tests of iron-molybdenum age hardening alloys reported by Sykes[9] are given in Table V.

Table V. Hardness of Iron-Molybdenum Alloys

Molybdenum, per cent	Hardness, Rockwell C	
	As-Quenched from 2597 F	Reheated 20 hr at 1157 F
10	7	25
15	10	35
20	23	51
22	26	59
25	35	63
30	40	65

Hardness tests of age hardening Fe-C-Mo alloys containing 0.07 to 0.08% C, 0.27 to 0.31% Mn, and 0.05 to 0.07% Si are shown in Table IV.

The Effect of Molybdenum on Medium-Carbon or High-Carbon Steels in the Pearlitic Condition. Alteration by molybdenum of the pearlitic structure of medium-carbon and high-carbon steels is the result of the formation of molybdenum-bearing carbides and retardation of the rates of nucleation and growth of pearlite. The interlamellar spacing of pearlite formed at 1200 F is noticeably increased by the addition of 0.15% Mo.[10, 11] Higher concentrations of molybdenum further increase the interlamellar spacing until, at 0.75% Mo, the structure is considerably modified. (See reference 11 for micrographs.) Partially bainitic structures can be formed in 0.30% Mo steels transformed at temperatures as high as 1100 F. The amount of bainite in the structure is increased as the molybdenum content is raised. Bainite does not form in plain carbon steels at these high temperatures. In molybdenum steels, the formation of bainite at such temperatures is the direct result of retardation of the pearlite reaction by molybdenum. Because of the long time required to complete transformation in molybdenum steels at these temperatures, some spheroidization occurs before transformation is complete; plain carbon steels transform at the same temperatures to lamellar products, which are spheroidized less readily than bainite.

In hypoeutectoid steels, the addition of 0.30% Mo affects the relative rate of nucleation and rate of growth of ferrite so that, in the range between 950 and 1100 F, ferrite no longer outlines the austenite grains, as in plain carbon steels, but tends to precipitate as an intragranular acicular constituent. It is for this reason that the Widmanstätten type of structure is readily formed in the medium-carbon molybdenum steels.

The formation of proeutectoid carbide in high-carbon steels is modified by molybdenum so that the development of acicular carbides is promoted.

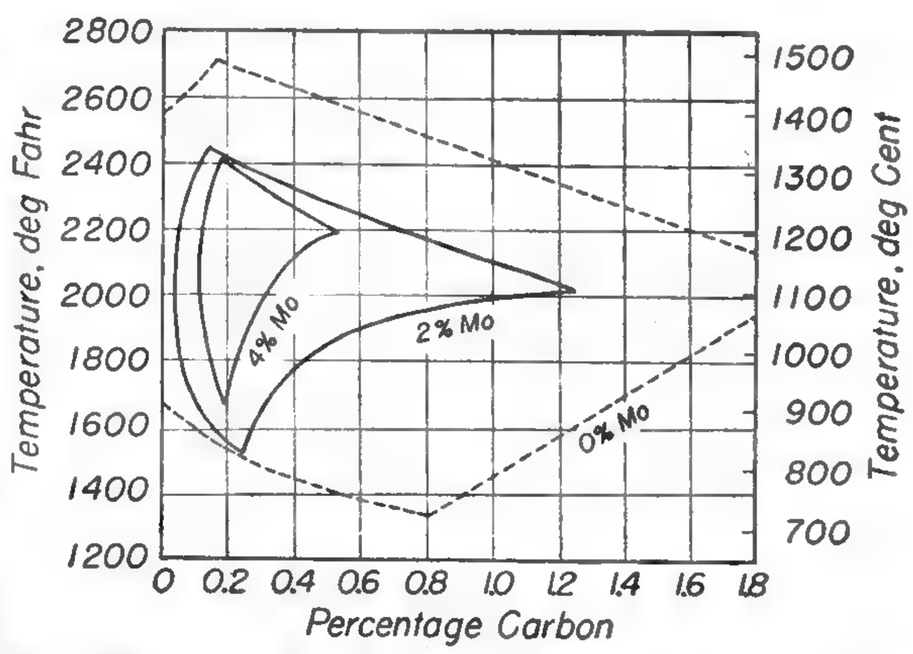

Fig. 1 Effect of molybdenum content on the temperature limits of the austenite phase field

The Effect of Molybdenum on Behavior During Heating for Hardening or for Normalizing. In heating a steel for hardening or for normalizing, the objective is to produce austenite free from ferrite. Residual free carbide in the austenite phase may or may not be desirable.

Figure 1 shows sections through the ternary Fe-C-Mo diagram, defining the composition and temperature limits of austenite free from ferrite and carbide.[12,16]

Figure 2 shows sections through the ternary diagram defining the composition and temperature limits for austenite free from ferrite but containing carbide as an equilibrium phase.[12,16] For the 2%, 4%, or 10% Mo regions of Fig. 2, compositions to the left of the Fe_3C solubility line, and within the area outlined, consist of austenite plus omega phase (Fe-Mo carbide), while compositions to the right of the solubility line consist of austenite plus omega plus Fe_3C.

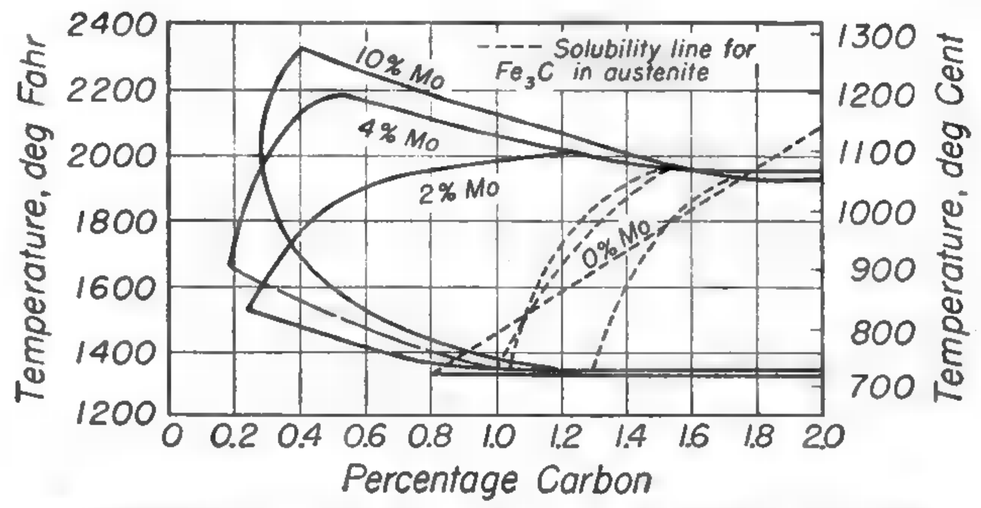

Fig. 2 Effect of molybdenum content on the temperature limits of the austenite-plus-carbide phase field

Bowman and Parke,[2, 3, 13] in a study of steels containing 0.38 to 0.83% C and as much as 1% Mo, showed that with molybdenum contents less than about 0.50%, some of the molybdenum was present in an orthorhombic carbide similar to cementite, Fe_3C, of the iron-carbon system, but that with molybdenum contents greater than about 0.50%, a face-centered cubic carbide $(Fe, Mo)_{23}C_6$ could be formed.

The rates of solution and the solubility limits of iron-molybdenum carbides in austenite have not been determined precisely. That molybdenum decreases the rate of solution of carbide in austenite is indicated in Table VI.*

In steel containing more than 0.50% Mo, it has been observed that solution of carbide is more difficult. For example, in a steel that contains 0.77% Mo, 0.78% C, more than 20 min would be required at a temperature of 2100 F to dissolve the carbides completely.

Table VI. Data on Solution of Carbide in Austenite

	Composition, percentage			
	Carbon	Manganese	Silicon	Molybdenum
Heat 1	0.73	0.69	0.17	0.017
Heat 2	0.74	0.70	0.18	0.29

Previous heat treatment of specimens: normalized at 1650 F, then annealed at 1450 F

Period in Furnace at 1410 F, minutes (Preheated to 1310 F)	Rc Hardness after Water Quenching		Microstructure after Water Quenching	
	Heat 1	Heat 2	Heat 1	Heat 2
3.5	30.6	29.6	M + P[a]	M + P
3.75	33.4	30.9	M + P	M + P
4.0	38.3	37.6	M + P	M + P
4.5	41.3	40.7	M + P	M + P
5.0	49.5	47.6	M + P	M + P
5.5	58.1	54.6	M + P	M + P
6.0	64.6	60.6[b]	M	M + P[b]

(a) M = martensite; P = pearlite
(b) Solution of carbide still incomplete. Development of peak hardness and fully martensitic structure in the steel that contains molybdenum would require longer time, higher temperature, or both.

The Effect of Molybdenum on Behavior During Cooling from the Austenitic State. Figures 3 to 14 show the effect of molybdenum on the structures formed during cooling from the austenitic state.[14] The specimens used in the investigation on which these charts are based were ¾ in. in diam by 1⅛ in. long, and had been normalized at 1800 F before the final heat treatment. Microstructures were observed at a point equidistant between the surface and center of the specimens.

* Climax Molybdenum Company, Laboratory Records

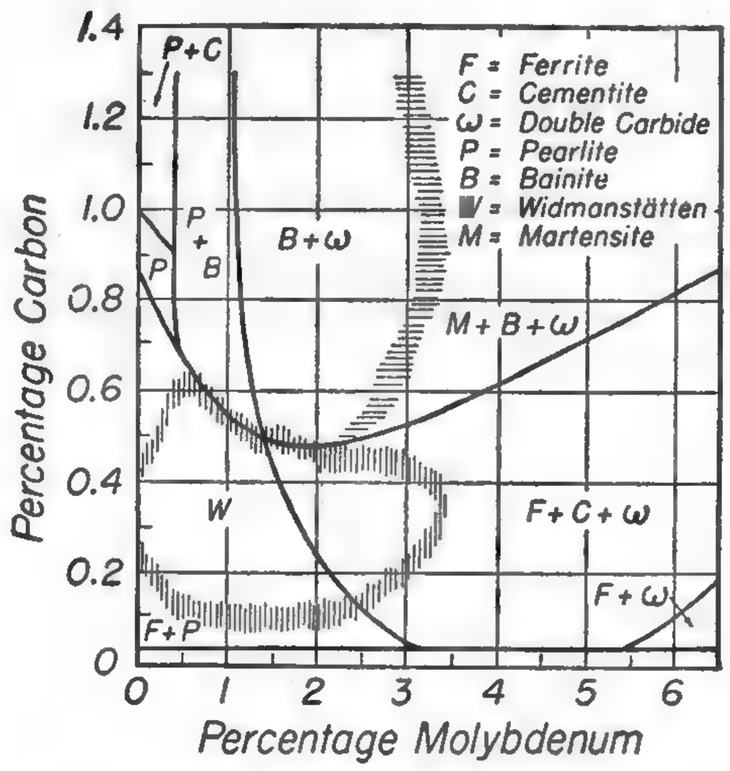

Fig. 3 Structural diagram for molybdenum steels cooled in air from 1850 F

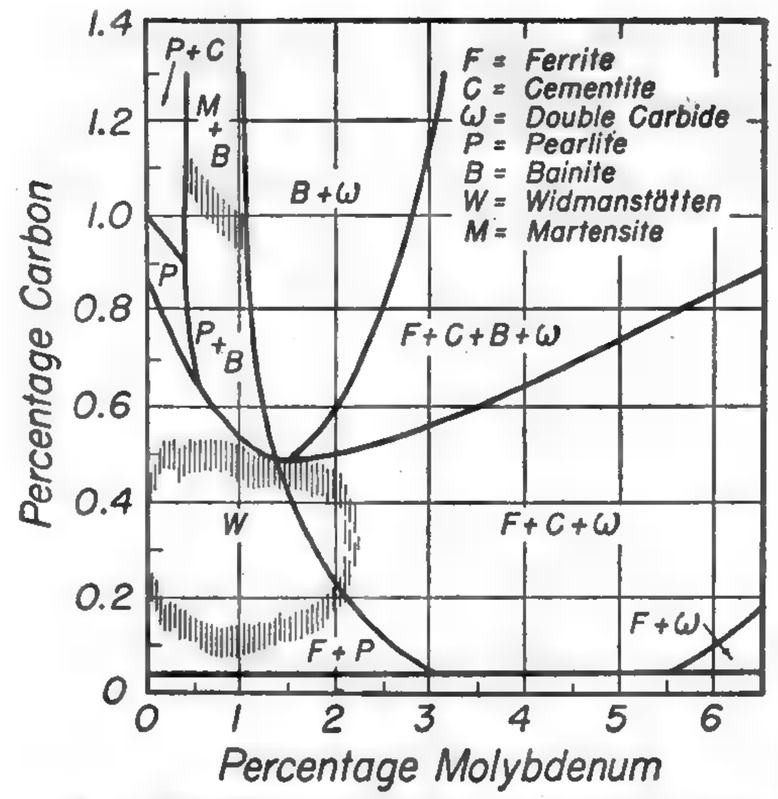

Fig. 4 Structural diagram for molybdenum steels cooled in air from 1750 F

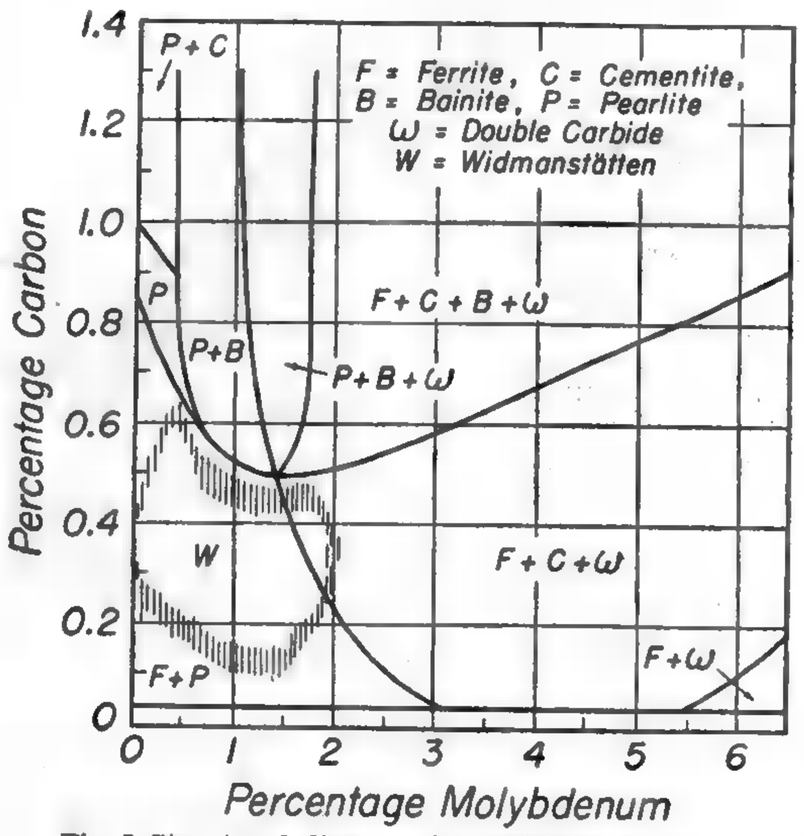

Fig. 5 Structural diagram for molybdenum steels cooled in air from 1650 F

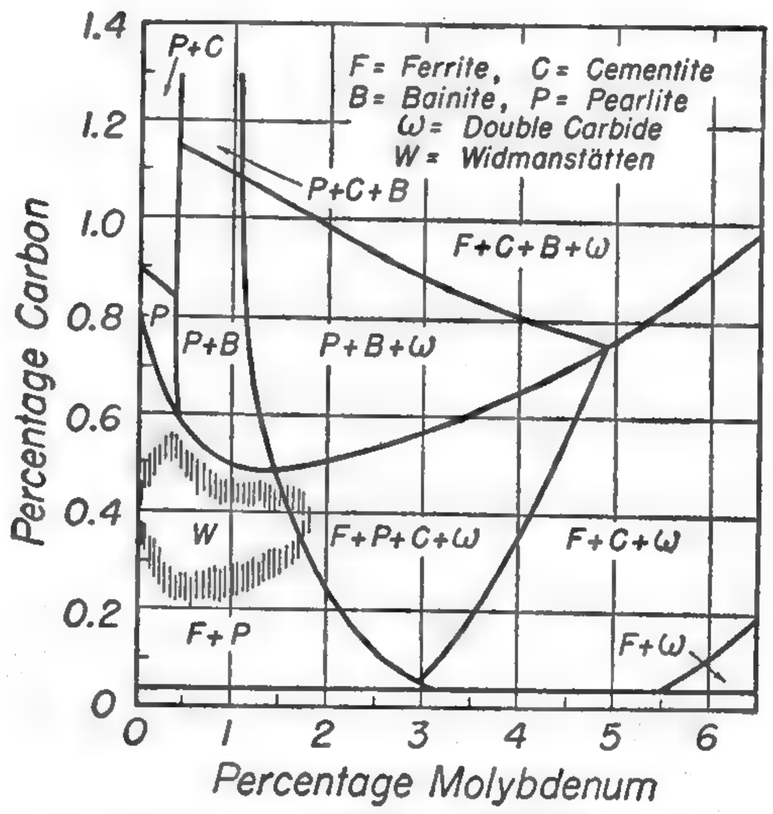

Fig. 6 Structural diagram for molybdenum steels cooled in air from 1550 F

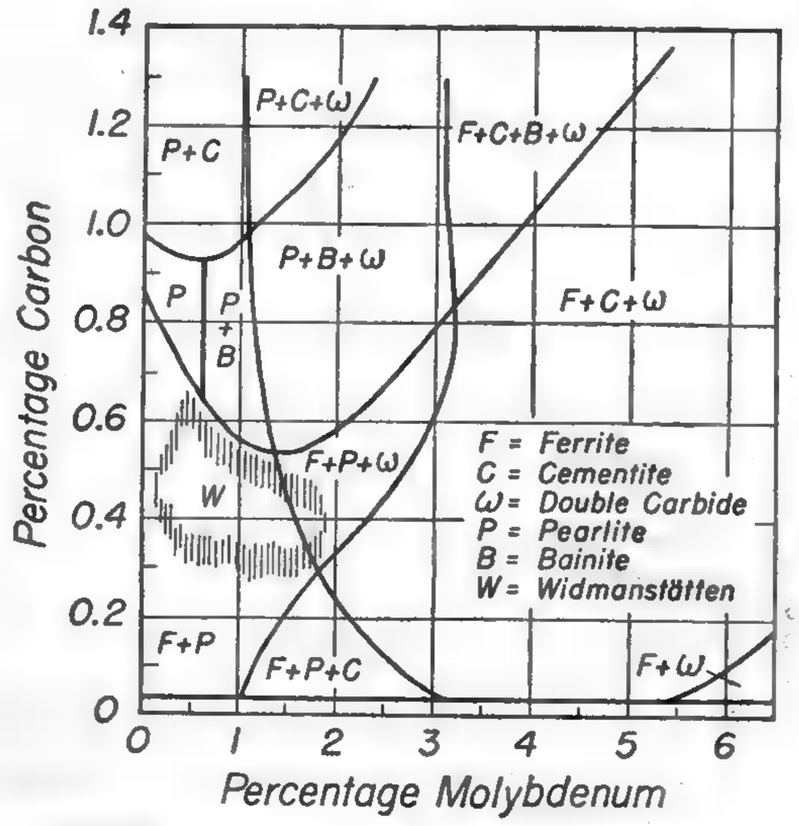

Fig. 7 Structural diagram for molybdenum steels cooled in air from 1450 F

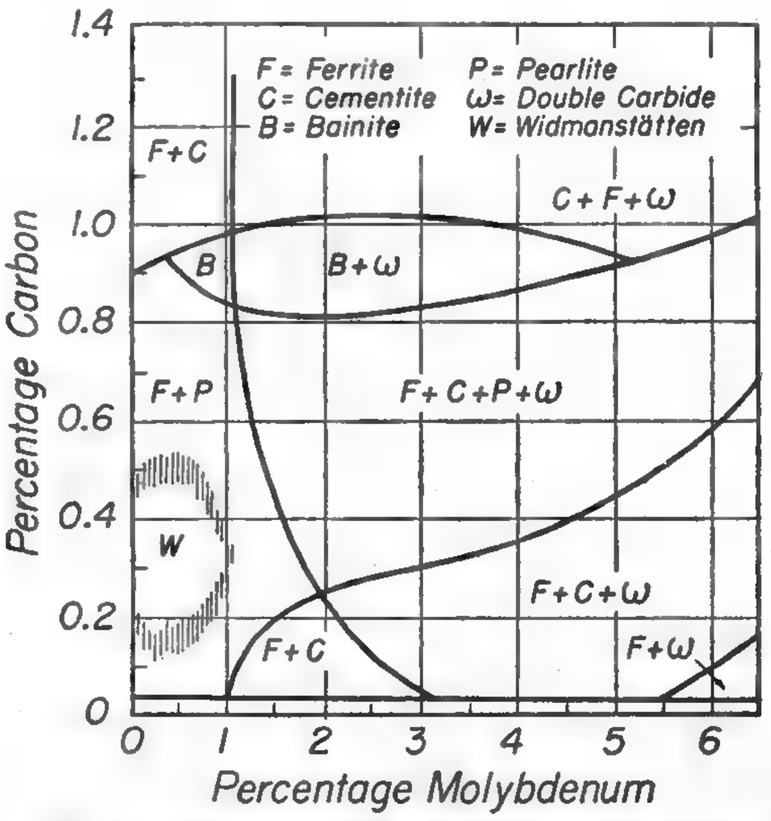

Fig. 8 Structural diagram for molybdenum steels cooled in air from 1350 F

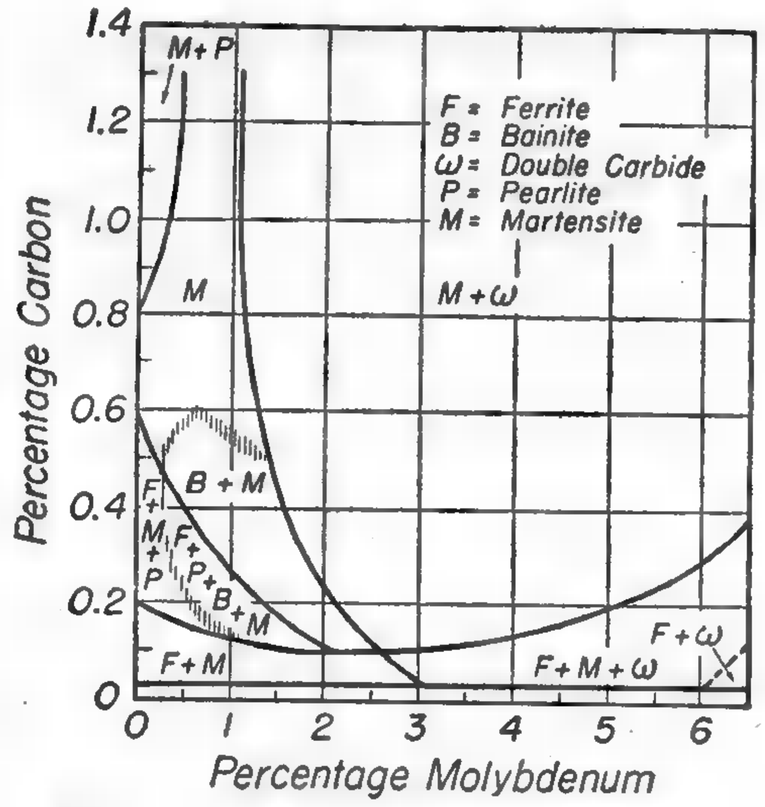

Fig. 9 Structural diagram for molybdenum steels quenched in water from 1850 F

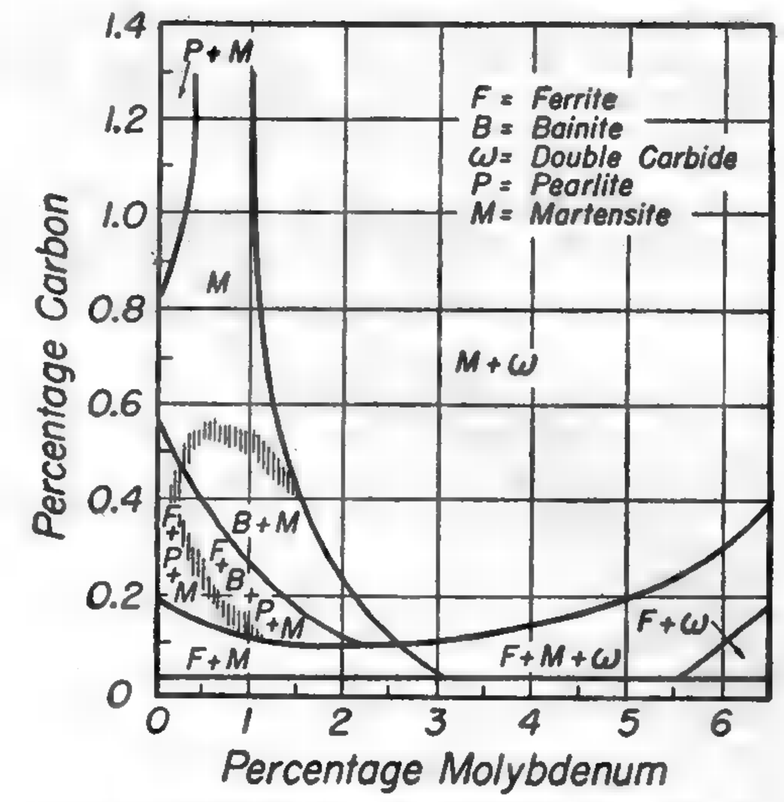

Fig. 10 Structural diagram for molybdenum steels quenched in water from 1750 F

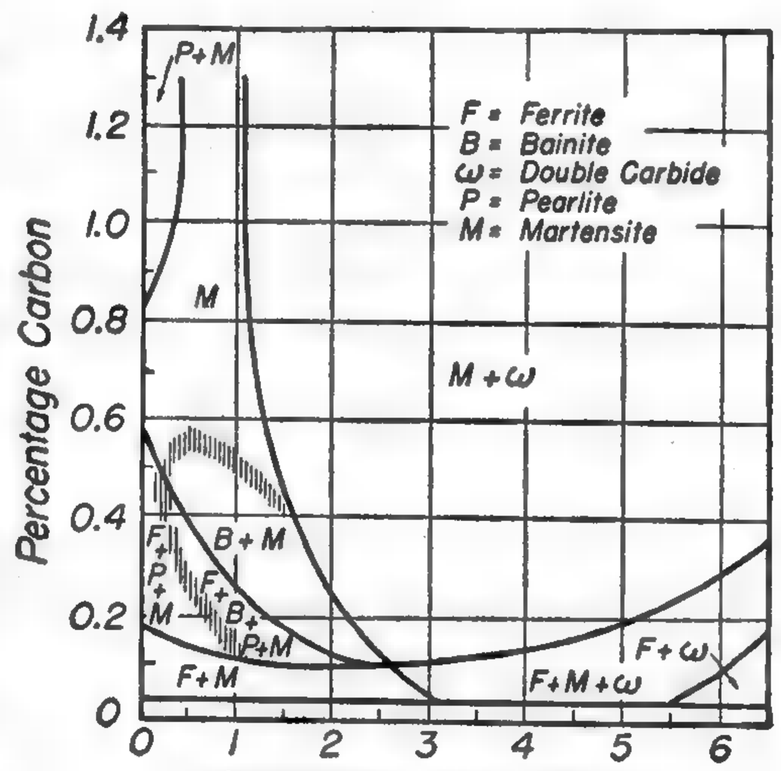

Fig. 11 Structural diagram for molybdenum steels quenched in water from 1650 F

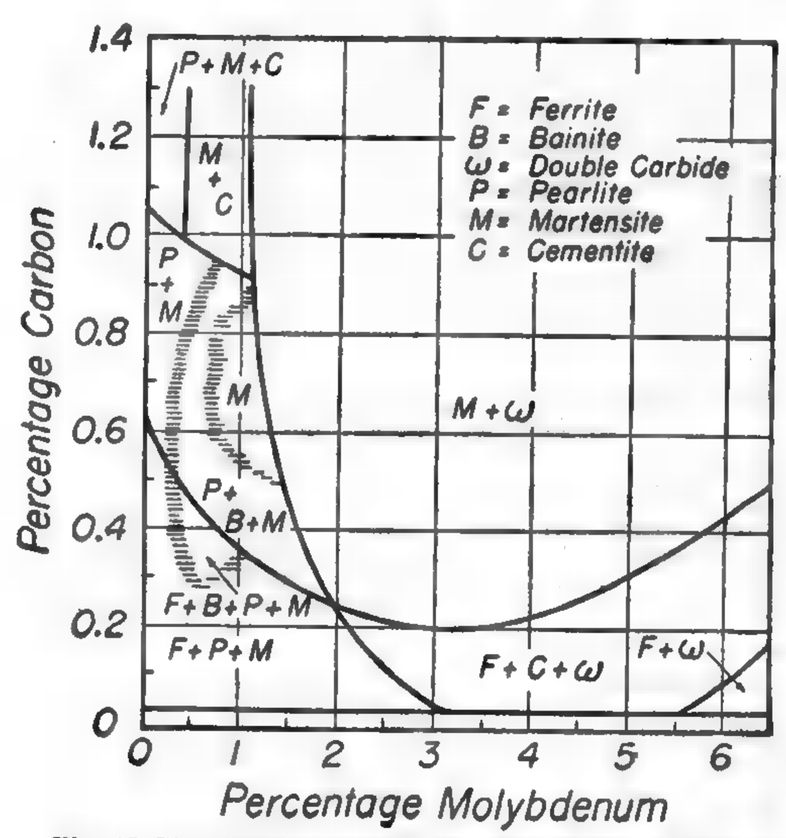

Fig. 12 Structural diagram for molybdenum steels quenched in water from 1550 F

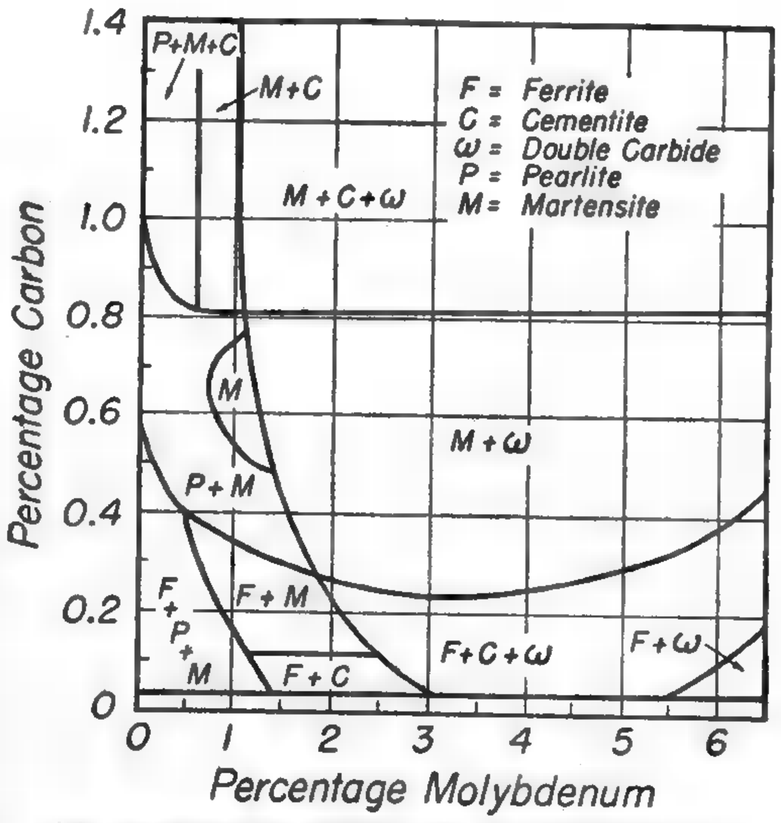

Fig. 13 Structural diagram for molybdenum steels quenched in water from 1450 F

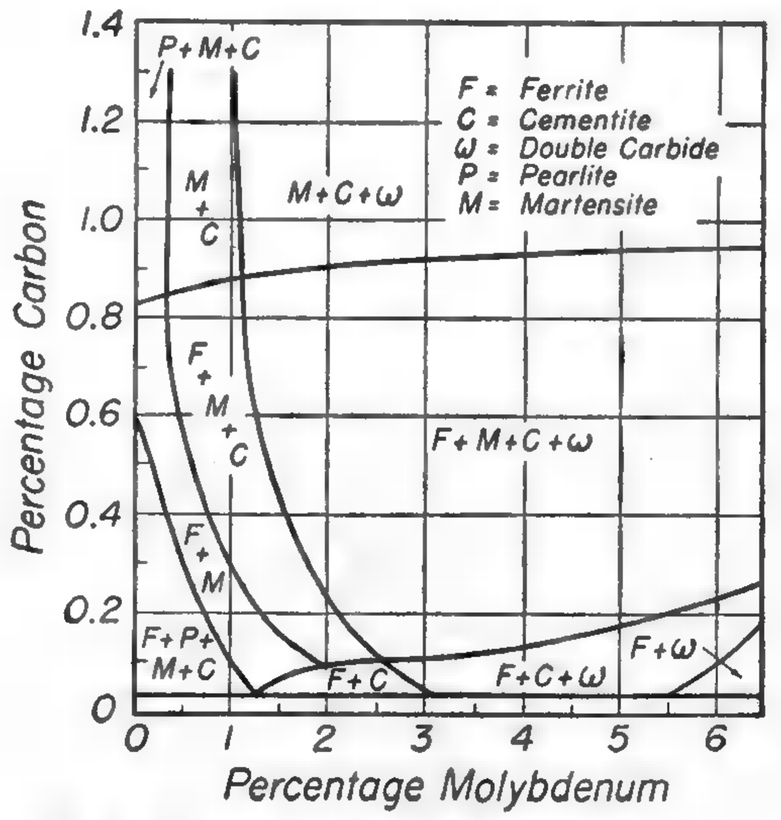

Fig. 14 Structural diagram for molybdenum steels quenched in water from 1350 F

In the Fe-C-Mo system, bainite is found in alloys containing about 0.70% C and 0.50% Mo or more, and air-cooled from higher than 1450 F. Water-quenched alloys contain bainite at lower concentrations of carbon and molybdenum.

The Effect of Molybdenum on the Tempering of Quenched Steels. At tempering temperatures of 450 F or less, a molybdenum content of 0.5% shows no important effect on the rate at which martensite decomposes in a eutectoid carbon steel.

At tempering temperatures higher than 500 F, molybdenum retards markedly the softening of martensite. Concentrations of molybdenum as low as 0.25% exert a significant effect on the hardness of martensitic medium-carbon and high-carbon steels when tempered within the range from 600 to 1200 F. In steels that contain 0.50% Mo, the retardation of softening is appreciably greater, and steels containing [illegible] to 5% Mo exhibit secondary hardening in the range from 750 to 1150 F.

Investigations of low-carbon (0.10 to 0.25%) steels have shown that molybdenum contents of 2 to 4% make the steels susceptible to secondary hardening effects. Secondary hardening is accomplished in both martensitic and non-martensitic prior structures, by tempering in the range from 1000 to 1150 F. This secondary hardening is accompanied by a loss of ductility as measured by notched-bar tests at room temperature. When the steels are tempered at higher temperatures, the hardness decreases fairly rapidly with rising temperature and ductility is restored.*

Molybdenum is a carbide-former and, at high tempering temperatures, it tends to segregate in the carbide phase. At 1300 F, tempering for long times may result in a high concentration of molybdenum in the orthorhombic cementite; or the face-centered cubic complex carbide $(Fe, Mo)_{23}C_6$ may be formed, if the molybdenum content is greater than 0.50%, as shown in Table VII.[2]

Table VII. Structure of Alloys Quenched and Tempered at 1300 F for 150 Hours

Carbon, per cent	0.82	0.78	0.74	0.83
Molybdenum, per cent	0.26	0.54	0.74	0.98
Molybdenum in ferrite, per cent	0.19	0.45	0.54	0.66
Molybdenum in carbide, per cent	0.73	1.29	2.23	2.81
Carbide Structure	Orthorhombic	Orthorhombic	Orthorhombic plus fcc	Fcc plus orthorhombic

Temper brittleness may be defined as the loss in notched-bar toughness that occurs in certain steels when they are exposed to temperatures in the range from 850 to 1100 F. The maximum rate of embrittlement occurs at about 950 F; the time required to lower notched-bar toughness a given amount at any temperature in the embrittling range varies with the composition of the steel.

Embrittlement may occur: (1) on tempering a susceptible steel in the range from 850 to 1100 F, (2) during slow cooling from a tempering temperature above 1100 F, or (3) on exposure to temperatures in the embrittling range after tempering at any temperature. Quenching after tempering at temperatures above 1100 F will minimize or eliminate temper brittleness by reducing the time the steel is subjected to temperatures in the embrittling range. If a steel is susceptible to temper brittleness, and if this steel must be tempered in the range from 850 to 1100 F to develop a desired hardness, embrittlement occurs during tempering. Quenching the steel after tempering in the embrittling range will not prevent or eliminate temper brittleness.

If embrittlement is fairly severe, the Izod and Charpy values at room temperature are appreciably lower when the steel is slowly cooled from tempering temperatures above 1100 F than when it is quenched from the same temperature. When a steel is only moderately embrittled, owing to low susceptibility or to short exposures to temperatures in the embrittling range, room-temperature Charpy and Izod values may not be significantly reduced, but the transition from a ductile to a brittle failure may occur at a higher temperature on the curve of Charpy value versus testing temperature.

Molybdenum minimizes temper brittleness in low-alloy steels. Molybdenum may retard the rate of embrittlement to such an extent that no loss of notched-bar toughness occurs under ordinary conditions of commercial heat treatment. Although chromium steels (0.75% Cr or more), chromium-nickel steels (with 0.75% Cr or more) and manganese steels are highly susceptible to temper brittleness, additions of molybdenum can reduce the susceptibility to a low order. When sufficient molybdenum is present, these steels may be tempered in the range from 850 to 1100 F, or they may be slowly cooled from tempering temperatures above 1100 F, without developing temper brittleness.

Special Effects of Molybdenum in Steel. *Properties at Elevated Temperature.* Molybdenum is the most effective alloying element that can be added to steel to increase the strength at elevated temperatures. Tests on vacuum-melted irons and iron-rich alloys of molybdenum and iron have shown that molybdenum in solid solution in ferrite increases the resistance to creep at 1000 F (*see* Table VIII).*

Table VIII

Effect of Molybdenum Content on the Creep Rate of Iron

Carbon, per cent	Molybdenum, per cent	Temperature, deg Fahr	Stress, psi	Creep Rate, per cent/1000 hr
0.012	0.0	1000	5,000	0.16
0.010	0.51	1000	7,500	0.032
0.009	1.01	1000	12,000	0.078

The magnitude of the effect in these 0.01% C alloys suggests that the contribution of molybdenum to the increased creep strength in steel does not depend on the presence of carbon. Molybdenum retards graphitization in steels intended for service at high temperature, although it is seldom used in percentages high enough to insure against graphitization for many years of such service.

The creep strength of carbon-molybdenum steels has been extensively investigated. An authoritative comparison with plain carbon steel is given in Table IX.[13]

The elevated-temperature hardness of the steels, compared in Table IX, is shown in Fig. 15.[13]

Table IX. Effect of 0.53% Mo on the Creep Strength of Steel

Composition, percentage					Temperature, deg Fahr	Stress, psi	
[illegible]	Mn	Si	S	P	Mo		Creep rate, 0.1%/1000 hr	Creep rate, 0.01%/1000 hr
0.35	0.55	0.19	0.03	0.016	...	850	7,600	3,400
0.16	0.66	0.24	0.027	0.015	0.53	850	28,500	20,000
0.16	0.66	0.24	0.027	0.015	0.53	1000	15,000	5,200

The same effectiveness in increasing the strength at high temperatures carries over to the use of molybdenum in the austenitic steels for applications at high temperature.

High Speed Steel. Compositions of high speed steel in which molybdenum is the principal alloying element have been widely used commercially. Molybdenum substitutes for tungsten in the function of imparting hardness at elevated temperatures ("red hardness") on the basis of one part of molybdenum to two parts of tungsten by weight. In commercial compositions, the substitution of molybdenum for tungsten is usually made only in part, since the steels often retain 1 to 6% W. The similarity in the hardness at elevated temperatures for a standard tungsten high speed steel and a 6% Mo, 6% W high speed steel is shown in Fig.

* Climax Molybdenum Company, Laboratory Records

16.[15] The greater susceptibility of molybdenum high speed steels to surface decarburization when heated in oxidizing atmospheres has been a major factor in retarding the more widespread use of such steels. Decarburization is overcome

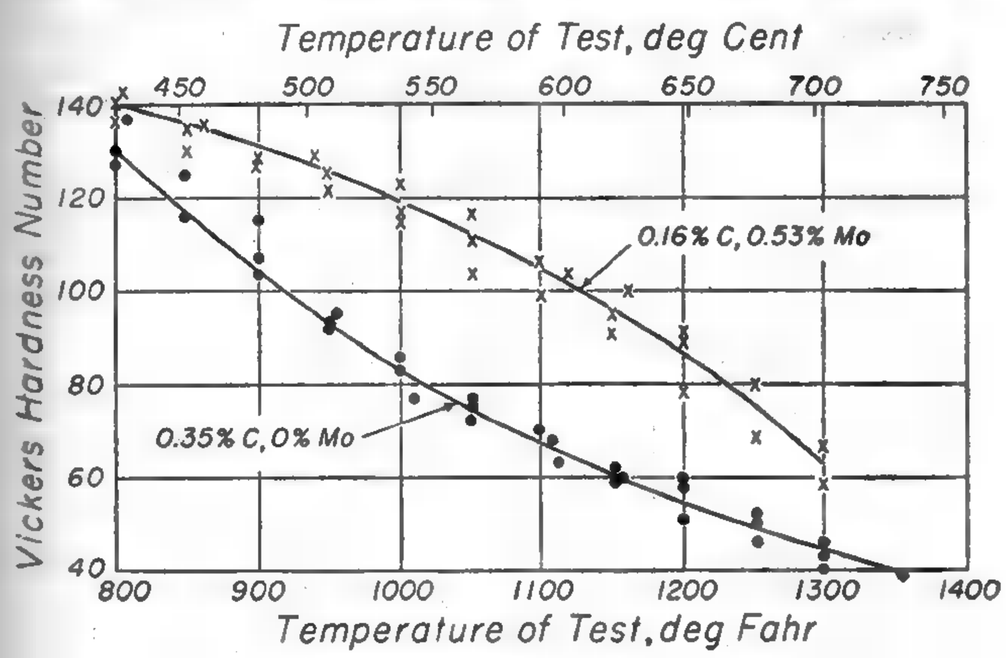

Fig. 15 Hardness of carbon steel and molybdenum steel at elevated temperatures

in commercial operations by the use of salt baths, borax coatings or controlled furnace atmospheres.

Resistance to Oxidation and Corrosion. Molybdenum steels, when exposed to oxidizing atmospheres, do not generate a tightly adherent protective scale.[8] Therefore molybdenum does not contribute toward resistance to oxidation, but the free-scaling characteristics of steels that contain molybdenum have been recognized as an advantage. In some forging operations, scale that does not free itself from the entire surface of the steel, sometimes has a serious effect on the accuracy of the forging. In cleaning operations, such as pickling and sandblasting, free-scaling characteristics are desirable. The detrimental effect of an adherent insulating scale during the hardening operation is widely recognized.

In some applications, marked improvement in resistance to corrosion is obtained by the addition of molybdenum to steel. In low-carbon steels that contain copper, experience indicates that molybdenum retards the rate of atmospheric corrosion. It has also been observed quite generally that a small addition of molybdenum to steel definitely increases the resistance to attack by 50% HCl; for example, in macro-etching. In stainless steels of the 18% Cr—8% Ni type, the use of molybdenum to enhance the resistance to certain types of corrosive mediums is also well established. The addition of 3% Mo to 18-8 steel contributes resistance to sulfite, sulfate, acetic acid, and acetate solutions. The same steels are less subject to pitting during corrosion in sea water. "Contact corrosion" or "differential aeration",

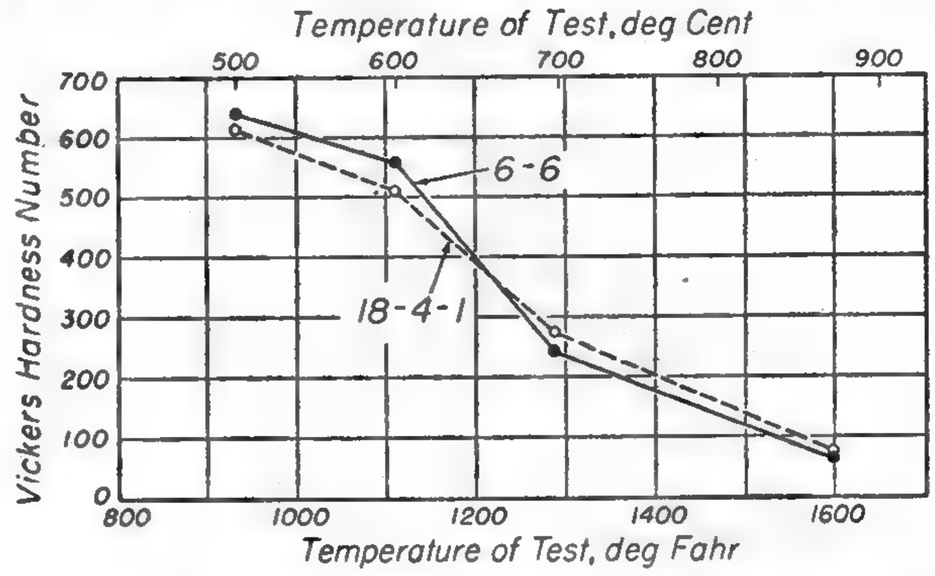

Fig. 16 Hardness of 18-4-1 and 6-6 high speed steels at elevated temperatures

resulting from the presence of foreign matter in corrosive mediums to which 18-8 steel is subjected, can be greatly minimized by the addition of molybdenum.

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Nickel in Steel

By J. W. Sands*

NICKEL is unique among the elements added to steel, in that it forms with iron a continuous series of solid solutions and has no demonstrated tendency to form compounds. Because of the effectiveness of nickel in depressing the temperature of the gamma-to-alpha transformation in iron, these solid solutions are wholly austenitic at room temperature, under any conditions of cooling, when the nickel content exceeds about 30%. Many of these austenitic alloys possess unusual magnetic, expansion and thermoelastic properties that make them of great value to industry. Although frequently referred to as "high-nickel steels", they are more properly iron-nickel alloys and, as such, are described in other sections of this Handbook.

Excluding the austenitic alloys, the major contributions of nickel to steel result from (1) the effects of nickel on ferrite, (2) the effects of nickel on the hardening reactions, (3) the effects of nickel on transformation temperature ranges, and (4) the effects of nickel on resistance to embrittlement at low temperature.

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Prepared for the Subcommittee on Alloying Elements in Steel

Nickel is ordinarily found only in the solid solution phase. Nickel is not a carbide-former. Apparently it does not greatly affect the diffusion rate of carbon in austenite, although the diffusion rate of nickel itself, which is very much slower than that of carbon, is affected markedly by variation in carbon content.[1] Nickel influences the rate of transformation of austenite more in the bainite temperature range than in the pearlite region. The effects of nickel may therefore be attributed, in the main, to the influence of nickel in ferrite and in the manner of formation and distribution of the carbide phase.

The Effect of Nickel in Ferrite and Low-Carbon Iron Alloys. When nickel is introduced in amounts up to approximately 5%, the effect of it in carbonless iron is to increase strength and hardness without inducing a comparable reduction in ductility. With contents beyond about

5% Ni, even slowly cooled alloys begin to assume a martensite-like nature, and strength and hardness increase more rapidly. With contents between about 15 and 20% Ni, slowly cooled alloys appear to consist almost entirely of such a martensitic structure[2, 3] and the maximum hardness of the system (about 300 Brinell) is attained. When the percentage of nickel is further increased, stable austenite appears

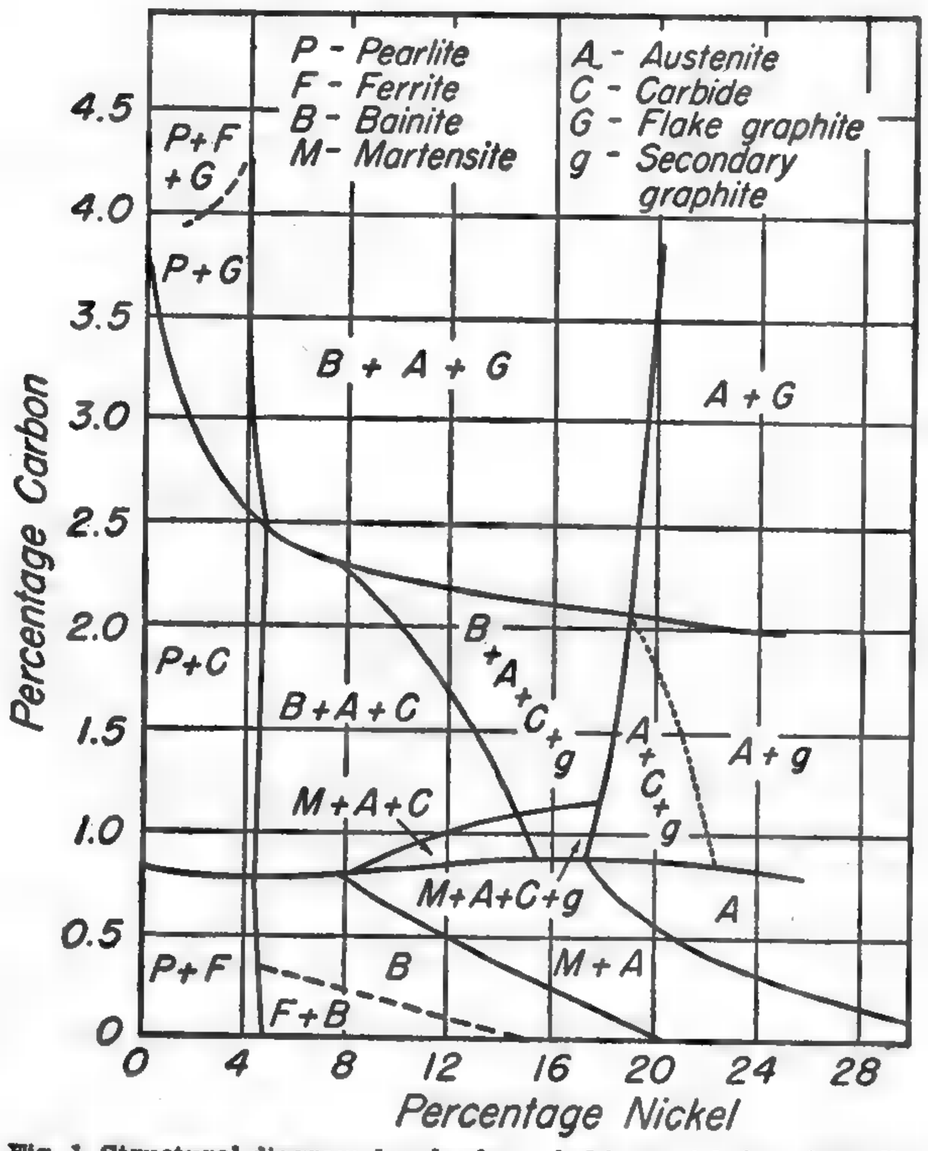

Fig. 1 Structural diagram for slowly cooled iron-nickel-carbon alloys. Specimens 1.2 in. in diam were cast into dry sand molds and cooled in the molds (Eash and Pilling)

in increasing quantities, with consequent decrease in hardness. Beyond about 35% Ni, the carbonless alloys are ordinarily wholly austenitic, not only at room temperature but at all subatmospheric temperatures. These changes are indicated by the zero carbon level in the Fe-Ni-C structural diagram shown in Fig. 1.

The transformation between the α and γ phases in the iron-nickel alloys containing less than 35% Ni, is so sluggish that there is a large hysteresis between the transformation temperature ranges during heating and cooling at ordinary slow rates. A region of two-phase equilibrium exists between α and γ, as indicated by the phase diagram of the iron-nickel system, page 1211 in this Handbook. The ranges of transformation temperature actually observed during slow cooling and slow heating are usually of more practical interest than the equilibrium lines. These ranges are shown in Fig. 2.*

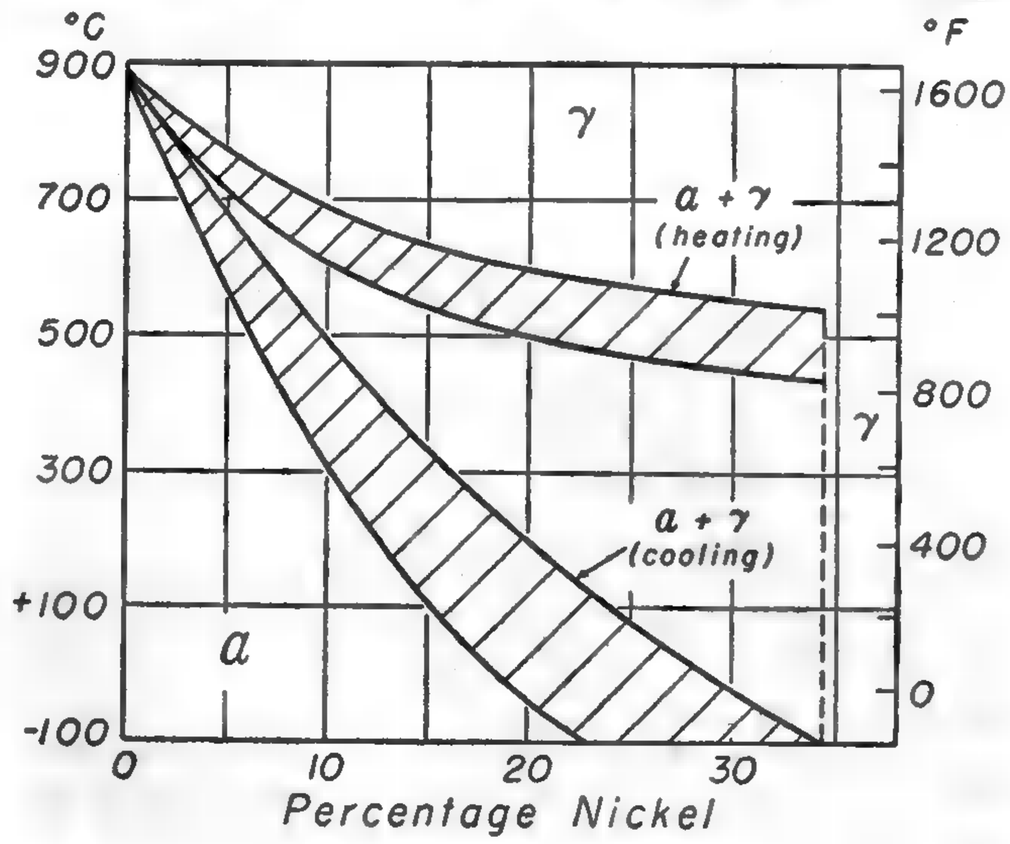

Fig. 2 Transformation temperature ranges of iron-nickel alloys during slow cooling and slow heating (Merica's selection of data)

In the ferritic alpha range it appears fairly well established that strength is increased about 4200 psi and hardness about 16 Brinell numbers for each 1% Ni. The relation is not strictly linear, however, as indicated by Fig. 3.

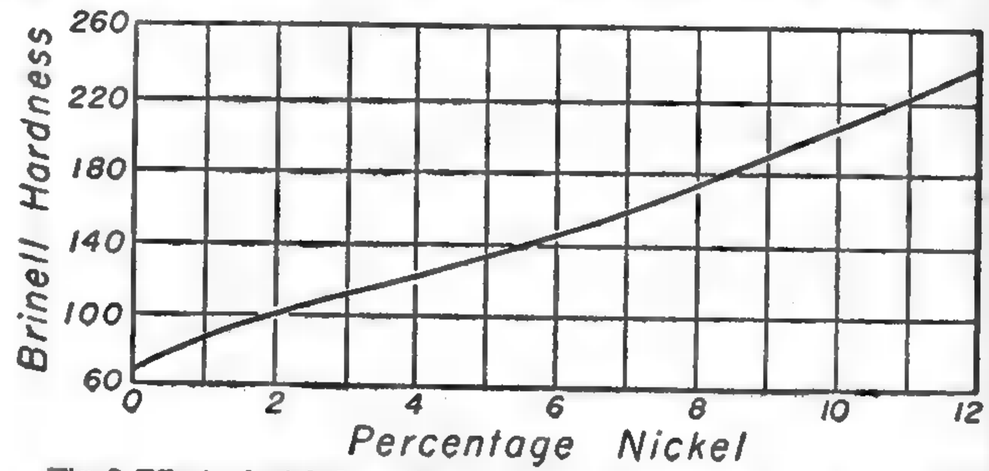

Fig. 3 Effect of nickel on the hardness of annealed pure iron. (Author's selection of the most probable values, based on references 2, 3, 4, 5, 6, 7, 8 and unpublished data)

Since nickel in steel has no affinity for carbon, the effect of nickel in low-carbon iron alloys is to superimpose this degree of strengthening and hardening upon the increases resulting from the additions of carbon. The effect of nickel on the tensile properties of annealed iron-carbon alloys that contain approximately 0.05% C is shown in Fig. 4.

The degree of strengthening imparted to iron by nickel, although less than the effect of carbon, is sufficient to be very useful when improved elastic properties are desired without deleterious effects on weldability, forming characteristics, or other factors adversely influenced by carbon. This is one of the major reasons for the extensive use of

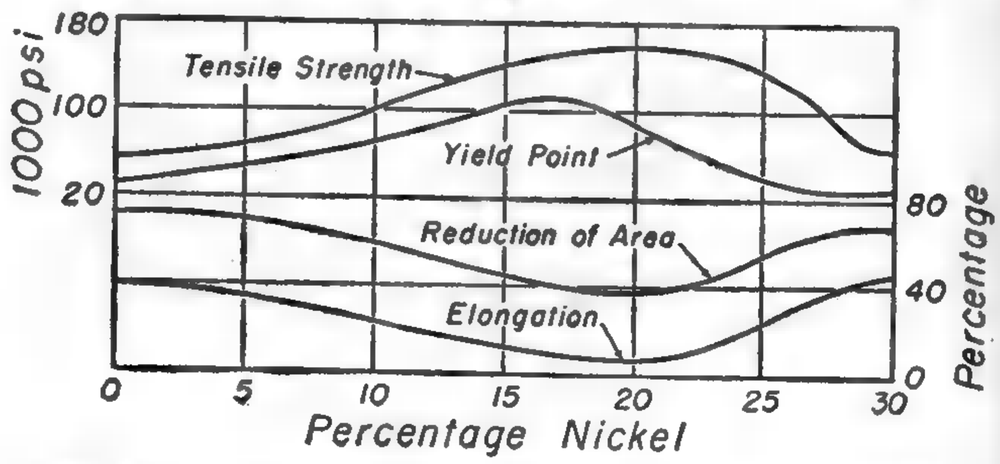

Fig. 4 Effect of nickel on the tensile properties of annealed low-carbon (0.05% C) steels. (Author's selection of the most probable values based on references 4, 5, 7, 8 and unpublished data)

nickel in the group of readily weldable, higher-strength structural steels currently in favor.

The Effect of Nickel on Medium-Carbon or High-Carbon Steels in the Pearlitic Condition. Pearlite in nickel steels is finer and therefore stronger and tougher than the pearlite of carbon steels, because it forms in a lower temperature range. Furthermore, nickel, in common with the other usual alloying elements, reduces the eutectoid carbon ratio; the reduction is approximately 0.04% C for each 1% Ni. Hence the structure of unhardened nickel steels contains a higher percentage of pearlite than plain carbon steels of similar carbon contents comparably treated. These two factors, particularly the fineness of pearlite, together with the strengthening of the ferrite, permit a given strength and hardness to be obtained in normalized nickel steels with considerably lowered carbon contents, thereby markedly increasing toughness and plasticity. Other advantages include improved resistance to fatigue. The following data

* P. D. Merica, 1939 Metals Handbook

are illustrative.[9] Both steels were normalized and tempered in the form of solid forgings 6 in. in diam.

Composition, per cent C	Mn	Ni	Tensile Strength, psi	Yield Point, psi	Izod Impact, ft-lb	Fatigue Limit, psi	Fatigue Ratio, per cent
0.46	0.62	...	86,200	51,300	17	40,000	46
0.24	0.94	2.70	86,300	63,000	105	54,000	■

The Effect of Nickel on Behavior During Heating for Hardening or for Normalizing. Since nickel is confined to the solid solution phase, it has no tendency to promote the formation of any complex carbides that might be difficultly soluble. Therefore, no special precautions are necessary in heating nickel steels for austenitizing. In fact, this operation is somewhat simplified by the fact that nickel lowers the transformation temperatures.

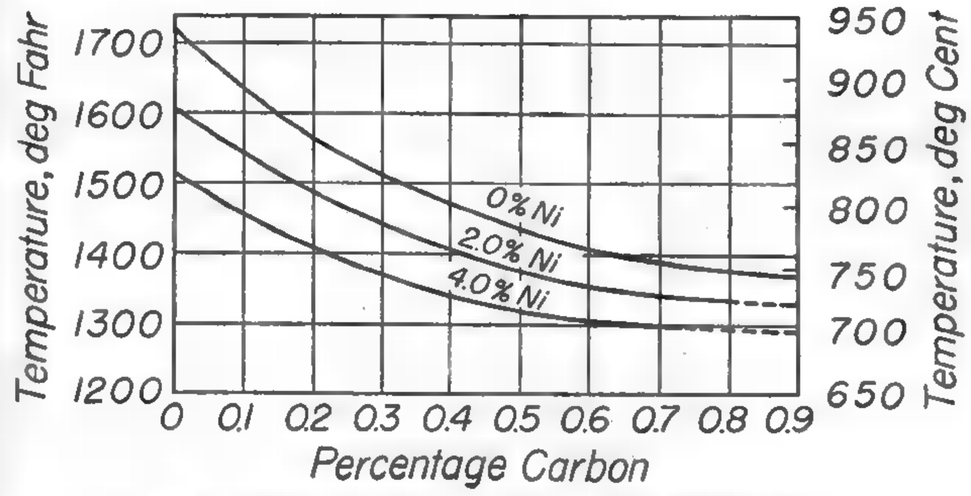

Fig. 5 Effect of nickel on the A_3 transformation during heating (Scott)

Nickel and manganese are the only two of the usual alloying elements that lower the eutectoid temperature,[10] and nickel is the more effective. Nickel steels thus allow lower heat treating temperatures, resulting in less scaling, warping and cracking, lowered fuel costs, and less wear on heat treating equipment. The degree to which nickel lowers the temperature of the A_3 range on heating, according to Scott,[11] is shown in Fig. 5.

Effect of Nickel on Behavior During Cooling from the Austenitic State. Nickel retards both pearlite and bainite transformations while steel is cooling from the austenitic state; the bainite is influenced more markedly than the pearlite. English investigators have reported that the high-temperature intermediate products formed by the decomposition of austenite in nickel steels at temperatures just lower than the pearlite range, appear to show less deterioration in mechanical properties, as compared with tempered martensite, than do steels that contain no nickel.[12] Thus nickel tends to minimize the deleterious effects of "slack" quenching.

The diagram presented as Fig. 1 shows the structures that result when Fe-Ni-C alloys are cast into dry sand molds in the form of arbitration bars, 1.2 in. in diam, and are cooled in the molds.[3] The diagram indicates what may be expected to result from commercial slow cooling; but it should be emphasized that the boundaries shown as lines do not represent sharp steps from one phase or group of phases to another. Instead these lines represent narrow transition zones where the constituents coexist. For contents lower than approximately 0.80% C, the diagram is relatively simple and reflects the strong austenitizing effect of nickel in conjunction with carbon.

Effect of Nickel on the Tempering of Quenched Steels. Nickel has no unusual effects on the tempering of martensite. No secondary hardening occurs in plain nickel steels and, consequently, there is no exceptional resistance to softening. With more carbon than the carburizing grades, the nickel steels exhibit the usual minimum in the curve of impact resistance versus tempering temperature, at about 500 F, because of decomposition of austenite retained after the quench.[13]

When quenched nickel steels are tempered for long periods of time, as is often necessary in treating heavy sections, care should be taken not to exceed the true Ac_1 temperature, which recent investigations have shown to be considerably lower than the apparent Ac_1 temperature indicated by *conventional* tests made under conditions of continuous heating.[14] This precaution is unnecessary when tempering periods do not exceed an hour or two; but longer holding at temperatures slightly higher than the true Ac_1 may result in the formation of enough austenite to produce a hardening of the steel during subsequent cooling, thereby necessitating a second tempering operation to break down the transformation products so formed. The Ac_1 temperature for 3½% Ni steel (2340, for example) is generally given as about 1280 F, but the safe upper limit for tempering temperature is actually only 1225 F. Safe upper limits for some other steels that contain nickel, together with the Ac_1 temperatures heretofore generally accepted, are given in Table I.

Table I. Apparent Ac_1 Temperatures and Maximum Tempering Temperatures for Steels Containing Nickel

Steel	Apparent Ac_1 Temperature, deg Fahr	Maximum Tempering Temperature, deg Fahr
2350	1280	1200
3140	1355	1275
3141	1350	1275
3250	1340	1275
3350	1290	1225
3440	1290	1225
4340	1350	1275
4640	1320	1250

Nickel appears to exert no curative effects when added to steel that is subject to temper brittleness, nor does it seem to induce or intensify this phenomenon.

Nickel will not induce graphitization in steels during the tempering operation, even if the steels are held within the tempering range during the extended periods necessary for tempering heavy sections.*

Special Effects of Nickel in Steel. *Carburizing Steels.* Nickel steels are particularly suitable for the case hardening process, as demonstrated by their popularity for the most exacting applications, such as aircraft engine gears and roller bearings of all sizes. Nickel steels provide strong tough cases, resistant to wear and fatigue, together with good core properties. The lower transformation temperature ranges and the smaller difference between transformation temperatures of case and core are conducive to simplified hardening treatments and lessened distortion. Nickel reduces slightly the rate of penetration of carbon into steel that is being carburized. Therefore the carburizing steels of higher nickel contents may require a somewhat longer carburizing period than carbon steels in order to obtain a given depth of case.

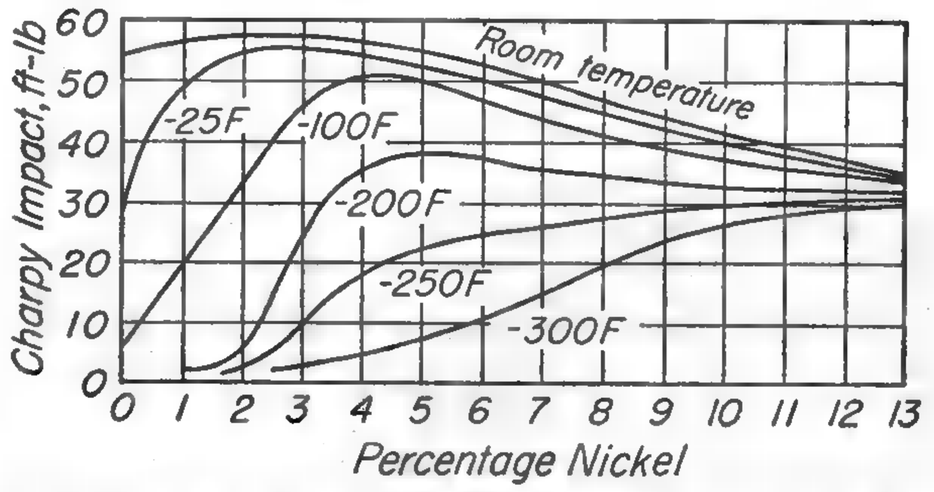

Fig. 6 Influence of nickel on the impact strength of normalized low-carbon (0.10 to 0.20% C) steels at low temperatures (Keyhole notch)

Resistance to Embrittlement at Low Temperature. As discussed in the article on page 204 in this Handbook, at reduced temperatures all ferritic steels suffer a deterioration in toughness that is most easily detected by the notched-bar impact test. This tendency to embrittlement

* Unpublished data from the International Nickel Company Research Laboratory

becomes important in connection with apparatus exposed to low atmospheric temperature or subatmospheric temperature artificially produced. Nickel is widely accepted as a specific for this difficulty and generous amounts appear indispensable for the very lowest temperatures.[15] Nickel is particularly effective in applications where quenching is not feasible and where normalized or normalized and tempered steels must be used. The effect of nickel on the impact resistance of normalized low-carbon steels at low temperature is indicated in Fig. 6.

Resistance to Corrosion. Nickel, in amounts ordinarily used in ferritic steels, is effective in imparting improved resistance to atmospheric corrosion, especially in industrial and marine atmospheres, as illustrated by the data plotted in Fig. 7.[16] In other environments no detrimental effects are observed, and in particular mediums, such as alkalies, there is a beneficial effect roughly proportional to the nickel content.

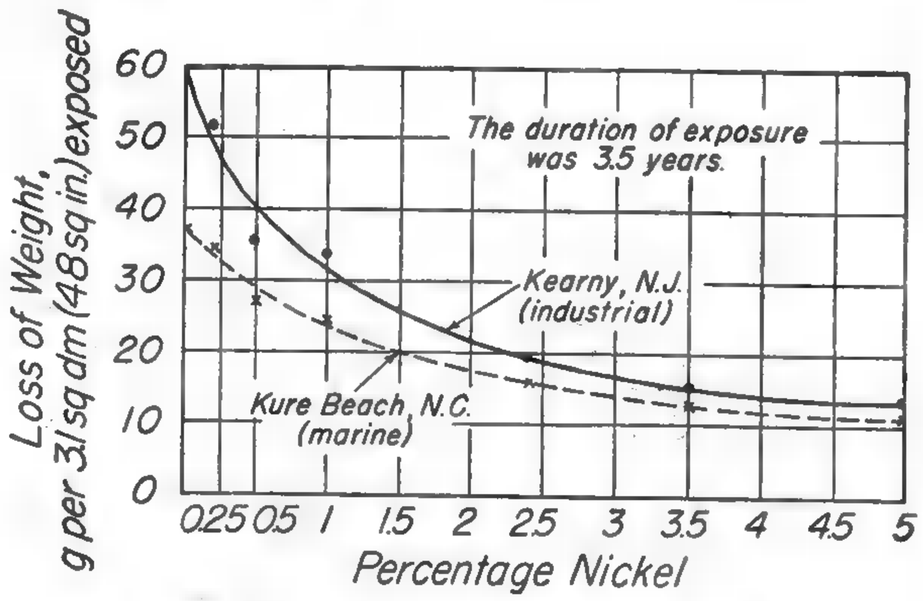

Fig. 7 Effect of increasing nickel content on corrosion in marine and industrial atmospheres (Larrabee)

Although few ferritic steels are used primarily for resistance to corrosion, this characteristic is obviously desirable, particularly when weight is reduced by the use of thinner sections of higher-strength steels. Many of the high-strength structural steels contain several alloying elements, and in these complex nickel steels, the beneficial effects of the individual elements on resistance to corrosion are mutually intensified.

In some steels improvement is essential both in resistance to corrosion and in strength. In the oil production field, for example, advantages are recognized in the use of nickel steels to provide a marked increase in resistance to corrosion fatigue in sucker rods, operating in contact with oil-well brines.

There are also applications in which it is economically preferable to use nickel steels, even when improved mechanical properties are not required. An illustration is the extensive use of nickel steels to resist attack by alkalies in chemical plants, petroleum refineries and pulp mills.

Precipitation Hardening. Nickel alone does not impart age hardening characteristics to steel, but it will do so in combination with certain elements, notably aluminum. This fact becomes an advantage in nitriding steels that carry aluminum as an essential constituent. By a fortuitous circumstance the optimum aging temperature coincides with the customary nitriding temperature. This allows an automatic hardening of the core during the nitriding operation, after fabricating operations have been carried out in the soft condition. Table II illustrates this effect in 3½% Ni nitralloy.

Table II. Core Properties of G and N Nitralloy[a]

	Nitralloy G Before and After Nitriding	Nitralloy N (with 3½% Ni)	
		Before Nitriding	After Nitriding
Tensile Strength, psi.....	138,000	132,400	190,250
Yield Point, psi.....	120,000	114,600	180,000
Elongation, % in 2 in.....	20	22	15
Reduction of Area, %	58	59	43
Brinell Hardness Number....	280	277	415

(a) Both steels quenched in oil and tempered at 1200 F

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Silicon in Steel

By Earl S. Greiner*

WHEN silicon is alloyed with iron under equilibrium conditions, the A_3 transformation is raised and the A_4 transformation is lowered. This results in a closed gamma "loop", having a gamma phase limit at 2.2% Si and 1170 C (2140 F).[1] Silicon forms a solid solution with the alpha phase and contracts the lattice.[2] The alpha phase solid solubility limit in the binary alloys varies from 15.2% Si at 600 C (1110 F) to 20.4% Si at 1030 C (1885 F).[3] The addition of carbon to iron-silicon alloys increases the solid solubility limit of the gamma phase to approximately 8% Si, at 0.5% C and 1160 C (2120 F).[4] The alpha can dissolve about 0.25% C in the alloy containing 10% Si at 1160 C (2120 F).[4] Silicon promotes graphitization in Fe-C-Si alloys.[5]

The Effect of Silicon in Iron and Low-Carbon Iron Alloys. According to data by Yensen,[6] the ductility of annealed iron-silicon alloys of high purity, containing from 0 to about 2.5% Si, is substantially the same as that of iron. The ductility decreases markedly, however, for alloys containing more than 2.5% Si. In general, the tensile and yield strengths of these annealed iron-silicon alloys increase with silicon contents to 4.5%, but decrease in the range from 4.5 to 6.5%.

The mechanical characteristics of four low-carbon steels (0.05 to 0.07% C) containing from 0.39 to 2.39% Si have been reported by A. Pomp[7] and are given in Table I. These steels were in the as-rolled condition, and the silicon was probably present in solution in alpha iron (ferrite). The increase of the Brinell hardness of these alloys with increasing silicon content is caused by silicon hardening the ferrite. The data in Table I also show that the addition of 2.39% Si, or less, to low-carbon alloys increases the tensile and yield strengths and decreases the reduction of area and impact values.

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Prepared for the Subcommittee on Alloying Elements in Steel

Table I. Mechanical Properties of Low-Carbon Structural Silicon Steel As-Rolled (Pomp[7])

Per Cent					Brinell Hardness	Tensile Strength, psi	Yield Strength, psi	Elongation in Approximately 3 in.,[a] per cent	Reduction of Area, per cent	Charpy Impact Value,[b] m-kg per sq cm
C	Si	Mn	P	S						
0.05	0.39	0.25	0.014	0.049	117	58,000	40,500	29.5	72	6.5
0.07	1.17	0.32	0.013	0.034	130	67,500	47,500	29.5	71.5	3.1
0.05	1.73	0.35	0.014	0.030	140	72,500	54,500	29.5	64	3.4
0.06	2.39	0.16	0.010	0.016	181	76,500	53,500	24.5	53.5	0.9

[a] Elongation in 70 mm determined [b] 10 by 11-mm cross section

The mechanical properties of as-rolled structural shapes of low-carbon, open hearth silicon steel have been reported by Meiser.[8] The averaged values of these properties for six steels that contained 0.15 to 0.19% C, 0.85 to 1.10% Si, 0.90 to 1.10% Mn, 0.030 to 0.035% P, and 0.030 to 0.040% S are as follows:

Tensile strength	77,800 psi
Yield strength (drop of beam)	56,500 psi
Elongation in approximately 8 in.	24.2%
Reduction of area	54.2%

The addition of silicon to iron promotes grain growth and increases the electrical resistivity. Yensen[9] reported the resistivity of iron-silicon alloys to be as follows:

Silicon, per cent	0	1	2	4	6
Resistivity, microhm-cm at 20 C (68 F)	9.6	23.0	34.2	56.5	78.7

The Effect of Silicon on Medium-Carbon or High-Carbon Steels in the Pearlitic Condition. Various investigators[10] have observed that silicon decreases the carbon content of the eutectoid. Bain[11] places the eutectoid in Fe-C-Si alloys containing 8% Si, at 0.33% C and 1120 C (2050 F).

According to Bain,[5] "the carbide is little modified by nickel, silicon or aluminum, except that graphitization is accelerated in their presence if little or no carbide-forming elements are present".

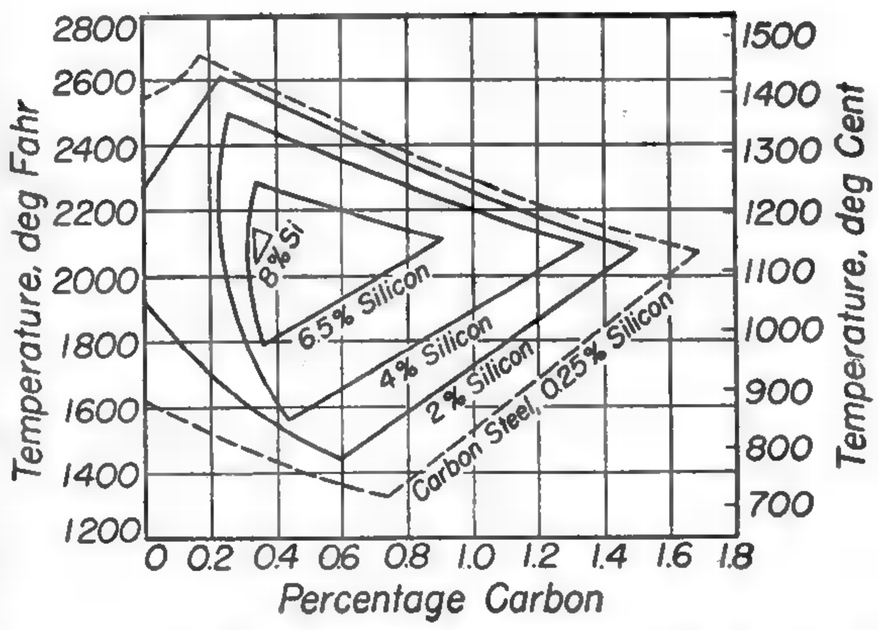

Fig. 1 Effect of several uniform silicon contents on the carbon limitations for pure austenite at elevated temperatures (after data of Satô; Bain[12])

The Effect of Silicon on Behavior During Heating for Hardening or for Normalizing. In connection with the heat treatment of steels for hardening or normalizing, it is necessary to heat the materials so as to transform the ferrite to austenite. The "triangles" in sections through the ternary Fe-C-Si equilibrium space model, according to the data of Satô,[12] define the composition and temperature limits for producing pure austenite in these alloys (Fig. 1). Compositions lying progressively to the left of the "triangles" in Fig. 1 will consist largely of austenite, but with increasing amounts of ferrite (α or δ iron). Those compositions lying progressively to the right of the triangles, at temperatures below the vertices at the right, will consist largely of austenite, but with increasing amounts of carbide or graphite, or both for some high-silicon alloys. In general, the sections in Fig. 1 show that silicon steels require higher austenitizing temperatures than plain carbon steels.

The Effect of Silicon on Behavior During Cooling from the Austenitic State. Kramer, Hafner, and Toleman[13] have shown that silicon promotes the hardenability of steels. For numerical data, see the article on page 494.

The Effect of Silicon on the Tempering of Quenched Steels. The curves in Fig. 2, from Bain,[14] show that increasing the amount of silicon in 0.50 to 0.55% C steels that have already been quenched, results in increasing the hardness after tempering at corresponding temperatures. This increase in the hardness of quenched and tempered medium-carbon silicon steels is probably caused by silicon strengthening the ferrite, which contains the carbide particles.

When some hardened alloy steels are tempered and slowly cooled from the tempering temperature, they are susceptible to a phenomenon known as temper brittleness. If this brittleness develops, the impact resistance of the steel decreases. The effect of silicon on the susceptibility of steels to temper brittleness is not well established. Experiments by Burns[15] on silicon-manganese steels containing 0.4 to 0.5% C indicate, however, that the susceptibility to temper brittleness increases with the silicon content, but it is mainly influenced by the manganese. Temper brittleness in silicon-manganese steels containing 1% Mn, does not become serious until the silicon approaches 1.5 to 2%. If the steels contain less than 0.6% Mn, as much as 3% Si may be present without serious susceptibility to temper brittleness.

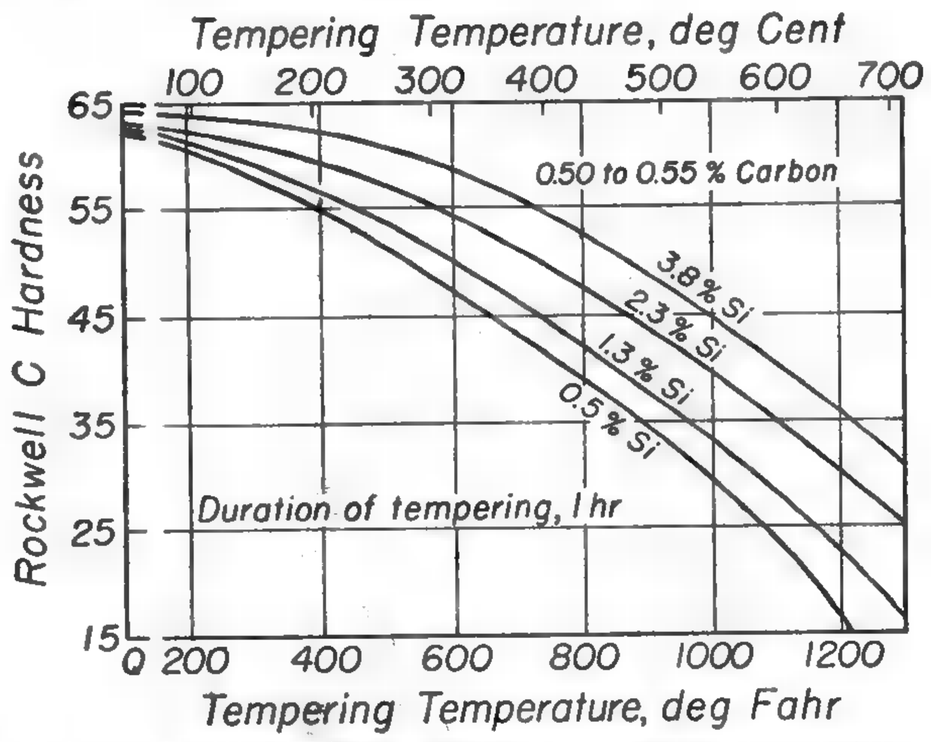

Fig. 2 The softening with increasing tempering temperature, of quenched 0.50 to 0.55% C steel as influenced by silicon content (Bain[14])

Special Effects of Silicon in Steel. *Resistance to Oxidation and Corrosion; Decarburization.* Silicon is added to chromium, chromium-tungsten and chromium-nickel steels to increase the resistance to high-temperature oxidation. This characteristic makes some of these materials useful for such applications as exhaust valves in internal combustion engines.[16] Tests by Mathews[17] indicate that the addition of about 2% Si, or less, to the 18% Cr, 8% Ni (18-8) stainless steel, increases the resistance to scaling at 980 C (1800 F). One of the commercially produced types of the 18-8 stainless steel contains from 2 to 3% Si.

According to Houdremont and Bennek,[18] silicon-manganese steels exhibit greater resistance to scaling and greater decarburization of the surface than similarly treated manganese steels. Comparative data on the scaling and de-

carburization of these materials after heating at 850 C (1560 F) for 10 hr are as follows:

Composition, per cent C	Si	Mn	Weight Loss Through Scaling, mg per hr per sq m	Decarburization mm	in.
0.47	1.54	0.56	38.4	0.51	0.0201
0.53	1.54	0.61	41.5	0.55	0.0216
0.35	0.32	1.75	76.0	0.00	0.00
0.60	0.37	1.73	75.8	0.00	0.00

For materials requiring resistance to corrosion by certain inorganic acids and other chemicals, the 14 to 16% Si cast irons, containing 1% C or less, have a wide field of application.[19] These alloys are not machinable, except by limited turning with tungsten carbide tools; hence castings must be finished by grinding. These materials are also used for apparatus requiring resistance to erosion as well as to corrosion.

Magnetic Characteristics. Alloys of iron and 0.5 to about 5% Si have lower hysteresis and eddy current losses than iron in alternating magnetic fields. Furthermore, the magnetic permeability in direct-current fields is satisfactory for many applications. Because of these features silicon steel is extensively used for electrical equipment.

Table II

Typical Uses and Magnetic Core Losses of Silicon Steels[20]

Grade	Typical Uses	Silicon, (nominal) per cent	Total Core Loss,[a] 60 Cycles, 10,000 Gausses No. 29 Gage (0.014 in.) Sheet, watts per pound
Armature	D-c motors of moderate efficiency; intermittent duty a-c motors	0.5	1.30
Electrical	A-c motors of moderate efficiency; d-c motors of high efficiency	1.0	1.17
Dynamo	Radio receiver power transformers. High efficiency rotating electrical machinery	2.5	1.01
Dynamo Special..	Stators of induction motors and small transformers	3.25	0.82
Audio Transformer "A" and "C".	Audio, current and instrument transformers	3.60	0.58, 0.72
Transformer "C".	Power and distribution transformers	4.25	0.72
Transformer "A" and "B".....	Power and distribution transformers	4.75	0.58, 0.65

[a] Guaranteed maximum

Silicon steel sheets and strip for electrical purposes are prepared commercially by a number of organizations. Some of the grades are listed in Table II, along with typical uses, nominal silicon contents, and maximum total core losses (hysteresis plus eddy current losses) for 0.014-in. sheet materials made by one commercial supplier.[20]

Among the deleterious impurities, carbon, sulfur and oxygen are considered to be the most harmful to the magnetic properties of silicon steel, and should therefore be eliminated or maintained in as small quantities as possible for such applications.

Silicon steel sheets are prepared either by hot rolling[21] or by hot rolling prior to cold rolling.[22]

The annealing of silicon steel sheet or strip for magnetic applications is important, and a number of practices are used, depending on the quality desired. These heat treatments remove the mechanical strains and improve the magnetic characteristics. One method[23] for annealing consists of heating the material, protected against oxidation, at 800 to 1000 C (1470 to 1830 F) or higher, and then cooling it slowly. Another treatment[22] for silicon steel, initially hot rolled and finally cold rolled by a special process, consists of coating the sheets with a refractory powder and then annealing them in flat packs at 1200 C (2200 F) for 60 hr in purified hydrogen. The material produced by the latter method has a high degree of preferred orientation of the crystals, which affects the magnetic properties.

Laminations from this silicon steel sheet are frequently annealed again after punching, in order to remove the harmful effects of the cold work on the magnetic and mechanical properties. One recommended treatment for improving the characteristics of silicon steel laminations[20] after stamping, consists of heating to 760 to 790 C (1400 to 1450 F) for 2 hr, under nonoxidizing conditions, and then slowly cooling. For additional information on magnetically soft materials, see the article on page 587.

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Titanium in Steel

By G. F. Comstock* and S. F. Urban*

UNTIL recently, titanium was used in the steel industry almost exclusively for deoxidation, leaving negligible residual amounts of titanium in the solid steel.[1] The earliest use of titanium as an alloying element was in austenitic stainless steel, where titanium contents greater than a critical minimum were found to prevent intergranular corrosion and embrittlement by stabilizing the carbon as titanium carbide.[2] Titanium has been used also for stabilizing the carbon in plain chromium steels, to prevent hardening during rapid cooling in air.[3] At present such applications of titanium are being extended to plain carbon[4] and other low-alloy steels.[5] To qualify as an alloying element in steel, titanium should be present in amounts of 0.025% or more; smaller titanium contents are typical of steels that have been deoxidized by titanium, in which the effect of the element as an alloy addition is not attained.

Titanium is discussed here as an alloying element in steel, exclusive of stainless and high-alloy types.

The Effect of Titanium on the Strength of Ferrite. In steel of very low carbon content or in ingot iron, which is not hardenable by heat treatment, titanium increases the hardness and strength by entering into solid solution in the ferrite. Titanium has been reported[6] to have a greater effect in this respect, per weight percentage in the ferrite, than any of the usual alloying elements except silicon and beryllium. The relative effects of the various alloying

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elements on the strength of ferrite are indicated by Fig. 1.[6] Since hardness is known to be closely related to tensile strength, these same relations may safely be assumed to apply with reasonable accuracy to the effects of the elements on hardness of ferrite, regardless of heat treatment.

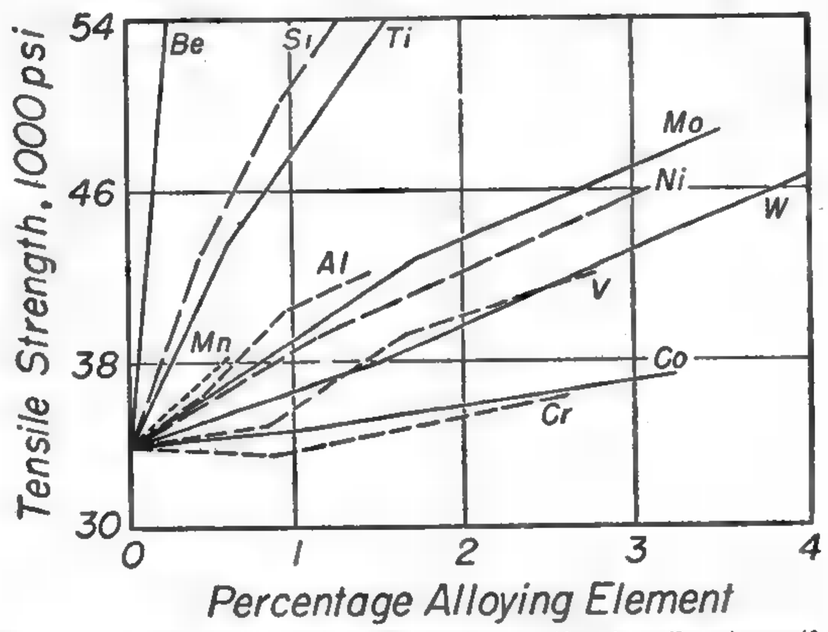

Fig. 1 Influence of alloying elements on the tensile strength of ferrite (Lacy and Gensamer[6])

Titanium in Age Hardening Reactions. The phase diagram of the iron-titanium system indicates a decrease in solubility of the compound Fe_2Ti in ferrite with decreasing temperature, so alloys that contain about 2.5 to 7% Ti can be temper hardened or age hardened by appropriate heat treatment. The effects of titanium content and aging or tempering temperature are shown in Fig. 2.[8]

Similar effects are obtained in medium-carbon and high-carbon steels, though perhaps through a more complicated set of reactions, since titanium does not form double carbides as do most alloying elements. Alloys that contain appreciable quantities of carbon can be age hardened if the quench before aging is from a temperature high enough to dissolve the titanium carbide. The minimum temperature required for accomplishing this end varies with the carbon and titanium contents and can be understood best from a study of the Fe-Ti-C system, discussed on page 1256 in this Handbook and in other technical publications.[10,11] One specific illustration of age hardening in 0.21 to 0.24% C steels is shown in Fig. 3.[11]

Elevation of Grain-Coarsening Temperature by Titanium. When used in sufficiently large amounts in steel, titanium produces a finer grain size. In this respect its action is similar to that of vanadium or aluminum. However, when titanium is added along with aluminum, the fine grain size is kept from coarsening at higher temperatures than when aluminum is used alone, even in abnormally large amounts. A comparison of the ASTM austenitic grain sizes in a titanium steel and a plain carbon steel not treated with aluminum, after normalizing at various temperatures, is given in Table I,[12] and the effects on

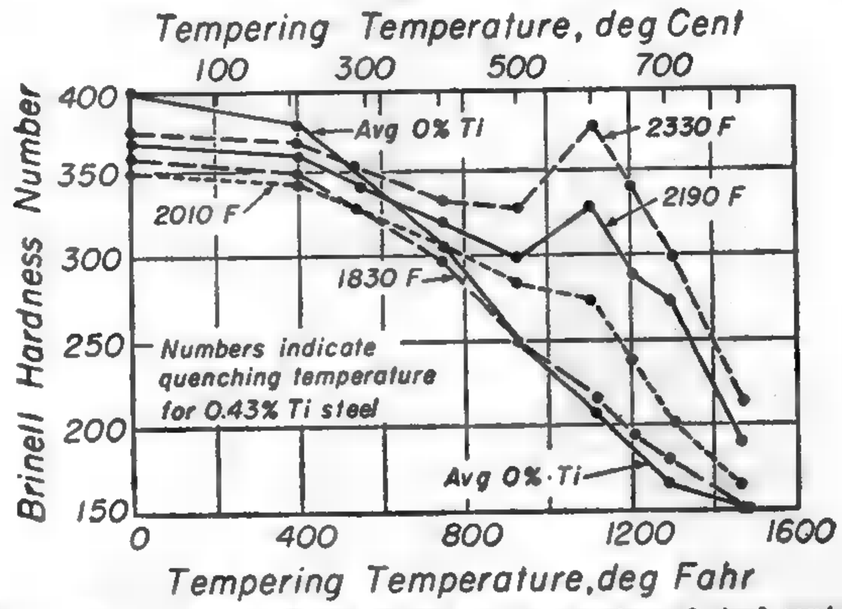

Fig. 3 Changes in hardness during the tempering of steel containing 0.21 to 0.24% C (Houdremont, Naumann and Schrader[11])
The numbered curves apply to 0.43% Ti steel after water quenching from different temperatures, and the other curve applies to plain carbon steel quenched from 1650 to 2330 F (900 to 1280 C).

Table I. Grain Sizes of Steels Normalized at Various Temperatures[12]

Steel	Composition, percentage C	Mn	Si	Ti	ASTM Austenitic Grain Size Normalized at 1600 F	1750 F	1900 F	2150 F
O	0.36	0.68	0.22	...	3	3 to 4	2 to 3	1 to 2
T	0.37	0.63	0.26	0.35	8 to 9	8	7 to 8	3 to 4

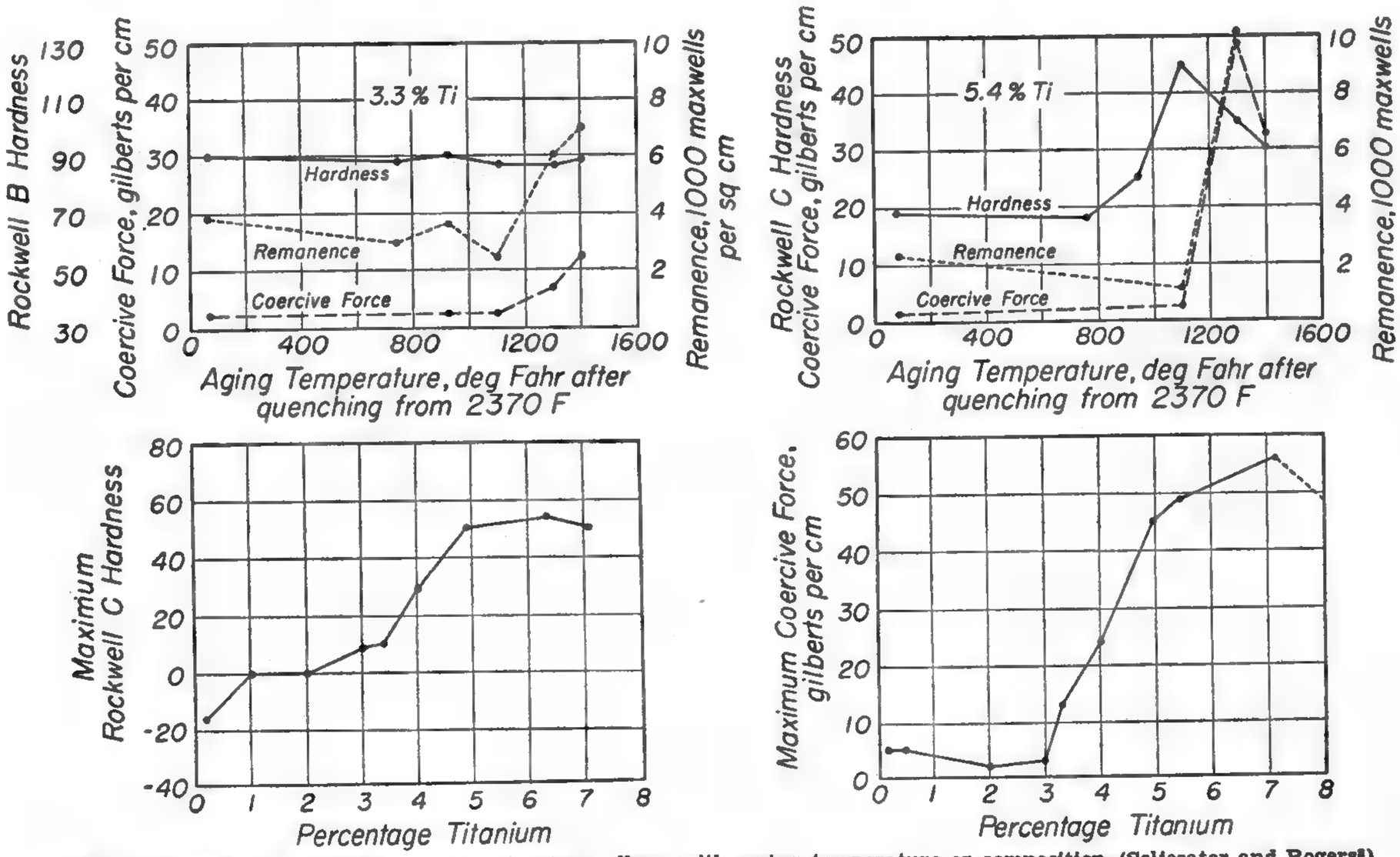

Fig. 2 Changes in properties of iron-titanium alloys with aging temperature or composition (Seljesater and Rogers[8])

Table II. Grain Sizes of Forged Steels Annealed 8 Hours[13]

0.35% C, 0.65% Mn and 0.25% Si (approximately)

Heat No.	Titanium Content, per cent	Aluminum Added, per cent	ASTM Grain Size After Annealing at the Following Temperatures, deg Fahr						Highest Temperature Before Grain Coarsening, deg Fahr
			1700	1750	1800	1850	1900	1950	
147	....	0.10	8	8	7 to 8	7 to 8	3 to 7	....	1850
149	....	0.15 (a)	7 to 8	7 to 8	7 to 8	4 to 8	3 to 7	....	1800
156	0.105	0.05	7 to 8	7 to 8	7	7	3 to 7	....	1850
155	0.105	0.10	8	7	7	6 to 7	4 to 7	....	1850
154	0.12	0.15	7	7	7	7	6	5	1900
151	0.15	0.15	7 to 8	7 to 8	5 to 7	4 to 7	4 to 7	....	1750
153	0.24	0.05	7 to 8	7 to 8	7 to 8	7	7	7	At least 1950
152	0.24	0.10	8	8	8	7 to 8	7	7 to 8	At least 1950
159	0.27	0.15 (a)	8	8	8	7 to 8	7	7	At least 1950
161	0.30	0.05	8	8	8	7 to 8	7	7	At least 1950
157	0.375	0.05	8	8	8	7 to 8	7	7	At least 1950
158	0.39	0.10 (a)	8	7 to 8	8	8	7	7	At least 1950
162	(0.036 Zr)	0.10 (a)	7 to 8	7 to 8	7	7	3 to 6	....	1850
163	(0.098 Zr)	0.075	6 to 7	3 to 7	2 to 7	2 to 6	2 to 6	....	1700

(a) Total aluminum contents were as follows: 0.13% for No. 149, 0.11% for No. 159, 0.10% for No. 158, and 0.05% for No. 162.

the grain-coarsening temperature when various amounts of titanium are present with aluminum, are illustrated in Table II.[13]

The results obtained from heat No. 149 in Table II show that the use of a larger amount of aluminum for deoxidation does not necessarily raise the grain-coarsening temperature. Increasing the titanium content, however, was effective in that direction. All the steels that contained more than 0.2% Ti had grain-coarsening temperatures at least as high as 1950 F, while one steel containing no more than 0.12% Ti did not coarsen at the temperature that produced coarsening in the aluminum-deoxidized or zirconium-deoxidized steels without titanium.

Effect of Titanium on Strain Aging and Embrittlement. One method of measuring the tendency toward strain aging is the "work brittleness" test.[14] A comparison of titanium steels with those deoxidized by aluminum is shown in Fig. 4. In this figure there is no comparison with semikilled steels, which are much more susceptible to "work brittleness" than either the titanium steels or those deoxidized with aluminum.[15] Another method for measuring the strain aging tendency is by the character of the stress-strain curve, or the knee of the stress-strain curve, for low-carbon steels.

Low-carbon steel containing more than enough titanium to combine with all the carbon, is extremely resistant to all kinds of strain aging, including the type revealed by the return of a definite yield point in sheets that are aged after cold rolling.* The effect of titanium on the yield point is illustrated by Fig. 5.[16] With more than 4.5 times as much titanium as carbon, steel has no definite yield point, but gives stress-strain curves like those characteristic of nonferrous alloys,[17] whether normalized, annealed, or aged after straining. Such steel, therefore, does not develop stretcher strains when deep drawn.

Tensile properties of titanium steel of this type, in the form of sheets produced by commercial methods from basic open hearth heats, are reported in Table III.[18] The test specimens were about 0.073 in. thick, 1.5 in. wide, and slightly more than 8 in. long between shoulders. The aging procedure consisted of holding the metal for three weeks at room temperature and for one hour at 450 F. The strength of this steel is shown generally to decrease slightly

* See "Aging of Iron and Steel", page 438.

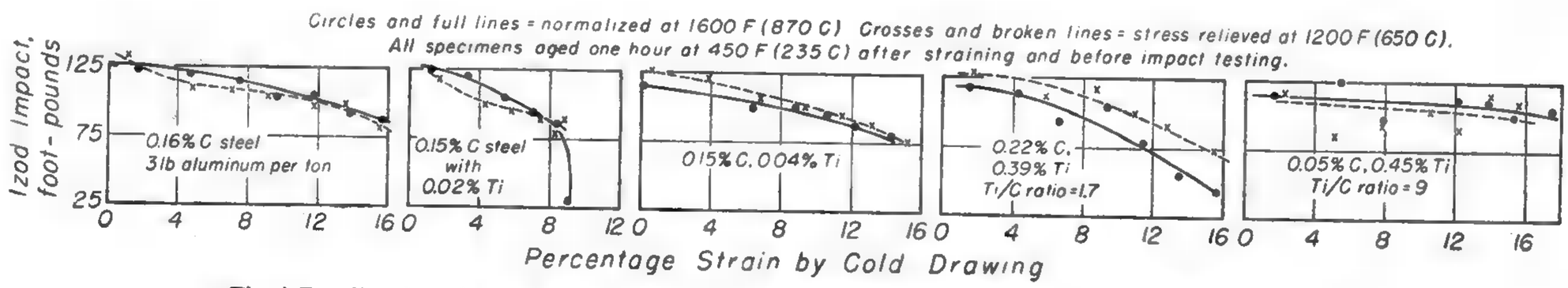

Fig. 4 Results of work-brittleness tests on an aluminum-deoxidized steel and several titanium steels

Table III. Changes in Tensile Properties of Titanium Steel Sheet Caused by Strain Aging[18]

Sheet steel samples from different mills	No. 1	No. 2
Carbon	0.054	0.045
Manganese	0.42	0.39
Silicon	0.025	0.06
Aluminum	0.031	0.065
Titanium	0.265	0.44

	Samples tested				
	Hot rolled No. 1	After normalizing ½ hr at 1600 F		Normalized and annealed 6 hr at 1150 F	
		No. 1	No. 2	No. 1	No. 2
Stress for 5% strain, psi	69,200	47,100	47,900	47,700	48,000
Properties after straining 5% and aging					
Yield strength, psi	68,000	45,900	46,800	46,200	47,100
Tensile strength, psi	70,900	54,900	55,900	54,400	55,900
Elongation in 8 in., per cent	11.9	33.5	28.1	28.1	27.1
Reduction of area, per cent	67.0	65.5	73.4	70.3	72.9
Percentage increase by aging					
Yield strength, psi	—1.7	—2.5	—2.3	—3.1	—1.9
Tensile strength, psi	—5.6	0	—0.5	0.5	0.4
Elongation, per cent	3.5	10.6	14.5	—6.3	3.4
Reduction of area, per cent	20.3	6.5	—0.1	12.8	4.1

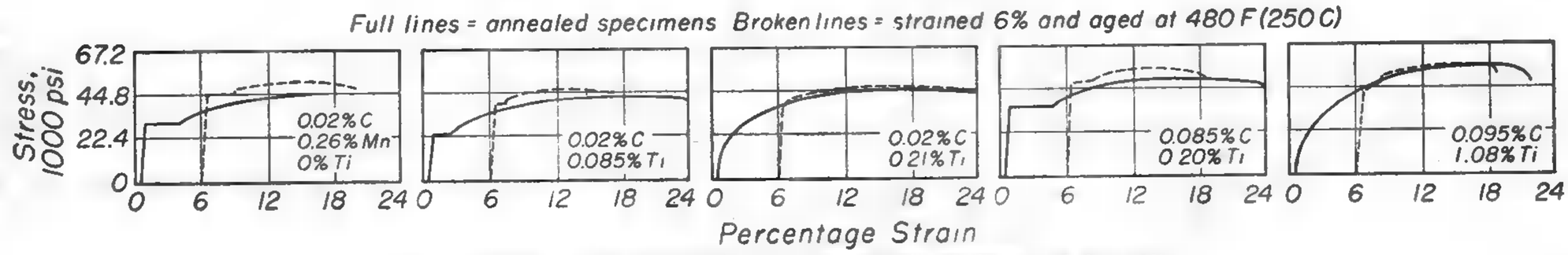

Fig. 5 Typical stress-strain diagrams (Edwards, Phillips and Jones[16])

on aging, with an improvement in ductility; whereas ordinary sheet steel, or even the so-called "nonaging" aluminum-killed steel, normally increases as much as 25% in yield strength during aging at 450 F after as much as 5% strain, and may lose half of its ductility.[18]

Titanium Enameling Iron. There are numerous references in technical publications to the possibility that "reboiling", in enameling, is related to liberation of hydrogen from the steel during the fusion of the cover coat on the ground coat. None of these references suggest the possible formation of hydrogen as a product of the reaction of water vapor with the carbides of steel. This water vapor may be in the atmosphere of the enameling furnace or may result from the combined water present in the enamel slip applied to the iron surface. Another hypothesis that associates carbides with reboiling, assumes that a reaction occurs between these carbides and oxides from the enamel; the union is presumed to result from diffusion at the enameling temperature and to produce carbonaceous gases. In any event, laboratory and commercial tests have indicated that low-carbon steel containing enough titanium to fix all the carbon, is always immune to reboiling,[19] by virtue of the

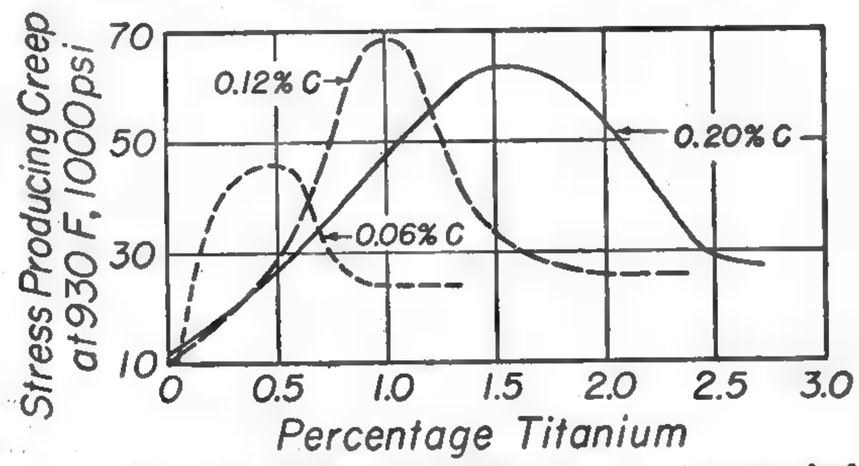

Fig. 6 Effect of titanium in low-carbon steels, water quenched from 2190 F (1200 C) and tempered at 1110 F (600 C), on the stress producing creep of 0.001% per hr between the 25th and 35th hr, under load at 930 F (500 C) and not more than 0.2% permanent set in 45 hr (Bardenheuer and Fischer[20])

extremely low reaction rate of titanium carbide with water vapor or oxides at the enameling temperature, compared with any other known carbide. This refers specifically to reboiling phenomena; another technical article[19] deals with such problems as adherence.

Strength at Elevated Temperature. The normalizing of titanium steels at temperatures higher than 2000 F develops rather high resistance to creep. This is probably a result of the precipitation hardening that occurs during tempering after the high-temperature heating. Figure 6 shows how the creep resistance varies with the titanium content in three different carbon steels heat treated as indicated.[20] Here it is evident that titanium-carbon ratios of 7 to 9 give the highest values. At the quenching temperature used (2190 F) this titanium-carbon ratio coincides approximately with the limit of the single-phase gamma field in each steel. Thus it appears that the creep strength rises with the titanium content of the gamma phase as long as no alpha is present, but drops when, because of still higher titanium content, the alloys also contain some alpha at the temperature used for the solution heat treatment.

The presence of other alloying elements with titanium in the steel improves the creep strength, as compared with the value obtainable from a single alloying element.[20,21]

Titanium steels have a high resistance to attack by hydrogen-hydrocarbon mixtures. "Resistance" in this connection means that decarburization and loss of ductility are low. The comparison between the stability of titanium steels in the presence of hot hydrogen and that of steels containing other elements is approximately proportional to the stability of the respective carbides.[9] Figure 7 presents a comparison, in this respect, of most of the common alloying elements in steel. As indicated in Fig. 7, titanium steels are of no special value for resisting hydrogen unless they contain at least four times as much titanium as carbon, so that no iron carbide occurs in them.

To illustrate more explicitly the effect of titanium on the loss of carbon and of ductility in steels exposed to hot

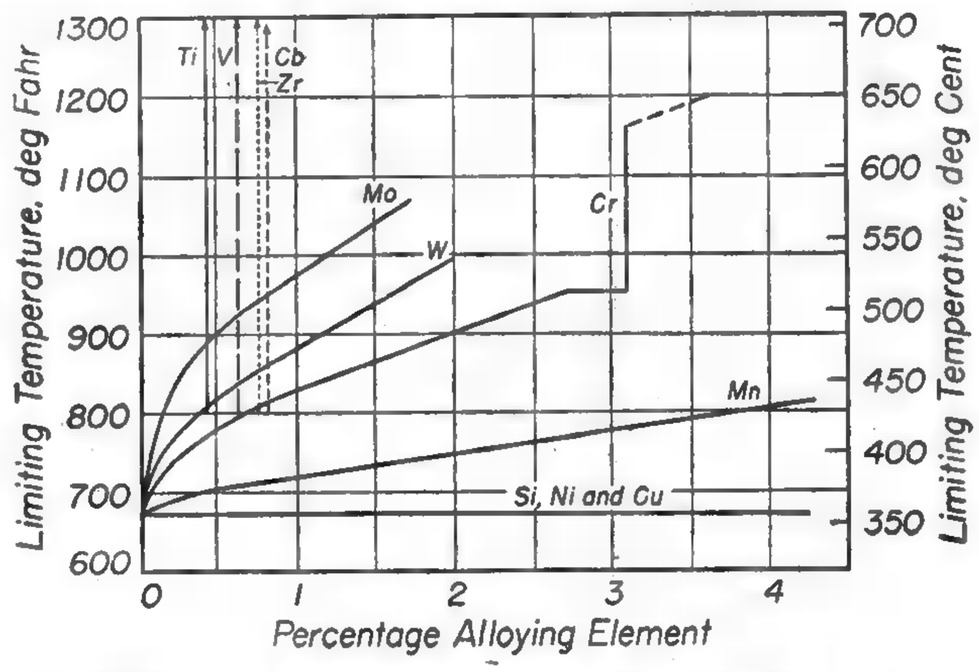

Fig. 7 Influence of alloying elements on resistance of 0.1% C steels to hydrogen at 4267 psi for 100 hr (Naumann[9])

hydrogen, the data in Table IV[9] are presented. These results from 100-hr experiments have been confirmed by recent American tests of thousands of hours duration and at various pressures and temperatures.[18] The results indicate that in all instances where all the carbon was stabilized by more than four times as much titanium, the steels have retained their normal ductility and other mechanical properties, provided nitrogen was not involved in the exposure.

Properties of Titanium Steels at Room Temperature. The variation in the properties of a 0.37% C steel with titanium contents in the range from 0 to 0.94% is illustrated in Fig. 8. These steels were all melted in large electric-arc furnaces and were deoxidized with aluminum for controlled grain size. The titanium steels came from the same heat but low-carbon ferrotitanium had been added to the ingot molds in different amounts. The steel that contained no titanium was made at a different mill. The compositions are reported in Table V.

Table IV. Influence of Titanium on the Carbon Content and Ductility of Steels Exposed to Hydrogen for 100 Hours Under 4267 psi Pressure at the Temperatures Noted[9]

Original Composition			Carbon Content after Annealing at		Loss in % Reduction of Area after Annealing at	
C	Ti	Ti/C	930 F	1110 F	930 F	1110 F
0.12	0.11	0.9	0.03	0.03	....	....
0.11	0.26	2.4	...	...	22%	65%
0.09	0.42	4.7	0.09	0.09	0	0
0.22	0.43	2.0	0.10	0.11	....	....
0.20	0.61	3.0	...	...	22%	60%
0.16	0.81	5.1	0.16	0.16	....	....
0.20	1.04	5.2	...	...	0	0.1%
0.80	1.59	2.0	0.39	0.40	38%	100%
0.80	3.70	4.6	0.80	0.80	0	0

The ingots were rolled to bars 1.5 in. in diam and were forged to bars ⅞ in. in diam before heat treatment. The mechanical properties are compared in four conditions of heat treatment, as indicated in Fig. 8. The strength of the titanium steel is shown to be greatly increased by normalizing at 2150 F, as compared with 1750 F, but the ductility is correspondingly reduced. The impact values of the titanium steels are very low after high-temperature normalizing, even though the grain size is not coarsened as much as that of the carbon steel. Thus it is evidently the solution of titanium or titanium carbide in the ferrite at high temperature that promotes notch sensitivity, rather than mere increase in grain size.

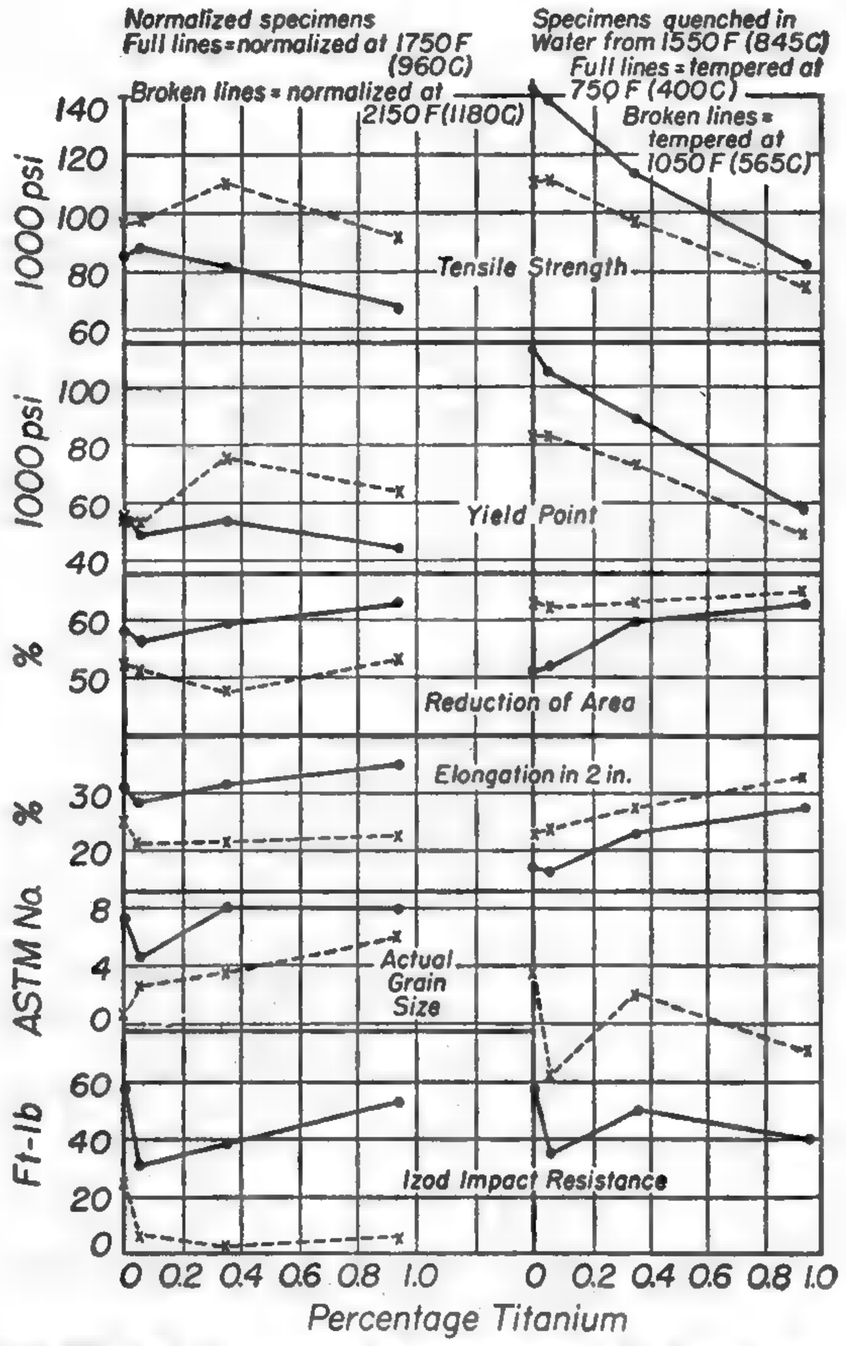

Fig. 8 Effect of titanium on the properties of forged and heat treated aluminum-deoxidized 0.37% C steel. (*See* Table V for chemical compositions.)

Table V. Compositions of Steels Referred to in Fig. 8

Steel	C	Mn	Si	Al	Titanium
Carbon	0.35	0.72	0.27	Present	None
Titanium	0.37	0.63	0.26	0.21	0.05
				0.26	0.35
				0.09	0.94

The Effect of Titanium on Hardenability. As indicated in one of the preceding sections, titanium raises the grain-coarsening temperature of steel. Because of this, hardenability is decreased by reason of a decrease in grain size. Thus the effect of titanium on hardenability is evident only when very high quenching temperatures are employed—high enough to dissolve the carbides. These temperatures are considerably higher than any normal heat treating range.

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Tungsten in Steel

By J. Y. Riedel*

TUNGSTEN was the first alloying element used in tool steels. Mushet steel, containing about 12% W, was the first commercial alloy tool steel. Great prominence was given tungsten alloy tool steels by the discovery of Taylor and White, in 1898, that high-temperature heat treatment of tungsten steels develops superior cutting ability. Thereafter, tungsten steels that had been given this special treatment were known as "high speed steels".

Tungsten alloys with iron in all proportions and combines with carbon to form complex carbides in steel. There are two principal ways in which tungsten produces useful properties in steel: (1) by enabling the steel to resist the effects of elevated temperatures and (2) by forming an extremely hard, abrasion-resisting carbide. The combination of these two effects produces the characteristics found in high speed steels. It should be noted that tungsten not only enables steels to maintain their strength at elevated temperature, but also tends to decrease the extent of softening that normally occurs during tempering.

Tungsten steels are used only where the properties produced by the tungsten addition are unique. No standard SAE or AISI alloy steels contain tungsten, because the properties desired in these steels can be more readily obtained by the use of less costly alloying elements. For many alloying purposes, tungsten is considered only one-half as effective, weight for weight, as molybdenum, the element which it most closely resembles in its effects on steel. Since for a number of years the price of tungsten has been twice that of molybdenum, it is obvious that marked advantages must be obtained from tungsten-bearing steels, compared with molybdenum-bearing steels, in order to justify their use. High speed steels containing 18% W are the most widely used tungsten steels. In European practice there has been some tendency to use Ni-Cr-W steels instead of the Ni-Cr-Mo steels commonly used in this country. However, this is undoubtedly because of the scarcity of molybdenum and the relative abundance of tungsten in Europe.

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Prepared for the Subcommittee on Alloying Elements in Steel

The Effect of Tungsten in Ferrite and Low-Carbon Iron Alloys. The solid-solution strengthening effect of tungsten in annealed low-carbon iron-tungsten alloys, as reported by Lacy and Gensamer,[1] is given below. On the basis of the data shown as weight percentage, tungsten appears to be a mild ferrite-strengthener by comparison with some other elements. However, if a comparison is made on the basis of atomic percentage, it is found that tungsten is surpassed only by titanium and beryllium.

Tungsten, weight %	0	1.44	3.05	3.99
Tensile strength, psi	33,900	37,750	43,550	46,300
Tungsten, atomic %	0	0.44	0.95	1.25

The following tabulation, from information reported by Bain,[3] shows the same effect when measured in terms of Brinell hardness numbers. It should be noted, however, that these data are estimates rather than actual test data. On the basis of weight percentage, tungsten is about one-half as effective as molybdenum in strengthening ferrite; but as indicated above, tungsten is more effective when comparing on a basis of atom for atom instead of weight for weight.

Tungsten, %	0	2	4	6	10	14	18	23
Bhn	70	80	90	100	115	130	145	160

In carbon-free alloys the maximum solid solubility of tungsten is 33% in ferrite at 2800 F (1538 C). This solubility decreases to about 4.2% at room temperature, so that the possibility of precipitation-hardening alloys in this range of composition is indicated. Actually, carbon-free iron-tungsten alloys from 10% to 50% W show marked precipitation hardening, because of precipitation of iron tungstide, Fe_3W_2. A Brinell hardness of approximately 500 can be developed in alloys of 30 to 40% W by water-quenching from 1500 C (2732 F) and aging at 700 C (1292 F), according to Sykes.[3]

The Effect of Tungsten on Medium-Carbon or High-Carbon Steels in the Pearlitic Condition. Tungsten additions to medium- or high-carbon steels tend to suppress the formation of definitely lamellar pearlite when these steels are cooled from above the transformation range, as, for example, after rolling or normalizing. Fairly rapid air-cooling produces structures of the Widmanstätten type. In these structures the ferrite is dispersed, showing little tendency to outline the original austenitic grains. Retarding the cooling rate produces little change except that the carbide is converted to a spheroidal form.

There are very few data on the properties of pearlitic tungsten steels, probably because tungsten is rarely used alone in an alloy steel. In general, tungsten increases the hardness and strength of normalized and annealed steels. Table I shows typical data illustrating this point.[4]

The Effect of Tungsten on Behavior During Heating for Hardening. The addition of tungsten to steel narrows the range where stable austenite can exist, and in turn, enlarges the range of stable ferrite. The iron-tungsten diagram exhibits a typical gamma loop, showing that no austenite can exist above 6% W. Tungsten is therefore classed as a ferrite-forming element in steel, as well as a carbide-forming element. The presence of 0.1% C enlarges the gamma loop to 10% W, while 0.3% C allows some austenite to exist in the presence of 20% W.

Some tungsten-bearing compositions show an unexpectedly low hardness after quenching. This is because at the quenching temperature the alloy is in a region of mixed austenite and ferrite. The inability to obtain complete austenitization results in low hardness. As an example of this, Gill and others[7] cite an instance where 18% W, 4% Cr, and 2% V steel with less than 0.50% C shows a low hardness after quenching; while with half this alloy content and the same carbon content and heat treatment a hardness of Rockwell C 60 can be attained.

Tungsten is considered one of the strongest carbide-forming metals. In steel, tungsten forms a complex carbide of varying composition, usually assumed to be Fe_4W_2C or Fe_3W_3C. Under some conditions, this complex carbide may decompose to form a simple tungsten carbide, WC.

Tungsten has a pronounced effect on the eutectoid temperature and the eutectoid composition of Fe-W-C alloys, as illustrated in Fig. 1 from Bain.[3] In common with other alpha-forming elements, tungsten raises the temperature of the eutectoid reaction, thereby requiring an increase in the heating temperature that is necessary for hardening. Increased tungsten content also lowers markedly the carbon content of the eutectoid. This fact, in addition to the abrasion-resisting character of the carbides, is important in explaining the great wear resistance of tungsten steels, since the lower the carbon content of the eutectoid, the greater the amount of free carbide in a steel of a given carbon content.

Although there are no quantitative data, it is known that the carbides in tungsten steels are dissolved in austenite only with great difficulty, and that extremely long times are required to approach conditions of equilibrium in an austenitizing treatment. This fact is believed to be responsible for the reputation of tungsten steels for exhibiting fine grain size. The relatively insoluble carbides

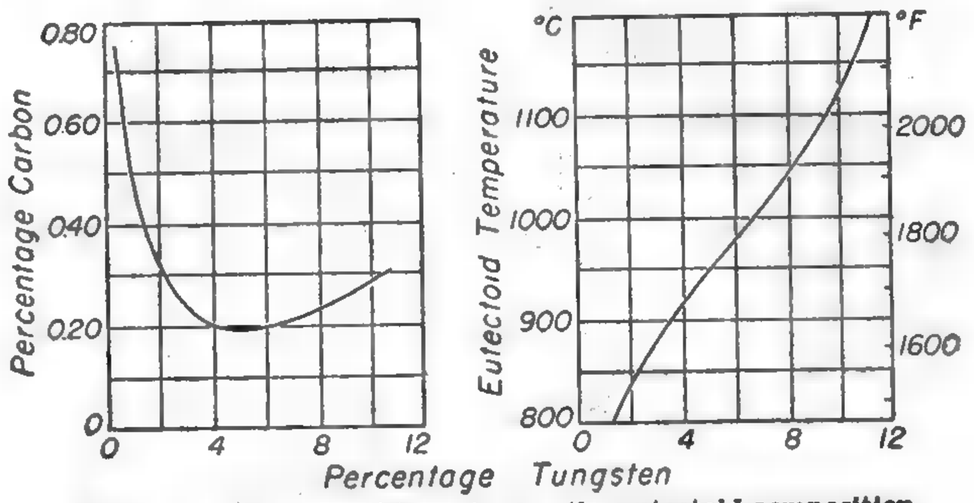

Fig. 1 The influence of tungsten on the eutectoid composition and eutectoid temperature

are so effective in restricting grain growth that in tungsten finishing steel it is possible to obtain a finer grain size than in any other type of steel.

The difficulty of dissolving the carbides in tungsten steels is probably also responsible for the confusion that exists in the literature concerning the effect of tungsten on hardenability. It is a recognized fact that at relatively low quenching temperatures, where very fine grain size is attained, a tungsten steel shows a more shallow depth of hardening than does a carbon steel of the same carbon content. On the other hand, high quenching temperatures combined with long holding times result in complete carbide solution, and the depth of hardening is considerably greater than in a carbon steel of the same carbon content, treated in the same manner. However, there are no quantitative data that measure the exact contribution of tungsten to hardenability, such as the Grossmann multiplying factors available for other elements.

The Effect of Tungsten on Behavior During Cooling from the Austenitic State. No reliable data are available to show the precise effect of tungsten on the behavior of steels during cooling from the austenitic state. In a general way it is known that when tungsten is in solution, transformation of austenite is very sluggish. This means that the upper portion, or "nose", of the "S-curve" is displaced to the right, resulting in a tendency towards air-hardening. When tungsten is not in solution, its effect on transformation of austenite is almost negligible. This has been shown by S-curves published by Payson and Klein,[5] where it will be noted that the curve for 1.14% C tool steel is almost identical with the curve for tungsten finishing steel.

Although tungsten is usually considered a strong carbide-forming element, there are circumstances where the complex carbide decomposes during annealing or slow cooling. Gregg[6] quotes several instances where tungsten carbide, WC, was formed in annealing 6% W steel, while Gill and others[7] cite instances where graphite was formed in the same type of steel.

The Effect of Tungsten on the Tempering of Quenched Steels. It is a widely known fact that tungsten enables steels to resist the softening that takes place during the tempering after quenching. Data from Bain,[8] shown in Fig. 2, illustrate this effect. The fact should be emphasized that, in order to produce this effect, the tungsten must be in solution. Tungsten present in undissolved carbides is totally ineffective in resisting the effects of tem-

Table I. Strength and Hardness of Tungsten Steels[4]

% C	% W	Tensile Strength, psi	Bhn
0.12	0.41	58,500	97
0.11	0.94	60,000	97
0.11	1.75	69,500	109
0.13	4.96	90,000	153
0.17	11.89	123,200	223
0.86	0.40	147,000	241
0.85	0.95	160,900	241
0.80	2.75	177,000	302
0.83	4.68	180,000	302
0.81	9.99	191,700	293

pering. It is believed that the temper resistance of tungsten steels results from the extreme reluctance of the complex tungsten carbide to precipitate and coalesce.

Many tungsten steels show a secondary hardening effect similar to that obtained in tempering high speed steels. Since virtually all the commercial tungsten steels contain other alloying elements in addition to tungsten, the contribution of tungsten in this respect is difficult to measure accurately, though it is undoubtedly considerable.

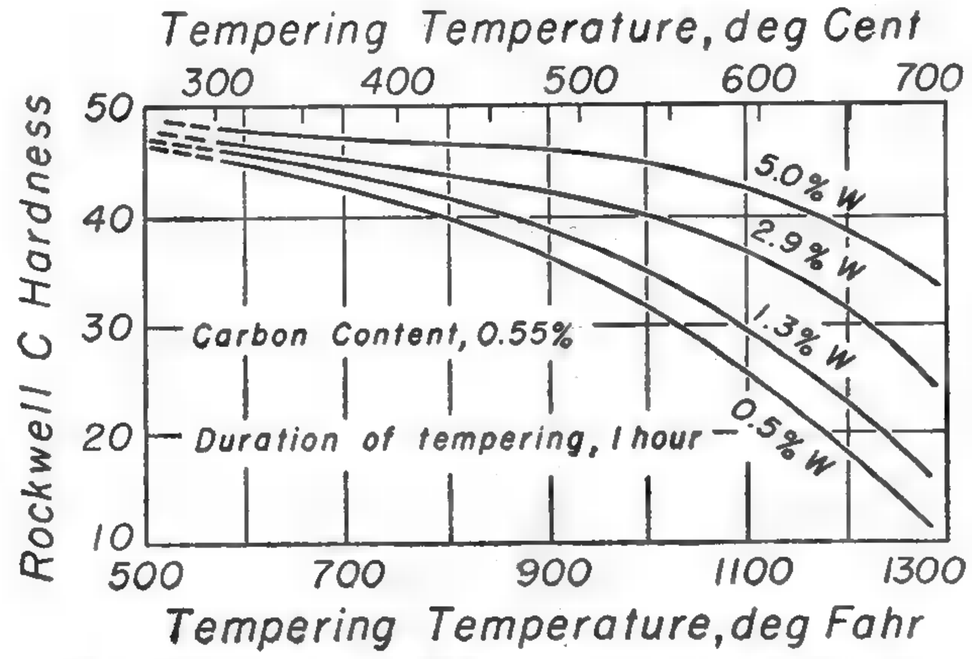

Fig. 2 The effect of tempering temperature on the hardness of quenched 0.55% C steels containing various amounts of tungsten

The superior resistance to tempering is responsible for two advantages of tungsten steels as compared with other steels; namely, greater strength at elevated temperatures and greater toughness at the same hardness. The ability to cut or deform materials depends on the hardness and strength of the tools at the operating temperatures of the working surfaces. Thus, greater strength at high temperatures makes tungsten steels suitable for cutting-tool and hot die applications. The greater toughness of tungsten steels is accounted for by the relief of residual stress previously developed in the quenching operation. High tempering temperatures are more effective than low temperatures in relieving stress; and if the stress can be relieved with no additional loss of hardness, the tool will have greater ability to withstand service stresses.

The effect of tungsten on temper brittleness is not accurately known. Some investigators report that tungsten does not affect the temper brittleness of a given steel; others report that it resembles molybdenum in that it reduces the susceptibility. However, it is known that tungsten is less effective than molybdenum in reducing the susceptibility to temper brittleness; therefore molybdenum is always chosen for this purpose in modern steels.

Special Effects of Tungsten in Steel. *High Speed Steels.* The outstanding application of tungsten is in high speed steel (typical composition, 18% W, 4% Cr, 1% V, 0.70% C). Although it is possible to make high speed steels without tungsten, it is generally agreed that some tungsten is necessary to produce a tool of highest cutting efficiency. The fact has already been mentioned that the characteristics of high speed steel depend on the combination of the resistance of the matrix to tempering and the wear resistance of the free carbides.

Hot Work Steels. The resistance of tungsten steels to tempering is obviously a useful property for a hot work steel (typical composition, 10% W, 3% Cr, 0.30% V, 0.35% C). In addition to this, tungsten steels are useful in hot work operations even where the surface working temperatures exceed the tempering temperature. This is because of the very slow rate of additional loss of hardness that occurs in service under these conditions.

Finishing Steels. The usefulness of the finishing steels (approximately 3.50% W, 1.35% C) for maintaining a keen cutting edge is obviously associated with the wear resistance of the free carbides. However, this type of steel also develops a peculiar slippery glazed surface during service. This phenomenon, which has not been scientifically evaluated, may be associated with the coefficient of friction and undoubtedly contributes to the wear resistance of this type of steel.

Creep-Resisting Steels. Tungsten might be expected to increase the creep strength of steel in the same manner as molybdenum. Two low-alloy, creep-resisting steels are commercially recognized in specification ASTM A 193-46T. Compositions of these steels are as follows:

Grade	C	Mn	Si	Cr	Mo	W	V
B11	0.42/0.49	0.25/0.40	0.20/0.35	1.00/1.50	....	1.70/2.30	0.20/0.30
B13	0.38/0.45	0.75/1.00	0.20/0.35	0.50/0.70	0.45/0.65	0.85/1.35	....

Recently a tungsten modification of a stainless steel has been found useful in resisting creep at temperatures as high as 1100 F. The approximate composition of this alloy is 0.12% C, 12.0% Cr, 2.0% Ni and 3.0% W.

Oxidation-Resisting, High-Temperature High-Strength Alloys. Various attempts have been made to improve the high-temperature strength of austenitic nickel-chromium steels by the use of tungsten. At present there are no standard AISI stainless steels containing tungsten, but one of the most widely used exhaust-valve steels is a modified austenitic stainless steel. The approximate composition of this steel is 0.45% C, 14.0% Cr, 14.0% Ni and 2.5% W.

It has been reported that during the past five years considerable research work has been started to develop alloys with high-temperature strength combined with oxidation resistance, primarily for use in gas-turbine parts. Although this work is far from complete, considerable progress has been made. The most promising alloys already developed (1946) are modified austenitic cobalt-nickel-chromium alloys, containing any or all of the following elements: tungsten, molybdenum, titanium and columbium. The tungsten content usually ranges from 1 to 4%. (*See also* pages 566 to 569 in this Handbook.)

Magnetic Properties. Tungsten has been added to steel for producing permanent magnets since the period between 1880 and 1890. One of the most widely used magnet steels was a 0.70% C, 5.5% W steel, and tungsten was also added to cobalt magnet steels in quantities of 3 to 9%. However, magnet steels containing tungsten have now been made virtually obsolete by cast or powdered metal alloys, such as the Fe-Ni-Al or Fe-Ni-Al-Co types.

Density. Because of its high density, tungsten increases the density of steels to which it is added. The weight of a given volume of 18-4-1 type high speed steel is calculated on the basis that the density is 10% greater than the density of ordinary steels. Although high density is often considered a disadvantage, it is because of the high density that the 18-4-1 type of high speed steel has been used for counterweights.

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Vanadium in Steel

By Jerome Strauss* and F. F. Franklin*

VANADIUM is used in steels because of two principal functions that sometimes appear to be not entirely distinct. These functions are (1) the refinement of the grain structure, and (2) the behavior of the vanadium carbide, principally its stability at elevated temperatures, and its solution in, and separation from, the metallic matrix of the steel.

Vanadium is soluble in ferrite; however, the tendency of vanadium to form carbide is so strong that except when an excess of vanadium is present, it is found mainly in the carbide phase. In addition to forming carbides, vanadium also forms oxides and nitrides, but the behavior of vanadium with oxygen and nitrogen in steels has been studied much less than the reactions of vanadium with carbon.

It has been demonstrated[1] that these carbides influence the characteristics of grain refinement in vanadium steels, although how much of the grain refinement may result from the properties of oxides and nitrides that may be formed, is among the facts not yet established. Nevertheless, it is well known that these fine structures are produced by vanadium in primary crystallization from the melt, as well as in phase transformations during heat treatment. Quite apart from the control of grain size in cast and wrought steels is the use of vanadium to produce fine carbide structures in hypereutectoid steels, thereby influencing the distribution of free carbide after hot working. Furthermore, the presence of carbide widens the hardening range of low-alloy steels that contain vanadium. In this respect there is some similarity between vanadium and the aluminum used in aluminum-treated steels, but with distinct differences that will be discussed later.

Differences of opinion exist concerning the relative deoxidizing power of vanadium when compared with other oxide-forming elements. However, in view of the fact that vanadium is too expensive to use as a commercial deoxidizer, it is sufficient to indicate that vanadium is far from being the strongest of these agents. It is much less active than aluminum, for example.

In the solid state vanadium and nitrogen form stable nitrides that have been utilized in the development of special steels for nitriding. In the molten steel bath, the procedure by which vanadium nitrides are formed and their subsequent reactions in the solid state have not yet been studied in detail, although a few facts have been established as indicated hereafter.

The Effect of Vanadium in Ferrite and Low-Carbon Iron Alloys. Vanadium and alpha iron are mutually soluble in all proportions in the solid state at temperatures higher than 1234 C, and are likewise soluble at temperatures lower than this, except in the range of composition in which the intermediate phase FeV exists. However, this range of vanadium content is beyond any thus far used in steels or other finished alloys; it is wholly in the composition range of the ferro-alloys that are used to introduce vanadium into liquid steel.

In working with binary alloys in which, though not determined, the carbon was asserted to be less than 0.01% and the other impurities correspondingly low, Lacy and Gensamer[2] found that vanadium increased the tensile strength of ferrite in the proportion of about 4000 psi for 1% V. Table I gives the tensile properties of the three iron-vanadium alloys, along with those of the iron of lowest manganese content, as a basis for comparison.

Edwards, Phillips and Jones[3] determined the properties of 0.025% C annealed alloy steels containing 0.26, 0.55 and 0.69% V. Their results are shown in Table II, along with the properties of a steel that has a very low aluminum content. This low-aluminum steel is the only one that contained no vanadium, in this series.

Investigating the effects of vanadium on annealed steels that contain slightly more carbon (0.10% C), Hougardy[4] found that the hardness is first raised to a maximum value at about 0.5% V, then is rapidly reduced, and is gradually increased thereafter by additional amounts of vanadium. Table III is an abstract of this work.

Although Vogel and Martin[5] stated that vanadium increased the solubility of carbon in ferrite to a considerable degree, subsequent work[6] has shown that such an increase is slight and that the solubility values of carbon in ferrite that contains vanadium, are very close to those of carbon in pure alpha iron.

Age Hardening. Although age hardening alloys probably exist in the iron-vanadium system (*see* page 1219 in this Handbook) the compositions that might be affected have not been studied from this standpoint. The influence of vanadium on the age hardening of carbon and rimming steels is not simply an effect of vanadium on ferrite and is described later in this article.

The Carbide Phase. The common form of vanadium carbide is V_4C_3. Another form, VC, is presumed to exist but specific information about it is lacking.

Table I. Tensile Properties of Annealed Iron-Vanadium Alloys

Alloying Element	Weight Per Cent	Tensile Strength, psi	Yield Strength, psi	Percentage Reduction of Area	Percentage Elongation	Grain Size (ASTM)
Mn	0.16	34,800	8,800	95	58	2 to 4
V	0.80	34,850	7,300	93	57	5
V	1.63	39,300	10,300	91	54	5
V	2.75	42,200	15,200	89	51	6 to 7

Table II. Effect of Vanadium Content on the Tensile Properties of Annealed Low-Carbon Iron

Steel No.	Composition, percentage C	Mn	P	S	Ni	Cu	V	Al
Al-Treated	0.025	0.26	0.010	0.023	0.09	0.09	...	0.02
1	0.025	0.30	0.010	0.023	0.09	0.09	0.26	...
2	0.025	0.32	0.010	0.023	0.09	0.09	0.55	...
3	0.025	0.26	0.010	0.025	0.09	0.09	0.69	...

	Aluminum-Treated	Vanadium 0.26%	Vanadium 0.55%	Vanadium 0.69%
Yield Point, psi	26,745	22,870	21,706	15,232
Tensile Strength, psi	44,320	42,381	44,307	44,822
Elongation, %	31.8	28.1	27.1	23.9

In affinity for carbon, vanadium stands between chromium and manganese on the one side, and titanium and columbium on the other. Likewise, vanadium carbide is less soluble in austenite than are carbides containing chromium and manganese, but vanadium carbide dissolves to a greater extent than titanium carbide.[1]

Table III. Hardness of Annealed 0.10% C Steel

Vanadium, %	0.0	0.5	0.7	1.6	2.7	4.7
Hardness R_B	61	72	65	65½	66	68

Apparently vanadium carbide is slightly soluble in ferrite; it dissolves to a considerably greater degree in austenite but the rate of solution is low and the individual particles that remain undissolved are a major cause of the restraint of grain growth.

Vanadium carbide is only slightly soluble in iron carbide. The double carbide formerly presumed to exist is an ex-

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Prepared for the Subcommittee on Alloying Elements in Steel

Table IV. Mechanical Properties of Carbon Steel and of Carbon-Vanadium Steel

Steel Type	Composition, percentage — Carbon	Manganese	Silicon	Vanadium
Carbon	0.50	0.71	0.19	...
Carbon-Vanadium	0.50	0.76	0.37	0.27

Heat Treatment	Annealed Carbon 1520 F Furnace Cooled	Annealed Carbon-Vanadium 1565 F Furnace Cooled	Normalized & Tempered Carbon 1520 F Air 1000 F Air	Normalized & Tempered Carbon-Vanadium 1565 F Air 1000 F Air	Quenched & Tempered Carbon 1520 F Water 1000 F Air	Quenched & Tempered Carbon-Vanadium 1565 F Water 1200 F Air
Vickers hardness	177	191	206	221	302	299
Tensile strength, psi	90,600	97,200	103,100	110,400	134,900	134,500
Yield point, psi	48,900	62,900	60,500	80,500	110,800	133,400
Yield-tensile ratio	0.539	0.648	0.587	0.730	0.821	0.992
Elongation, %	23.3	28.3	25.8	25.8	18.3	18.3
Reduction of area, %	37.8	43.5	48.3	54.4	54.1	56.6
Izod impact, ft-lb	13.5	32.5	18.0	42.0	54.0	63.5

tremely fine mechanical mixture of vanadium carbide and iron carbide.[5]

Effect of Vanadium on Medium-Carbon and High-Carbon Steels in the Pearlitic Condition. The effects on mechanical properties of steel when vanadium is used as the principal alloying agent are illustrated in Table IV, which lists the properties of plain carbon and carbon-vanadium steels identical in carbon contents, after these steels have been quenched and tempered to a given tensile strength, normalized and tempered, and annealed.

Vanadium is used in steel castings, especially in the production of certain alloy grades, to prevent the formation of hard spots caused by localized martensite, with consequent improvement in machinability. In welded steels, vanadium serves a similar purpose by preventing hardening and embrittlement of the zone affected by heating during the welding operation. This elimination of hard spots and the resistance to hardening in welding operations are probably caused by the influence of vanadium on phase transformations, which is discussed in a later section.

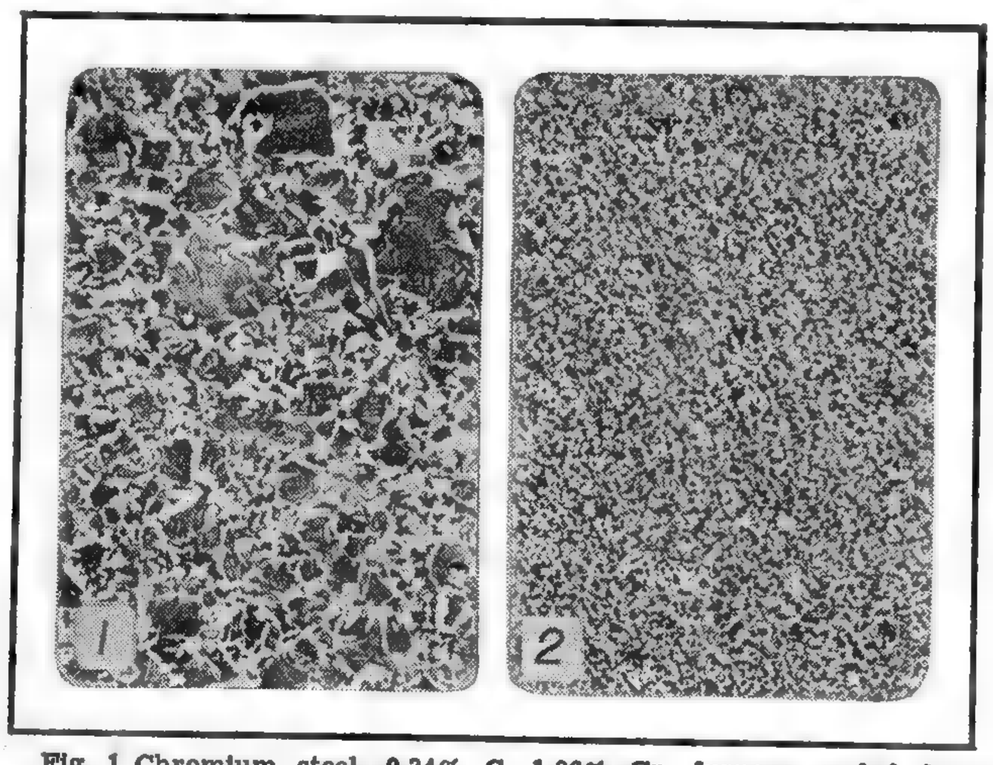

Fig. 1 Chromium steel, 0.34% C, 1.06% Cr, furnace cooled from 1550 F

Fig. 2 Chromium-vanadium steel, 0.34% C, 1.09% Cr, 0.26% V, furnace cooled from 1550 F

The effects of vanadium on the properties of a steel when more than one principal alloying element is present are indicated in Table V, which shows the effects of vanadium on a chromium steel when annealed, and when quenched and tempered.

Figures 1 to 4 show the effects of vanadium on the microstructure of chromium steels that have identical carbon contents, when furnace cooled from 1550 F and 1850 F.

The Effect of Vanadium on Behavior During Heating for Hardening or for Normalizing. Vanadium raises the A_3 point and lowers the A_4 point progressively to close the gamma loop. The solubility of vanadium in carbon-free gamma iron is limited to about 1%. Carbon increases the extent of the gamma field, but this increase may be offset by the addition of vanadium in approximately the ratio of vanadium to carbon in V_4C_3.

The rate at which vanadium carbides dissolve during austenitizing depends on their amount, size and dispersion in the matrix. Zimmerman, Aborn and Bain[9] found, in heating ■ 0.27% V, 0.87% C steel, that these carbides were only partly dissolved at 1700 F and that it was necessary to increase the temperature to 2000 F for effective solution. Table VI gives a comparison of the rates of solution of carbides in plain carbon and vanadium steels of eutectoid composition, when heated within and above the transformation range.

The fine austenitic grain sizes inherent in vanadium steels have been attributed by some investigators to nucleation effects of vanadium carbides, and by others to vanadium nitrides or oxides, or both. It now seems that any one or more of these phases may be responsible, providing they are properly dispersed in the matrix.

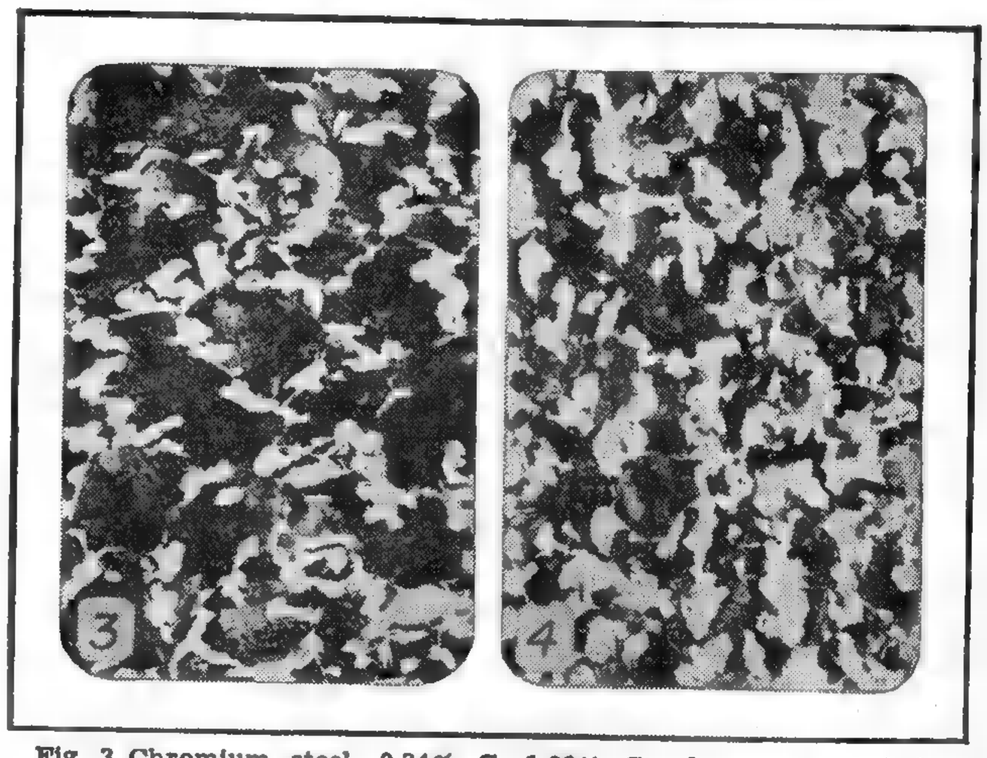

Fig. 3 Chromium steel, 0.34% C, 1.06% Cr, furnace cooled from 1850 F

Fig. 4 Chromium-vanadium steel, 0.34% C, 1.09% Cr, 0.26% V, furnace cooled from 1850 F

Stabilization of the fine grain structure by the presence of vanadium in austenitized steels, permits retention of ex-

Table V

Mechanical Properties of Chromium-Vanadium Steel

Steel Type	Composition, percentage — C	Mn	Si	Cr	V
Chromium	0.49	0.76	0.21	1.07	...
Chromium-Vanadium	0.50	0.79	0.31	0.98	0.20

	Annealed at 1545 F, Furnace Cooled Cr	Cr-V	Oil-Quenched from 1545 F Tempered at 800 ■ Cr	Cr-V
Vickers hardness	210	198	457	481
Tensile strength, psi	107,700	99,500	220,900	232,800
Yield point, psi	47,100	64,100	200,700	224,200
Yield-tensile ratio	0.437	0.645	0.911	0.963
Elongation, %	19.2	28.4	9.6	10.4
Reduction of Area, %	35.9	59.0	35.9	43.1
Izod impact, ft-lb	10.5	44.0	12.0	12.0

cellent ductility and impact resistance during the development of high tensile strength and yield strength. Vanadium increases the hardening range of pearlitic steels. Aluminum is the only other element commercially capable of producing and stabilizing grain refinement to a similar extent. In vanadium steels, however, the hardening range, although widened, remains consistently within well-defined values,

Table VI. Effect of Vanadium on the Solubility of Carbide in Austenite

Quenching Temperature, deg Fahr	deg Cent	Grain Size (ASTM) Carbon Steel	Grain Size (ASTM) Vanadium Steel	State of Carbides Carbon Steel	State of Carbides Vanadium Steel
1400	760	6	10 to 11	Partly dissolved	Undissolved
1500	815	6	9 to 10	Essentially dissolved	Undissolved
1600	870	5	8	Essentially dissolved	Undissolved
1700	925	4	7	Essentially dissolved	Partly dissolved
1800	980	3 to 4	6 to 7	Essentially dissolved	Partly dissolved
1900	1040	3 to 4	3 to 4	Essentially dissolved	Largely dissolved
2000	1095	2 to 3	2 to 3	Essentially dissolved	Essentially dissolved
2100	1150	2 to 3	0	Essentially dissolved	Essentially dissolved

and the upper limit is not so high as to create difficulty in grain coarsening preparatory to machining, by normalizing at moderate temperatures with subsequent recovery of fine grain structure by customary heat treatment. In carburizing operations at the usual temperatures, vanadium steels retain their fine grain size and develop high strength without loss of ductility and impact resistance, when quenched directly from the carburizing box.

The effects of vanadium on grain size are observed in quenched steels and in steel cooled more slowly from the austenitizing temperature, as shown in Fig. 1 to 4.

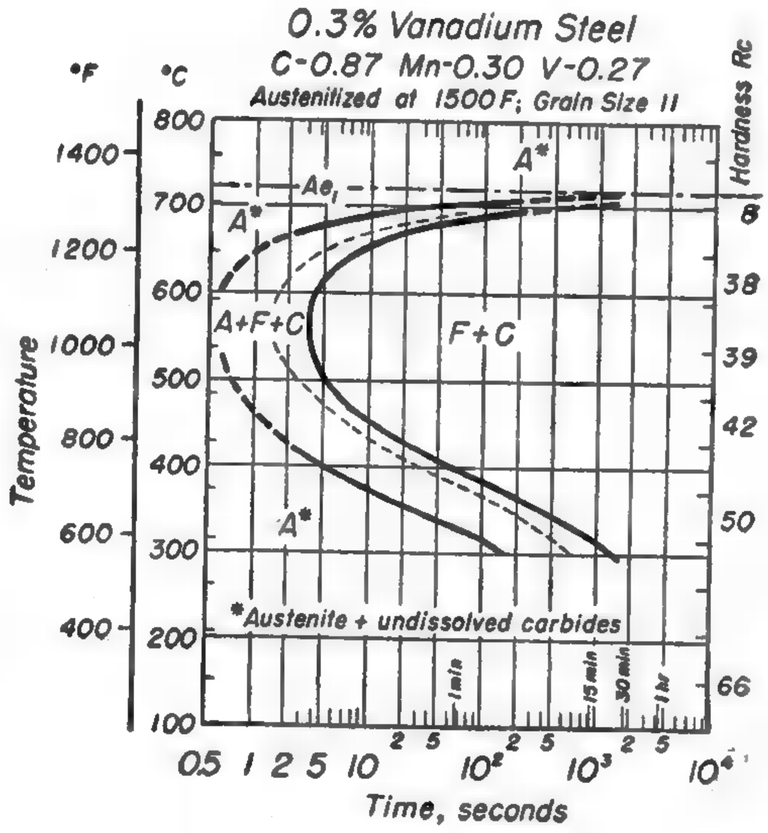

Fig. 5 Isothermal transformation diagram for a vanadium steel, austenitized at 815 C (1500 F) (U. S. Steel Corporation Research Laboratory)

The Effect of Vanadium on Behavior During Cooling from the Austenitic State. Vanadium held in solution in austenite retards the transformation of austenite during rapid cooling. Undissolved vanadium, dispersed throughout the austenite as particles of carbide or other compounds, acts as nucleating material which tends to prevent supercooling, and in this manner increases the rate of austenite transformation. Furthermore, since the undissolved carbides contain both vanadium and carbon, the matrix is impoverished in these elements and the rate of austenite transformation is correspondingly greater for this reason than the rate for austenite that contains all the vanadium and carbon in solution. Figures 5 and 6 illustrate the effects of these factors on the rate of transformation of austenite.

The Effect of Vanadium on the Tempering of Quenched Steels. Vanadium retards softening during the tempering of martensitic structures. This effect is seen in steels containing several alloying elements, as well as in those where vanadium is the principal alloying constituent. Figure 7 shows the effects of vanadium on the properties of quenched and tempered nickel steel.[7]

Secondary hardening may be observed within the tempering range from 900 to 1150 F, and has been attributed to precipitation. In certain compositions, for example in tool steels, hardness of the steel is actually increased, but in most commercial operations involving low-alloy steels, a retardation is observed in the loss of strength with increasing tempering temperatures.

According to Crafts and Lamont,[8] vanadium is more effective than any other element in retarding the softening of a steel during the tempering operation. Their investigation indicated that 0.03% V would retard softening of 0.30%

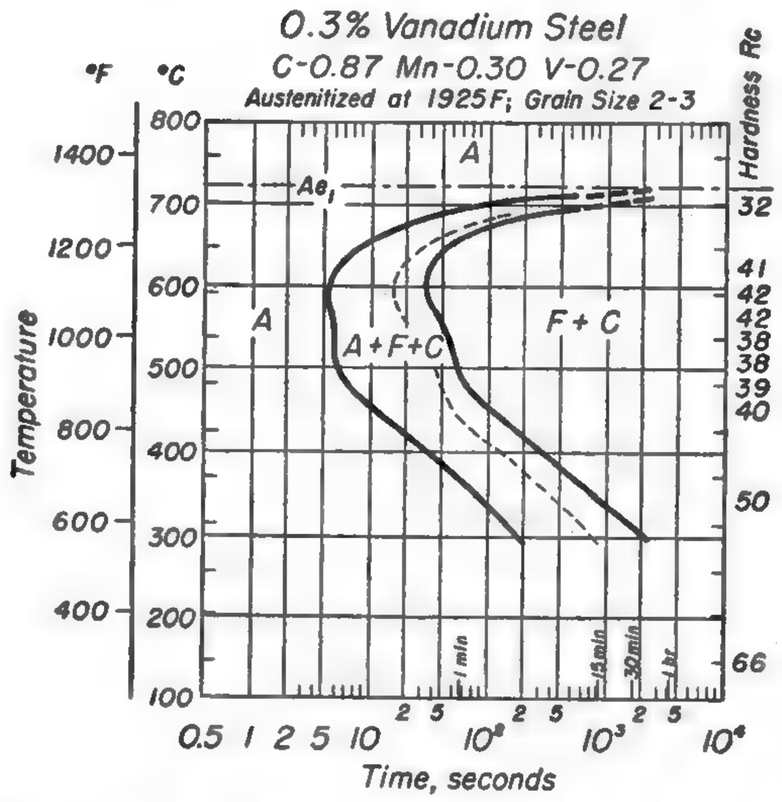

Fig. 6 Isothermal transformation diagram for a vanadium steel, austenitized at 1050 C (1925 F) (U. S. Steel Corporation Research Laboratory)

C steel by one Rockwell C unit after two hours at tempering temperatures of 1100 and 1200 F.

The retardation of the rate of softening, according to Zimmerman, Aborn and Bain,[9] is caused by the precipitation of vanadium-rich carbide, which has low diffusivity, wide dispersion and slow coalescence. This retarding effect has been ascribed also to the increase in solubility of carbon in ferrite, caused by the presence of vanadium, and subsequent precipitation during tempering within this range. Carbon-free iron-vanadium alloys of low vanadium content do not undergo secondary hardening.

It must be pointed out that only the vanadium that is held in solution is effective in retarding softening during tempering, and that this effect will not be developed to a substantial degree unless proper precautions have been taken during the austenitizing operation to dissolve an adequate amount of vanadium carbide.

The ability of vanadium steels to retain their hardness at elevated temperatures reflects the influence of vanadium in tempering.

Special Effects of Vanadium in Steel. *Properties at Elevated Temperatures.* The effect of vanadium on hardness at elevated temperatures has been noted previously. Table VII shows the creep rate at 850 F of a plain carbon steel in comparison with that of a vanadium steel.[10]

This retention of strength and hardness is responsible for the extensive use of vanadium steels for springs operating at elevated temperatures, such as exhaust-valve springs in internal-combustion engines and locomotives.

Tool Steels. Vanadium is added to tool steels to improve their serviceability and to refine the carbide structure,

which is otherwise extremely difficult to break up during the hot working of the steel. Small amounts of vanadium are sufficient to refine the carbide structure, but greater additions are used to obtain hardness at elevated tempera-

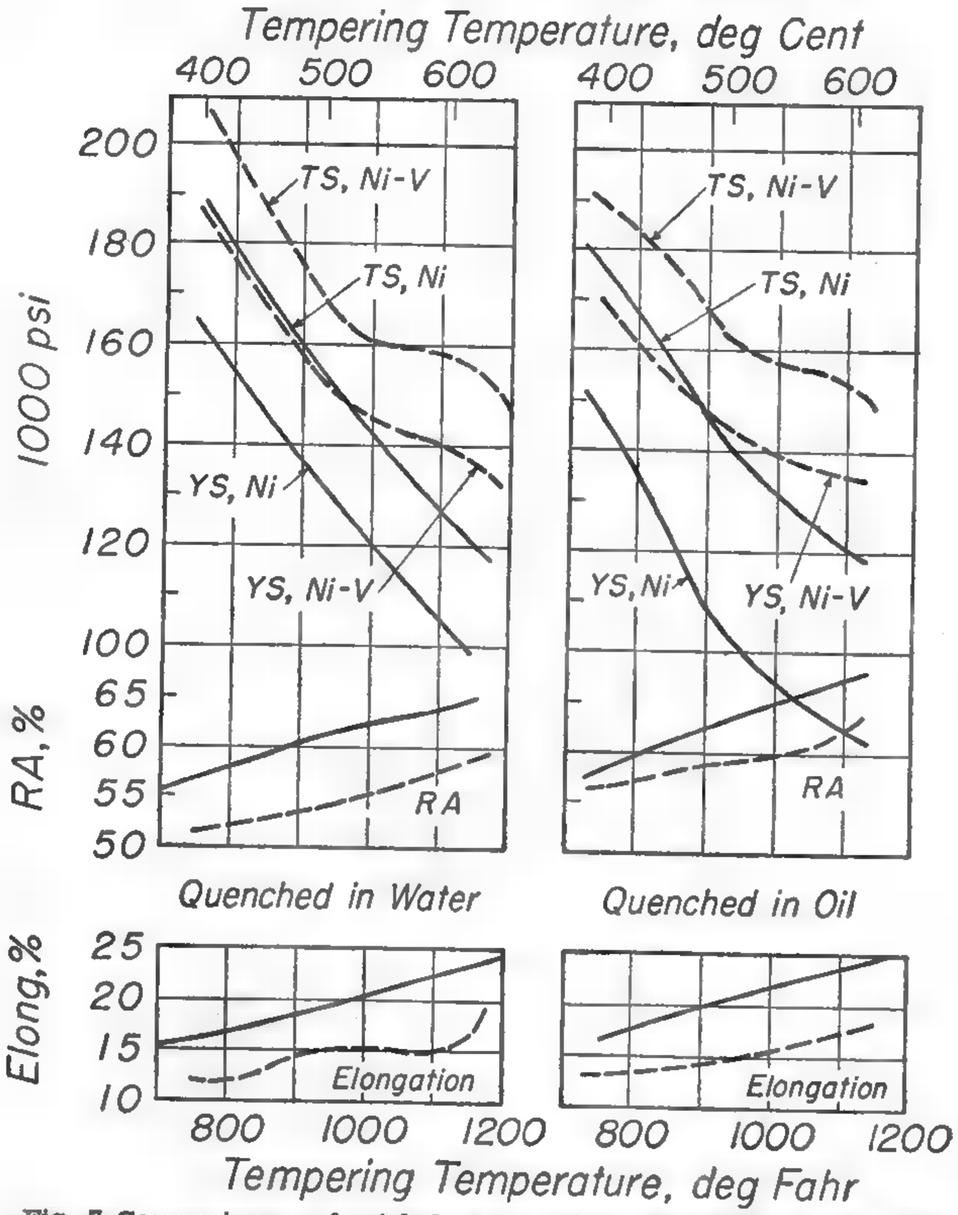

Fig. 7 Comparisons of nickel and nickel-vanadium steels, water quenched and oil quenched. Solid lines, SAE 2330, 0.30% C, 0.65% Mn, 3.50% Ni, quenched from 1450 F. Dashed lines, 0.29% C, 0.45% Mn, 3.41% Ni, 0.20% V, quenched from 1600 F, then from 1520 F ("Nickel Alloy Steels", and Bullens[7]).

tures ("red hardness") as well as resistance to wear at both low and high operating temperatures.

The effects of 1 and 2% V on the hardness of high speed steels at elevated temperatures, as described by Harder and Grove,[11] may be seen in Table VIII.

A tungsten high speed steel recently developed, containing 12 to 14% W, 5% V, 5% Co, 1.5% C, has exceptionally high Brinell hardnesses of 677 at 1000 F and 462 at 1200 F.

Endurance Limit. Vanadium raises the endurance limit and the ratio of endurance limit to tensile strength not only in very low-carbon steels but also in medium carbon and moderately high-carbon constructional steels. Many steels do not have high endurance properties unless quenched and tempered, but carbon-vanadium steels possess endurance ratios of about 50% when normalized and

Table VII. Creep Rate of Vanadium Steel

Composition, percentage C	Mn	Si	V	Load, psi	Rate of Deformation at 500 Hours, % per hour	Average Total Deformation after 500 Hours, per cent
0.35	0.55	0.19	...	10,000	0.00058	0.5231
0.37	0.70	0.16	0.18	10,000	0.00006	0.120

tempered and medium-carbon manganese-vanadium steel, specially designed for use in large sections, after being normalized and tempered, has an endurance ratio of 55 to more than 60%.

The characteristic uniformity of structure and composition of vanadium steels contributes significantly to these uniformly high endurance values.

Resistance to Oxidation. Vanadium slightly retards oxidation at high temperatures, but not sufficiently to be of commercial importance. On the other hand, the scale that is formed on the surface of vanadium steels is well defined and very easily removed, a fact that is of commercial importance in hot working by rolling and forging.

Resistance to Corrosion. Like titanium and columbium, vanadium, if used in the proper proportions, will increase the resistance of austenitic stainless steels against inter-

Table VIII

Hardness of High Speed Steels at Elevated Temperatures

By Mutual Indentation (Brinell)

Type of Steel	1110 F	1200 F	1290 F
18-4-1	480	320	160
18-4-1	470	304	220
14-4-2	435	338	250
18-4-2	445	346	260

granular corrosion, by stabilization of the carbides. Payson[12] has reported, however, that vanadium also lowers somewhat the general corrosion resistance of these steels.

In low-alloy steels, vanadium seems to have a slight retarding effect on corrosion but not enough to be of commercial importance.

Age Hardening. Vanadium is used to prevent age hardening in low-carbon rimmed steels. Epstein[13] showed that vanadium-treated, low-carbon rimmed steel possesses nonaging properties equal to those of fully killed aluminum steels, and yet retains the essential characteristics and manufacturing advantages of rimmed steels.

Table IX. Nonaging Vanadium Steel

	As Skin-Passed	As Aged at 212 F for 24 hours
Yield strength, psi	30,000	30,300
Elongation at yield point, %	0	0
Rockwell B hardness	46	46

After adding 0.05% V to a heat of this type of steel, Epstein found 0.032% V in the final product. The tensile strength of 44,900 psi at room temperature was reduced to 38,600 psi at 400 F, and sheets of this steel, skin-passed to about 1% elongation, showed no significant increase in yield strength after aging at 212 F for 24 hours, as shown in Table IX. Epstein's findings have been confirmed by the production experience in numerous plants.

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HARDENABILITY OF STEEL

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Methods and Application of Hardenability Testing

BY THE SUBCOMMITTEE ON HARDENABILITY

THE capacity of steel to harden, when cooled from above the transformation range, is known as "hardenability" and is generally evaluated from the hardness produced by different cooling rates in a given piece. For purposes of measurement, the factors affecting the cooling rates must be controlled, such as the composition, temperature and velocity of the quenching medium, and the type and thickness of scale.

In general, the hardenability of steel depends on the composition and grain size of the transforming austenite; the hardenability of the SAE and AISI grades of alloy steels can be calculated approximately by the methods discussed in the article on page 494 of this Handbook. Because of factors which are not taken into account in the calculations and which may cause erroneous results, the current practice among steelmakers and users of steel is to determine experimentally the hardenability of steels subject to specifications for hardenability.

Steels subject to hardenability specifications include the extremely shallow water-hardening tool steels, the medium-carbon steels, the oil-hardening automotive and constructional alloy steels of the SAE and AISI grades, and alloy tool steels. The grades of tool steels that harden deeply in air and that are used for die blocks, cold forming tools with large sections, and extrusion tools such as rams, mandrels, and dummy blocks, have only recently been the subject of hardenability studies. Several methods for measuring the hardenability of steel are in use at the present time; in general, each of these methods is designed primarily to amplify differences in the hardenability of a single type of steel. A test designed primarily for the oil-hardening grades of steel will not be sensitive when applied to the shallow-hardening grades or to steels that harden deeply in air. Likewise, other tests devised especially for shallow-hardening or for air-hardening steels will not be useful if applied to other steels.

Methods of Test

Jominy End-Cooled Test for Medium-Hardening Steels. Medium-hardening or common alloy steels are usually tested for hardenability by the end-cooled method,[1] which involves heating a test bar 1 in. in diam to the proper austenitizing temperature and then cooling only the end face with water. The hardness is then measured at intervals of 1/16 in. from the water-cooled end to determine how far from this end the increased hardness extends.

The standard test that is specified both by the ASTM (Tentative Method A255–46T) and SAE (1947 SAE Handbook, page 303) consists briefly of using either of the test specimens shown in Fig. 1 and 2. The test specimen is normalized at about 150 °F above the Ac_3 point, then machined to remove any decarburization and to obtain the correct dimensions. Following this, the specimen is heated to about 75 °F above the Ac_3 point in a closed container that has a layer of cast-iron chips in the bottom. The specimen is held at this temperature 30 min and is cooled immediately thereafter on the hardenability fixture. The time spent in transferring to the fixture should not be more than 5 sec. This fixture is constructed so that the test specimen is held 1/2 in. above the water opening, in order that a column of water may be directed against the bottom of the piece. The water opening is 1/2 in. in diam and adjustment is made so that before the specimen is placed over it, a column of water 2½ in. high

comes from the opening. The water temperature is kept at 75 F plus or minus 5 °F and a condition of still air is maintained around the specimen during cooling. The piece is permitted to remain on the fixture until cold, or at least for 10 min, and is then quenched in cold water.

After cooling, two parallel flats, 180 deg apart and 0.015 in. deep, are ground along the entire length of the bar, and hardness measurements are taken at intervals of 1/16 in. for the first inch, then usually at intervals of 1/8 in. for the second inch, and 1/4 in. for the remainder of the bar. These hardnesses may be plotted to give a standard hardenability curve. (*See, for instance,* Fig. 3.) Care must be taken to avoid tempering when the parallel flats are ground. After grinding, it is good practice to etch the flats with 5% nital or other suitable etchant, to determine whether grinding has caused any tempering.

The standard test bar (1 in. in diam) should be used whenever possible, but other sizes may be used to make comparisons of hardenability. Bar diameters as low as 1/2 in. can be used with the standard water-cooling equipment. Sizes as small as 1/4 in. may be used by inserting a nozzle with an opening 1/8 in. in diam instead of the standard 1/2-in. nozzle. These bars, of course, will not be comparable with the standard 1-in. specimen, but can be compared with one another.

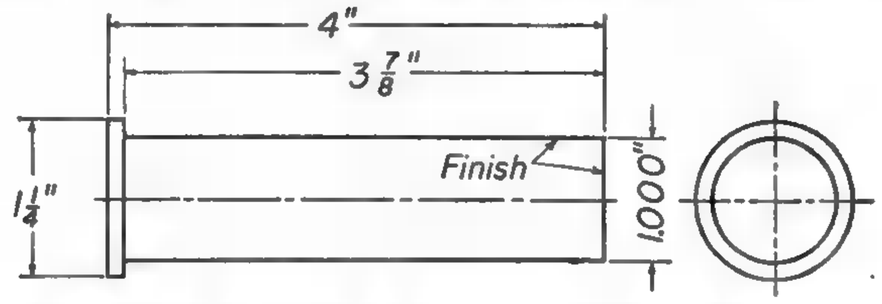

Fig. 1 Preferred specimen for Jominy end-cooled hardenability test

If it is desirable to obtain a result comparable with the standard specimen, 1 in. in diam, a smaller specimen may be machined to the dimensions shown in Fig. 4 and inserted into a standard 1-in. bar that has been properly drilled. About 0.2 grams of low-melting alloy is placed in the bottom of this hole and the bar is heated to about 212 F. The smaller specimen is then inserted into the hole, a small piece of asbestos is placed on top of the insert, and the tong-hold piece is screwed down fairly tight. The entire assembly is then heated to the austenitizing temperature and cooled in the standard manner. After the insert has been removed by heating to about 212 F, hardness measurements are taken as they would be for any standard bar.

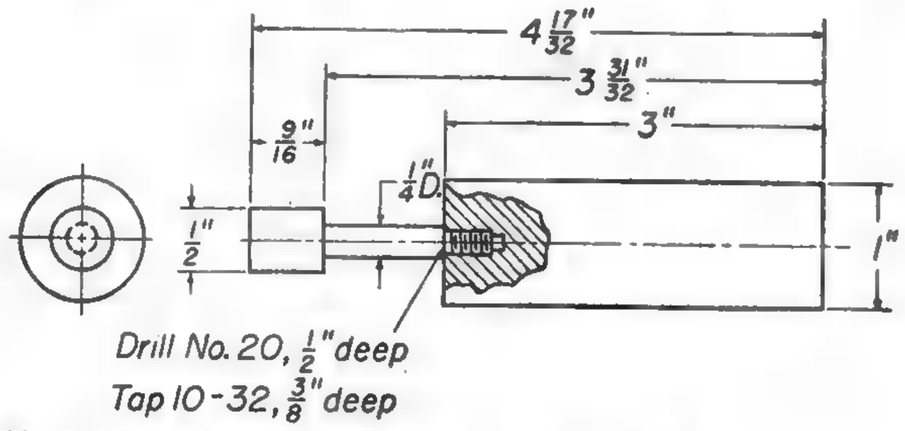

Fig. 2 Optional specimen for Jominy end-cooled hardenability test

The Society of Automotive Engineers and the American Society for Testing Materials have written hardenability specifications for the end-cooled test that are alike in the main. They do not correspond in a few details, which might make a difference with some steels. The SAE requires that samples taken from larger bars or billets be forged to 1¼ in. in diam; whereas the ASTM does not require this. The SAE specifies heating the test specimens on a piece of graphite; the ASTM, on cast-iron chips. The forging operation is difficult for many consumer plants, since frequently such plants have no forge shop. For very large pieces, however, the forged bars give more reproducible results. Heating on graphite will result in a temperature higher than that of the furnace, if the furnace atmosphere is air.

Segregation of carbon, manganese and other chemical elements occurs in the ingot, and the hardenability of the steel in these segregated portions will differ from that in the remainder of the steel. In general, specimens taken from the top of the ingot will have higher hardenability than the steel from the middle, and specimens from the bottom of the ingot will have lower hardenability than steel from the middle.

It is possible with cast test specimens to obtain results that will indicate the hardenability of the steel in the as-forged condition. In the cast test bar to be used for such purposes, grain size, which is important, is controlled by the thickness of the mold and the size of the hot top. A mold successfully used was made of cast iron,

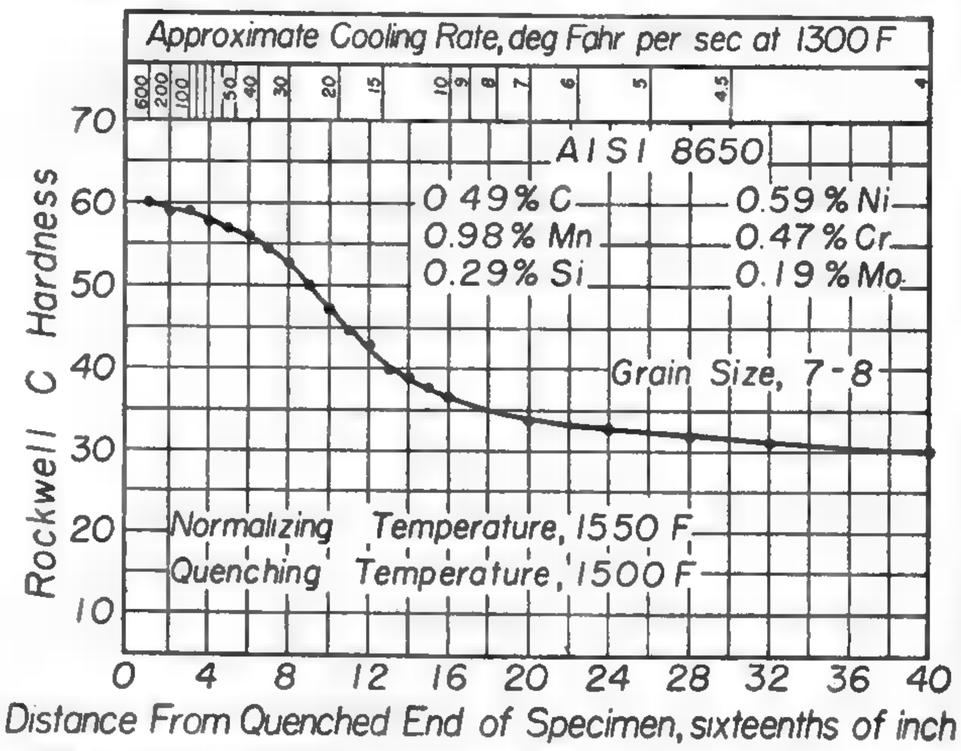

Fig. 3 Typical end-quench hardenability curve for AISI 8650 steel

as shown in Fig. 5. Hardenability tests made on pieces cast in this mold gave results consistently in good agreement with those obtained from the bars rolled from the heat of steel. It is common practice to perform a Jominy test on billets or rolled bars made of a particular grade of steel, using the recommended austenitizing temperatures (AMS, SAE or AISI) for this particular grade. The heat treatment of the cast specimens is changed, if necessary, to make the resulting hardness curves of both cast and forged specimens the same.

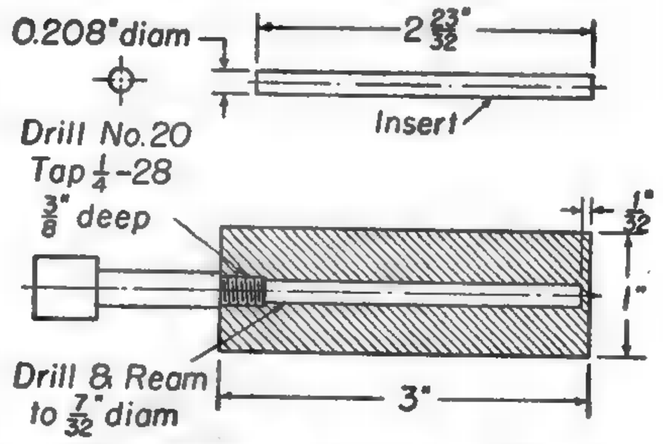

Fig. 4 Insert-type specimen for Jominy end-cooled hardenability test of steel available only in small sizes

Shallow-Hardening Steels. ***The Rockwell-Inch Test.*** The Rockwell-inch test has been used considerably for discriminating among the characteristics of the simple carbon steels ranging from 0.30 to 0.60% C, both in coarse-grained and fine-grained types. Following is a brief description of how the test is made and applied:

A prolongation is forged from the full section of a bar or billet to produce about a 10-in. length, 1⅛ in. in diam. After normalizing, the round is turned to 1 in. in diam plus or minus 0.003 in. and is smoothed with No. 3 emery cloth. A 4-in. length of this bar 1 in. in diam is then used as the specimen.

The specimen is heated to 1550 F plus or minus 10° in an ordinary atmosphere, then quenched and equalized in agitated water held between 65 and 95 F.

The untempered specimen is then cut transversely with

an abrasive wheel; precautions are used to avoid localized tempering. Overheating can be detected by employing a 5% nital etchant on the cut surface.

The cut end and the opposite end should be parallel. The specimen is then probed with a Rockwell C hardness penetrator across at least two diameters at 90 deg to each other. A surface reading is made on the lightly polished outside diameter. One half of the surface reading and of the reading at the center are added to the seven intermediate readings and the total figure is divided by eight. This gives a Rockwell-inch reading that actually

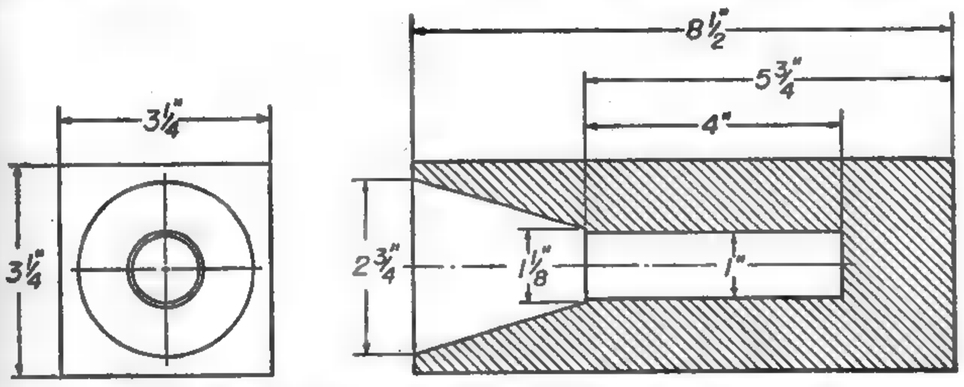

Fig. 5 Mold for casting hardenability test specimens

represents the area under the hardenability curve and usually gives a figure from 32 to 60 for carbon steel containing 0.30 to 0.60% C.

When duplicate tests are conducted on the same bar or billet, they will usually check within less than one Rockwell-inch. Checks made by different laboratories on the same billets will usually agree within less than two Rockwell-inches. On the other hand, two mill heats of almost identical composition, except for the cumulative

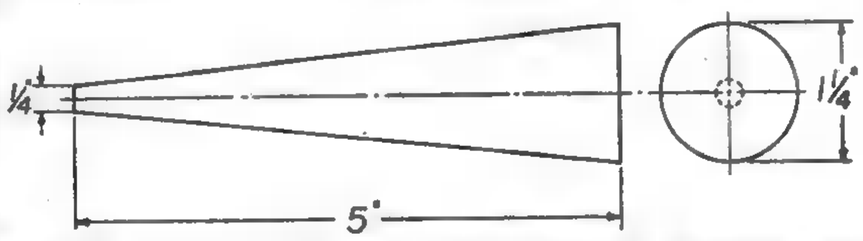

Fig. 6 Specimen for cone test (Post, Green and Fenstermacher)

total of permissible residual elements, may check as far apart as 8 Rockwell-inches.

A mill heat of 42 Rockwell-inches in hardenability might harden successfully to the surface intensity and depth required without cracking in a 3/4-in. section; whereas a mill heat of similar composition, but having variables as mentioned above, would crack if a piece of the same size were quenched in water. Quench cracking is not always related to a particular hardenability, but experience indicates that beyond a certain hardenability, the hazard of quench cracking is intolerable.

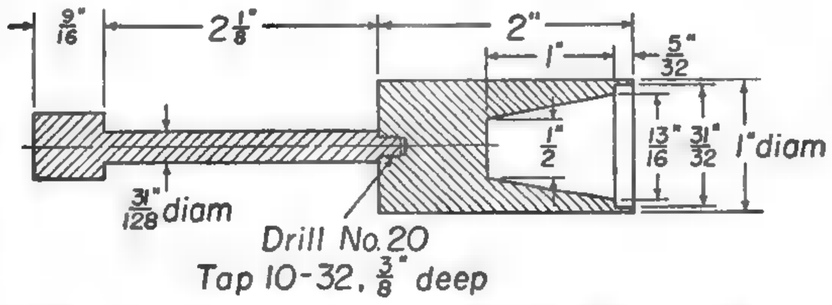

Fig. 7 Type L specimen for end-cooled hardenability test

The Cone Test of Green and Post.[3] The cone test was developed to measure the hardenability of shallow-hardening steels of the 1.10% C type. It consists in quenching a cone 5 in. long by ¼ in. in diam at the small end and 1¼ in. in diam at the large end into a brine flush (Fig. 6). The cone is then split longitudinally and the Rockwell C hardness is determined along the longitudinal axis. It is important for the specimen not to be tempered in these cutting and grinding operations.

The hardness penetration can be measured by etching with a light acid. An electromagnetic testing device[4] has been used to determine the hardenability of the hardened cones without slicing or grinding the cones. Rates of cooling past 1300 F have been determined for all points along the axis of the cone test specimen. These data make it possible to specify the cooling velocity that will yield a given Rockwell hardness in the steel specimen.

The duration of heating the cone and the temperature used should correspond with those to be used in production operations. It is customary to heat steels of the 0.60 to 1.30% C grades to 1450 F during a total heating period of about 30 min, including a 10-min soak at temperature. Steels of the 1.10% C type are generally pretreated by oil quenching from 1600 F.

The brine flush used consists of a standard 3-in. flushing pipe with about a 1-in. overflow of brine. The brine solution contains 10% NaCl by weight and is at room temperature. Cones are flushed with the small end down.

The L-Bar of Jominy.[5] This test was designed to measure the hardenability of the more shallow-hardening plain carbon steels. The standard Jominy specimen that has a flat end is used. This specimen, which has had a tapered hole drilled in the water-cooled end, is hardened on the regular end-quench test equipment. The dimensions for such a test bar are shown in Fig. 7. In order to use this bar on the regular end-quench cooling equipment, a longer adapter is necessary, as shown in the figure. The

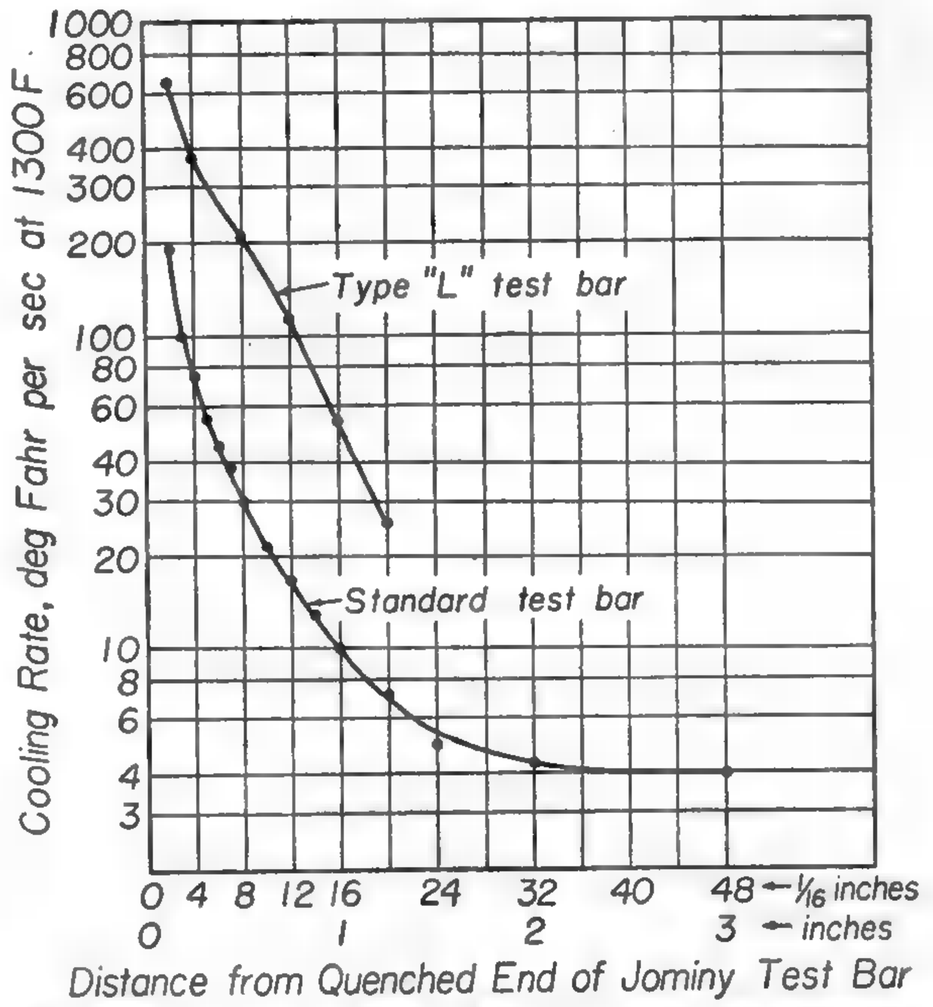

Fig. 8 Cooling rates at different distances from the quenched end of the Type L and the standard test bars

important feature of this specimen is the shape of the hole cut in the end. This hole produces a wall thickness of 3/32 in. at the extreme end to 1/4 in. at the top of the hole. The specimen is heated to whatever austenitizing temperature is desired, and is then hung vertically in the fixture on the hardenability equipment while water at 75 F plus or minus 5° is sprayed into the hole on the end. It is recommended that the height of the water column be increased to 4 in. before making a test with this type of bar. The time of heating and the temperature used should correspond to those to be used in production operations. The structure of the steel to be tested should correspond to the structure that will be present in the steel in production immediately before hardening.

After hardening, parallel flat surfaces 0.015 in. deep are ground on the surface of the outside layer of the test bar, and Rockwell C hardnesses are determined. The Rockwell C hardnesses are then plotted in a convenient manner to show the distance of each from the water-cooled end. As in the cone test described above, the cooling velocity necessary to yield a Rockwell C hardness from the specimen of steel can be determined from these measurements.

Figure 8 shows the cooling rates obtained with the type L test specimen and with the standard test specimen.

Shepherd Disk Hardenability Test. The hardenability of shallow-hardening steels is determined by quenching slabs of various thicknesses in a special spray of brine. After hardening, these slabs are sectioned with a thin grinding wheel and etched to show depth of hardening. The hardenability is reported as the number of thirty-seconds of an inch thickness of the thinnest slab that shows a soft core 5/64 in. wide or larger.

(*a*) *Prehardening Treatment.* Slabs are heated 40 min at 1600 F, and oil-quenched. Scale is removed from slabs.

(*b*) *Hardening Operation.* A final hardening consists of quenching slabs from 1420 F in brine. Slabs are austenitized in a gas-heated lead pot containing a thermocouple and using a 20-min heating cycle.

The Shepherd Penetration-Fracture (P-F) Test.[6] This test consists of hardening in brine four samples machined to 3/4 in. in diam by 3 in. long. One specimen each is quenched from 1450, 1500, 1550 and 1600 F. Each specimen is notched in the middle and fractured by impact. One half of each is examined for grain size of the case as compared with a standard set of Shepherd fracture standards. Penetration tests are made on the other half of each specimen by grinding and polishing the fractured face, then etching 3 min in a 50% HCl solution at 180 F. The hardness penetration is measured in 1/64 in.

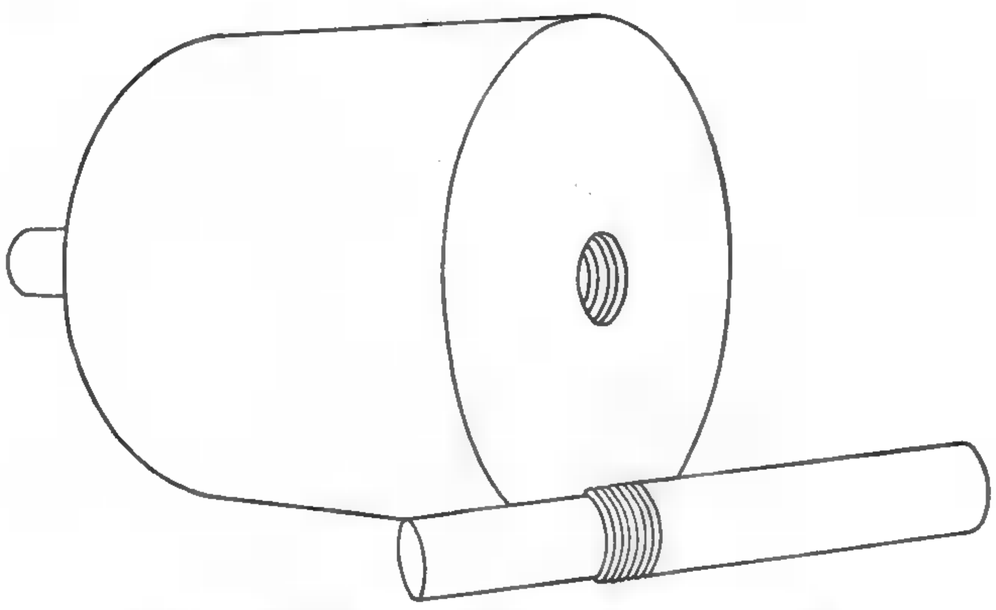

Fig. 9 Specimen for gradient-cooling air hardenability test

For determining the penetration-fracture values of 1.10% C tool steels, the specimens are generally pretreated by oil quenching from 1600 F after soaking for 40 min at temperature. The steel is then hardened after a heating cycle of 25 min for each austenitizing temperature.

Deep-Hardening Alloy Steels. The air hardenability test developed for deep-hardening steels, consists of taking a slug of 32% Ni-Fe alloy, 6 in. in diam by 6 in. long, drilling a hole 0.058 in. in diam through its center, and tapping about 1 in. at each end. The hardenability specimen itself is 7 in. long by 1 in. in diam; 4 in. of this length extends from the end of the 6-in. slug and the remaining 3 in. (0.856 in. diam) reaches into the center of the slug (Fig. 9). Two specimens are inserted into the 6-in. diam slug, one at each end; the assembly is then heated to the hardening temperature, soaked, removed from the furnace, placed on an elevated wire screen and air cooled. The specimens are then unscrewed, ground flat on two opposite sides, and hardnesses are taken at locations corresponding to definite cooling rates past 1000 F.

Cooling rates have been determined along the surface of the specimen. As with the other tests described above, a determination of the Rockwell hardness along the length of the hardenability specimen, permits a statement of the cooling rate that will yield the required Rockwell hardness for that particular steel specimen. Unlike the shallow-hardening grades and more deeply oil-hardening grades of steel, the air-hardening types are relatively insensitive to slight changes in chemical composition, as far as the resulting hardenability is concerned. In air-hardening steels, it is necessary only to determine the air hardenability of a given type composition. Air hardenabilities for several types of air-hardening steels are listed in Table I in terms of S/V, where S is surface area and V is volume.

Correlation. A number of tests have been made on the medium-hardening steels to correlate the results from the end-cooled specimen with results obtained by quenching cylinders and making a hardness traverse of the cross section of the cylinder.[8] For purposes of comparison, Fig. 10 shows the relationship between distance on the

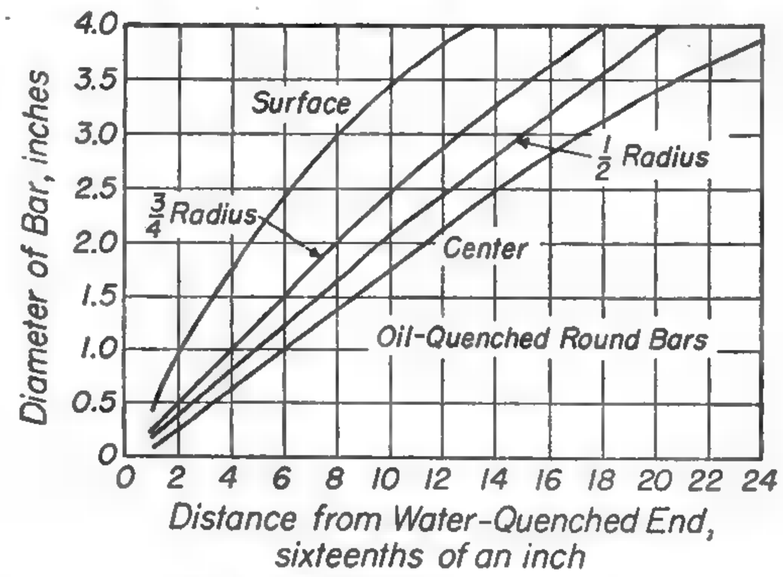

Fig. 10 Relationship between distance on the Jominy bar and points at the surface, ¾ radius, ½ radius and center of round bars quenched in still oil

Jominy bar and points at the surface, ¾ radius, ½ radius and center of round bars quenched in still oil; Fig. 11 shows corresponding relations for bars quenched in still water. A theoretical method has been developed[9] to calculate the hardenability curve on the end-cooled bar from a knowledge of the critical diameter of the steel. This information is discussed in the article on page 494.

The experimental correlation of the cone test, the Jominy L-bar, the Shepherd P-F and the Shepherd disk tests are given in Table II.

Application of Test Data

In the selection of steel for any part that requires heat treatment, the hardenability of the steel becomes a first consideration. The design of the part usually determines whether water quenching or oil quenching is preferable, and the design and size of the part determine the rate of cooling at any point in the part.

The choice of steels[10] is limited to those that will harden at the required rate of cooling and often the steel selected

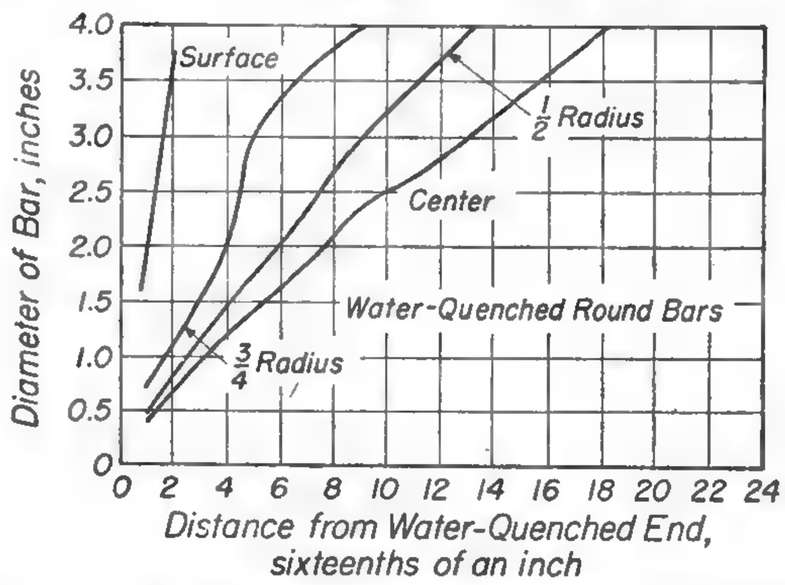

Fig. 11 Relationship between distance on the Jominy bar and points at the surface, ¾ radius, ½ radius and center of round bars quenched in still water

is the least expensive one that will harden at the necessary rate. Unfortunately few available data give the cooling rates of various parts. The rate of cooling of some of the common sizes of bars has been determined at the surface and center and at various points between surface and center.[11,12,13] For convenience, Table III has been prepared, giving the rate of cooling of several common sizes of specimen computed from Scott's work.[12]

Table I. Compositions, Treating Temperatures and Hardnesses Attainable in Various Air-Hardening Steels as a Function of S/V

Steel Designation	Percentage C	Mn	Si	Cr	Ni	W	Mo	Hardening Temp, deg Fahr	Minimum S/V for Minimum Rockwell C of 64	62	60	55	50	45	40
A	0.93	0.62	0.24	5.04	0.20		0.93	1700	3.0	1.4	1.1	<1.0	..	..	..
								1750	3.0	1.0	<1.0	<1.0	..	..	..
								1800	no	no	<1.0 to 1.4	<1.0	..	..	..
								1850	no	no	no	no	<1.0	..	..
B	0.39	0.40	0.99	5.10	0.09		1.22	1800 to 1900	no	no	no	<1.0	..	..	..
C	2.16	0.40	0.40	12.00	0.48		0.087	1700	no	3.0	2.2	1.7	1.6	1.3	1.1
								1750	3.8	2.7	2.4	2.0	1.7	1.4	1.1
								1800	2.6	2.1	2.0	1.7	1.5	1.1	1.0
								1850	no	2.3 to 3.3	2.0	1.6	1.2	1.1	1.0
D	1.50	0.35	0.36	12.09	0.35	....	0.83	1850	1.6	<1.0	..	..	..	..	..
E	1.13	0.42	0.34	16.70	0.36	0.02	....	1975	no	no	1.41	<1.0	..	..	..
F	0.35	0.41	0.40	12.90	0.50	....	0.26	1850	no	no	no	1.4	<1.0	..	..
G[a]	0.104	0.36	0.26	1.54	3.67	....	....	1550	no	1.3	<1.0	..	..	..	..
H	0.57	0.56	0.71	7.45	0.22	7.77	0.15	1900	no	1.0	<1.0	..	..	..	..
J	0.71	0.47	1.17	3.04	0.33	....	5.63	1900	2	<1.0	..	..	..	..	..
K	0.26	0.49	0.17	1.24	4.28	....	....	1525	no	no	no	no	no	no	<1.0
T	0.69	2.09	0.35	1.08	0.15	....	1.57	1550	<1.0	..	..	..	..	..	..

(a) Carburized at 1650 F, 8 hr; hardness taken 0.015 in. below surface at about 0.90% C.

When parts are very near the size and shape of one of these specimens, the rate of cooling may be approximated. In Fig. 8 the rate of cooling is given for various points on the end-cooled bar, and it is possible, by reference to this figure, to determine on the end-cooled bar the location that corresponds to any desired cooling rate.

By obtaining the hardenability curve of various steels by means of the end-cooled bar, it is possible to select a steel that hardens satisfactorily with the desired cooling rate. From the standpoint of hardenability such a steel will be satisfactory for the intended part. If the part is to be water-quenched, it is likely that one of the shallow-hardening specimens will be used in determining the correct cooling rate.

Another method of applying hardenability data, as described by Boegehold,[14] is to make an experimental part from a steel for which the end-cooled hardenability curve has been determined. A hardness traverse is made from the surface to the center of this part and the hardnesses so obtained are compared with those obtained on the end-cooled bar. It may be assumed that points of equal hardness will have the same cooling rate, and the cooling rate can thus be determined at the various points from the surface to the center of the part.

The following is an example of the application of hardenability data: An axle shaft, 5 in. in diam and 3½ ft long, is required in a machine. The engineering analysis indicates that the torsion requirements will approach a maximum of 30,000 psi and that the bending stresses will reach a maximum of 100,000 psi. What must be the hardenability pattern of the steel used in this part?

Since the shear stress in torsion is about one-half that in bending, the latter will be the primary consideration. In bending, stresses approach zero in the neutral axis; therefore the steel need not be hardened completely to the center. This is helpful because distribution of stress in quenching will favor bringing the part out whole and, after tempering, should leave the exterior layers in compression.

In order to withstand a fatigue load of 100,000 psi in bending, a minimum Rockwell C hardness of 44 is required. This hardness should be obtained by tempering ■ structure as quenched, containing not less than 95% martensite which, it is believed, should be present to at least the half-radius position in the shaft. In a steel containing 0.45% C this means an as-quenched hardness of Rockwell C 55.

Reference to published charts (SAE and AISI) will show that in order to harden a bar 5 in. in diam to half-radius, a composition will be required that will harden

Table II. Chart for Correlation of Shallow Hardenability Locations of Equal Hardenability

Cooling Velocity, °F per sec at 1300 F	Cone Test, mm	L Bar, 1/32 in.	Shepherd P-F, 1/64 in.	Shepherd Disk Test, 1/32 in.
250 to 280	34 to 40	9 to 10	7 to 9	10
225 to 250	40 to 45	11 to 12	9 to 11	11
190 to 220	47 to 53	13 to 14	11 to 14	12
170 to 190	55 to 61	15 to 16	14 to 18	13
140 to 160	65 to 72	17 to 18	Through	14
100 to 130	75 to 90	20 to 22	Through	15
90 to 115	83 to 95	22 to 26	Through	16

with ■ cooling rate of 7° per sec at 1300 F. Translated in terms of a standard end-quenched specimen (Jominy bar), this means a minimum of Rockwell C 55 at 20 sixteenths.

Therefore, the choice of steel is narrowed to a composition equivalent in hardenability to SAE 4345. Special surface hardening of a lower-alloy steel might be an alternate approach.

The rates of cooling at surface and center of a block of steel are governed by the surface per unit volume (S/V) factor for the shape in question. The rates of cooling blocks past 1300 F and 1000 F as a function of S/V has been determined for S/V ratios from 1.0 (represented by a specimen 6 in. in diam by 6 in. long) to 4 (represented by a long bar 1 in. in diam). It has also been

Table III. Rates of Cooling of Common Sizes of Bars

Bar Size, inches	Rate of Cooling at 1022 F, Quenched from 1508 F into Agitated Water: At Surface, °F per sec	At 0.04 in. Below Surface, °F per sec	At 0.16 in. Below Surface, °F per sec	At Center, °F per sec	Rate of Cooling at 1328 F, Quenched in Still Water from 1607 F: At Center, °F per sec	Rate of Cooling at 1022 F, Quenched from 1508 F into Agitated Oil: Surface °F per sec	Center, °F per sec	Rate of Cooling at 1328 F, Quenched from 1607 F into Still Oil: At Center, °F per sec
½	...	...	...	320	330	...	115	115
¾	...	...	...	180	185	...	88	72
1	1800	790	183	101	108	135	49	47
1½	...	...	...	48	54	...	29	29
2	...	650	115	27	31	...	■	18
3	...	560	104	13	14	...	9.4	9.2
4	...	495	99	...	8.5	...	...	5.5

shown that the high-alloy steels of the air-hardening type are fairly insensitive to slight variations in chemical composition, at least in regard to the hardness developed in any size of block after air hardening. This makes it possible to write down the hardenability of various air-hardening types in terms of the expected hardness to be developed in any size block of known S/V ratio. Such data are shown in Table I.

Table IV. Rockwell C Hardness for Various Carbon Contents and Percentages of Martensite

Percentage Carbon	Percentage Martensite				
	50	80	90	95	99.9
	Rockwell C Hardness				
0.18	31	35	37.5	39	43
0.23	34	37.5	40.5	42	46
0.28	36.5	40.5	43	44.5	49
0.33	39	43.5	46.5	48.5	52
0.38	42	46	49	51	54
0.43	44	48	51	53.5	57
0.48	46.5	52	54	57	60

Hardenability Specifications. Hardenability specifications may be developed so that a given hardness is required within a range of cooling rates or distances on the end-cooled bar, or so that a minimum hardness will be obtained at not less than a given distance on the end-cooled bar.

For instance, an aircraft specification on SAE 8740 steel requires a hardness of not less than Rockwell C 50 for a minimum distance of 7/16 in. from the cooled end of the Jominy specimen, when the steel has been normalized at 1700 F and subsequently quenched from 1525 F. This is expressed by stating that the hardenability shall be J50=7 minimum when determined by the standard end-quench test. In Fig. 3 showing the hardenability of AISI 8650 steel, J55=6.

An aircraft specification of an SAE 3312 steel states that the hardenability shall be J41 max and J32=6. Steel purchased under this specification will never harden to more than Rockwell C 41 and will have a hardness of not less than Rockwell C 32 at the center of a bar 1 in. in diam quenched in still oil.

Table IV[15] may be used as a guide in choosing the hardness for reference points in steels of different carbon contents. Such data are of interest in the formulation of specifications for hardenability.

As part of the steel specification, hardenability specifications are growing in popularity, since they insure better control of the hardening process.

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The Calculation of Hardenability

By John M. Hodge*

THIS article discusses the calculation of hardenability from chemical composition and grain size. The method to be described was developed in 1942. It is based on the principle that each chemical element in the composition has a multiplying effect on the hardenability.

This method has been found to work very well on plain carbon and low-alloy steels. However, irregularities, still unexplained, have been observed in steels of high hardenability and in steels containing less than 0.20% C. Following is a detailed discussion of some of the factors, such as uncertainties in the measurement of hardenability values, particularly those of the pure iron-carbon alloys, and the possibility of incomplete solution of carbides, which are involved in these irregularities. These factors are of such a nature that one investigator, working with one set of conditions, may derive a factor apparently different from that derived by another investigator working with another set of conditions, particularly in work with the more highly alloyed steels. It is not yet known, however, whether these irregularities actually reflect a departure from the principle of multiplying factors.

The Factors Affecting Hardenability. The principal factors affecting hardenability are as follows:

1 The composition of the austenite
2 The grain size of the austenite
3 The homogeneity of the austenite

It is obvious that, if the individual and cumulative effects of these factors on hardenability can be evaluated quantitatively, it would be possible to calculate or predict hardenability from a knowledge of these factors alone.

* Research and Technology Dept., Carnegie-Illinois Steel Corporation, Pittsburgh. Prepared for the Subcommittee on Hardenability.

The Evaluation of Hardenability Effects. The individual effects of any of the factors enumerated above may be evaluated by studying the manner in which hardenability changes with changes in a single variable. This involves the measurement of hardenability in a series of steels in which all the variables (carbon content, alloying elements and grain size) are held constant except one. The effect of this single variable on hardenability is then expressed as the quotient of the hardenability value at a given value of the single variable, and the hardenability value at zero percentage (or at a fixed value of the variable). This quotient thus becomes a multiplying factor that serves as a numerical expression of the hardenability effect of the single variable studied.

As an illustration of this method, the hardenability values of two series of steels in which the phosphorus content is the single variable are shown in Fig. 1. It will be noted that the hardenability increases regularly as the phosphorus content increases. Furthermore, the rate of increase of hardenability with increasing phosphorus content is greater in the steel having the higher base hardenability. This is necessarily true if the hardenability effect of phosphorus is to be represented by a single series of multiplying factors.

The multiplying factors for phosphorus, which express the manner in which hardenability changes with changes in the phosphorus content, are shown in Fig. 2. These have been derived by dividing the hardenability values at the various percentages of phosphorus by the base hardenability at zero phosphorus in each series of steels.

In order for this method of evaluation of hardenability effects to be valid it is necessary that the hardenability values be measured and expressed in terms of fundamental

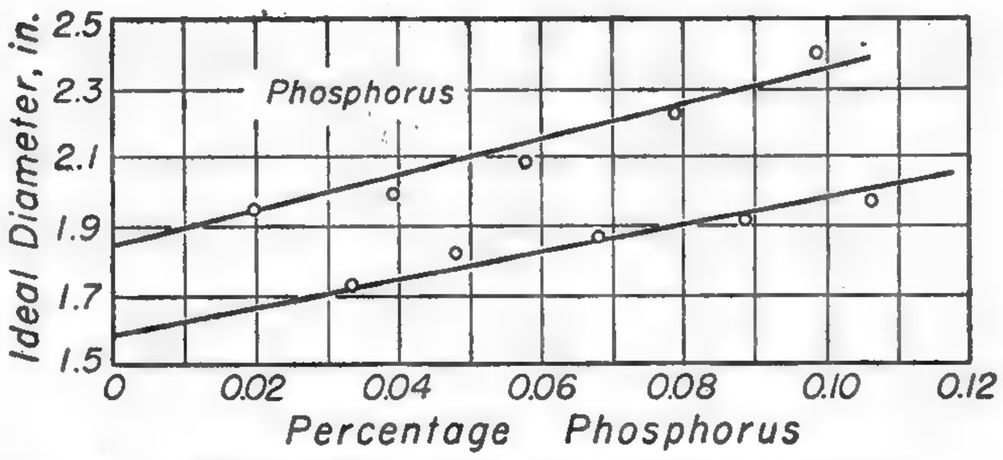

Fig. 1 Hardenability as a function of phosphorus content in two series of steels

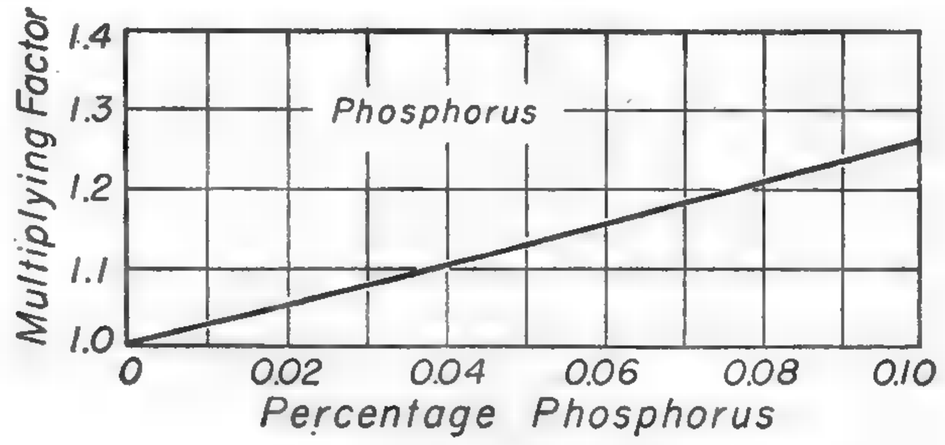

Fig. 2 Multiplying factors for phosphorus

and mutually consistent units. The expression most commonly used for this purpose is "ideal diameter" (D_I). This is the diameter of an infinitely long cylinder which, in an ideal quench, will just transform to a given specific microstructure at the center. An ideal quench is one in which the rate of heat transfer at the surface is infinite; that is, one in which the surface comes instantly to the temperature of the quenching medium. This expression furnishes a very useful single, numerical, fundamental unit for the evaluation of hardenability, which can be derived from the results of standard measurements of hardenability in the laboratory, by using known cooling rate relationships.

The most direct method of measuring hardenability in terms of ideal diameter is the cylinder series method. In this method a series of round bars of increasing diameter are quenched under a standardized set of quenching conditions and the diameter of the bar is determined that just quenches to the desired microstructure at the center. This diameter is known as the "critical diameter" (D).

In order to convert this critical diameter value into terms of the more fundamental expression of ideal diameter, it is necessary to evaluate the quenching conditions quantitatively. The expression used for this purpose is the "severity of quench factor" or H value. This value can be determined from a cylinder series by means of the chart of Fig. 3. This chart is used in the following manner. The D_u/D values (the ratio of the diameter of the center portion that remains unhardened to the full diameter) for several of the bars of the series, are plotted against the D values (the full diameter) on transparent paper with the same co-ordinates as the chart. This curve, formed by the points on the transparent paper, is then moved until it matches one of the curves of the chart. The H value will then be the quotient of the HD value of any point on this curve and the corresponding actual diameter.

Table I. Severity of Quench (H Value)

Agitation	Oil	Water	Brine
None	0.25 to 0.30	0.9 to 1.0	2.0
Mild	0.3 to 0.35	1.0 to 1.1	2.0 to 2.2
Moderate	0.35 to 0.40	1.2 to 1.3	....
Good	0.4 to 0.5	1.4 to 1.5	....
Strong	0.5 to 0.8	1.6 to 2.0	....
Violent	0.8 to 1.1	4.0	5.0

Although, wherever possible, this H value should be measured by the method described above, typical values of this coefficient, which may be used as a guide, are shown in Table I.

When the H value of the quench has been determined, the hardenability values in terms of critical diameter can then be converted into values of ideal diameter by means of the curves of Fig. 4, which show the relationships among critical diameter, H value, and ideal diameter.

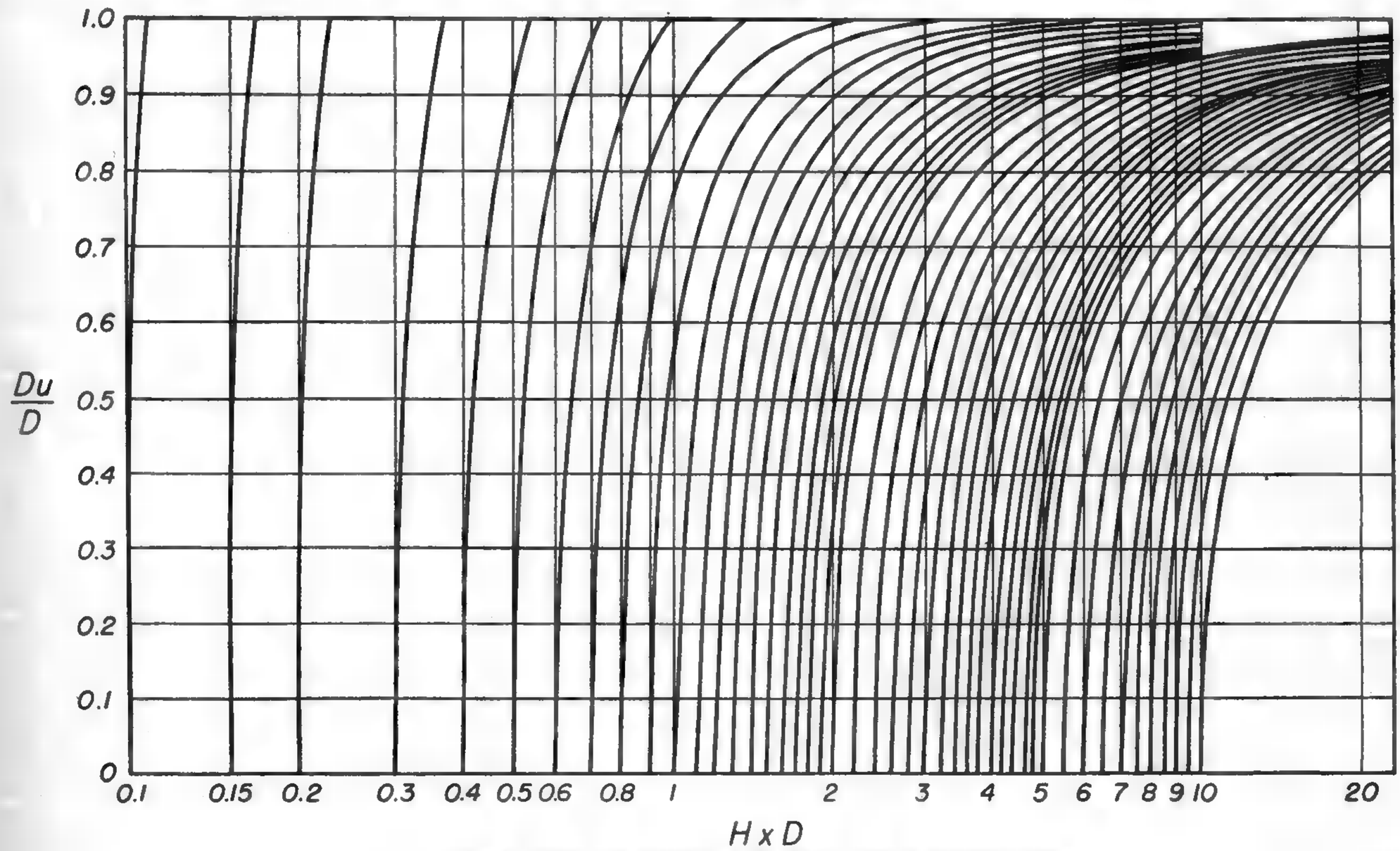

Fig. 3 Chart for estimating H value from a cylinder series

By means of these curves, this ideal diameter value can then be used likewise to evaluate the size of round that can be quenched to this microstructure at the center under any quenching conditions of known *H* value.

It should be emphasized, however, that these values of hardenability are all in terms of the microstructure at the center of the bar, and that, except in through hardening to full martensite, there will be a continuously changing series of microstructures from the surface to the center. Thus a bar that has a 50% martensite microstructure at the center might have a surface layer of considerable depth that is completely martensitic, and in many instances the microstructure of this surface portion may determine the performance of the part. Therefore, although it is more convenient to use the microstructure at the center as a criterion in measuring and expressing

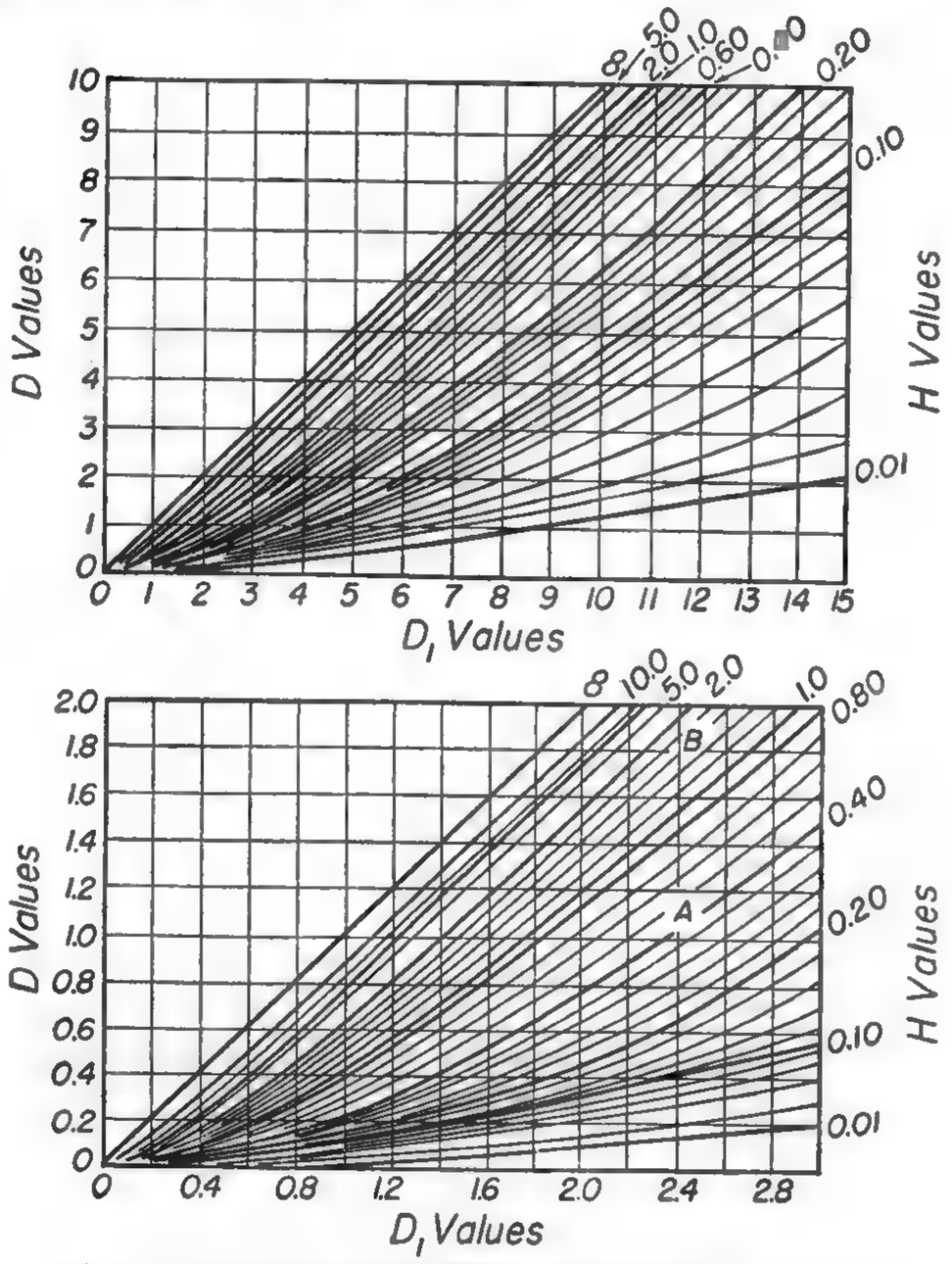

Fig. 4 Relationship among critical diameter, ideal diameter and *H* value.

hardenability, it is nevertheless important that the over-all microstructure of the piece be considered in applying the results of hardenability measurements or calculations.

Although the cylinder series method, just described, is the most direct method of measuring hardenability values in terms of ideal diameter, the method of hardenability measurement that is now by far the most commonly used is the end-quench test developed by Jominy and Boegehold. This test consists of heating a specimen 1 in. in diam by 4 in. long to the desired hardening temperature and then quenching the specimen in a fixture by impinging a stream of water on one end. The quenched bar is ground to a depth of 0.015 in. below the surface and hardness readings are taken 1/16 in. apart along the length of the specimen. (See the article on page 489.)

Measurements of end-quench hardenability may be converted to values of ideal diameter by means of the correlation curve of Fig. 5. This conversion requires measuring the distance from the quenched end of the end-quench test to the point of the desired microstructure and reading the corresponding ideal diameter from the correlation curve. The accuracy of this conversion is questionable at distances nearer than 0.3 in. from the quenched end, and a revised curve (dashed) is also presented. This dashed-line curve, based on an actual comparison of cylinder series and end-quench tests, is probably more accurate in this region.

The microstructure that has been most commonly used as a criterion in these various methods of measurement has been a mixture of 50% martensite and 50% products formed at higher temperatures. This microstructure should be located preferably by metallographic examination but several indirect methods may be used, permitting a more rapid and convenient determination of its location. This location may be determined from a cross-sectional fracture or etch test by noting the point at which a marked change occurs in the appearance of the fracture or etched surface. It will correspond to the point of steepest slope (the inflection point) in a cross-sectional hardness survey, or in an end-quench hardenability curve. Finally, the hardness values corresponding to this microstructure in plain carbon and alloy steels have been determined as a function of carbon content (Fig. 6). This curve furnishes a fairly accurate method of locating the 50% martensite microstructure in plain carbon steels, but the variations in the nature and hardness of the nonmartensitic products in alloy steels lead to considerable variation in the hardness value for a given carbon content in these steels.

Similar curves are shown in Fig. 7, representing the hardness values that correspond to other microstructures

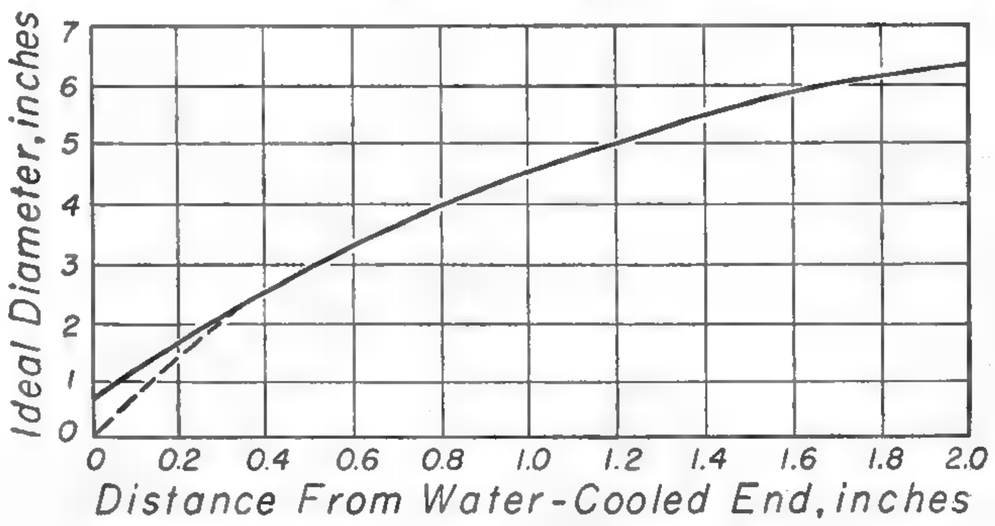

Fig. 5 Correlation between distance from the water-cooled end of a standard end-quench specimen, and ideal diameter

in terms of the percentage of martensite, as determined in a number of low-alloy and medium-alloy steels. The curves may be used as a general guide in locating these microstructures from a cross-sectional hardness curve or an end-quench hardenability curve.

It will thus be seen that, although the principle of multiplying factors furnishes a straightforward method for the numerical evaluation of hardenability effects, the methods of measurement involve several uncertainties that make a precise determination of these numerical values difficult. Such uncertainties leave in question many experimentally determined values of multiplying factors.

In the first place, the numerical values of the multiplying factors depend entirely on an accurate evaluation of the hardenability of the base composition at zero content of alloying elements. These hardenabilities will usually be relatively low, and unfortunately it is in this low hardenability range that the difficulties of accurate measurement are most pronounced. If the cylinder series method is used, the *H* value must be accurately determined and this determination is both indirect and particularly difficult with a series of small cylinders. If the end-quench test is used, the significant values of distance will fall near the quenched end, and the correlation between these values and ideal diameter is questionable in this region.

Using measurements of hardness as a criterion of the location of the microstructure containing 50% martensite, is a practice that has been followed in many of these determinations with resulting uncertainty since, as was shown above, there may be wide variations in the hardness values corresponding to this microstructure in alloy steels.

Still another factor, apparently very important in the uncertainties of these results, is the possible heterogeneity of the austenite. In many of these determina-

tions, particularly those involving alloy steels that contain carbide-forming elements, the homogeneity of the austenite is uncertain, and obviously the full hardenability effect of an element will not be realized unless it is completely dissolved in the austenite. The carbon and alloying elements contained in undissolved carbide are unavailable for increasing hardenability; instead these carbide particles may act as nuclei for transformation and decrease hardenability still further. Any heterogeneity in the austenite, even though visible undissolved carbide may not be present, will tend to decrease hardenability, since transformation will take place first in the areas of low alloy or carbon content. Therefore completely homogeneous austenite is essential to an accurate evaluation of the full effects of the alloying elements on hardenability. However, the homogeneity of the austenite is difficult to evaluate and this uncertainty leaves many of the determined hardenability factors open to question.

Multiplying Factors for the Alloying Elements. The multiplying factors for the individual elements, as determined by the several investigators in this field, are depicted graphically in Fig. 8 to 18.

The earlier values of Kramer[4] are omitted from this summation, since they have been superseded by the more recent work of Kramer, Siegel and Brooks.[15]

The methods of measurement used by these investigators were as follows:

Investigator	Method of Measurement	Method of Locating 50% Martensite
Grossmann	Cylinder series	Critical hardness
Crafts and Lamont	End-quench test	Metallographic
Kramer, Siegel and Brooks	Cylinder series and end-quench test	Critical hardness

In the numerical values of many of the hardenability factors as determined by the different investigators, the rather large differences reflect the uncertainties involved in the methods of measurement and, particularly in the carbide-forming elements, the numerical values are influenced by heterogeneity of the austenite, as described above. The cross-hatched areas in the curves for chromium, molybdenum and vanadium represent the effects of inhomogeneous austenite, as observed in the determination of these factors.

The wide discrepancy between the multiplying factors for manganese, as determined by Grossmann, and by Crafts and Lamont, and those determined by Kramer, Siegel and Brooks, illustrates still another source of uncertainty in these results. In the original work of Grossmann, the manganese factors were determined from rather limited data and were then used in the evaluation of the effects of carbon content in a series of commercial steels in which carbon content was the only variable. However, because of the difficulties involved in the measurement of the very low hardenabilities of pure iron-carbon alloys, the effect of carbon content in the absence of manganese was not actually determined. These factors for manganese and carbon were then applied to a number of plain carbon-manganese steels covering a wide range of manganese contents, and the effect of manganese content was thereby verified. It will be seen, therefore, that the numerical values of the factors for manganese depend on the values for carbon, which were not actually measured. Likewise, in the work of Crafts and Lamont the factors for manganese were based on the assumption that the original values for carbon were correct, and the values for manganese as determined by these investigators, are essentially similar to those presented by Grossmann. In the work of Kramer, Siegel and Brooks, however, the hardenability of several iron-carbon alloys was actually measured by the cylinder series method. The values indicated by these measurements were considerably higher than the original values of Grossmann, and the values for manganese are correspondingly lower. However, it should be noted that over a considerable range of carbon and manganese contents, the product of the values for carbon and manganese is essentially the same, whether these values or the original values for carbon and manganese are used.

The Effect of Carbon Content and the Cumulative Effects of the Alloying Elements. When the effects of the individual alloying elements have been evaluated in terms of multiplying factors, all that is needed to permit calculation or prediction of the hardenability of a steel is an evaluation of the hardenability of the iron-carbon base, and the cumulative effects of the alloying elements and of grain size on this base hardenability.

As mentioned above, the hardenabilities of the plain iron-carbon alloys, in terms of 50% martensite microstructures, have been evaluated by Grossmann and by Kramer, Siegel and Brooks. The effect of grain size has also been evaluated and these base hardenability values at the different grain-size levels are shown in Fig. 19, 20 and 21. It should be emphasized that, because of their interdependence, these higher carbon values of Kramer, Siegel and Brooks, should be used only in conjunction with their lower manganese values, and that likewise the lower

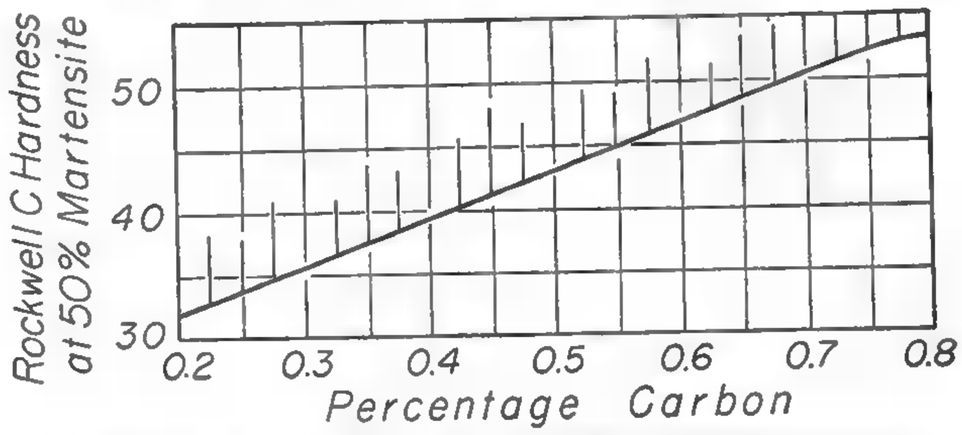

Fig. 6 The hardness of 50% martensite microstructures as a function of carbon content.

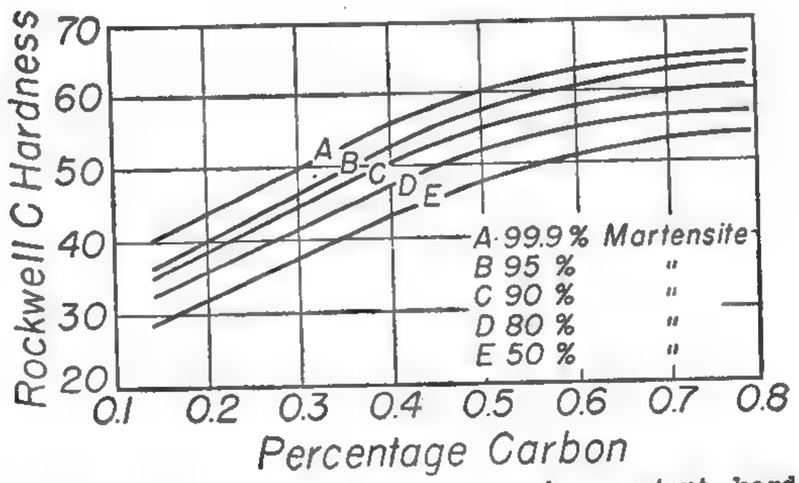

Fig. 7 Average relationships among carbon content, hardness and percentage of martensite.

carbon values of Grossmann should be used only in conjunction with the higher manganese factors.

When the base hardenability and the multiplying factors for the alloying elements have been evaluated, the cumulative effects are represented by the product of the base hardenability and these multiplying factors. Thus, to calculate the hardenability of a given composition, the base hardenability value corresponding to the actual carbon content and grain size should simply be multiplied progressively by the multiplying factors for each of the alloying elements making up the composition. The answer will then be the hardenability value in terms of ideal diameter for a microstructure of 50% martensite.

Representative values of the multiplying factors for the alloying elements, as chosen by the American Iron and Steel Institute, are shown in Fig. 25. These values are based on the original carbon values of Grossmann and should, of course, be used only in conjunction with these carbon values. The factors for manganese contents as high as 1.20%, for nickel as high as 2.00%, and for molybdenum, are those of Grossmann, while the values for silicon and chromium are those of Crafts and Lamont. The factors for manganese contents greater than 1.20% and for nickel contents greater than 2.00% represent compromise values between those of the various investigators. Experience has shown that these factors, if used with due regard for the precautions and limitations enumerated below, will permit a reasonable prediction of the hardenability of steels of medium hardenability, but will not predict accurately the hardenability of steels

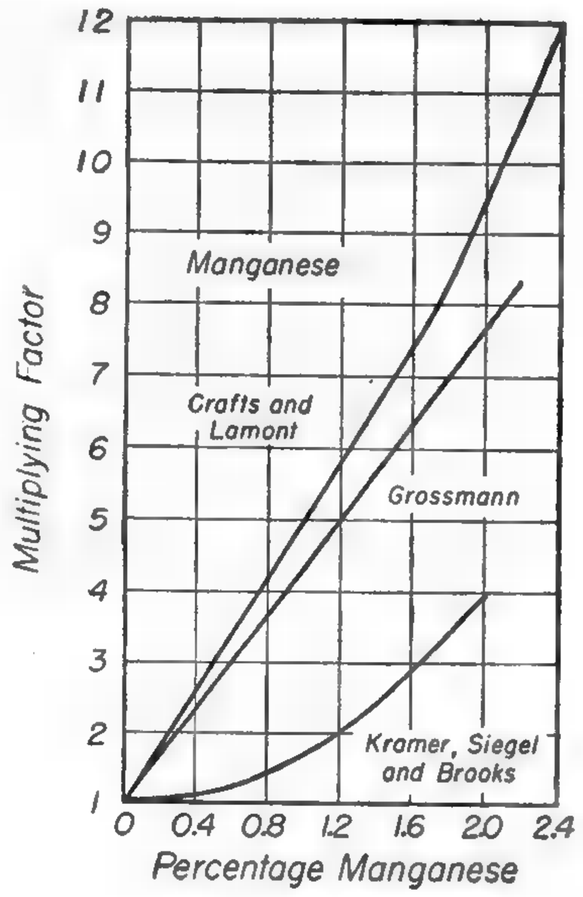

Fig. 8

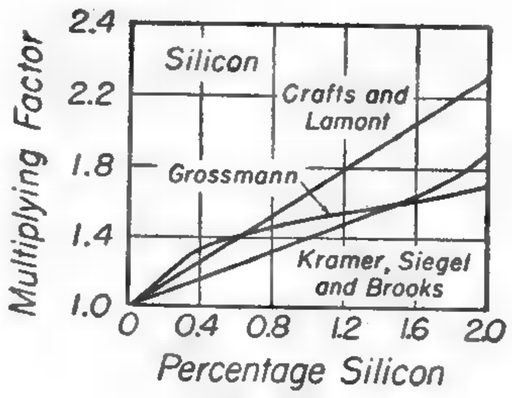

Fig. 9

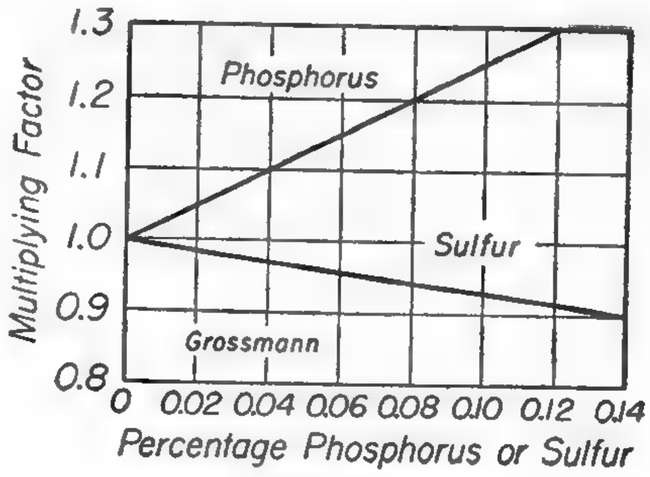

Fig. 10

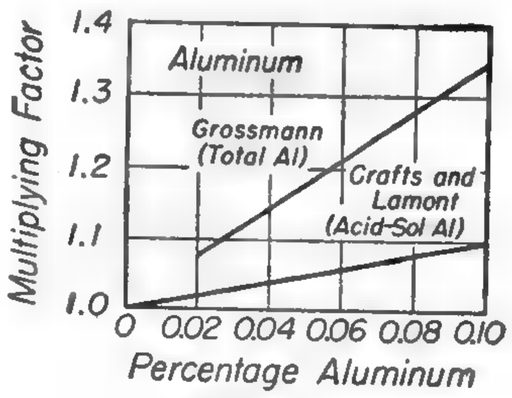

Fig. 11

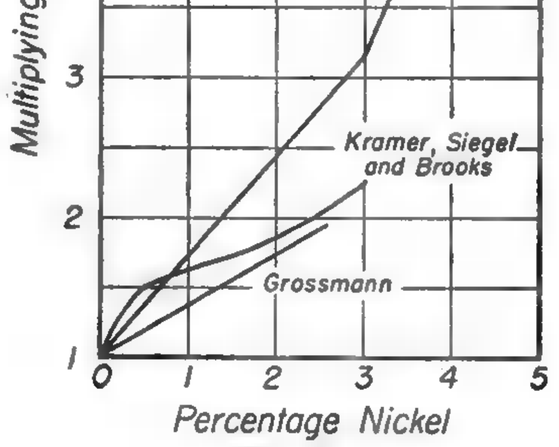

Fig. 12

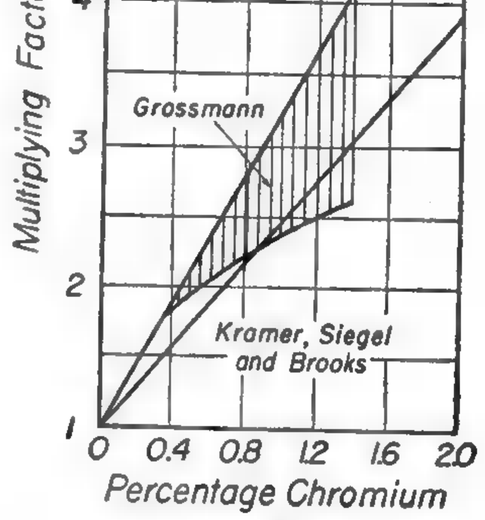

Fig. 13

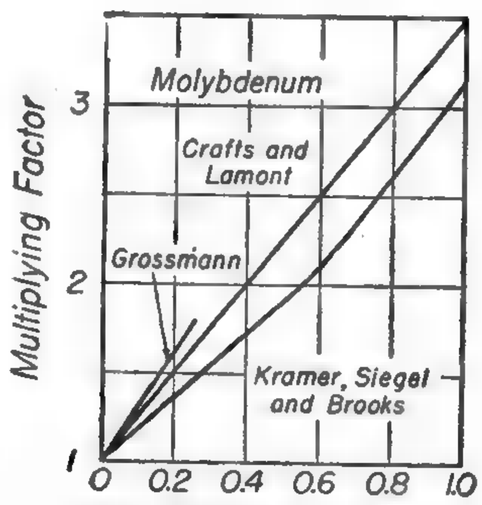

Fig. 14

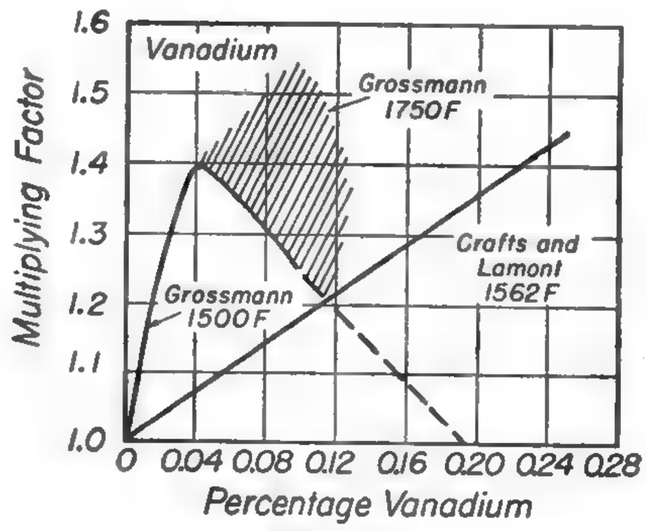

Fig. 15

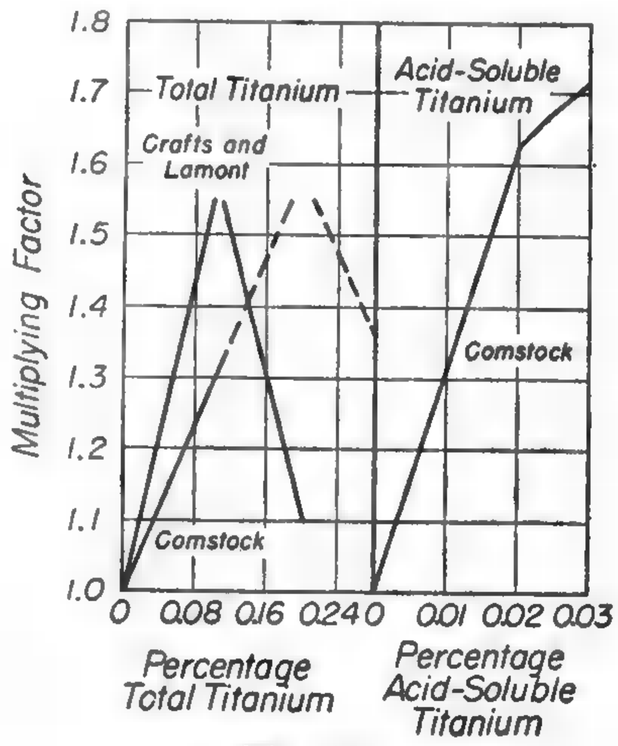

Fig. 16

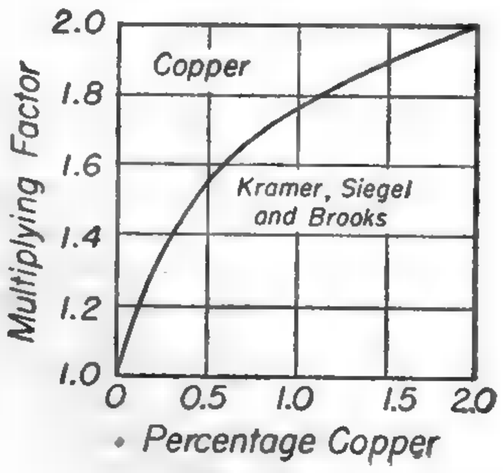

Fig. 17

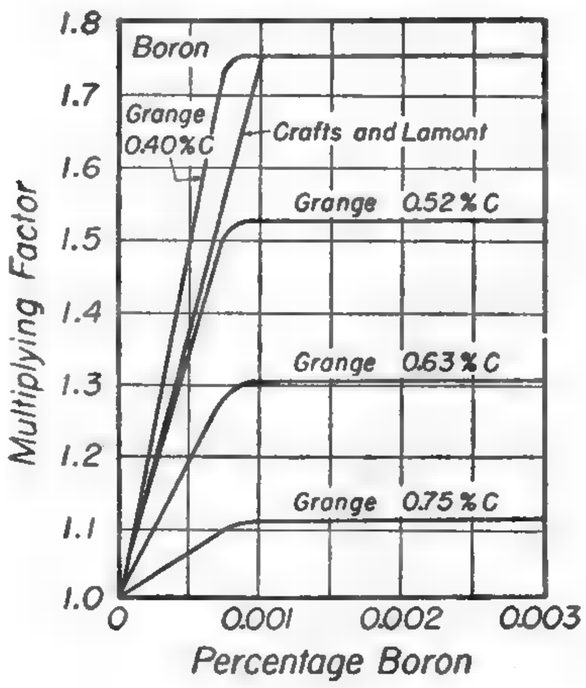

Fig. 18

Fig. 8 to 18 Multiplying factors for individual elements in steel, as determined by the several investigators. In the numerical values of many of the hardenability factors as determined by the different investigators, the rather large differences reflect the uncertainties involved in the methods of measurement and, particularly for the carbide-forming elements, the numerical values are influenced by heterogeneity of the austenite, as described in the text. The cross-hatched areas in the curves for chromium, molybdenum and vanadium represent the effects of inhomogeneous austenite, as observed in the determination of these factors. The wide discrepancy between the multiplying factors for manganese, as determined by Grossmann, and by Crafts and Lamont, and those determined by Kramer, Siegel and Brooks, illustrates still another source of uncertainty. *See text.*

possessing high hardenability, particularly those containing relatively large percentages of carbon-forming elements, nor of steels containing less than 0.20% C.

Limitations of Hardenability Calculations. The principle of multiplying factors has been repeatedly checked and does permit a reasonably accurate prediction of hardenability based on composition and grain size in plain carbon and low-alloy steels, if the following limitations and precautions are observed.

1 Since all the alloying elements in the composition will have a cumulative effect on hardenability, it is essential that all elements, including residuals, be taken into account.
2 If substantial amounts of carbide-forming elements are present, the actual hardenability will depend on the degree of solution of the carbides and cannot be accurately predicted.
3 The grain size at the hardening temperature must be known.
4 In applying the results to practice, the factor for severity of quench must be evaluated accurately.
5 The results are in terms of ideal diameter for a microstructure of 50% martensite and must not be applied to other criteria.

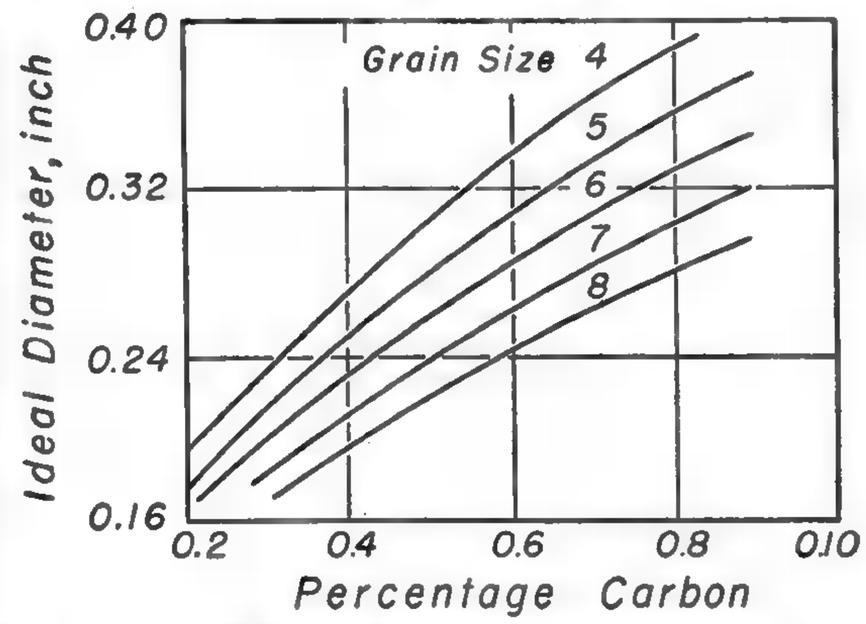

Fig. 19 The hardenability of pure iron-carbon alloys as a function of carbon content and grain size (Grossmann).

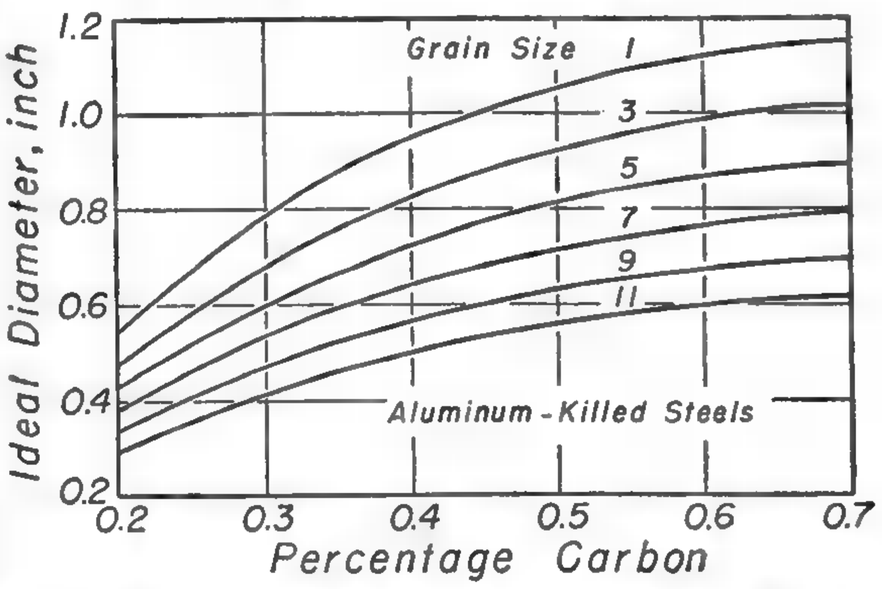

Fig. 20 The hardenability of pure iron-carbon alloys as a function of carbon content and grain size in aluminum-killed steels (Kramer, Siegel and Brooks).

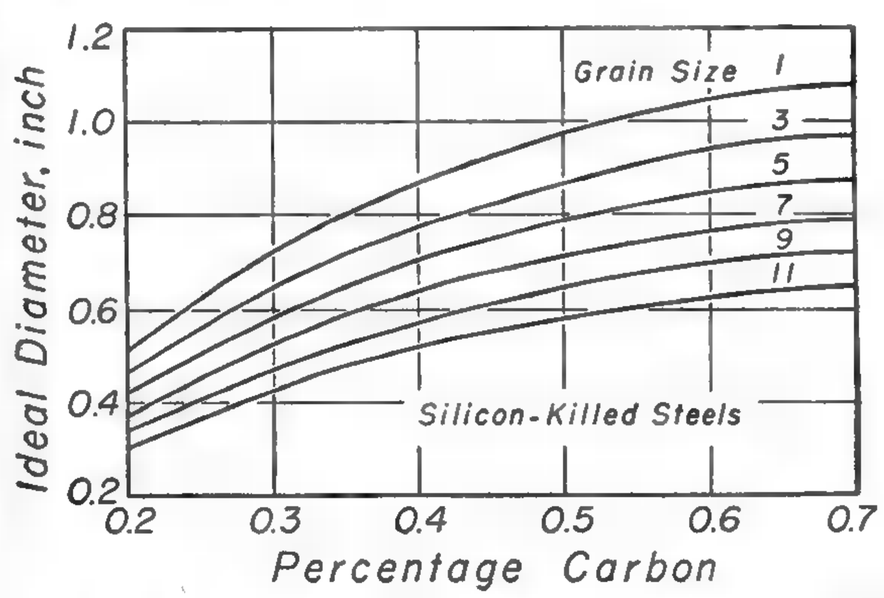

Fig. 21 The hardenability of pure iron-carbon alloys as a function of carbon content and grain size in silicon-killed steels (Kramer, Siegel and Brooks).

This limitation to microstructures containing 50% martensite may be serious, particularly in steel of higher hardenability, since in such steels the differences will be relatively large between hardenability values in terms of this microstructure and hardenability values in terms of the full martensite criterion associated with the optimum properties of tempered martensite. However, the relationship among hardenability values based on criteria of 50, 95 and 99.9% martensite have been studied in a number of low-alloy and medium-alloy steels and the average relationships are shown in Fig. 22. These data will serve as a guide to the application of hardenability values based on the criterion of 50% martensite to steels in which the optimum properties of tempered martensite are desired. Furthermore, recent work by Hodge and Orehoski indicates strongly that the values of the multiplying factors for the alloying elements are essentially independent of the criterion of hardenability used in their determination; that is, that an individual alloying element will affect hardenability in terms of a 50% martensite microstructure in a manner essentially the same as it affects hardenability in terms of a microstructure containing 95% martensite. Thus, knowing the base hardenability values for iron-carbon alloys, in terms of the specific microstructure of interest, hardenability values in terms of this microstructure may be calculated by multiplying this base value for carbon by the multiplying factors for the alloying elements as described above. Such hardenability values for iron-carbon alloys at a grain size of 8, in terms of microstructures of 50, 95, and 99.9% martensite, as evaluated by Hodge and Orehoski, are shown in Fig. 23. It should be noted that the values for 50% martensite are similar to those determined by Kramer, Siegel and Brooks and that, therefore, their lower manganese values should be used in conjunction with these carbon values.

Thus, there are now two methods of estimating values of hardenability in terms of microstructures other than 50% martensite, and the principle of multiplying factors may be applied to the calculation of hardenability in terms of microstructures that correspond more closely to optimum properties.

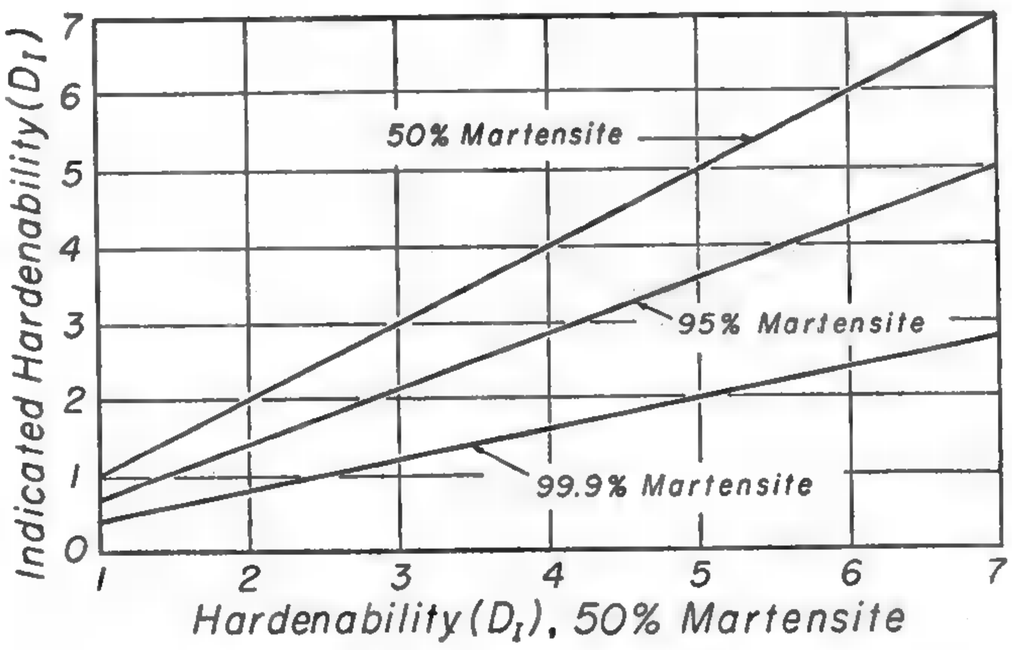

Fig. 22 Average relationships among hardenability values in terms of 99.9, 95 and 50% martensite microstructures.

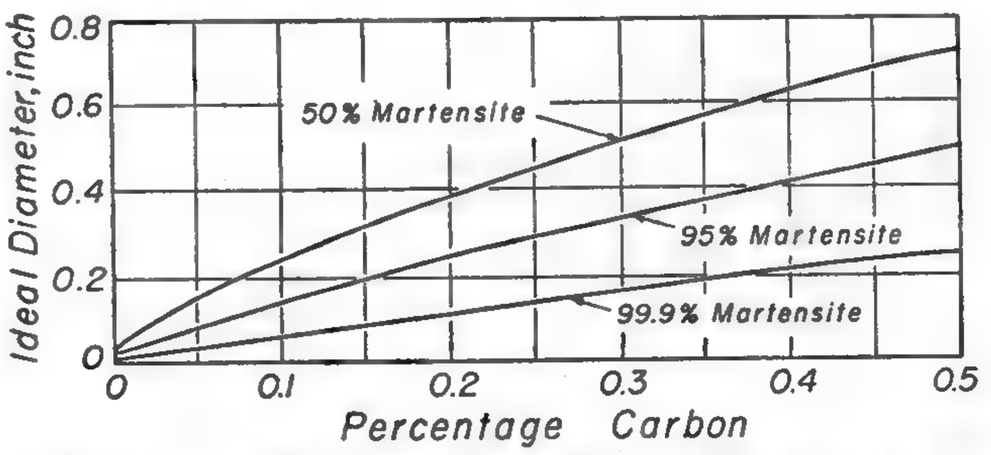

Fig. 23 Hardenability of iron-carbon alloys as a function of carbon content and microstructure—grain size No. 8 (Hodge and Orehoski).

An aluminum-killed, low-alloy steel of the following composition, at a grain size of 8, will serve to illustrate these methods: 0.40% C, 0.80% Mn, 0.20% Si, 0.20% Mo.

The hardenability corresponding to 50% martensite will be the product of the base carbon value for 50% martensite and the multiplying factors for the manganese, silicon and molybdenum, as follows:

$$0.6 \times 1.45 \times 1.2 \times 1.5 = 1.57 \text{ in. } D_I$$

According to Fig. 22, this would correspond to a hardenability of 1 in. D_I on the basis of 95% martensite or 0.6 in. on the basis of 99.9% martensite.

Using the carbon values of Fig. 23, the hardenability values in terms of 95 and 99.9% martensite would be calculated as follows:

1 For 95% martensite
$0.4 \times 1.45 \times 1.2 \times 1.5 = 1.05$ in. D_I

2 For 99.9% martensite
$0.21 \times 1.45 \times 1.2 \times 1.5 = 0.55$ in. D_I

Calculation of the End-Quench Hardenability Curve. As a result of statistical studies of the relationship between calculated hardenability and the corresponding end-quench hardenability curves, Joseph Field has developed factors that permit a reasonable prediction of the actual end-quench curve from the composition and grain size of the steel. These factors express the relationship between the hardness value at 1/16 in. from the quenched end of the test specimen, which is characteristic of the carbon content, and the hardness values at distances of 2 in. or less from the quenched end. The factors used in these calculations are shown in Fig. 24, 25, 26 and 27. The base carbon values, which are those of Grossmann, are repeated in order that all the factors for this type of calculation may be together. The multiplying factors for the alloying elements are those that have been found by the statistical studies to correlate most closely with the end-quench curves.

The calculation is carried out as follows:

1 The D_I is calculated by multiplying the D_I value for the carbon and grain size progressively by the multiplying factors for the alloying elements.

2 The hardness at 1/16 in. is determined from the curve correlating this value with carbon content.

3 The ratio between this hardness and the hardness values at ¼, ½, ¾, 1, 1¼, 1½, 1¾ and 2 in. from the quenched end, is read from the curve correlating this IH/DH ratio with calculated hardenability.

4 The actual hardness values at these locations are determined by dividing the initial hardness value by the IH/DH ratio.

This method will permit a reasonably accurate prediction of the end-quench curve, except in steels containing less than 0.20% C or in plain carbon steels. Low-alloy steels of 0.20 to 0.30% C have also been found to indicate hardness values somewhat higher than the actual results.

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2 Walter Crafts and J. L. Lamont, The Effect of Silicon on Hardenability, Trans AIME, 154, 386 (1943)

3 Walter Crafts and J. L. Lamont, The Effect of Some Elements on Hardenability, Trans AIME, 158, 157 (1944)

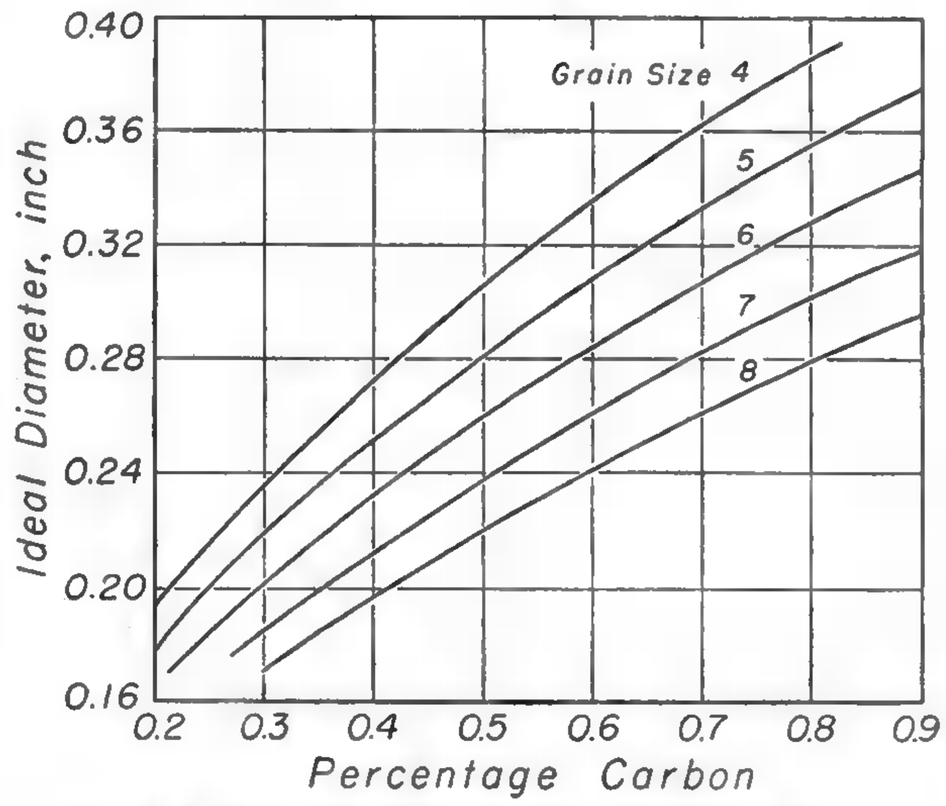

Fig. 24 Hardenability values of pure iron-carbon alloys as a function of carbon content and grain size (Grossmann).

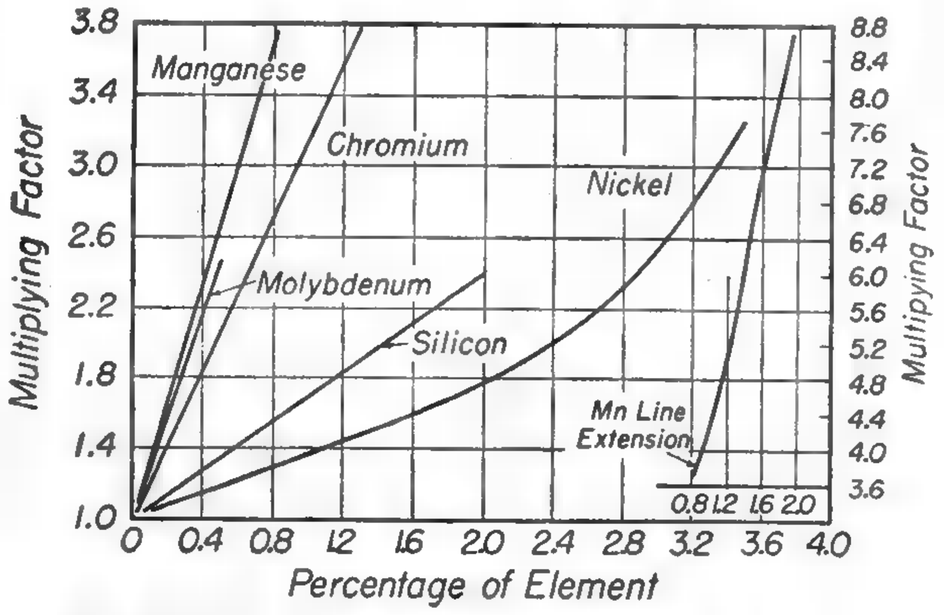

Fig. 25 Multiplying factors for alloying elements, as used in the calculation of the end-quench hardenability curve.

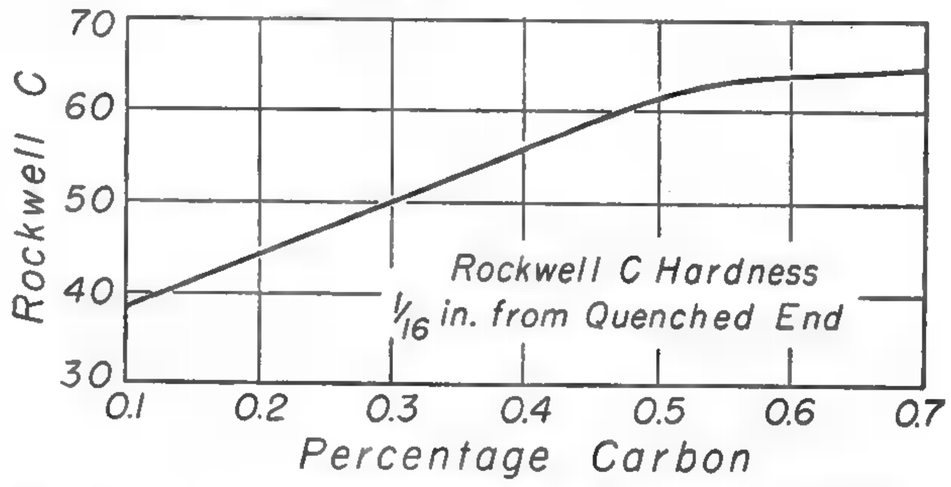

Fig. 26 Average Rockwell hardness at $\frac{1}{16}$ in. from the quenched end of a standard end-quenched specimen as a function of carbon content.

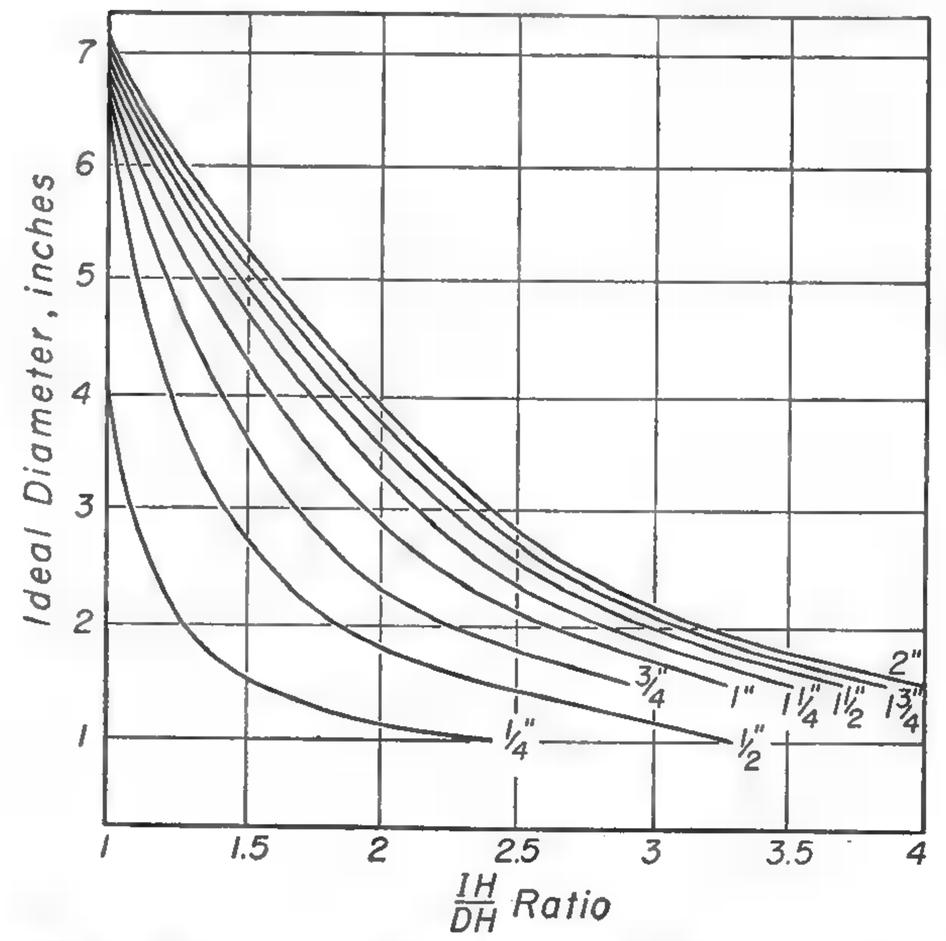

Fig. 27 The ratio of the initial hardness to the hardness at various distances from the quenched end (IH/DH) as a function of calculated hardenability.

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7 J. M. Hodge and M. A. Orehoski, Relationship between Hardenability and Percentage of Martensite in Some Low-Alloy Steels, Trans AIME, 167, 627 (1946)

8 G. E. Comstock, The Influence of Titanium on the Hardenability of Steel, Trans AIME, 167, 719 (1946)

9 G. R. Brophy and A. J. Miller, An Appraisal of the Factor Method for Calculating the Hardenability of Steel from Composition, Trans AIME, 167, 654 (1946)

10 W. Crafts and J. L. Lamont, Addition Method for Calculating Rockwell C Hardness of the Jominy Hardenability Test, Trans AIME, 167, 698 (1946)

11 R. A. Grange and T. M. Garvey, Factors Affecting the Hardenability of Boron-Treated Steels, Trans ASM, 37, 136 (1946)

12 J. H. Hollomon and L. D. Jaffe, The Hardenability Concept, Trans AIME, 167, 601 (1946)

13 Contributions to the Metallurgy of Steel—No. 12, Calculation of the Standard End-Quench Curve from Chemical Composition and Grain Size, AISI, Feb 1946

14 J. M. Hodge and M. A. Orehoski, Hardenability Effects in Relation to the Percentage of Martensite, Trans AIME, 167, 502 (1946)

15 I. R. Kramer, S. Siegel and J. G. Brooks, Factors for the Calculation of Hardenability, Trans AIME, 167, 670 (1946)

The Hardenability of AISI-SAE H Steels

AISI-SAE H Steel	Diameter of Round Bar That Will Just Harden to the Indicated Structure at the Center with an Oil Quench, inches		AISI-SAE Minimum End-Quench Hardenability Data for R_c Hardnesses at the Indicated Distance from Quenched End, inches								
	50% Martensite	90% Martensite	1/16	1/4	1/2	3/4	1	1 1/4	1 1/2	1 3/4	2
2512H	0.70	0.35	36.5	26.5	....	....	....	....	....	....	....
2515H	0.80	0.45	37.5	29.0	....	....	....	....	....	....	....
2517H	0.80	0.45	39.0	31.0	21.5	....	....	....	....	....	....
3310H	3.10	0.80	35.5	33.0	28.0	26.0	25.0	24.5	24.0	24.0	24.0
3316H	>4.00	1.00	40.0	37.0	32.5	30.5	29.5	28.5	28.5	28.5	28.5
4130H	0.80	0.35	46.5	39.0	30.0	26.0	23.0	21.0	20.0	....	....
4132H	0.80	0.35	48.0	40.0	32.0	28.0	25.0	23.0	22.0	20.5	20.0
4135H	1.25	0.60	50.0	46.0	38.0	31.0	28.5	27.5	26.5	26.0	25.5
4137H	1.35	0.60	51.5	47.5	40.0	33.5	30.5	29.0	28.5	28.0	27.0
4140H	1.55	0.70	52.5	50.0	43.5	37.5	34.0	32.0	31.0	30.0	29.5
4142H	1.60	0.80	54.0	52.0	45.5	39.5	36.0	34.0	32.5	31.5	30.5
4145H	1.80	1.00	55.0	53.5	48.5	42.0	38.0	35.5	34.0	33.0	32.5
4147H	2.00	1.05	56.5	55.0	51.0	44.5	40.0	37.0	35.5	34.5	34.0
4150H	2.15	1.25	58.0	57.0	53.0	46.5	42.0	39.0	37.0	36.0	35.5
4317H	0.60	0.20	40.0	28.5	21.0	....	....	....	....	....	....
4320H	0.70	0.35	41.5	31.0	24.0	20.0	....	....	....	....	....
4340H	>4.00	3.10	52.5	52.5	52.0	51.0	50.0	48.0	46.0	44.5	43.0
4620H	0.20	0.15	40.5	22.0	....	....	....	....	....	....	....
4640H	1.05	0.60	52.5	49.0	37.5	31.0	27.5	26.5	25.0	24.0	24.0
4815H	0.80	0.45	38.0	30.0	22.5	....	....	....	....	....	....
4820H	0.90	0.45	40.5	35.0	26.5	23.0	20.5	....	....	....	....
8620H	0.20	0.15	40.5	24.0	....	....	....	....	....	....	....
8622H	0.35	0.15	42.0	27.5	21.0	....	....	....	....	....	....
8625H	0.45	0.15	43.5	31.0	23.5	....	....	....	....	....	....
8627H	0.60	0.20	45.5	35.0	26.5	22.0	....	....	....	....	....
8630H	0.80	0.45	46.5	39.0	29.0	24.5	22.0	20.5	....	....	....
8632H	0.90	0.45	48.0	42.0	31.0	26.0	23.0	21.5	20.5	20.0	....
8635H	1.00	0.50	49.5	44.5	33.5	27.5	24.5	23.0	22.0	21.5	21.0
8637H	1.00	0.50	51.5	47.0	35.5	29.5	26.5	24.5	23.5	22.5	22.5
8640H	1.05	0.60	52.5	48.5	38.0	31.0	27.5	26.0	25.0	24.0	24.0
8642H	1.15	0.60	54.0	50.5	40.5	33.5	29.5	27.5	26.0	25.5	25.5
8645H	1.25	0.60	55.0	51.5	43.0	35.5	31.0	29.0	28.0	27.5	27.5
8647H	1.35	0.70	56.5	53.5	45.5	38.5	33.5	31.0	29.0	28.5	28.0
8650H	1.55	0.80	58.0	55.0	48.5	41.0	36.0	32.5	31.0	30.0	29.5
8720H	0.35	0.15	40.5	25.5	20.5	....	....	....	....	....	....
8722H	0.45	0.20	42.0	29.0	22.5	....	....	....	....	....	....
8725H	0.60	0.20	43.5	32.5	25.0	21.0	....	....	....	....	....
8727H	0.60	0.35	45.5	35.5	26.5	22.5	20.0	....	....	....	....
8730H	0.90	0.45	46.5	40.0	30.0	25.0	23.0	21.5	21.0	20.5	....
8732H	1.00	0.50	48.0	43.0	33.0	28.0	25.0	23.0	22.0	21.5	21.0
8735H	1.05	0.60	49.5	45.5	36.0	29.5	26.5	25.0	23.5	23.0	22.5
8737H	1.15	0.60	51.5	48.0	38.0	31.5	28.0	26.0	25.0	24.5	24.0
8740H	1.25	0.60	52.5	49.5	40.0	33.0	29.5	27.5	26.5	26.0	25.5
8742H	1.35	0.70	54.0	51.5	43.0	36.0	32.0	29.5	28.5	28.0	28.0
8745H	1.45	0.80	55.0	53.5	45.5	38.5	34.0	31.5	30.0	29.5	29.5
8747H	1.60	0.90	56.5	54.5	48.0	41.0	36.0	33.0	32.0	31.0	31.0
8750H	1.80	1.05	58.0	56.5	51.0	43.5	38.5	35.0	33.5	33.0	32.5
9420H	0.20	0.15	40.0	23.0	....	....	....	....	....	....	....
9422H	0.20	0.15	42.0	26.0	....	....	....	....	....	....	....
9425H	0.35	0.15	43.5	29.0	22.0	....	....	....	....	....	....
9427H	0.45	0.15	45.5	32.0	23.5	20.0	....	....	....	....	....
9430H	0.60	0.20	46.5	36.0	27.5	23.0	20.0	....	....	....	....
9432H	0.70	0.20	48.0	38.5	29.5	25.0	21.5	....	....	....	....
9435H	0.70	0.35	49.5	41.0	31.5	26.0	23.0	21.0	....	....	....
9437H	0.80	0.45	51.5	43.5	33.0	27.5	24.0	22.0	21.0	20.5	20.5
9440H	0.90	0.45	52.5	46.5	35.0	29.0	25.0	23.0	22.0	21.5	21.0
9442H	1.00	0.45	54.0	48.5	38.0	31.0	27.0	25.5	24.5	24.0	23.5
9445H	1.05	0.50	55.0	51.0	41.0	34.0	30.0	28.0	26.5	26.0	26.0
9447H	1.15	0.60	56.5	52.0	43.5	36.5	32.0	29.5	28.0	27.5	27.5
9450H	1.35	0.60	58.0	54.0	46.0	39.0	34.0	31.5	30.0	29.5	29.5

Correlation of hardness values on standard end-quenched specimens and oil-quenched round bars, taken from the 1946 SAE Handbook. H = 0.35 approx. Hardness values for 50% and 90% martensite are taken from Fig. 7 on page 497 of this Handbook. The AISI-SAE minimum end-quench hardenability data are taken from the minimum curve of the AISI-SAE Tentative Hardenability Bands.

Maximum Diameters (in inches) of Bars of Required As-Quenched Hardness at the Center (H Steels)*

COMPILED BY A. L. BOEGEHOLD*

Martensite in Microstructure at Center	Steel	After Oil Quench (Present SAE Correlation) Minimum Hardenability	After Oil Quench (Present SAE Correlation) Maximum Hardenability	After Water Quench Minimum Hardenability According to Revised Correlation of Cooling Rates	After Water Quench Minimum Hardenability According to Present SAE Correlation	After Water Quench Minimum Hardenability According to Revised Correlation of Cooling Times	After Water Quench Maximum Hardenability
Maximum Diameter of Bar That Will Harden at Center to Rockwell C 25							
Less than 20%	4620H	0.40	2.50	0.75	1.00	1.00	3.50
	8620H	0.50	2.70	0.90	1.10	1.10	3.40
	8720H	0.60	3.15	1.00	1.20	1.20	4.00
	8622H	0.75	3.50	1.30	1.40	1.60	4.00+
	8722H	1.00	4.00+	1.55	1.60	1.85	4.00+
	8625H	1.20	4.00+	1.75	1.85	2.15	4.00+
	8725H	1.40	4.00+	2.00	2.10	2.40	4.00+
	8727H	1.60	4.00+	2.20	2.30	2.60	4.00+
	8730H	2.15	4.00+	2.85	2.85	3.20	4.00+
	8732H	2.65	4.00+	3.45	3.40	3.70	4.00+
	8735H	3.15	4.00+	4.00	4.00	4.00+	4.00+
Maximum Diameter of Bar That Will Harden at Center to Rockwell C 30							
20%	4620H	0.25	1.25	0.45	0.65	0.65	1.90
	8620H	0.35	1.50	0.60	0.80	0.80	2.25
	8720H	0.40	1.80	0.75	1.00	1.00	2.50
Less than 20%	8622H	0.40	1.95	0.75	1.00	1.00	2.70
	8722H	0.50	2.35	0.90	1.10	1.10	3.05
	8625H	0.70	2.50	1.15	1.30	1.40	3.25
	8725H	0.75	3.15	1.30	1.40	1.60	4.00
	8627H	1.00	3.15	1.55	1.60	1.85	4.00
	8727H	1.00	4.00	1.55	1.60	1.85	4.00+
	8730H	1.40	4.00+	2.00	2.10	2.40	4.00+
	8732H	1.80	4.00+	2.40	2.50	2.85	4.00+
	8735H	2.05	4.00+	2.75	2.80	3.10	4.00+
	8737H	2.35	4.00+	3.05	3.05	3.40	4.00+
	8740H	2.65	4.00+	3.45	3.40	3.70	4.00+
	8742H	3.25	4.00+	4.10	4.00	4.25	4.00+
Maximum Diameter of Bar That Will Harden at Center to Rockwell C 35							
65%	8622H	0.25	1.15	0.45	0.65	0.65	1.85
	8722H	0.35	1.40	0.90	1.10	1.15	2.10
50%	8625H	0.40	1.60	0.75	1.00	1.00	2.30
	8725H	0.45	2.00	0.75	1.00	1.00	2.70
40%	8627H	0.60	2.00	1.00	1.20	1.20	2.70
	8727H	0.60	2.35	1.00	1.20	1.20	3.05
35%	8630H	0.75	2.35	1.30	1.40	1.60	3.05
	8730H	0.85	3.00	1.40	1.50	1.75	3.75
25%	8732H	1.20	3.85	1.75	1.85	2.15	4.00+
	8735H	1.50	4.00+	2.00	2.20	2.50	4.00+
	8737H	1.65	4.00+	2.30	2.35	2.75	4.00+
	8740H	1.90	4.00+	2.55	2.60	2.90	4.00+
Less than 20%	8742H	2.35	4.00+	3.05	3.05	3.40	4.00+
	8745H	2.65	4.00+	3.45	3.40	3.70	4.00+
	8747H	3.00	4.00+	3.60	3.80	4.00	4.00+
	8750H	3.40	4.00+	4.00+	4.00+	4.00+	4.00+
Maximum Diameter of Bar That Will Harden at Center to Rockwell C 40							
75%	8627H	0.30	1.40	0.60	0.80	0.80	2.10
	8727H	0.40	1.60	0.75	1.00	1.00	2.30
70%	4130H	0.50	1.40	0.90	1.10	1.10	2.10
60%	4132H	0.60	2.25	1.00	1.20	1.20	3.00
70%	8630H	0.60	1.60	1.00	1.20	1.20	2.30
	8730H	0.60	1.95	1.00	1.20	1.20	2.70
60%	8632H	0.75	1.95	1.30	1.40	1.60	2.70
	8732H	0.75	2.45	1.30	1.40	1.60	3.15
50%	8735H	1.00	3.00	1.65	1.60	2.05	3.80
45%	8737H	1.20	3.65	1.75	1.85	2.15	4.00+

(Continued at Right)

Martensite in Microstructure at Center	Steel	After Oil Quench (Present SAE Correlation) Minimum Hardenability	After Oil Quench (Present SAE Correlation) Maximum Hardenability	After Water Quench Minimum Hardenability According to Revised Correlation of Cooling Rates	After Water Quench Minimum Hardenability According to Present SAE Correlation	After Water Quench Minimum Hardenability According to Revised Correlation of Cooling Times	After Water Quench Maximum Hardenability
Maximum Diameter of Bar That Will Harden at Center to Rockwell C 40 (continued)							
35%	8740H	1.40	4.00+	2.00	2.10	2.40	4.00+
25%	8742H	1.60	4.00+	2.30	2.30	2.75	4.00+
[illegible]%	8745H	1.95	4.00+	2.65	2.70	3.05	4.00+
Less than 20%	8747H	2.35	4.00+	3.05	3.05	3.40	4.00+
	8750H	2.65	4.00+	3.45	3.40	3.70	4.00+
Maximum Diameter of Bar That Will Harden at Center to Rockwell C 45							
85%	4130H	0.25	1.15	0.45	0.65	0.85	1.85
	8730H	0.25	1.40	0.45	0.65	0.65	2.10
	4130H	0.30	1.60	0.60	0.80	0.80	2.30
87%	8632H	0.40	1.40	0.75	1.00	1.00	2.10
	8732H	0.40	1.60	0.75	1.00	1.00	2.30
	8635H	0.60	1.65	1.00	1.20	1.20	2.40
82%	8735H	0.60	1.95	1.00	1.20	1.20	2.70
	4135H	0.70	2.60	1.15	1.30	1.40	3.30
80%	8637H	0.75	1.95	1.30	1.40	1.60	2.70
	8737H	0.75	2.50	1.30	1.40	1.60	3.25
	4137H	0.90	3.85	1.40	1.50	1.75	4.00+
70%	8640H	0.90	2.35	1.40	1.50	1.75	3.05
	8740H	1.00	3.00	1.55	1.60	1.85	3.80
60%	8642H	1.00	3.00	1.55	1.60	1.80	3.80
70%	4140H	1.15	4.25	1.75	1.85	2.15	4.00+
60%	8742H	1.20	4.00	1.75	1.85	2.15	4.00+
45%	8645H	1.20	3.50	1.75	1.85	2.15	4.00+
60%	4142H	1.40	4.00+	2.00	2.10	2.40	4.00+
45%	8745H	1.40	4.00+	2.00	2.10	2.40	4.00+
50%	8647H	1.40	4.00+	2.00	2.10	2.40	4.00+
45%	4145H	1.75	4.00+	2.45	2.50	2.85	4.00+
50%	8747H	1.60	4.00+	2.20	2.30	2.60	4.00+
30%	8650H	1.70	4.00+	2.30	2.40	2.75	4.00+
50%	4147H	2.10	4.00+	2.75	2.80	3.15	4.00+
30%	8750H	1.95	4.00+	2.65	2.70	3.05	4.00+
30%	4150H	2.35	4.00+	3.05	3.05	3.40	4.00+
70%	4340H	4.00	4.00+	4.00+	4.00+	4.00+	4.00+
Maximum Diameter of Bar That Will Harden at Center to Rockwell C 50							
92%	8637H	0.25	1.40	0.50	0.65	0.70	2.10
	4137H	0.25	2.35	0.45	0.70	0.65	3.05
	8737H	0.40	1.80	0.75	1.00	1.00	2.50
90%	8640H	0.40	1.70	0.75	1.00	1.00	2.40
	8740H	0.40	2.15	0.90	1.00	1.15	2.85
85%	8642H	0.60	2.15	1.00	1.20	1.30	2.85
90%	4140H	0.60	4.00	1.00	1.20	1.30	4.00+
85%	8742H	0.75	2.65	1.25	1.40	1.60	3.40
80%	8645H	0.75	2.50	1.30	1.40	1.60	3.25
85%	4142H	0.80	4.25	1.40	1.40	1.75	4.00+
80%	8745H	1.00	3.40	1.50	1.60	1.90	4.00+
75%	8647H	1.00	3.00	1.50	1.60	1.90	3.80
80%	4145H	1.15	4.25	1.75	1.85	2.15	4.00+
75%	8747H	1.20	4.00+	1.75	1.85	2.15	4.00+
70%	8650H	1.20	3.50	1.75	1.85	2.15	4.00+
75%	4147H	1.40	4.00+	2.00	2.10	2.40	4.00+
70%	8750H	1.40	4.00+	2.10	2.10	2.50	4.00+
70%	4150H	1.75	4.00+	2.40	2.50	2.85	4.00+
90%	4340H	2.85	4.00+	3.65	3.60	3.85	4.00+
Maximum Diameter of Bar That Will Harden at Center to Rockwell C 55							
95%	4147H	0.60	4.00+	1.00	1.20	1.30	4.00+
90%	4150H	1.00	4.00+	1.50	1.60	1.90	4.00+

* Published originally as a METAL PROGRESS Data Sheet, February 1947. * Head, Metallurgy Department, Research Laboratories Division, General Motors Corporation, Detroit.

NOTE. Values in columns headed "Revised Correlation of Cooling Rates" and "Revised Correlation of Cooling Times" were taken from an NDRC report describing work that was done to determine more accurately the cooling rates and cooling times in the hardenability bar and in water-quenched sections.

FERROUS METAL PRODUCTS

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Wrought Iron

By A. W. F. Green*

WROUGHT IRON is a ferrous material, aggregated from a solidifying mass of pasty particles of highly refined metallic iron with which a minutely and uniformly distributed quantity of slag is incorporated without subsequent fusion.

Manufacturing Terms. The following terms are particularly applicable to wrought iron and the products manufactured from it:

puddled ball. The agglomerate cellular mass of refined iron intimately mixed with a siliceous slag, which is the result of hand puddling, mechanical puddling, or the pouring of molten refined iron into a siliceous slag as in the Aston or Byers process.

bloom. The product that results from the squeezing of the *puddled ball.*

muck bar. A bar rolled from a squeezed *bloom.*

busheling. The process of heating to a welding heat in a suitable furnace, miscellaneous iron, steel or a mixture of iron and steel scrap cut into small pieces. (The welded mass is then squeezed into a *bloom* and rolled into scrap bar for piling or *fagoting.*)

fagoting. The making of a "fagot" or "box", the bottom and sides of which are formed of *muck bars* or scrap bars and the interior, of miscellaneous iron scrap or a mixture of iron and steel scrap.

slab pile. A pile built up wholly of flat bars of iron, all running the full length of the pile.

box pile. A pile, the outside of which is formed of flat bars and the interior of which is formed of a number of small bars, all running the full length of the pile. Used in the manufacture of wrought iron bars.

refined bar iron or refined wrought iron bars. Iron bars rolled from a *muck bar pile* or from a *box pile,* of muck bars and wrought iron scrap free from steel; all bars run the full length of the pile.

double-refined iron. Iron to be classed as "double refined" should be all new wrought iron, which should be rolled first into *muck bars.* These bars should then be twice piled and rolled. All iron should be free from steel and from foreign scrap.

common iron. Iron made from rerolled scrap iron or a mixture of iron and steel scrap, when no attempt is made to separate the iron and steel scrap.

Methods of Manufacture. Five methods have been employed for the making of wrought iron: (1) hand puddling, (2) mechanical puddling, (3) the Aston or Byers process, (4) busheling and (5) fagoting.

Hand Puddling Process. In early times wrought iron was produced directly from the ore by reduction with carbonaceous fuel. In later times wrought iron has been produced by a variety of processes, usually by indirect means; that is, the ore is first reduced to pig iron and the pig iron is then transformed to wrought iron by puddling or by some other process.

Henry Cort of England is credited with the invention of the reverberatory type of furnace for the production of puddled wrought iron. The date given for this invention is 1784. Hand puddling was employed with only slight modification until about 1930, by which time the process had been almost entirely abandoned.

Mechanical Puddling Process. The first attempts to use mechanical puddling involved retaining the furnace as it was and substituting mechanical for manual power in manipulating the rabbles or stirring rods. The early developments that showed the most promise centered about the use of revolving furnaces. These were of three types: (1) those having a variable axis of revolution, (2) those having an approximately vertical axis, and (3) those having a horizontal axis.

The reactions in mechanical puddling procedures are virtually the same as those in the hand puddling procedure. The metal is refined in the furnace and, because of a decreasing content of impurities, the charge solidifies to form a pasty mass of iron and slag, which is then agglomerated by mechanical working.

The Aston or Byers Process. The most important invention having to do with the making of wrought iron is known as the Byers or Aston process. The work that resulted in this invention started about 1918. The Byers or Aston process is very different from puddling either by hand or by mechanical means. The metal is melted in cupolas. The molten metal is then carried in suitable ladles where it is desulfurized and, immediately thereafter, is poured into Bessemer converters where it is refined according to regular steel procedure. Silicon, manganese and carbon are oxidized in this refining operation. The blown metal is then tapped into a ladle and taken to the processing platform, where it is poured into the ladle of the processing machine. The molten refined iron is poured at a predetermined rate into the ladle that contains molten slag. The temperature of the slag is maintained several hundred degrees lower than the freezing point of the refined metal, so the metal is continuously and rapidly solidified. This rapid solidification of the metal liberates dissolved gases with sufficient force to shatter the metal into small fragments, which settle to the bottom of the ladle. Because of the heating temperature and fluxing action of siliceous slag, these fragments weld together, making an agglomerate cellular mass in the

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form of a sponge. Immediately after the pouring, the ladle is transferred and excess slag is poured off into an adjoining empty ladle. The sponge ball, weighing from 6000 to 8000 lb, is dumped, at the rate of one every five minutes, on a platform of an electrically driven 900-ton press, where the ball is squeezed, collecting the mass into solid blooms for rolling.

Squeezing. Three types of squeezers are used for compressing the sponge balls into suitable shape for rolling into muck bar, bloom or billet sizes. The first is the small so-called "coffee mill" type that has a drum operating on a vertical axis. The second is a generally larger type with a drum that operates on a horizontal axis. The third type includes steam, electric or hydraulic presses where pressures are applied on the ends as well as on the four sides of the ball.

Table I. Typical Compositions of Wrought Iron

Type of Iron	Composition, percentage C	Mn	Si	P	S	Slag by Weight
Byers No. 1.....	0.08	0.015	0.158	0.062	0.010	1.20
Mechanical iron..	0.08	0.029	0.183	0.115	0.015	2.85
Hand-puddled iron	0.06	0.045	0.101	0.068	0.009	1.97

Chemical Composition. Genuine wrought iron is distinguished by its low carbon and manganese contents. Many specifications written to cover wrought iron compositions, lay particular stress on the manganese content. It is generally conceded that freedom from contamination by steel or by poor quality wrought iron can be shown if the manganese content is less than 0.07%. Some typical chemical compositions are shown in Table I.

Carbon. A carbon content greater than 0.10% is usually construed to mean imperfect refining, or causes suspicion that steel scrap has been used in making up the customary "piles".

Manganese. Well-made wrought iron contains less than 0.10% Mn. If more than that amount is present, imperfect refining may be indicated, or adulteration by use of steel in busheling or piling.

Phosphorus. The phosphorus content of wrought iron is largely in the incorporated slag. Good wrought iron will

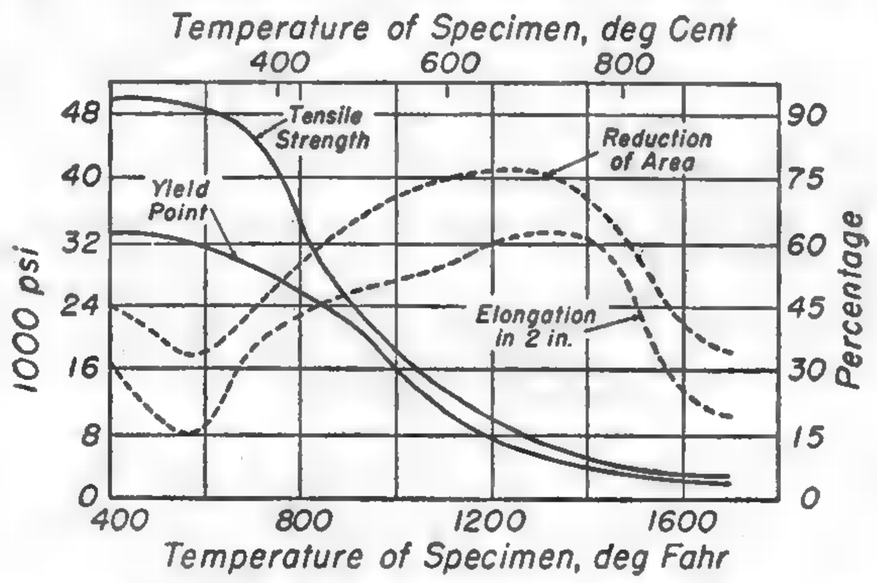

Fig. 1 Tensile properties of wrought iron at elevated temperature

contain from 0.08 to 0.160% P, of which from 40 to 30% will be combined with the slag.

Sulfur. High-grade wrought iron contains as much as 0.035% S. Larger amounts indicate imperfect refining and are known to produce "red shortness".

Silicon. The amount of silicon is usually from 0.10 to 0.20%. The proportion associated with the base metal is virtually nil. The presence of less than 0.10% Si indicates either that the amount of slag is less than normal or that the composition of the slag is not suitable for properly refined wrought iron. The presence of approximately 0.20% Si may indicate poor distribution of slag, probably because of improper mechanical working.

Slag. A considerable amount of slag is present in wrought iron. A typical percentage composition of the slag found in wrought iron is as follows: SiO_2, 14.58; Fe, 58.72; FeO, 70.49; MnO, 1.51; Al_2O_3, 2.72; CaO, 2.59; P_2O_5, 0.80; S, 0.08; Cu, trace; and Fe_2O_3, 5.65. The amount of slag present in wrought iron, by weight, varies from 1% to as much as 4%, and is generally about 2%.

Alloy Wrought Iron. The most prominent of the alloy wrought irons are those containing up to about 3½% Ni. Molybdenum has been alloyed successfully and nickel and molybdenum have been used together. Copper is often found in wrought iron. It is possible to alloy copper in the making of wrought iron. There is a question as to whether or not the presence of copper has a deleterious effect on the "red shortness" characteristic. Numerous experiments have shown, however, that copper does not affect this condition appreciably in percentages as high as about 0.3% and it is possible that the presence of copper is desirable from the standpoint of corrosion. The presence of 3½% Ni raises the elastic limit and tensile strength substantially. Molybdenum does not seem to have a marked effect on physical properties, and no concise data have been found that show the presence of molybdenum to have a substantial effect on the general quality of wrought iron. A typical percentage composition of nickel wrought iron is as follows: C, 0.06; Mn, 0.035; P, 0.070; Si, 0.18; S, 0.011; Ni, 3.25; and slag, 1.90.

Table II. Mechanical Properties of Wrought Iron

Material	Endurance Limit, Rotating Beam, psi	Axial, psi	Tensile Strength, psi	Charpy Notched Bar, ft-lb	Brinell Hardness Number
Wrought iron, longitudinal	23,000	16,000	46,900	17.5	105
Wrought iron, transverse	19,000	11,000	34,400	4.8	105
Ingot iron, as rolled	26,000	17,000	42,400	19.3	69
Structural steel, 0.18% C (as rolled)	28,000	.....	61,500	...	...

Tensile Properties at Low and High Temperature. The tensile properties of wrought iron without nickel are as follows: tensile strength, 42,000 to 52,000 psi; yield point, 26,000 to 35,000 psi; elongation in 8 in., 25 to 40%; and reduction of area, 40 to 55%.

When approximately 3.25 to 3.50% Ni is added, the values are about as follows: tensile strength, 55,000 to 60,000 psi; yield point, 45,000 to 50,000 psi; elongation in 8 in., 25 to 30%; and reduction of area, 35 to 45%.

Results of tensile tests at high temperatures are given in Fig. 1.

Repeated Stress. From the indications of laboratory tests alone, wrought iron is about the weakest ferrous material under repeated stress. Moore has determined the endurance limits in rotating-beam and axial-loading tests, as shown in Table II.

The presence of slag does not greatly reduce the resistance of wrought iron to fatigue as long as the applied stress is longitudinal.

Impact Strength. The results of impact tests on wrought iron are listed in Table III.

Physical Properties.

Specific gravity	7.70
Melting point	2750 F
Coefficient of thermal expansion, 18 to 100 C.....	11.40×10^{-6}
Heat conductivity at	
16 C	0.152
18 C	0.144
100 C	0.143

Bend Tests. Bend tests are included in the testing of wrought iron to indicate not only the ductility but also quality, correct piling, and freedom from adulteration with steel. These tests are made both hot and cold and also by the nicking of cold bars.

Hot bend tests on wrought iron of highest quality require bending the sample flat on itself from a temperature of 1700 to 1800 F. The poorer grades of wrought iron are bent around a pin, equal in diameter to the diameter or the thickness of the bars being tested. It is sometimes required that hot bend tests be made at temperatures of 1400 to 1500 F to determine whether or not the iron is "red short", a condition that is not uncommon.

Pickling. The usual procedure for the pickling of

Table III. Izod Value for Wrought Iron
Longitudinal Test. Average of Three Tests

Type of Iron	Original Size	Izod Values, ft-lb *A*, Notch at Right Angles to Flat Plane of Piling; *B*, Notch at 90 deg to *A* — *A*	*B*
Staybolt	1 in. diam	45	44
Enginebolt	1 in. diam	41½	42
ASTM 84-27C	1 in. diam	44½	53
Busheled iron	1 in. diam	51½	56
Busheled iron	1 in. sq	51½	65
Busheled iron	2 by ½ in. flat	58½	58½
Common iron	1 in. diam	63½	70
Common iron	1 in. sq	62½	71
Common iron	2 by ½ in. flat	43	51

wrought iron pipe, rod, and bar, is to use a 4 to 5% solution of sulfuric acid at 160 to 170 F. The pickling time for pipe varies from 1 to 1¼ hr and for rods or bars, 30 to 45 min. After the pickling, material should be washed in water, and then passed through a bath of ½% caustic soda and ¾% trisodium phosphate by volume.

Carburizing. Wrought iron can be case hardened. The usual process is to pack the parts in suitable compounds and to quench from the carburizing box in water, or to cool the material in the box, to reheat to a suitable temperature and then to quench in water.

The type of iron to be case carburized should be selected carefully since best results are obtained from iron made from box piles. The temperatures for carburizing and hardening are much the same as would be used for carburized 1010 steel.

Protective Coatings. Protective coatings adhere firmly to wrought iron. This is to be expected because of the nature of the material. In general, any protective coating that is applied to steel can be applied to wrought iron.

Welding.* The ease with which wrought iron can be welded is attributed to the relative purity of the base metal and the siliceous slag, which confers a self-fluxing quality easily observable in hammer and pressure welds. Because of this self-fluxing quality, uniform strong welds are rapidly secured.

Wrought iron is readily welded by oxyacetylene and arc methods. With most metals a fluxed or greasy surface is ordinarily an indication that the temperature is high enough for starting to apply fused secondary or weld-rod metal. However, this is not true of wrought iron since the self-fluxing characteristic causes a greasy appearance initially at a somewhat lower temperature.

Resistance to Corrosion. Through centuries of application, wrought iron has exhibited great resistance to progressive corrosion, primarily because of the distribution of slag throughout the mass. Where wrought iron is exposed to corrosive mediums it is quickly coated with a film of oxide or rust. As corrosion proceeds, additional oxide is formed but the slag filaments begin to function as rust-resisters. The initial oxide film is securely fastened to the surface of the metal by the pinning effect of the slag filaments, thus serving to protect the metal from further oxidation.

All grades of wrought iron do not offer the same resistance to progressive corrosion. Busheled and fagoted iron, especially the types known as "common iron", do not have high resistance to progressive corrosion. Resistance to progressive corrosion is limited to wrought iron that has not suffered by adulteration through working.

Applications and Forms Available. Wrought iron is used by the railroads, by shipbuilding industries, oil industries, and public utilities, as well as for architectural purposes and for farm implements.

Wrought iron is available in blooms and billets, in all types of hammered bars and forms, and in hot rolled shapes, including sheets and plates; also in the form of wire for nails, barbed wire and general manufacture.

Weight of Wrought Iron. In calculating the weight of wrought iron bars and shapes, it is common practice to use the tables that are applicable to steel and to subtract 2% from the weight shown in such tables.

* *See also* page 371.

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Cast Iron

By H. Bornstein* and J. W. Bolton*

THE GENERAL term "cast iron" includes gray irons, pig irons, white cast irons, chilled (white face) cast irons and malleable iron. Cast irons are alloys of iron, carbon and silicon in which more carbon is present than can be retained in solid solution in austenite at the eutectic temperature. Therefore cast irons contain eutectiferous components, or decomposition products of such components. The carbon content is usually more than 1.7% and less than 4.5%.

The ductility of cast irons as cast is relatively low, from virtually zero in white irons to possibly 2% in lower-carbon gray irons. No irons can be wrought at room temperature as cast; the majority are not usefully malleable at any temperature. However, they can be cast into complicated shapes, certain types of which cannot be made by forging, rolling, stamping, extrusion or other forming processes even when more ductile and malleable metals are used.

Pig Iron.† Pig iron is produced by reduction of iron ore in the blast furnace. Most of the molten metal is cast into pigs (ingots) for remelting. A small percentage of molten pig iron is used directly in castings and, for that reason, is known as "direct metal". Some pig iron

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† *See* "The Iron Blast Furnace Process", page 315 in this Handbook.

is transported in the molten state and used in open hearth processes of steelmaking. A large amount of solid pig iron is remelted and refined in open hearth furnaces and converters in steelmaking processes. Most of the remainder is used as the basic material in the manufacture of gray iron and malleable iron.

Gray Iron. Gray iron is the most widely used of cast metals. Its tonnage production exceeds that of all other cast metals combined.

The term "gray iron" covers a series of eutectiferous alloys that offer a wide selection of mechanical properties together with economy in the production of cast shapes and in subsequent machining.

Composition and processing are adjusted so that usually the matrix structure is largely pearlitic, with many graphite flakes dispersed throughout. The presence of graphite flakes imparts the characteristic "gray" fracture, promotes ready machinability, and imparts useful damping properties and resistance to wear.

Typical applications of gray iron are in the automotive industry (cylinder blocks, and other parts), in machine tools, agricultural implements, cast-iron pipe, flanges, fittings and the like. Gray iron castings are used in all the manufacturing, transportation, chemical, power, and mining industries, as well as in every household and on every farm.

The wide range of strengths in gray irons (from 20,000 to more than 60,000 psi) plus manufacturing economy, explain the extensive use of these irons where high resistance to dynamic stress is not a governing factor.

Gray irons are usually made within the composition ranges of 1.00 to 2.75% Si, and 2.70 to 3.60% total C.

Alloy Iron. The term "alloy iron" is used to designate cast iron to which chromium, nickel, molybdenum, copper or other elements have been added deliberately to modify or augment the properties attainable by the "normal" elements—iron, carbon, silicon, manganese, phosphorus and sulfur.

Austenitic Cast Iron. These are gray cast irons containing sufficient and suitable percentages of alloying elements to lower the eutectoid transformation temperature to such an extent that austenite is retained as the matrix at room temperature, with graphite flakes dispersed throughout the structure. Nickel is the alloying element commonly used for this purpose. Copper, chromium and molybdenum may be used to abet the action of nickel, or to modify the properties, or both. Austenitic cast irons have unusual magnetic properties and corrosion resistance.

White Cast Iron. In white cast iron almost all the carbon is in the combined form. The presence of free cementite or iron carbide (Fe_3C) makes this metal hard and nonductile. White iron may be classified further according to the process. Chilled cast iron is produced by casting the iron against metal chills. When cast into a sand mold, such iron may be gray iron, but the chills cause rapid cooling at the adjacent areas; consequently cementite is formed there.

Besides chilled irons and white irons for the manufacture of malleable cast iron, other irons, white throughout as cast, are used for special purposes, particularly for resistance to wear and abrasion. When maximum hardness is desired, alloying elements are usually added, both to promote the formation of the cementite and to increase the hardness of the matrix. (*See* section under Alloy Cast Irons.) Special white iron rods are used for welding white iron layers to various ferrous metals. The very high-chromium cast irons (25% Cr and more), used for their resistance to corrosion, are white irons, properly speaking, yet are not much harder than some gray irons.

Malleable Cast Iron. This term is applied to castings in which all the combined carbon in a special white cast iron has been changed to free or temper carbon (temper graphite) by suitable heat treatment. (See the article "Malleable Iron", on page 520 in this Handbook.)

Manufacture and Uses of Cast Iron

Cupola Melting.[2] Most of the gray iron produced in this country is melted in the cupola furnace. The cupola is a vertical, cylindrical type of furnace, consisting of a steel shell lined with firebrick (*see* Fig. 1). Usually the charging door is located 15 to 25 ft above the bottom plate. At the lower end of the furnace is the wind box or air box as shown in the diagram. Air enters the cupola through openings called tuyeres. Some cupolas are equipped with a single row of tuyeres; others have an auxiliary upper row of tuyeres. Opinion is divided as to whether a single or a double row is more desirable. A patented cupola known as the "balanced blast cupola", developed by the British Cast Iron Research Association, has three rows of tuyeres. A number of furnaces of this type have been installed in this country.

The cupola is a simple and economical melting unit, because the fuel and the metal are in intimate contact with each other.

Fuel, metal and flux enter the cupola through the charging door. The initial charge of coke is known as the "bed charge". The metal is deposited on the coke. Then alternate layers of coke and iron are added. Generally a flux

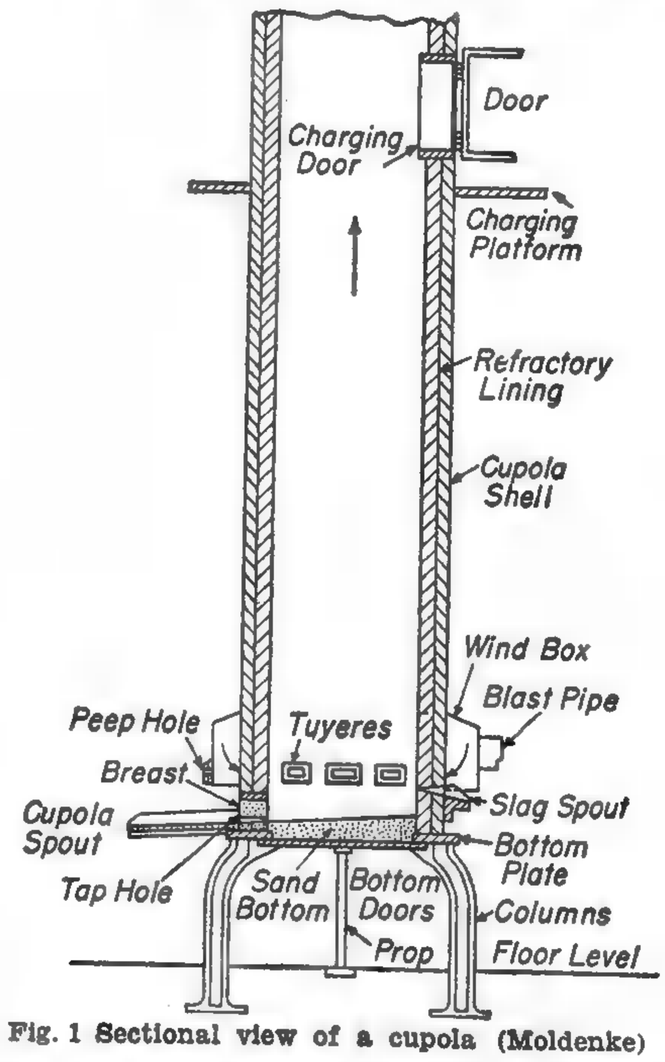


Fig. 1 Sectional view of a cupola (Moldenke)

is charged on the coke and the coke bed is ignited by means of kindling wood or an oil torch. This bed usually extends from 36 to 60 in. above the top of the lower tuyeres. The make-up of the charge and the charging are most important in obtaining uniform results in melting. Careful weighing and placing of the components of the charge are essential. The method of charging the materials into the cupola is important. Good results can be obtained both by hand charging and by mechanical charging but the tendency is towards the mechanical practice.

There is an optimum charge of coke for each size of cupola and the size of the metal charge depends on the ratio of metal to coke. The cupola sizes, designated according to the inside diameter of the lining of the cupola, may range from 18 to more than 100 in. ID. The sizes used for commercial practice usually range from 42 to 84 in. ID. The rated capacities of these sizes are from 5 to 25 tons of metal melted per hour.

The amount of metal charged into the cupola varies considerably because of many conditions and opinions. Following are sizes of charge that can be considered typical: 48-in. cupola, 1500-lb charge; 60 in., 2000 lb; 72 in., 3000 lb. The size of a charge may vary considerably from these figures and still be considered good practice. The tendency has been towards smaller charges to obtain greater uniformity of metal and economy of fuel.

The quantity of metal charged depends on the quantity of coke between charges. The bed charge is a definite

height above the lower tuyeres. Consequently, this portion of the coke goes in by volume, but the succeeding charges of coke are put in by weight. The proportion of metal to coke will usually range from 7:1 to 12:1.

The metal charged into the cupola ordinarily consists of returns (sprue and local scrap), purchased gray iron scrap, and pig iron. Steel scrap is used also, particularly where increased strength is desired. The proportions of gray iron scrap, pig iron and steel scrap are governed by the type of castings desired. Ordinarily the mixtures of metals differ considerably, even among foundries making the same class of work. Availability of certain types of scrap is frequently a controlling factor.

The mixture of metal to be charged into the cupola is determined by the composition of the metal desired for the finished castings. The base of the charge is usually pig iron. Charges are seldom entirely of scrap metals. Since the pig iron is of known composition, the greater the amount of pig iron and the smaller the amount of purchased scrap, the more uniform will be the composition of the resulting castings. For high-grade castings, such as automobile cylinders, the percentage of pig iron may range from 25 to 45% of the charge, while for castings such as sash weights, almost no pig iron will be used.

Limestone is ordinarily used as a flux in the operation of a cupola. The purpose of the flux is to form a slag with the dirt, impurities in the metal, and the coke ash. Fluorspar (calcium fluoride) is sometimes used as a fluxing agent, in combination with the limestone, to thin the slag and also to aid in the removal of sulfur. Soda ash is used as a cupola flux together with limestone. A number of available proprietary fluxes are also commonly used in connection with limestone. Soda ash, sometimes used as a flux in the ladle, reduces the sulfur content and improves the fluidity of the metal. Proprietary fluxes are also used for this purpose.

Air is introduced into the cupola through the tuyeres, to aid in the combustion of the coke, which in turn melts the metal. The volume of air introduced is important and governs the melting rate of the cupola. About 30,000 cu ft of air is required to melt one ton of metal. Under ordinary conditions the blast pressure will range from 8 to 20 oz, depending on the height of the cupola, the number of charges and the character of the metal charged. In some of the larger production foundries, where blast pressure has been increased to obtain greater capacity from the cupola, blast pressures in the neighborhood of 30 oz are frequently employed.

Auxiliary devices may be used for controlling the weight of air entering the cupola. The weight of the air is more important than the volume, and control of the weight is considered essential for good operation of the cupola. The weight of air can be determined by means of a volume meter and knowledge of air pressure and temperature. In the hot blast cupola the air is preheated to temperatures between 350 and 500 F. This results in more uniform operation of the cupola and in improved fuel economy. Balanced blast cupolas also have resulted in more uniform operation and fuel economy. The control of moisture for the cupola air blast is being practiced more widely; this has resulted in more uniform melting and in more uniform properties of castings.

Summary of Cupola Furnace Data for Cast Iron. The following figures are given for typical operations of a cupola. Cupola practice varies considerably; consequently the figures shown are given only as a guide. Wider limits beyond these figures may be used and may still be consistent with good practice.

Area of melting zone of cupola in square inches multiplied by 0.75, gives a suitable weight in pounds for the iron charge.

One pound of coke is required to melt 6 to 10 lb of iron; this includes both the coke in the bed and that between the charges.

To burn 1 lb of coke to carbon dioxide, 125 cu ft of air is needed.

Approximately 30,000 cu ft of air is required per ton of metal melted.

To melt 10 lb of iron per square in. of cupola area per hour is considered a good rate.

The tuyere area for a 36-in. cupola may be ⅛ of the cupola area, and for an 84-in. cupola may be 1/10, with other sizes in proportion.

Electric Furnace Melting. Although the electric furnace is used to only a limited extent for melting cast iron, this type of furnace affords accurate control of composition and temperature. In some instances large quantities of scrap, such as borings, can be utilized. The lower cost of scrap metals for electric furnaces helps to compensate for the higher cost of melting, as compared with the cost of melting in the cupola.

Table I. Typical Compositions of Some Commercial Gray Iron Castings

Casting	Composition, percentage							
	T C	Si	Mn	P	■	Ni	Cr	Mo
Auto cylinder, plain iron	3.25	2.25	0.65	0.15	0.10	....	....	....
Auto cylinder, Ni-Cr iron	3.25	2.25	0.65	0.15	0.10	0.75	0.30	....
Auto cylinder, Ni-Cr iron, heavy duty	3.25	1.90	0.65	0.15	0.10	1.75	0.45	....
Auto cylinder, Ni iron	3.25	1.80	0.65	0.15	0.10	1.25	....	....
Auto pistons, plain iron	3.35	2.25	0.65	0.15	0.10	....	....	....
Auto pistons, Mo iron	3.35	2.25	0.65	0.15	0.10	....	....	0.50
General castings (auto), soft iron	3.40	2.60	0.65	0.30	0.10	....	....	....
Piston rings (auto), individually cast	3.50	2.90	0.65	0.50	0.06	....	....	....
Brake drums (auto)	3.30	1.90	0.65	0.15	0.08	1.25	0.50	....
Brake drums (auto)	2.75	2.25	0.70	0.15	0.08	....	....	0.50
Cams	3.10	1.50	0.65	0.15	0.10	2.00	0.60	....
Machinery iron:								
Light service or thin section	3.25	2.25	0.50	0.35	0.10	....	....	....
Medium service or heavy section	3.25	1.75	0.50	0.35	0.10	....	....	....
Heavy service with heavy section	3.25	1.25	0.50	0.35	0.10	....	....	....
Water pipe, sand-cast:								
Light and medium	3.60	1.75	0.50	0.80	1.08	....	....	....
Heavy	3.40	1.40	0.50	0.80	0.08	....	....	....
Chilled plowshares	3.60	1.25	0.55	0.40	0.10	....	....	....
High-strength iron, plain	2.75	2.25	0.80	0.10	0.09	....	....	....
High-strength Ni iron	2.75	2.25	0.80	0.10	0.09	1.00	....	....
High-strength Mo iron	2.75	2.25	0.80	0.10	0.09	....	....	0.35
Heat-resistant iron, fire pots, and kettles	3.50	1.15	0.80	0.10	0.07	....	....	....
Pots for caustic, Ni-Cr	3.30	0.70	0.50	0.10	0.08	1.50	0.60	....
Pots for caustic, plain iron	3.60	1.00	0.75	0.20	0.07	....	....	....
Ingot molds	3.50	1.00	0.90	0.20	0.07	....	....	....
Car wheels	3.35	0.65	0.60	0.35	0.12	....	....	....
Air cylinders, ammonia cylinders, plain iron	3.25	1.25	0.65	0.20	0.10	....	....	....
Heavy compressor cylinders, Ni iron	3.00	1.10	0.80	0.20	0.10	2.00	....	....
Light compressor cylinders, Ni-Cr	3.30	2.10	0.55	0.25	0.10	1.25	0.45	....
Light forming and stamping or forging dies, Ni-Cr iron	3.30	1.50	0.60	0.20	0.10	2.00	0.60	....
Heavy forming and stamping or forging dies, Ni-Cr iron	3.00	1.25	0.60	0.20	0.10	2.75	0.80	....
Light forging dies, Mo iron	3.30	2.00	0.60	0.20	0.10	....	....	1.00
Heavy forging dies, Mo iron	3.10	1.50	0.60	0.20	0.08	....	....	1.00
Valves and fittings (medium)	3.30	2.00	0.50	0.35	0.10	....	....	....

Two types of electric furnaces are in general use—the three-phase direct arc and the single-phase indirect arc of the rocking type.

In some instances, the electric furnace is used for the entire melting process; in other instances a duplex method is used. In the duplex method all or part of the charge is melted in the cupola and the molten metal is superheated in the electric furnace. Alloying elements and steel may be added to the metal in the electric furnace. For steady production the duplex method is usually more economical because of the lower cost of melting in the cupola.

Air Furnace Melting. The air furnace, employed to a limited extent in the production of gray iron castings, permits accurate control of composition and is sometimes used for making castings of higher strength.

Horizontal rotary furnaces (cylindrical in shape) heated with pulverized coal or oil, are used to a considerable extent in Europe. Two well-known furnaces of this type are the Brackelsberg and Sesci, which permit good control of composition and temperature. The Brackelsberg furnace has not been widely used in the United States.

Uses. Gray iron castings, used for a large variety of articles, vary in weight from a fraction of a pound to many thousands of pounds. A few of these applications are automobile cylinders and pistons, locomotive cylinders, agricultural machinery, machine tool castings, stove castings, car wheels, dies, engine frames and beds, flywheels, water pipe, soil pipe and hardware (*see* Table I).

White and Chilled Irons

Virtually all the carbon in white cast irons exists in the combined form, chiefly as free cementite (Fe_3C) and as pearlite or one of its transitional forms. The presence of a large amount of cementite makes the material hard and brittle.

"Chilled iron" is cast iron in which the carbon is retained in the combined form in desired areas so that a mottled or white structure is obtained. For accomplishing this result, means are employed to accelerate cooling to such an extent that normal graphitization is prevented in the chilled areas.

White cast iron is produced by proper adjustment of composition. A low silicon content is usually required. Elements that stabilize carbide—for example, chromium—may be added. For methods used in producing white iron in the malleable iron industry, see the article on "Malleable Iron" in this Handbook.

"Completely white" cast irons are limited in engineering applications because of brittleness and lack of machinability. These irons are ordinarily employed where resistance to wear is a major problem and the service does not require ductility. Castings of "completely white" cast iron are usually finished by grinding.

In many castings, it is desirable that a portion of the surface (or the complete surface) should be extremely hard in order to combat certain types of abrasive wear. It is possible to produce castings that have hard white iron surfaces and tough gray iron cores. Such castings, called "chilled castings", are produced by rapid cooling of the surface, usually by means of metal "chills". The depth of the chilled portion depends not only on the composition and thickness of the casting but also on the rate at which the "chills" abstract heat. The thickness of the chill (usually cast iron) and its initial temperature are important. The compositions used for the castings are such that a gray fracture would result if the metal were cast into sand molds without the use of "chills". The hardness of the chilled surface and the strength of the gray iron core may be increased by proper additions of alloying elements.

The carbon content of the metal for both white and chilled iron castings is important. As the carbon content increases, the hardness usually increases. The lower carbon contents (about 2.5% C), such as are used for malleable white iron, generally result in relatively lower hardness. For such white irons, the hardness will be approximately 350 Bhn. When the carbon content is increased to about 3.50%, the hardness of the white or chilled iron areas will be greater than 500 Bhn, and may be increased further by addition of alloying elements.

Among the more common chilled and white iron castings are chilled rolls, chilled car wheels, plowshares, balls, stamp shoes, dies, and wearing plates of various sorts.

Some Physical and Metallurgical Properties

Transformation Ranges. The values given for transformation ranges of cast iron have been determined by means of thermal phenomena exhibited during slow cooling of ordinary gray irons.

1 The initial solidification point varies with the composition, and is lowered by an increase in carbon and silicon content. This point may be as low as about 2066 F in an iron of eutectic composition, and as high as about 2500 F in a white iron containing 2.00% C and 0.85% Si.
2 The "final" or eutectic solidification occurs within the range from 2066 to 2102 F, according to the composition of the metal.
3 Steadite formation occurs at about 1750 to 1800 F.
4 Transformation of austenite (nonmagnetic) to pearlite (magnetic) occurs between 1325 and 1350 F in most slowly cooled irons.

Under very slow cooling conditions, that is, when rates permit equilibrium, the austenite-pearlite transformation range is not depressed and occurs at somewhat higher temperatures, from about 1400 to 1450 F for 2% Si, 3% C iron. Increase in carbon and silicon contents raises and

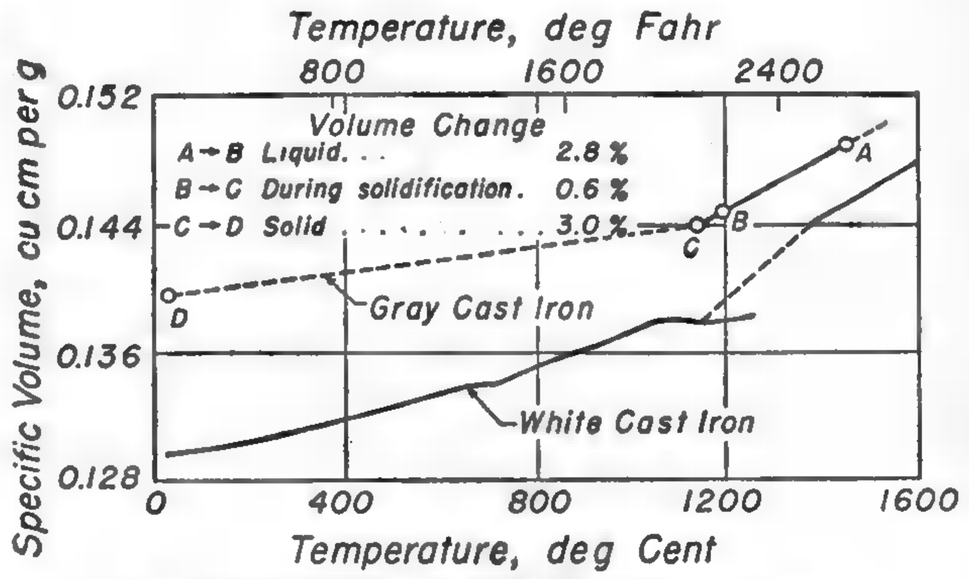


Fig. 2 Volume changes in cast iron (Ash and Saeger[6])

widens the transformation temperature range. The addition of alloying elements affects the transformation appreciably. For one example, high percentages of nickel depress the transformation range to considerably below room temperature so that as cast, the material is austenitic and remains so in spite of any thermal treatments.

Contraction and Expansion. Patternmakers' rules allow ⅛ in. per ft for linear contraction of gray iron, and $\frac{5}{16}$ to ¼ in. per ft for white iron (⅛ in. per ft is about 1%). Often this allowance is found inaccurate in practice, and more adequate allowance must be made for mass, composition, and effects of shape, mold and core. Generally contraction is less with increase in mass and, in gray irons, increases with increase in tensile strength.

Three contraction phenomena are exhibited during the cooling of a cast iron from the molten state to room temperature: (*a*) in the liquid, (*b*) during solidification, and (*c*) subsequent to solidification. These contractions are illustrated in the charts made by Ash and Saeger (Fig. 2).

Shrinkage in volume during solidification ranged from negative shrinkage in "soft" irons to +1.94% in an iron containing about 0.90% combined C. The white irons had 4.0 to 5.5% contraction in volume within the same range of temperature.

Coefficient of Expansion. The coefficient of expansion of gray irons in the range from 0 to 500 C (32 to 932 F) is about 13×10^{-6} per °C. The expansion is about 10.5×10^{-6} per °C in the range from 0 to 100 C (32 to 212 F). The expansion varies somewhat with the type of iron and is somewhat higher in the softer and higher-carbon irons.

For the temperature range from 1070 C (1958 F) to room temperature, the coefficient of expansion varies from 0.0000092 to 0.0000169 per °C. At room temperature the

commonly used figure of 0.000010 per °C is sufficiently accurate for ordinary changes in temperature.

Density. The density (grams per cubic centimeter) of gray irons at room temperature, varies from about 6.95 for open-grained high-carbon gray irons to 7.35 for close-grained low-carbon irons. The density of white iron is about 7.70. The density of liquid cast irons just above the final solidification temperature is about 6.23. For conversion to the weight in pounds per cubic foot, the values for density should be multiplied by the factor 62.428. A gray iron with density of 7.20 weighs about 450 lb per cu ft.

Fluidity. The fluidity, or "running qualities", of cast iron is important from a foundry viewpoint and depends generally on the degree of superheat and the composition of the metal. Increasing the percentage of carbon and silicon as high as the eutectic concentration, increases the fluidity of the metal. Spencer and Walding found that, contrary to the general assumption, higher phosphorus content did not increase the fluidity, aside from its influence in lowering the freezing point. Saeger and Ash found that various metals "run" better in dry sand molds than in green sand molds.

Thermal Conductivity. The thermal conductivity is approximately 0.11 cal per cm per °C per sec.

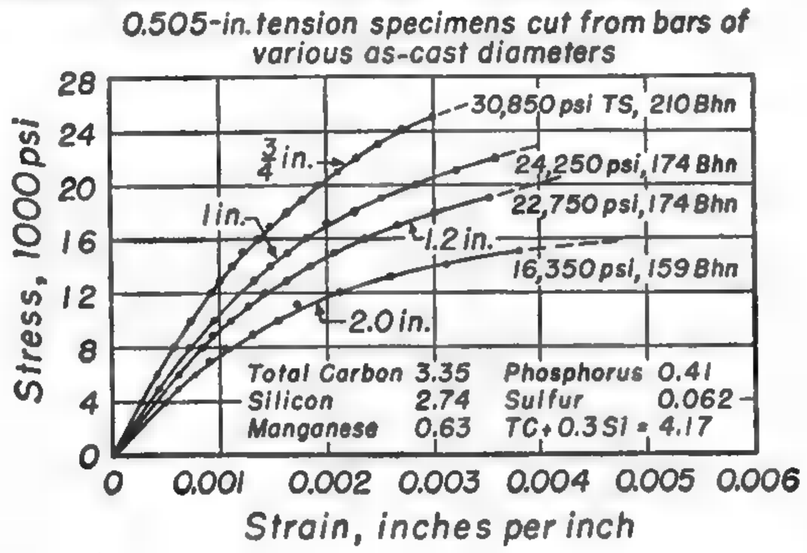


Fig. 3a

Fig. 3a Stress-strain characteristics of gray iron. Rigidity is approximately proportional to tensile strength. (Bolton[4])

Electrical and Magnetic Properties. As compared with that of other ferrous metals, the resistivity of gray iron is relatively high, apparently because of the amount and distribution of the graphite content. Increases in total carbon content and in silicon content increase resistivity. The austenitic cast irons are nonmagnetic.

Hatfield states as follows ". . . the magnetic properties of cast iron may vary within very wide limits, ranging from those of materials having low permeability and high coercive force suitable for permanent magnets, and those having high permeability, low coercive force, and low hysteresis loss suitable for electrical machinery".

Highest magnetic induction and permeability are found in annealed white irons, such as malleable cast iron. Flake graphite, as in gray iron, does not affect the hysteresis loss but prevents the attainment of high magnetic induction. The flakes and attendant discontinuity cause small demagnetizing forces.

As is evident from the preceding discussion, in order to achieve any desired combination of characteristics, the type of cast iron desirable for each application must be selected judiciously.

Mechanical Properties

Tensile Strength. The majority of commercial gray irons have tensile strength within the range from 25,000 to 50,000 psi. Specifications cover seven classes, from 20,000 psi min to 60,000 psi min. In special instances, gray irons have been made with tensile strength as high as 100,000 psi, but such irons are limited in commercial use. Irons above 40,000 psi in tensile strength are usually considered "high-strength irons", and are somewhat more expensive to produce and more difficult to machine.

Gray irons do not exhibit a definite "yield point" as do most mild steels. A stress-strain diagram (Fig. 3*a*) indicates that curvature is exhibited at very low stresses; thus definite moduli of elasticity cannot be established. A usual practice is to ascertain the relative modulus at 25% of the expected tensile strength. As suggested by Fig. 3*b* this modulus is different with different tensile strengths and increases with increase in tensile strength. Such relative moduli lie within the range from 12,000,000 psi for the lower-strength irons to between 25,000,000 and 29,000,000 psi for the higher-strength types.

Gray iron exhibits the phenomenon of set, or permanent deformation. As shown in Fig. 3*b*, the usual stress-strain diagram consists of two components—permanent set and an elastic component (dotted line in Fig. 3*b*). When stresses are relatively high and extreme dimensional accuracy is necessary, prestressing may be resorted to before final machining and alignment.

It has been shown that, at room temperature, gray iron can sustain loads up to 80% of its tensile strength without perceptible continued creep.

Temperatures as high as 650 F and slightly above, do not lower the tensile strength of gray irons.

Shear Strength. The shear test is of value in "exploring" a casting; that is, specimens are taken from the casting itself. The ratio of shear strength to tensile strength varies, and is higher for the weaker irons. In a series of studies dealing with irons of various tensile strengths, the ratio of shear strength to tensile strength varied from 1.64 for the weakest iron tested (20,000 psi tensile strength) to 1.01 for the strongest iron tested (60,000 psi tensile strength).

Compression Strength. Cast iron is much stronger in compression than in tension. In a series of tests dealing with many types of cast iron, the compression strength

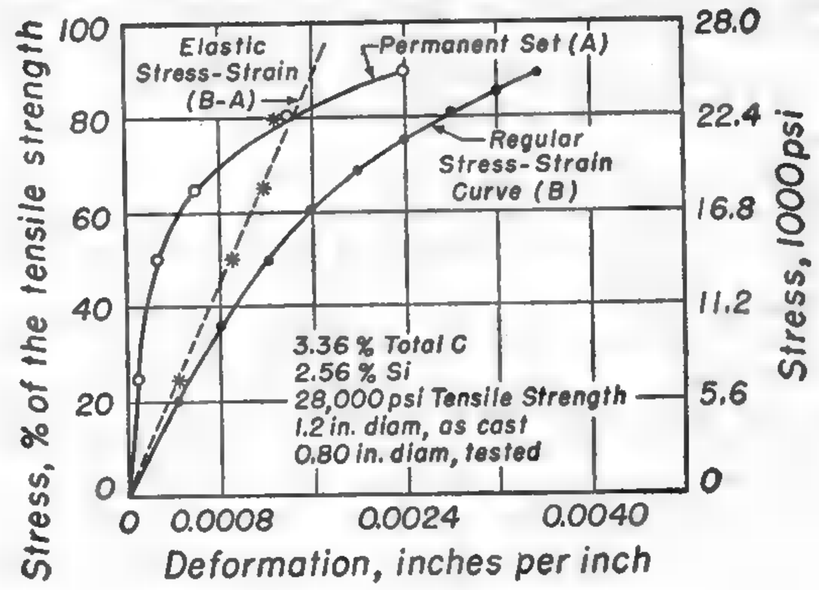


Fig. 3b

Fig. 3b Stress-strain diagram showing elastic and permanent deformations for gray iron (Bolton[4])

ranged from 65,000 to 160,000 psi. The ratio of compression strength to tensile strength varied from about 4.5:1 for the weaker irons to 2.5:1 for the stronger irons.

Hardness. The Brinell hardness test is a useful one for gray iron castings. The Rockwell test also is used, employing the B scale. In the as-cast condition commercial (nonalloy) gray iron castings range from 150 to 220 Bhn. The alloy cast irons are harder and heat treated irons may be harder than 600 Bhn. Ordinary white irons range from 321 to 534 Bhn while alloy white irons may be as hard at 700 Bhn. Fully annealed gray irons may range from 100 to 140 Bhn.

Endurance Limit. The endurance limit, or fatigue strength, appears to vary linearly with the tensile strength. For the endurance limit, values from 0.4 to 0.6% of the tensile strength have been reported. The values for endurance limit are not greatly reduced by temperatures up to 800 F.

Impact Strength. In general, the resistance to impact increases with tensile strength, although this is not true in all instances. For example, cast irons of high phosphorus content are lower in impact strength than lower-phosphorus irons of equivalent tensile strength.

Fig. 4 Graphite in gray iron (× 100) Fig. 5 White iron (× 175) Fig. 6 Pearlite, ferrite and cementite in cast iron (× 1500) Fig. 7 Phosphide eutectic in cast iron (× 1000) (reduced one-third in reproduction) (R. M. Allen[7])

Transverse Bend Tests. For a discussion of the application of bend tests to cast iron and to other metals that have low ductility, the reader may refer to the article on page 125 of this Handbook. Additional information on the mechanical testing of cast iron is included in the article on "Mechanical Testing of Castings", page 136.

General Comments on the Engineering Properties of Gray Iron. Gray iron combines melting and molding at low cost with ease of casting into intricate shapes. It has good rigidity, great compressive strength and ready machinability.

Shrinkage defects may occur when a large section changes abruptly into a smaller section. When designing gray iron castings, it is desirable to use uniform sizes of section if possible.

A close-grained iron, low in total carbon content, is the strongest, toughest and best-finishing type of material. The structure and strength of gray irons are controlled largely by composition and cooling rate. The composition can be controlled in making up the charge. The cooling rate depends on section, size, and somewhat less on pouring temperatures. Hence, castings that are not uniform in section may exhibit diversity in physical properties, and in the same section there is often some difference between the outside and the center of the section. Proper composition will tend to minimize the variation between outside and center.

Effects of Common Alloying Elements

Carbon. Most commercial cast-iron castings contain from 2.70 to 3.60% total C. This carbon may exist as free carbon (graphite) (Fig. 4); as combined carbon (cementite) as found in free massive cementite (Fig. 5), and in the cementite lamellae of pearlite (Fig. 6); or in solution in molten iron and in austenite.

Graphitic carbon is soft and not tenacious, and in gray iron is found as black flakes (Fig. 4).

Cementite is very hard and possesses little ductility. Under certain conditions it may be decomposed into iron and carbon (graphite).

At subcritical temperatures iron can hold only a few hundredths per cent of carbon in solution. This solubility increases rather abruptly to about 0.85% or less at the A_3 transformation temperature (approximately 1350 F, depending on composition) and the solubility increases further as the temperature is raised.

The structure of a given cast iron depends largely on the amount, size and distribution of the various forms of carbon. The amount depends both on the percentage in the charged metal and on the melting process. The size and distribution of the various forms depend on the temperatures, time and other factors involved in the melting process, and on the rate of cooling the metal from the molten condition, as well as on the composition, and on the presence of inoculants. These factors are discussed in detail in various later sections.

Silicon. Because of the relation between the carbon and silicon contents, silicon is a very important element in the metallurgy of gray iron. Silicon promotes the decomposition of the combined carbon (in pearlitic and massive cementite) to ferrite and graphite. Irons that contain no silicon usually have a white (cementitic) fracture. In changing white iron to gray, silicon makes commercial production of gray iron practicable. For strong irons, just enough silicon should be used to ensure decomposition of all massive cementite, but not enough to cause decomposition of the cementite in the pearlite. Excessive decomposition of the pearlite to graphite and ferrite, gives a weak, soft metal.

Silicon also reduces the carbon content of the eutectic by about 0.30% for each per cent of silicon. This means that higher-silicon pig irons are often lower in carbon than lower-silicon irons. It is easier to produce low-carbon cupola metal with higher silicon contents. Silicon raises the eutectic temperature slightly.

An increase in silicon content lowers the percentage of carbon in the eutectoid approximately 0.07% for each per cent of silicon.

Manganese. Manganese may be present in the carbide phase in gray iron or may occur as manganese sulfide in small slate-colored inclusions throughout the metal. In ordinary commercial ranges, manganese has little effect on the mechanical properties of gray iron. About 0.30% more Mn than is required theoretically for combination with sulfur (which is 55/32 times the sulfur percentage) is necessary for mitigating the effects of sulfur. Most American irons contain 0.06 to 0.12% S; hence the usual range of 0.50 to 0.80% Mn is sufficient.

Sulfur. Sulfur occurs largely as manganese sulfide, and rarely as iron sulfide. Under proper operating conditions, sulfur does not seem to exert harmful effects on gray iron in amounts up to 0.16 or 0.18%, provided manganese is present in amounts sufficient to prevent chill. In the absence of enough manganese, sulfur has a marked stabilizing action on the cementite and promotes chill.

Phosphorus. The phosphorus range in most American irons is from 0.10 to 0.90%. The irons from northern ores usually are low in phosphorus, and some of the irons from southern ores are higher in phosphorus. The phosphorus content of many foreign irons is much higher than that

of typical American irons. Virtually all the phosphorus is present in the constituent known as "steadite", the effects of which will be discussed in greater detail under that heading. Phosphorus does not have a marked effect on the static strength of ordinary commercial irons except those of higher strength. High percentages of phosphorus apparently lower the impact strength appreciably.

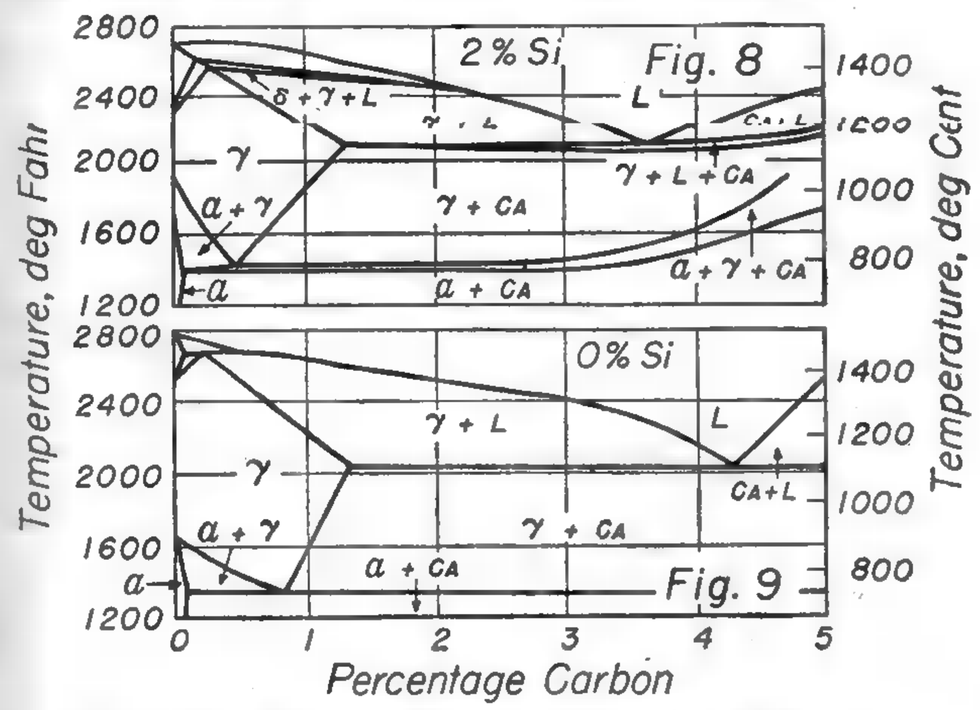


Fig. 8 and 9 Sections through the iron-carbon-silicon system at 2% Si and 0% Si (Greiner, Marsh and Stoughton[8])

Phosphorus increases fluidity at any given temperature and thus increases the castability of thin sections. Where considerable variation exists in sections of a given casting, some foundrymen prefer to use medium-phosphorus or low-phosphorus irons, and to employ higher pouring temperatures.

The present trend is toward greater usage of lower-phosphorus irons. In the automotive industry some foundries are using 0.15% P max increasingly, whereas 0.20% P max was common several years ago. Also, as mentioned above, wider use of higher-strength grades, with attendant employment of higher percentages of steel in the charges, naturally results in less phosphorus in the final composition of the iron.

Structure of Gray Irons

Mode of Formation. Gray iron is essentially a series of alloys of iron, carbon and silicon. The major structural components of the usual castings are pearlite, ferrite and graphite. The mode of formation of these and other components will be apparent from the iron-carbon and iron-carbon-silicon phase diagrams. Figure 8 shows a section through the iron-carbon-silicon metastable ternary diagram at 2% Si. If this is compared with Fig. 9, the diagram for iron-carbon without silicon, it will be noted that the carbon concentration of the eutectic is lower (effect of silicon) and that the temperature ranges of eutectic solidification and of austenite transformation are somewhat higher. In the presence of silicon, there is a range, at the eutectic solidification, where gamma iron, liquid and carbide are coexistent; at the eutectoid transformation, alpha iron, gamma iron and carbide coexist.

Figures 8 and 9 illustrate the metastable (iron–iron carbide) equilibrium. In stable alloys austenite and graphite are in equilibrium above the eutectoid and below the eutectic. In the eutectoid transformation range, ferrite, austenite and graphite coexist.

Under commercial conditions of casting, gray irons us-

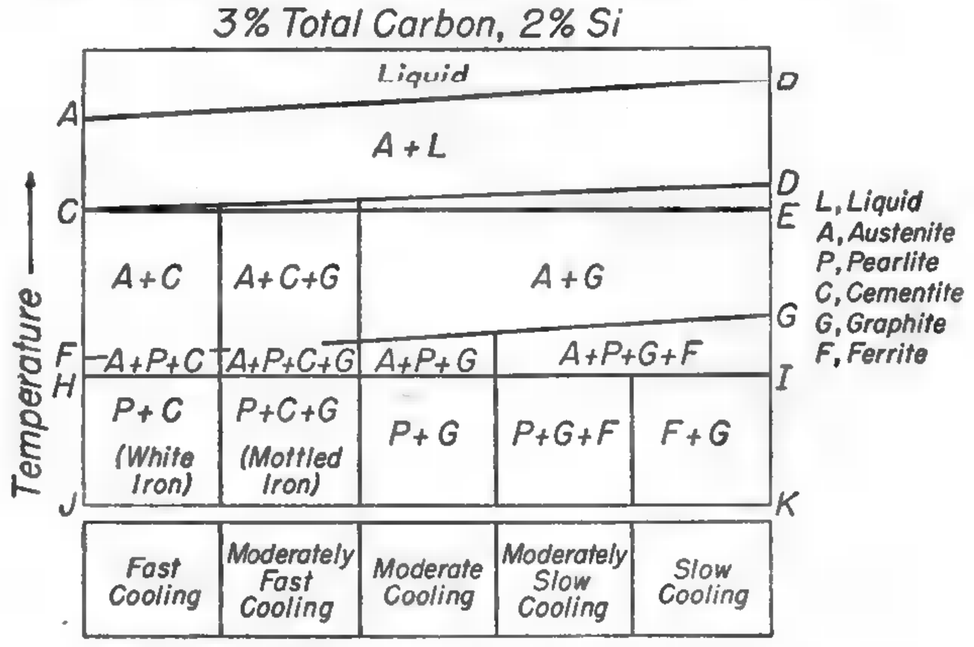


Fig. 10 Transformations during the solidification and cooling of cast iron (C. H. Lorig[9])

ually solidify at rates that do not permit equilibrium. Hence the structures are intermediate between the stable and metastable diagrams. This is illustrated in Fig. 10. The line *AB* represents the liquidus. The area *CDE* represents the final or eutectic solidification. The area *HFGI* represents the eutectoid transformation range.

The qualitative relationship of strength and hardness to the structural conditions outlined in Fig. 10, are shown in Fig 11.

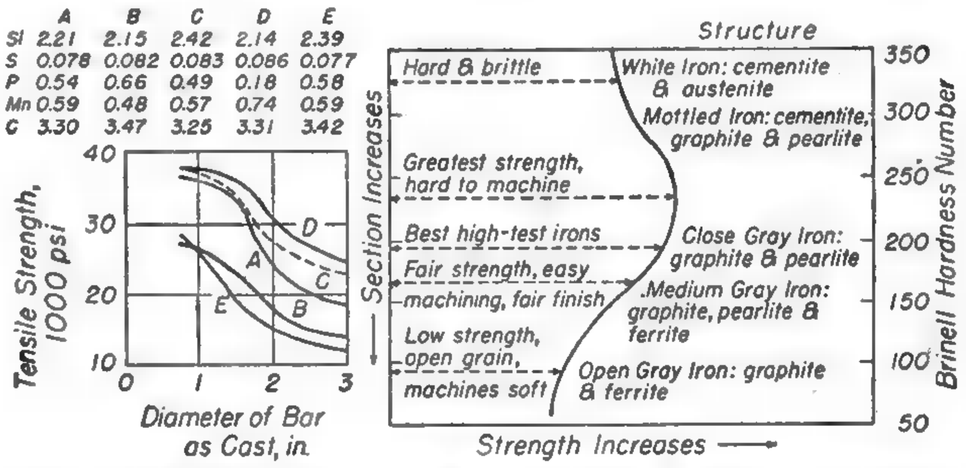


Fig. 11 Qualitative relationships among size of section, structure, tensile strength and hardness of gray iron.

The normal or usual microstructure of gray iron is a pearlitic matrix with graphite flakes dispersed throughout. Too rapid cooling (with respect to carbon and silicon contents) produces mottled iron, consisting of a pearlitic matrix with both free cementite (carbide) and graphite. Very slow cooling of irons that contain larger percentages of

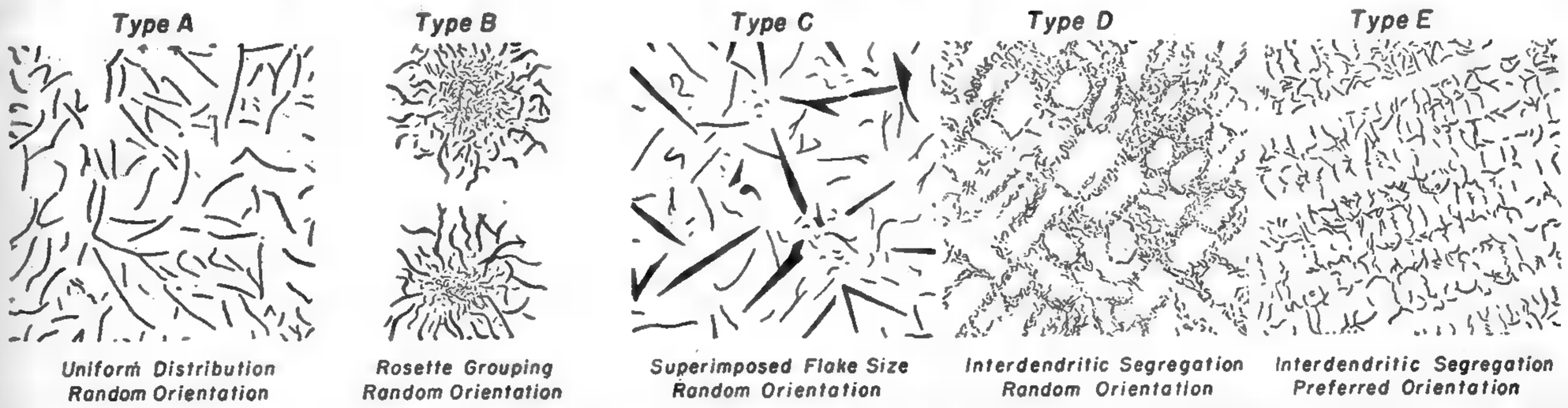


Fig. 12 Chart illustrating the types of graphite flakes in gray cast iron (AFA-ASTM). In the recommended practice,[10] these charts are shown at a magnification of 100 diameters. They have been reduced to one-third size for reproduction here.

silicon and carbon, is likely to produce considerable ferrite as well as pearlite throughout the matrix, together with coarse graphitization. Under some conditions, very fine (so-called "pseudo eutectic" or AFA Type D) graphite may be formed near casting surfaces (Fig. 12). Frequently such graphite is surrounded by a ferrite matrix; hence soft spots result. The deeper layers of metal may show random flakes and pearlitic matrix. Inoculation (*see* page 515) is often effective in preventing formation of Type D graphite and the localized ferritic soft spots.

The action of various alloying elements may retard or even suppress the transformation of austenite to pearlite. The mechanism of transformation of austenite in gray irons and in steels is essentially the same. For a discussion of isothermal transformation diagrams, the reader may refer to page 607.

Suppression of the transformation of austenite (by cooling rates and by additions of alloying elements) may result in the formation of intermediate products, especially martensite. Addition of some alloying elements, notably nickel, in sufficient amounts, may lower the transformation temperature range to such an extent that austenite, rather than pearlite, becomes the matrix constituent.

Pearlite and Ferrite. The combined carbon in ordinary gray irons occurs in the cementite lamellae of the pearlite. Because of the influence of other structural formations and the presence of silicon and manganese, a gray iron of pearlitic matrix may have from 0.50 to about 0.80% combined C. As in steel, with other factors equal, the strength and hardness are increased with increase in the amount of pearlite. Except for martensitic and other special cast irons, the highest strength irons are almost wholly of pearlitic matrix. However, because of the influence of graphite flakes and other factors, pearlitic matrix alone does not ensure maximum strength.

Ferrite, lower in strength and softer than pearlite, is usually situated along the graphite flakes. Highly ferritic gray irons are deficient in strength, hardness and wear resistance; however, they are usually highly machinable.

Steadite. Steadite, a structural component in cast iron that contains phosphorus, is identified by certain white dendritic formations distributed throughout the metal. These formations sometimes form a loosely joined network. The distribution of the formations indicates that they have concentrated in the portion of the metal that was last to solidify.

Steadite is a ternary eutectic structure that consists of alpha iron, cementite and iron phosphide (Fe_3P). In irons of low phosphorus content (less than 0.50%) some of the phosphorus is in solid solution. In irons that contain higher percentages of phosphorus, much of the phosphorus is present in the cellular steadite eutectic (Fig. 7), containing about 10.2% P. The melting point of this eutectic is about 1800 F.

Steadite is hard and improves resistance to some types of wear. If continuous, it may somewhat improve resistance to corrosion and oxidation also.

Free Cementite. White and mottled irons contain free cementite, which causes the metal to be hard and brittle.

Graphite. The metallic matrix of gray irons is filled with thousands of curved flakes of graphitic carbon. These flakes are soft and weak and are similar in crystalline make-up to natural graphite (plumbago). Graphite flakes are responsible for the typical dark gray fracture of gray iron, for the lack of appreciable ductility in gray iron, and for the ease with which it can be machined. By breaking up the matrix, these flakes decrease the strength of the iron; in fact their influence is so pronounced that it often outweighs all other factors controlling strength. Graphite flakes produce these effects in various degrees, according to their size, distribution and amount.

Structure of Cast Irons

Effects of Mass and Cooling Rate. Gray irons (and the related iron-carbon-silicon alloys, such as mottled and white irons) are affected markedly by the rate of cooling from the casting temperature. In these alloys, the stable structure is ferrite and graphite. As mentioned above, compositions are chosen with respect to cooling rates so that the usual cast iron is structurally somewhere between the metastable and stable systems. Very rapid cooling (also low silicon and carbon contents) promotes retention of the metastable structure, free carbide (cementite) and some pearlite (or martensite, or even some retained austenite) as found in white irons. Very slow cooling promotes approach to the stable system, ferrite and graphite. The rate of cooling also influences grain size and the size of graphite flakes. Just as in other metals, slow cooling produces coarser structural formations.

In ordinary commercial practice, the rate of cooling depends largely on size of section. Heavier sections cool more slowly than light sections. In simple shapes, the relative cooling rates can be compared on the basis of the V/A relationship, where V = volume in cubic inches, and A = area of exposed surface in square inches. The volume is approximately proportional to the amount of heat to be dissipated. The area is the surface through which the heat must flow.

The more slowly a given gray iron casting cools from the pouring temperature, the lower in strength and hardness it is likely to be. This is frequently referred to as "effect of mass" or "effect of section size"; a more accurate term is "effect of cooling rate".

The more slowly a given iron is cooled through the graphitization range, the more complete the graphitization will be. Furthermore, during slower cooling there is greater opportunity for grain growth, including grain size and degree of lamination of pearlite, and grain or flake size of graphitic carbon. These effects on the structure are reflected in the mechanical properties (Fig. 11), which indicate loss of strength with increase in size of section.

Changes in strength and structure with variation in size of section, are much less apparent in irons of comparatively low total carbon content. For example, when properly made, an iron that contains 2.75% C, 2.25% Si and no alloying elements, can be cast into a 0.5-in. diam test bar with no trace of chill and into a 3.0-in. diam bar with pearlitic matrix that has good strength and hardness throughout. Quite frequently the intelligent use of alloying elements is also beneficial in the maintenance of uniformity in strength and hardness over a range of sizes.

The foregoing discussion indicates that the composition of the metal must be chosen so that it is suitable for the particular sizes of section to be cast. For example, an iron composition fully suited for a lathe bed, may be chilled and useless if cast into automotive piston rings, and an iron composition suited for piston rings may be weak, soft and open-grained if cast into a lathe bed. For similar reasons, it is undesirable to have extensive heavy and light sections in the same casting.

Alloy Cast Irons and Inoculated Irons

Because the term "alloy cast iron" has been used imprecisely, it is desirable to define both plain cast iron and alloy cast iron.[1]

Plain Cast Iron. "Cast iron" is essentially an alloy of iron and carbon in which the carbon is present in excess of the amount that can be retained in solid solution in austenite at the eutectic temperature.

Alloy Cast Iron.[1] "Alloy cast iron" is cast iron that contains a specially added element, or elements, in sufficient amount to produce a measurable modification of the physical or mechanical properties of the iron in the section under consideration. Silicon, manganese, sulfur and phosphorus, as normally obtained from raw materials, are not considered alloy additions.

Alloying elements are added to cast iron for improvement of mechanical properties or for development of a special characteristic, such as resistance to corrosion, heat or wear. The alloying elements that have important effects on the structure of the metal, should be added to well-made cast irons in order to improve them. Such additions to poorly made cast irons are not economical.

Additions of alloying elements have a marked effect on graphitization. Some alloying elements will accelerate graphitization while others will retard this transformation. The control of graphitization is one of the important reasons for the use of alloying elements in cast iron.

Some of the more common alloying elements will be discussed here; many others may be used in cast iron.

Chromium. Chromium, a powerful carbide former, increases the combined carbon and intensifies the chilling propensities of cast iron. When added to cast iron, chromium forms complex iron-chromium carbides, which are more stable than Fe_3C. The chromium irons graphitize less readily than plain cast iron.

Because of the effect of chromium on structure, small amounts of chromium increase strength, hardness, depth of chill, and resistance to heat and to wear, but decrease machinability. For general improvement in mechanical properties, chromium is used in amounts from 0.15 to 1.00%, with or without other alloying elements. Chromium in amounts from 1 to 1.5% is added for moderate resistance to the softening and scaling effects of heat at temperatures up to 1400 F. In the production of special irons to resist corrosion or high temperatures, or both, as much as 35% Cr has been used.

To illustrate carbide-forming characteristics of chromium additions, the following effects on a soft gray iron may be cited:

Percentage Chromium	Structure
0	Ferrite and coarse graphite
0.3	Less ferrite, some pearlite and finer graphite
0.6	Fine graphite and pearlite
1	Fine graphite, pearlite and small carbide
3	Disappearance of graphite
5	Much massive carbide
10 to 30	Fine carbide

An important use of chromium is the addition to base irons where additional hardness or resistance to wear is required. A nonalloy iron containing 2.25% Si and 3.40% total C may be satisfactory for most castings that are light in section. Increased hardness and better structure are required for heavier sections. Additions of chromium ranging from 0.30 to 1.0% are frequently made in order to increase hardness and improve the structure. In heavy sections, the use of chromium helps to give a more uniform structure and tends to eliminate porosity.

The stability conferred to the carbide by chromium is useful in the heat treatment of gray iron castings because it tends to prevent excessive graphitization.

Chromium is used in conjunction with other elements, such as nickel, copper, molybdenum and vanadium. Typical combinations are nickel-chromium, chromium-molybdenum, nickel-chromium-molybdenum, copper-chromium and nickel-chromium-vanadium.

Copper. Copper promotes the formation of graphite and has about one-tenth to one-fifth as much graphitizing ability as silicon. The usual range of copper contents is from 0.25 to 2.5% for engineering applications. The amount that can be alloyed is limited by the solubility of copper in liquid cast iron; the maximum is about 3.75%.

Copper is a mild strengthener in cast iron, acting to break up massive cementite spots and also strengthening the matrix. Copper may harden or soften the cast iron, depending on the structure of the base metal. If the iron has a tendency to chill, copper will reduce hardness; however, in normal gray irons copper will increase hardness and resistance to wear and will combat certain types of corrosion.

Copper, frequently used with other alloying elements, is effective when used with those that form carbide. Some typical combinations are copper-chromium, copper-chromium-molybdenum, copper-molybdenum, copper-manganese and copper-vanadium. Proper balance should be maintained between the addition of copper and elements that stabilize carbide. Copper additions should be from three to six times as large as the chromium additions, depending on carbon content. The higher ratios should be used with the lower carbon contents (below 3%). Copper will balance equal additions of molybdenum or manganese but ten parts copper are required for one part vanadium.

Molybdenum. Molybdenum, a mild stabilizer of carbides, tends to increase the depth of chill in cast iron. Under no circumstances does it act as a graphitizing agent. Improvements in mechanical properties of cast iron can be obtained by the use of molybdenum, in most instances without changing the normal melting practice.

The addition of molybdenum to gray iron increases tensile strength, transverse strength and deflection, and hardness. Molybdenum, usually added in quantities from 0.25 to 1.25%, is the most effective alloying element added to gray iron to increase strength. Molybdenum additions are also considered beneficial in improving resistance of gray iron to fatigue.

Molybdenum is used in combination with other alloying elements, for instance, nickel-molybdenum, chromium-molybdenum, nickel-chromium-molybdenum, copper-molybdenum, copper-chromium-molybdenum and molybdenum-vanadium.

The addition of molybdenum to cast iron promotes structural uniformity in heavy sections. As a result, good density, high Brinell hardness and high strength are maintained throughout the cross section. Molybdenum promotes machinability by improving structural uniformity and because it does not result in massive carbides.

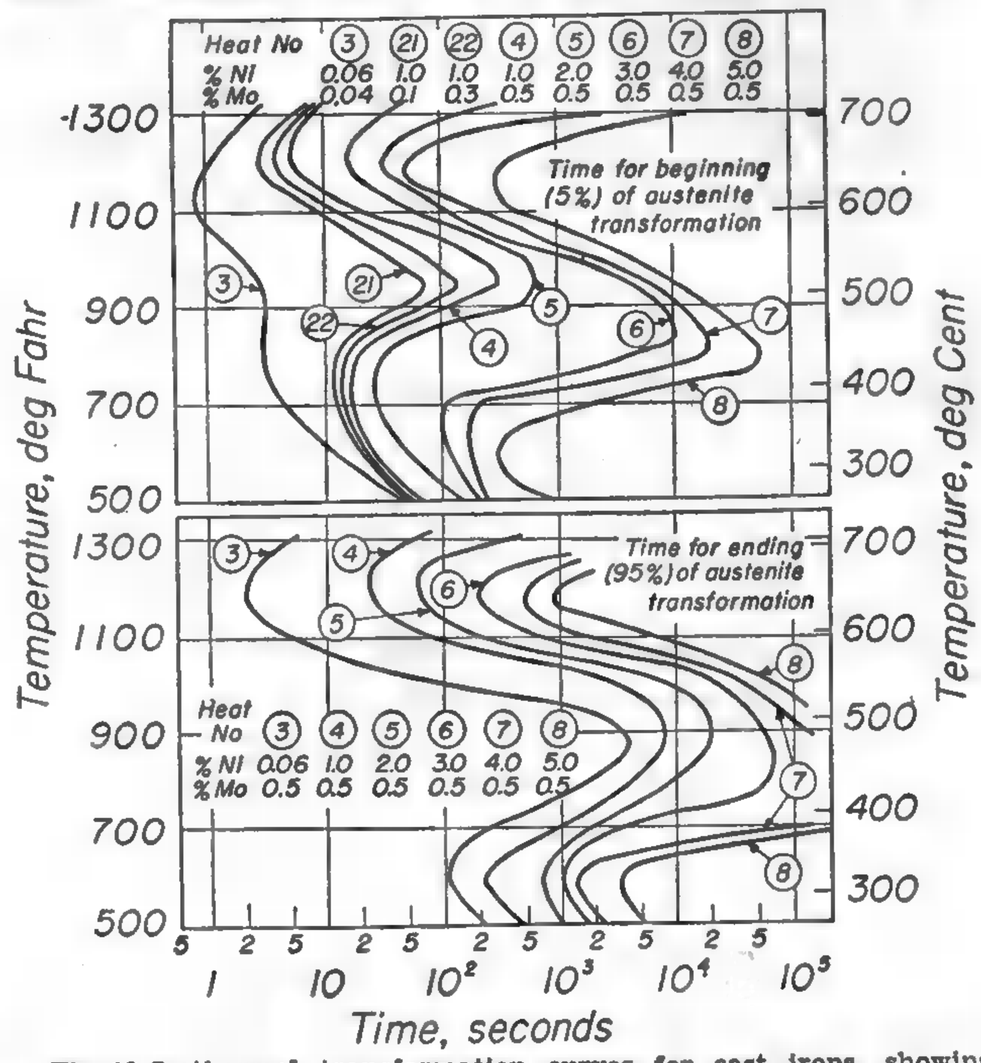


Fig. 13 Isothermal transformation curves for cast irons, showing the effect of nickel and molybdenum on the times for the beginning (5%) and ending (95%) of austenite transformation at constant subcritical temperatures. Base composition: 2.5% total C, 2.5% Si, 0.85% Mn, 0.10% S and P (Flinn, Cohen and Chipman[5])

Molybdenum retards the rate of transformation of austenite, thereby increasing the hardness and strength in the as-cast or heat treated condition. Molybdenum, in cast iron as in steel, contributes to the retention of strength at elevated temperatures.

Molybdenum is of value in the heat treatment of gray iron castings because of hardenability, freedom from cracking and distortion, and slight carbide stability. Freedom from cracking is a result of the sluggishness of the transformation of matrix austenite, which reduces the probability of quenching cracks.

Nickel. Nickel is a graphitizer and does not form a carbide. It acts effectively to reduce chill and to eliminate hard carbide spots, chilled areas and mottled areas. Small additions of nickel, 0.10 to 1.0%, are effective in refining the grain and the size of graphite flakes.

Nickel may replace or supplement silicon in making castings graphitic. Two parts of nickel are generally equivalent to one part of silicon in reducing chill.

The major fields of application of nickel cast irons are in the engineering gray irons (0.5 to 6.0% Ni), the martensitic white irons (about 4.5% Ni) that resist abrasion, and the austenitic gray irons (14 to 38% Ni) that resist heat and corrosion and have low expansivity.

Table II. Effect of Nickel on the Hardness of Gray Cast Iron
1.20-in. diam sand-cast sections

T C	C C	Si	Ni	Bhn
2.24	0.73	2.34	1.07	273
2.27	0.68	2.36	2.07	286
2.33	0.74	2.29	3.06	293
2.27	0.71	2.22	4.10	302

Engineering Cast Irons. The primary function of nickel in engineering cast irons is to control structure by (1) retarding transformation of austenite, (2) stabilizing pearlite and (3) maintaining combined carbon at eutectoid quantity.

Quantitative evidence of this control of structure is shown in Fig. 13 and 14 and Table II.

In Fig. 13, S-curves of gray irons with increasing amounts of nickel (plus molybdenum) exhibit retarded austenite transformation in both the pearlite and the acicular regions. By increase in the nickel content, the structure may be changed from coarse pearlite to fine pearlite, to acicular products or to martensite. Figure 14 shows the effects of nickel content and size of section on the microstructure of cast iron that contains 1% Mo.

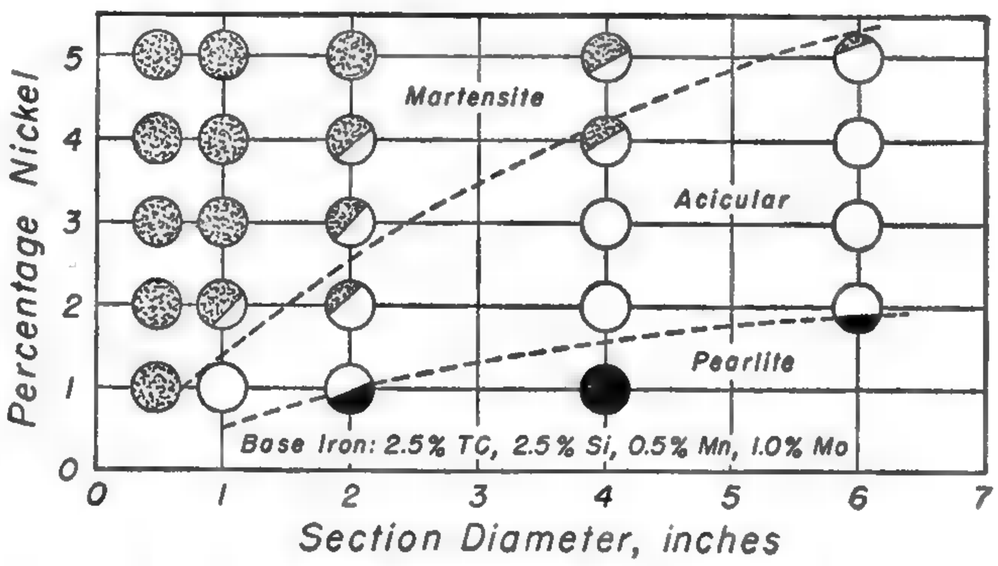


Fig. 14 Effect of nickel content and section size on the as-cast structure of cast iron containing 1% Mo (Flinn, Cohen and Chipman[5])

The same effect is obtained at higher carbon levels (about 3.5% total C) but Brinell hardness is lower (225 to 275 Bhn) because of the greater quantity of graphitic carbon. These types of cast iron have moderate machinability at high hardness.

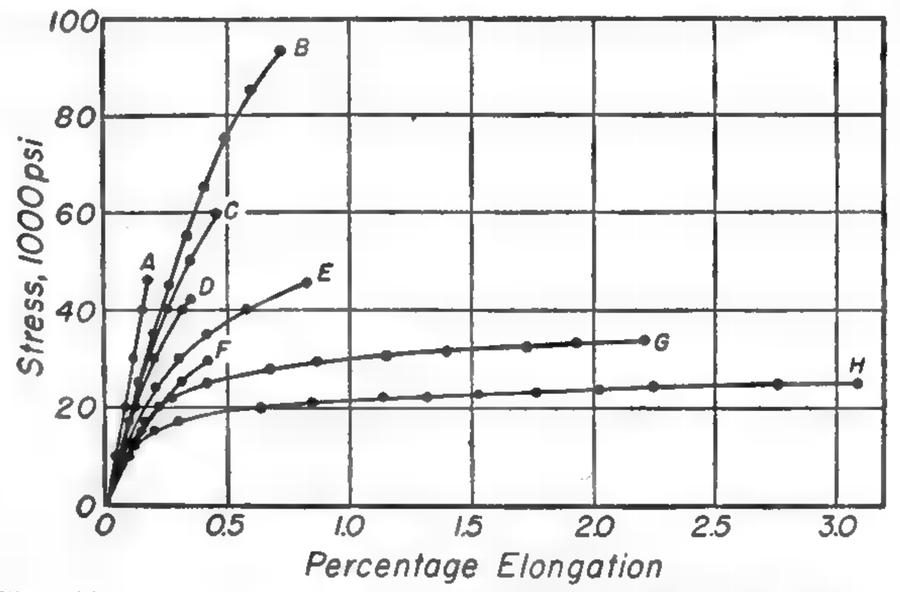
The stress-elongation relationships shown in Fig. 15 also illustrate the influence of nickel in cast iron.

For engineering applications, nickel is frequently used with alloying elements that form carbide. Typical combinations are nickel-chromium, nickel-molybdenum, and nickel-chromium-molybdenum.

Martensitic White Irons for Resisting Abrasion. The combination of iron carbides in a martensitic matrix results in a good combination of hardness (600 to 750 Bhn), abrasion resistance, strength, and toughness. Combinations of 4.25 to 4.75% Ni and 1.4 to 2.5% Cr may be used in either low-carbon (2.9% total C max) or high-carbon (3.0 to 3.6% total C) irons. Composition and mechanical properties are shown in Table III.

Austenitic and Low-Expansivity Cast Irons. Austenitic cast irons are formulated to accommodate a variety of properties such as high or low expansion, high electrical resistance and nonmagnetic response, as well as resistance to heat, acids, alkalies and other chemicals. These irons have about the same mechanical properties as gray iron except that they are much tougher. The various types are indicated in Table IV.

Vanadium. Vanadium, one of the most powerful carbide formers, stabilizes cementite and restrains graphitization.



No.	Material	TC	Si	Ni	Cr	Mo	Cu
		Chemical Composition, %					
A	1.5% Cr white cast iron	3.40	0.68	....	1.55	....	....
B	High-strength Ni-Mo gray iron	2.34	2.64	2.93	0.25	0.97	....
C	Quenched and tempered gray iron	3.51	0.72	....	....	....	....
D	3.10% C, Si-Cr heat-resistant iron	3.10	3.57	....	1.94	....	....
E	High-carbon Ni-Mo gray iron	3.66	1.82	1.52	....	1.06	....
F	3.54% C, Si-Mo heat-resistant iron	3.54	3.38	....	1.95	....	....
G	Austenitic gray iron: 18 Ni, 3 Cu, 2 Cr	2.89	1.81	18.38	2.28	....	2.74
H	Austenitic gray iron: 20 Ni, 2 Cr	2.91	1.68	20.45	2.11	....	....

Fig. 15 Curves of tensile stress versus strain for gray irons of different matrices (Flinn and Chapin[11])

When vanadium is added to cast iron in amounts ranging from 0.10 to 0.50%, the following effects are observed:

1 Interference with graphitization and stabilization of cementite
2 Smaller graphite flakes and more uniform distribution of graphite
3 Promotion of sorbitic structure
4 Decreased grain size of matrix
5 Smaller, less pronounced, and less perfectly aligned dendrites in the surface layers of chilled castings. Because of this and (1) above, greater depth, hardness, toughness and resistance to wear of chill result.
6 Resistance of the carbide to decomposition at high temperatures

Additions of vanadium increase tensile strength, transverse strength and hardness of gray cast iron. For most commercial applications, the vanadium content is 0.10 to 0.25%. Amounts up to 0.12% V are added to highly alloyed irons for the purpose of improving machinability. Vanadium promotes fine lamellar pearlite in compositions that might otherwise be acicular.

Table III. Composition and Properties of Martensitic White Cast Irons

Chemical Composition	High-Carbon	Low-Carbon
T C	3.0 to 3.6	2.9 max
G C	nil	nil
Si	0.4 to 0.7	0.5 to 1.0
Mn	0.4 to 0.6	0.4 to 0.6
S	0.15 max	0.15 max
P	0.4 max	0.4 max
Ni	4.25 to 4.75	4.25 to 4.75
Cr	1.4 to 2.5	1.4 to 2.5

Properties[a]

	Sand-Cast	Chill-Cast	Sand-Cast	Chill-Cast
Bhn[b]	550 to 650	600 to 725	525 to 625	575 to 725
Tensile[c]	40 to 50,000	50 to 60,000	45 to 55,000	60 to 75,000
Transverse[c]	4000 to 5000	4500 to 6800	4500 to 5500	5500 to 7000

(a) After stress relieving at 400 F
(b) With tungsten carbide Brinell ball
(c) Bars 1.2 in. in diam

Table IV. Austenitic Cast Irons

Type[a]	Percentage Ni	Cu	Cr	Si	Designed for	Application
1[b]	14	6	2	...	Max expansivity (19.3 x 10^{-6} per °C)	Containers for strong acids
2[b]	20	...	2	...	Freedom from contamination by copper	Containers for foods, caustic, rayon, plastics
2B	20	...	3–6	...	Heat resistance to 1500 F	
3	30	...	3	...	Matched expansivity with plain iron and steel	Chemical equipment that is cyclically heated and cooled
4	30	...	5	6	Resistance to staining	Foods
5	36	...	...	...	Low expansivity	Precision machine tools

(a) All types except 2B have good resistance to galling and wear, good machinability and high damping capacity.
(b) Nonmagnetic

Table V. Typical Compositions of High-Strength Cast Irons

Approximate Tensile Strength, psi	Composition, percentage							
	T C	Si	Mn	■	P	Ni	Cr	Mo
50,000.....	3.15	2.25	0.70	0.10	0.15	1.00	0.50	0.80
50,000.....	3.05	1.70	0.75	0.10	0.20	....	0.50	0.50
55,000.....	3.05	2.10	0.80	0.10	0.10	0.50	0.90	0.50
60,000.....	3.00	2.15	0.80	0.10	0.14	1.60	....	0.80
70,000.....	2.70	2.30	0.85	0.08	0.10	0.80	0.20	1.00

Vanadium is used in combination with other alloying elements such as nickel, copper, chromium and molybdenum.

Inoculated Irons. "Inoculated", "processed" or "treated" cast irons have assumed increasing importance. Inoculants are materials that, when added to molten cast iron, modify the structure and thereby change the physical and mechanical properties to an extent not explained on the basis of the change in composition resulting from their use.

Late additions to molten cast iron, usually in the ladle, have a definite effect on the structure and mechanical properties of the metal. It is possible for inoculants to change the structure effectively with little change in chemical composition. For equivalent tensile strengths, inoculated irons are usually lower in hardness than irons not inoculated.

One of the early inoculants was ferrosilicon. If an iron is purposely melted with a lower silicon content than desired in the casting, and a part of the silicon is added to the ladle as ferrosilicon, there is a definite improvement in structure. The mechanical properties are improved and the tendency toward chilled edges and corners is reduced,

Table VI. ASTM Classification of Gray Cast Irons

Class Number	Minimum Tensile Strength, psi	Class Number	Minimum Tensile Strength, psi
20	20,000	40	40,000
25	25,000	50	50,000
30	30,000	60	60,000
35	35,000		

thus producing better and more machinable castings. Other inoculants used for many years are calcium-silicon, ferromanganese-silicon and zirconium-silicon.

Proprietary inoculants containing a combination of graphitizing elements, have been used in the foundry and some of these inoculants are more effective than ferrosilicon. They are known as "graphitizing inoculants" and are sold under various trade names. These materials have become quite popular since the production of inoculated irons has been increasing.

Another type of inoculant contains some element that stabilizes carbide—for instance, chromium. Depending on the composition, such an inoculant can increase or decrease the hardness of the metal. The advantage of reduction in chill is retained together with the alloying effect of the chromium; a stronger, harder and more machinable casting may be the result. This type of inoculant is sold under various trade names.

Inoculants are not a cure-all for the foundry. It is necessary to control carefully both the base iron and the addition of the inoculant in order to secure optimum results. Inoculants do provide a useful tool in the production of quality castings.

Table VII. Minimum Breaking Loads for Transverse Tests of Cast Irons

Transverse test bar...	0.875-in Diam,	1.2-in. Diam,	2.0-in. Diam,
Span Length	12-in. Supports	18-in. Supports	24-in. Supports
Class No.	Breaking Load at Center, min, lb	Breaking Load at Center, min, lb	Breaking Load at Center, min, lb
20	900	1800	6,000
25	1025	2000	6,800
30	1150	2200	7,600
35	1275	2400	8,300
40	1400	2600	9,100
50	1675	3000	10,300
60	1925	3400	12,500

High-Strength Cast Irons

The term "high-strength cast iron" is usually employed to indicate cast irons that have a tensile strength greater than 40,000 psi. The term is rather vague and the ASTM classification (*see next section*) is more desirable.

During the past 15 years, considerable progress has been made in the manufacture of high-strength irons. Many foundries are now regularly producing cast iron that has a tensile strength greater than 50,000 psi. Tensile strengths greater than 70,000 psi may be obtained "as-cast".

The irons of higher strength are more difficult to produce than the irons of medium strength (30,000 to 35,000 psi) and the cost is higher. The machinability usually decreases with increased strength and hardness. Consequently these irons should not be specified except where they are needed and where the increased cost is justified.

The size, shape, distribution and quantity of graphite in cast iron greatly influence the strength. Cast irons higher

Table VIII. Test Bars Used for Gray Cast Iron

Controlling Section of Casting, in.	Test Bar	Nominal Diameter of Test Bar as Cast, in.
0.75 max	A	0.875
0.75 to 1.25	B	1.20
1.25 to 2.00	C	2.00

than 50,000 psi in tensile strength usually have total carbon contents of 3% or lower. It is possible to produce an iron of 50,000 psi minimum tensile strength by making suitable alloy additions to an iron of medium strength. In general, high-strength irons are produced by means of low carbon content or suitable alloying elements, or both.

Table V lists a few typical compositions of high-strength cast irons. Many other compositions have been used successfully.

High-strength irons may be produced in various melting furnaces—the cupola, air furnace and electric furnace. The high-strength irons require closer metallurgical control than the common grades of cast iron. Some high-strength irons are being produced by a combination of inoculation and the addition of alloying elements.

Classification of Gray Cast Irons

The most important classification of gray irons, from an engineering viewpoint, is that employed in the ASTM Specification A 48, where gray iron castings are classed according to the minimum tensile strengths of test bars, as listed in Table VI.

Table IX. Dimensions of Test Bars for Gray Cast Iron

Test Bar	Cast Diam, in.	Diam of Tensile Specimen in Reduced Section, in.	Cast Length, in.	Distance Between Supports in Transverse Test, in.
A	0.875	0.505	15	12
■	1.20	0.750	21	18
C	2.00	1.25	27	24

Transverse tests are optional, and the minimum breaking loads indicated in Table VII, are specified.

By agreement between manufacturer and purchaser, deflection values in the transverse test may be specified.

Three sizes of test bars are specified in order to obtain various cooling rates representative of various thicknesses of castings. If the manufacturer and purchaser agree on the controlling section of the casting, the corresponding test bar used is as listed in Table VIII.

For sections of castings larger than 2.00 in., test bar *C* may be used, or ■ larger test bar may be chosen by agreement between the manufacturer and the purchaser. The dimensions of the test bars are given in Table IX.

It is recognized that there is no definite factor for correlation between tensile and transverse strengths for various types of cast iron. Tables included in the specification give minimum values only.

It is the intent of these specifications to subordinate chemical composition to mechanical properties. By agree-

ment between the manufacturer and the purchaser, the quantities of any chemical elements in cast iron may be specified.

Other ASTM Specifications. The ASTM has developed other specifications for various types of gray iron castings, as indicated in Table X.

Other possible bases for the classification are composition, hardness, and structural features. From an engineering viewpoint there are many definite reasons for the classification employed in the ASTM Specification A 48. Other classifications may serve useful purposes. Advances in the technology of cast irons will undoubtedly encourage development of such classifications.

Wear of Gray Cast Iron*

The term "wear" has general rather than specific significance. "Wear" signifies a gradual removal or dissolution of a structure by the action of agents applied mechanically. Often mechanical wear and deterioration by corrosion act concurrently. The wearing agent may be a fluid (gas or liquid) or a solid.

With a perfect film of lubrication there can be no wear. When there is no lubricant, wear occurs, or when the lubricant film breaks down, or when the lubricant is imperfect and a carrier of wearing agents (abrasives).

In metal-to-metal wear caused by absence of lubricant, gray cast iron is very useful. Its highly heterogeneous structure effectively inhibits seizure and galling. It wears well not only against cast iron, but also in contact with many other alloys. Gray cast iron may cut much softer

Table X. Other ASTM Specifications for Gray Cast Iron

ASTM Designation	Title of Specification
A 44	Specification for Cast-Iron Pipe and Special Castings
A 126	Specification for Gray Iron Castings for Valves, Flanges and Pipe Fittings
A 142	Specification for Cast-Iron Culvert Pipe
A 159	Specification for Automotive Gray Iron Castings
A 278	Gray Iron Castings for Pressure-Containing Parts for Temperatures up to 650 F
A 190	Gray Iron Castings, Light Weight and Thin Sectioned
A 74	Cast-Iron Soil Pipe and Fittings

alloys, but usually works well with alloys as hard or harder than itself. This property of gray iron is among those responsible for the extensive use of this metal in machine tools, where fairly heavy pressures and imperfect lubrication occur; and in automobile cylinders, where temperature and partial breakdown of lubricant are influential factors. An example of metal-to-metal wear is in automobile brake drums. With hardness and lubrication equal, gray iron, with its graphitic structure, is less likely to seize than the nongraphitic ferrous alloys.

The properties in gray cast iron that are associated with low rate of wear are pearlitic matrix, suitable hardness, and high strength. If other factors are equal, an iron with a pearlitic matrix will resist wear better than one that contains free ferrite.

Comparison of dissimilar irons indicates that hardness is not always related directly to wear. However, for the same type or composition of cast iron, higher hardness frequently results in a much lower rate of wear.

Heat treatment or special additions of alloying elements that produce martensite and other hard matrices, improve resistance to wear. Usually some increase in resistance to metal-to-metal wear may be expected from such increased hardness. However, the major gain is from increased resistance to abrasive action (for example, of sand or grit). Localized heat treatment (flame hardening) has proved useful.

White cast irons are relatively resistant to abrasion. Some of the alloyed hard white irons are resistant not only to abrasive influences but also to galling and seizure.

Because there are many types of wear, it is virtually impossible to set up any laboratory test that will measure adequately the resistance of a material to wear in service. However, laboratory tests have been of value in helping to develop better materials for resisting wear. Some of the conclusions from laboratory tests are, as follows:

1 Resistance to wear increases with hardness of matrix
2 With increasing combined carbon content, the resistance to wear of gray irons increases rapidly up to 0.60% combined C and then slightly up to 0.85%.
3 Increasing silicon content decreases resistance to wear.

* See also the article "Wear of Metals", page 216.

Machinability of Gray Cast Iron

Cast irons have wide ranges of machinability. Ease in the machining of cast iron is usually inversely proportional to the strength. Machinability of various metals has been studied with reference to (1) tool life, (2) type of finish obtained, and (3) power required. Since differences in machinability affect tool life, these differences are of great practical importance.

The composition, structure, and mechanical properties of cast iron extend over a wide range. Depending on these factors, cast iron varies from one of the most readily machinable to one of the most unmachinable of ferrous materials. At one extreme of this range, the most readily machinable is cast iron that has been cast in permanent molds and completely annealed; at the other extreme is white or chilled cast iron and iron hardened by heat treatment without having been tempered. Annealed permanent mold cast iron has excellent machinability because the structure consists of iron that contains no combined carbon, and is broken up by a high percentage of finely divided flakes of graphite, besides being free from burned-in sand at the surface. Chilled or white iron is extremely difficult to machine because its structure is composed largely of hard iron carbide in massive form, unbroken by any flakes of free carbon. The machinability of a cast iron depends on the proportions and arrangement of the hard and soft microstructural components. Cast irons may be classified according to microstructure (and in order of decreasing ease of machinability) as follows:

1 Ferritic (free carbon and silicoferrite)
2 Pearlite-ferritic (free carbon, silicoferrite, and pearlite)
3 Pearlitic (free carbon and pearlite)
4 Mottled iron (pearlite, free carbon, and enough massive cementite to produce a mottled fracture)
5 White iron (pearlite and massive cementite)

With lower percentages of silicon or of both silicon and chromium, addition of nickel or copper or both permits the machining of irons of higher hardness than could be machined without this addition. The reason for the ability to machine irons of 225 to 250 Bhn in alloy compositions is that no massive carbides exist in the matrix. As soon as the plain cast iron exceeds a hardness of about 220 Bhn, it usually contains hard carbides, especially at the edges and corners of light castings.

Chromium is a carbide former, and if as much as 0.25% is added to a plain cast iron that is already at the limit of machinability, the iron may become difficult to machine. Therefore, where machinability is a factor, care should be taken in adding chromium. However, as much as 0.50% Cr may be added to many soft irons, with little danger of great difficulty in machining.

Although they are white irons structurally, the high-chromium irons (such as 35% Cr) are softer and more readily machinable than other white irons.

The austenitic gray irons have approximately the same machinability as regular gray irons of equivalent tensile strength. However, the austenitic irons are subject to surface work hardening when surface distortion is incurred without proper removal of metal. Use of improperly sharpened tools should be avoided, as well as rubbing action by tools or by chips. Shot-blasting also may cause complications.

The high-silicon (15% Si) cast irons are quite difficult to machine and, formerly, grinding was usually resorted to. The newer carbide tools may facilitate the machining of these irons.

Frequently molybdenum is used as an alloy addition in cast iron to increase strength and resistance to wear. Where molybdenum is used to increase hardness and strength without the formation of carbides, machinability

will usually be inversely proportional to the hardness and strength produced.

The surface condition of iron castings is most important in determining the machinability. Often castings are condemned as not machinable when the metal itself is quite machinable, and the true source of difficulty is the presence of burned-in sand on the casting. Where burned-in sand is present, any attempt to make light surface cuts will cause rapid failure of the tool. Cutting should be deep enough to ensure that the point of the tool is well below the surface of the casting. For this reason, too scant finish allowances may prove expensive with respect to replacement of tools.

The character of the surface finish obtainable in the machining of cast iron depends on the size of the graphite flakes and on the total amount of the graphite. A high-carbon, high-silicon cast iron with large graphite flakes will show a pitted surface when machined, because particles of metal are torn from between the graphite flakes.

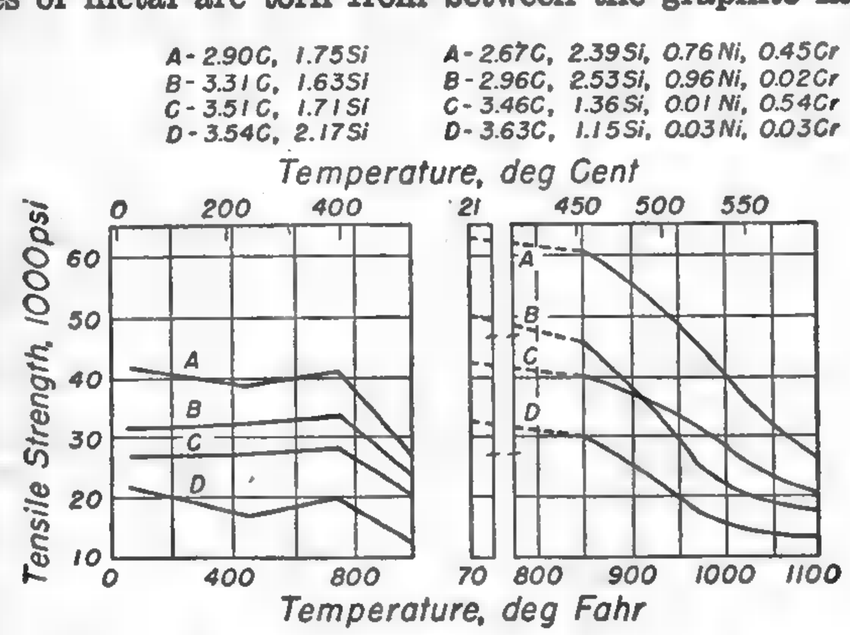


Fig. 16 Tensile strength of gray iron at elevated temperatures. Curves on right were obtained after heating the specimens 500 hours.

Heavy cuts taken on coarse-grained cast iron will exaggerate the pitted appearance by tearing out small particles of iron. Subsequent grinding may cover the coarse-grained appearance of the metal. The lower-carbon irons will have a much better appearance after machining.

Newer types of tool materials, such as tungsten carbide and other carbides, and newer machine-tool designs, permit removal of metal, in some operations, at rates that were not attainable with older tool materials and with older types of machine tools. The newer carbide tools are more resistant toward the abrasive action of small carbide particles, toward the hard phosphorus-rich component, steadite, and toward burned-in sand. The resistance of cast irons to deformation and fracture, usually does not produce high tool pressures. Cast iron is not likely to seize and crater on tool faces. Newer tools and newer machines permit considerably greater speed in the machining of many types of cast iron.

Effects of Temperature on Cast Iron

The effects of temperature on cast irons may be manifested in two ways: (1) effects on mechanical properties and (2) deterioration of the material because of certain structural and chemical changes that may occur at elevated temperature. In some instances, these factors are interrelated.

Codes based on ASME recommendations do not permit the use of cast iron for structures that contain pressure and must withstand more than 250-lb pressure for steam service at temperatures above 450 F. This regulation, based on certain findings by the ASME in 1909, may be unduly restrictive for many modern cast irons. A code proposed in California for unfired pressure vessels permits the use of suitable classes of iron for temperatures up to 650 F.

After having made a survey of service records of gray iron parts used at temperatures above 450 F, a special ASTM Committee concluded that irons of suitable strength and composition are adequate for use in parts that contain pressure, as high as 650 F (*see* ASTM Spec A 278).

In other applications requiring considerable mechanical strength, cast irons of suitable type are frequently used successfully at temperatures up to about 850 F. Above 850 F nearly all ordinary cast irons deteriorate enough to make questionable their utility for severe mechanical duty.

The ordinary lower-strength gray irons are much more susceptible to "growth" and other deteriorating influences than are the classes listed in ASTM Specification A 278. In general, higher percentages of carbon and of silicon increase the likelihood of deterioration. A lower carbon content and use of a carbide former, such as chromium, are relatively effective in promoting stability.

When judged by short-time tensile tests, cast irons show very slight changes in their original tensile strengths at temperatures up to 800 F. This is shown in Fig. 16.

The "creep" curves in Fig. 17 and 18 indicate that cast irons have marked resistance to creep at 600 F. Creep resistance is somewhat lower at 800 F. The curves marked "High Test" and "Nickel" irons in Fig. 17, represent irons that were stressed to 10,000 psi. The iron represented in Fig. 18 was stressed also at 10,000 psi at 600 F. All three irons referred to were in the 40,000-psi gray iron tensile class. The material marked "Gray Iron" was in the 30,000-psi tensile class, and was therefore stressed higher in proportion to its tensile strength than the others.

Endurance or "fatigue" limit is not greatly decreased up to 800 F, and the Brinell hardness number is unchanged. Apparently the compressive strength decreases appreciably within this range. Resistance to wear is one of the unique characteristics of gray irons, and evidently is maintained at moderately elevated temperature. The satisfactory resistance to wear of gray cast irons is demonstrated by their successful applications in cylinders and pistons for automotive, Diesel, and steam engines.

Because of low ductility and comparatively low resistance to impact, cast iron should not be employed to resist high dynamic stresses at elevated temperature, in applications where failure would result in hazard to life or equipment.

Heat-Resistant Cast Irons. The ability of cast irons to resist heat becomes an important factor when the metal

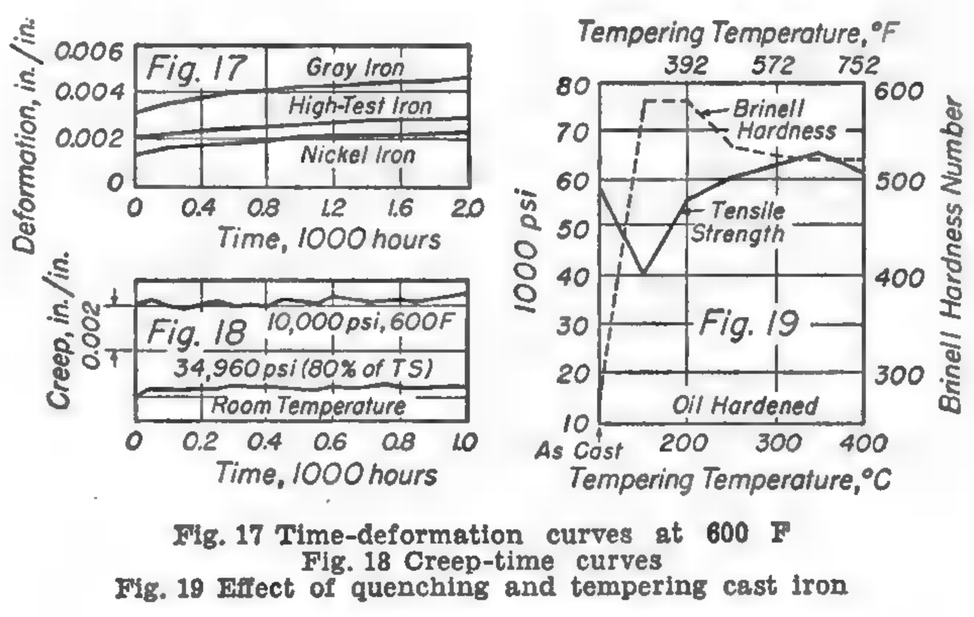


Fig. 17 Time-deformation curves at 600 F
Fig. 18 Creep-time curves
Fig. 19 Effect of quenching and tempering cast iron

is used in air at temperatures above 800 F, or in superheated steam even at lower temperatures. Resistance to heat depends largely on resistance to certain corrosive influences—chiefly oxidation, which may result in serious scaling; and on resistance to growth, which is a permanent increase in size.

In cast irons, growth results both from graphitization and from infiltration of corrosive gases. When ordinary gray iron is heated repeatedly to temperatures above 800 F (depending on the type of iron) it usually exhibits growth also. In a given iron, the amount of growth is ordinarily proportional to the maximum temperature reached, and to the number of heatings. Castings exhibiting growth are weak, misshapen and brittle. Some have been known to increase 50% in volume.

The irons most resistant to growth are found to have stable carbides and close dense grain structure with low total carbon content. Factors that stabilize carbides and produce close grain structure retard growth.

Among commercial engineering irons, those in the higher tensile classes with lower total carbon content are usually more resistant to growth and may be satisfactory in this respect up to about 850 F for long periods. Low silicon content is usually desirable and small percentages of chromium frequently prove advantageous. Under certain conditions, high phosphorus content retards growth somewhat, but because of various disadvantages, high-phosphorus irons are not widely favored for use at elevated temperature.

It is obvious that white irons, with carbon entirely in the combined form, are more resistant to growth than gray irons, which contain graphite flakes. Some white irons are limited in application because of their extreme hardness, brittleness and low strength.

Special irons have been developed that possess extraordinary resistance to growth. Perhaps the most widely used of these irons are the austenitic cast irons containing 14% Ni or more, about 5% Cu, and 1 to 4% Cr. Since they are austenitic, these irons do not expand and contract in passing through the range from 1325 to 1350 F, where the pearlitic transformation in regular gray irons occurs. Austenitic cast irons resist oxidation well, even up to 1500 F. When properly made, these irons are more ductile than regular gray irons.

The British have developed a special 6 to 8% Si cast iron, reported as offering excellent resistance to heat. The resistance of this material to deterioration results from (1) ■ completely ferritic matrix, since there is no carbide to decompose, (2) the raising of the transformation temperature above the working range, (3) fine-grained graphitic structure, and (4) a dense matrix. The effectiveness of very high silicon content is demonstrated by the following comparison of growth in two irons after ten heatings up to 1832 F.

Carbon, %	Silicon, %	Growth, %
2.1	3.7	0.923
2.5	6.1	—0.011

The high-silicon material known as Silal, must not be confused with so-called high-silicon gray irons, which rarely contain more than 3.0% Si. In true gray irons, silicon promotes growth, as mentioned previously.

Irons that contain 6 to 8% Si are rather brittle. Irons that contain 14% Si resist growth and scaling but are quite brittle.

The development of the stainless steels has emphasized that high percentages of chromium are accompanied by high resistance to oxidation. Also chromium stabilizes carbide, as mentioned above. It is therefore not surprising that high-chromium cast irons (15 to 35% Cr) resist both growth and scaling. In spite of a white iron structure, certain of these alloys can be made machinable, and they have been advocated for use at temperatures up to 1800 F.

Certain irons with moderate percentages of chromium (0.30 to 1.00%) have been found much more resistant to growth than unalloyed gray irons, and possibly somewhat more resistant to scaling.

Corrosion of Gray Cast Iron

Gray iron is more resistant to many types of corrosion than are carbon and low-alloy steels. Although gray iron forms a rust coating rather readily in moist atmospheres, continued penetration by rust and consequent disintegration are usually quite slow in comparison with similar effects in steel—perhaps because the underlying graphite flakes form a protective (and adherent) coating.

Cast-iron water pipe has given excellent service; cast-iron soil pipe usually lasts much longer than steel pipe.

Although different classes of gray iron do not vary much in resistance to a given water or soil, different waters and different soils vary quite widely in their corrosive effects. For example, some mine waters contain small percentages of sulfuric acid; others contain copper salts. In these and similar instances, highly alloyed metals may be required for resisting the corrosive solutions.

As with all common metals, the resistance to corrosion of gray iron is impaired when stray electric currents are encountered (chiefly in cities). These currents are particularly severe in their effects when contaminated water and the gray iron act as conductors so that an electrochemical cell is set up.

Many crude oils and refinery products are relatively noncorrosive toward gray iron. High-sulfur oils containing moisture, and some of the crude oils containing salt are rather corrosive toward gray iron and steel.

Gray irons are usefully resistant to most natural and artificial gases.

Although it is resistant to strong sulfuric acid (60 to 66 Bé), gray iron is attacked rapidly by more dilute sulfuric acid. Hot fuming sulfuric acid (oleum) attacks and disintegrates gray iron. This metal is fairly resistant to cold concentrated phosphoric acid and nitric acid but impurities such as hydrofluoric acid and chlorides, impair its resistance appreciably. Dilute phosphoric and nitric acids attack gray iron quite rapidly, and it is not resistant to hydrochloric (muriatic) acid in any concentration.

Gray iron resists many alkaline and caustic solutions—for example, sodium hydroxide, lye, soda ash and ammonia—and is not embrittled by exposure to strong hot caustics. Where some slight discoloration (caused by solution of traces of iron) is not objectionable, gray iron has proved very useful in contact with alkaline fluids employed in the manufacture of glass, sodium silicate, soap, viscose rayon, paper, dyestuffs, textiles, and in the treatment of petroleum and the like. In general, fine close-grained irons (as in the 30,000 to 40,000-psi tensile classes) are more resistant to corrosives than are the lower-strength, more open-grained types.

With few exceptions, small amounts of alloying elements are of little or no benefit in improving the resistance to corrosion of gray irons.

Increase in temperature of corrosive fluids usually increases their corrosive effects.

Frequently gray irons are used at elevated temperatures. At quite high temperatures (850 to 900 F and higher) ordinary gray irons are subject to growth. Above approximately 1100 F, gray irons usually scale rather rapidly, particularly where combustion gases contain corrosives, such as oxides of sulfur.

Several types of special cast iron have been developed to resist various types of corrosives. Prominent among these are the austenitic gray irons, known commercially as Ni Resist and Causul Metal. These are manufactured in several compositions, included within the following range: 14 to 30% Ni, 4 to 7% Cu, 0.5 to 3.5% Cr, and as much as 1.0% Mo. Some of these austenitic gray irons are usefully resistant to sulfuric acid, over the entire range, dilute to concentrated; however, they do not resist attack by hot oleum. They are resistant to the less severely corrosive solutions of hydrochloric (muriatic) acid and to some phosphoric acids but nitric acid attacks these austenitic gray irons severely. They have fair resistance to some organic acids, such as acetic, oleic, stearic and red oils. Types containing 18% Ni or more (with or without other alloying elements) are nearly immune to the corrosive effects of alkalies and caustics, weak or strong. However, these high-nickel types are subject to stress-corrosion in strong hot caustics. If stresses are kept lower than about 10,000 psi, austenitic gray irons of high nickel content can be used safely with boiling concentrated caustics.

Though not immune to rust, these irons form rust slowly, and do not disintegrate by rusting. They are resistant to scaling at elevated temperatures and are not subject to growth. In many services, austenitic irons are economical substitutes for some high-alloy stainless steels.

High-silicon irons (usually about 15% Si) resist many acids; exceptions are hydrofluoric acid and hot concentrated hydrochloric (muriatic) acid. High-silicon irons are useful for conditions where free "wet" chlorine is encountered, and are unusual in their effective resistance to solutions containing copper salts; however, their resistance to hot strong caustics is not good. Furthermore, high-silicon irons have the disadvantages of being hard and brittle, costly to manufacture, and so fragile that they require careful handling in installation and usage.

The high-chromium irons (usually 24 to 35% Cr) resist many corrosives, including nitric acids (except fuming)

and solutions containing free chlorine. High-chromium irons are nearly immune to rust and highly resistant to scaling; however, they are attacked by strong caustics.

Corrosive conditions vary so widely that specific recommendations should be made only after study of the particular problem. Therefore this discussion should be used only as a general guide.

Heat Treatment of Cast Iron

Cast iron may be compared with steel in its reaction to heat treatment. However, cast iron contains (1) graphite flakes and (2) substantially higher percentages of silicon, requiring a higher austenitizing temperature. The graphitizing effect of the silicon is so powerful that an unalloyed iron may become completely graphitized below the A_1 temperature during heating for austenitizing. Thus an unalloyed iron requires a longer interval at the quenching temperature for reabsorption of the desired carbon content in the austenite, because silicon retards the absorption of carbon in austenite.

The lower-silicon irons respond best to heat treatment, and successful hardening of cast iron requires close control both of silicon content and of temperature.

The heat treatment of cast iron may be divided broadly into four general classifications: stress relieving, annealing, quenching, and special heat treatments.

Relieving Residual Stresses. The heat treatment that relieves residual stresses is commonly called "aging", "normalizing" or "mild annealing"; the term "stress relieving" is more accurately descriptive. This treatment can be accomplished by heating the cast iron to between 800 and 1100 F, holding at temperature from 30 min to 5 hr, and cooling slowly in the furnace. This treatment will cause only a slight decrease in hardness, very little decomposition of cementite, and only a slight change in the strength of the metal at room temperature.

Annealing. Sometimes it is desirable to soften the casting in order to facilitate machining. Frequently the production heat treatment of cast iron is performed for this purpose. The temperature range most commonly used is 1400 to 1500 F, although temperatures as low as 1200 to 1250 F have been used satisfactorily. Highly alloyed irons are sometimes annealed at temperatures as high as 1800 F. In all annealing, care should be taken to prevent oxidation of the casting.

In general, softening for machinability is attended by a decrease in strength and in the amount of combined carbon, and by an increase in graphite content. Irons that contain carbide-forming alloying elements, such as chromium, are more resistant to softening than the ordinary gray iron, and therefore must be annealed at considerably higher temperatures.

Completely annealed ordinary cast iron may have a Brinell hardness number from 120 to 130, whereas completely annealed alloy irons may have a Brinell hardness number from 130 to 180, depending on the composition.

Quenching and Tempering. In order to increase the hardness and resistance to wear, cast iron is quenched from above the transformation temperature range. The addition of alloying elements, such as chromium, molybdenum, nickel and vanadium, has a marked effect on the response to heat treatment. It is not customary to quench the common soft gray irons, although they may be hardened to a martensitic structure. Such soft irons would require higher hardening temperatures and longer time at temperature in order to obtain the desired carbon content in the austenite.

For optimum results, the graphite flakes should be small and well distributed; the matrix should be pearlitic or sorbitic. The combined carbon should be from 0.50 to 0.80%. The hardness increases with increasing rate of cooling from above the transformation temperature. After the hardening treatment, softening proceeds uniformly as the tempering temperature is increased above 350 F. The strength and impact resistance are distinctly improved by tempering.

The material as quenched usually has lower strength than the material as cast. The deterioration in strength is restored by tempering (Fig. 19). Thus by suitable hardening and tempering, the strength may be improved appreciably.

The castings should be heated uniformly to the quenching temperature. In common practice, the quenching temperature range is from 1500 to 1600 F. The quenching medium commonly used is oil; however, water is used to a limited extent and some castings may be quenched in air.

The castings are usually rough machined before hardening and are finished by grinding. Growth occurs during heat treatment, so allowance must be made for this in leaving stock for finish grinding.

Cylinder liners for use in heavy-duty internal combustion engines, have been heat treated to secure a marked increase in hardness and resistance to wear. The range of hardness after heat treatment is from 375 to 500 Bhn.

Special Heat Treatments. *Flame Hardening.** Flame hardening is being used where a hardened surface is desired for resistance to wear. The treatment is particularly applicable where only certain portions of a casting are to be hardened, as on a camshaft. In flame hardening, the time interval is short, so the structure of the casting should be of eutectoid composition in order to secure maximum hardness.

Induction Hardening. Gray iron castings may be heated by induction methods, similar to flame hardening in application.

Austempering. This is a trade name for a patented heat treating process that is applied to gray iron castings for the purpose of increasing strength and resistance to wear. The castings are heated between 1500 and 1600 F, and then are quenched in a salt bath maintained at 500 to 550 F. It is usually necessary to leave the castings in the hot bath for a period of 15 min to 1 hr, depending on the composition of the casting and the size of the section.

Nitriding. Castings may be nitrided in order to increase resistance to wear. The nitriding process consists in subjecting the castings to temperatures from 950 to 1100 F during contact with anhydrous ammonia gas, for a period of 20 to 90 hr. Irons of special composition must be used for the nitriding process.

Welding of Cast Iron. Welding is used for the salvage of castings and also for the repair of castings that have failed in service. Usually only minor welds are permitted for the salvage of gray iron castings. Some purchasers of gray iron castings permit no welding.

For information concerning the welding of cast iron see page 371 in this Handbook.

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* See also the article "Flame Hardening", page 647.

Malleable Iron

By H. A. Schwartz*

MALLEABLE IRON consists almost entirely of ferrite and temper carbon. Temper carbon is graphite in a nodular form instead of in the flaky form in which it exists in gray iron. The reason for the nodular form is that the graphite was separated from cementite (Fe_3C) while the alloy was solid, thus preventing the growth of flakes.

Melting Furnaces. Malleable iron, as made to meet ASTM Specification A 47-33, is usually melted in the reverberatory furnace or in the electric furnace, either of which may be charged with solid metal or liquid metal from the cupola. In some instances a mixture of cupola metal and Bessemer steel is charged, but this process, called "triplexing", is no longer much used. Charging with cupola metal is called "duplexing". A limited amount of malleable iron is melted in open hearth furnaces, and the solid charge is sometimes melted in a modified type of reverberatory furnace that consists of a rotating cylindrical drum. These rotating furnaces have the advantage that the charge is brought in contact with the brickwork, which has just been superheated by contact with the flame; thus the metal is heated while cooling the bricks. Such a furnace is capable of making metal without requiring such high refractoriness of the lining as is required in ordinary reverberatory furnaces.

The fuel of reverberatory furnaces is ordinarily pulverized coal, though a few furnaces are still hand-fired, and some furnaces burn oil.

Cupola malleable iron, as made to meet ASTM Specification A 197-39, is used largely for the manufacture of pipe fittings and similar parts where fluidity and soundness of the casting are more important than high tensile strength or elongation. The cupola is not adapted to the making of low-carbon iron as required for the maximum of strength and ductility.

The advantage of duplexing methods is that they furnish a continuous stream of metal. This is particularly desirable in the mechanized foundries where molds are poured on conveyers. Duplexing is somewhat better adapted to the making of moderately high-carbon iron than of low-carbon iron, although it has been applied for producing low-carbon iron. Where quite low carbon content is wanted, batch-type furnaces of the reverberatory or rotating types, or open hearth or electric furnaces are preferable.

Where batch-type reverberatory furnaces are used, the charge consists of pig iron, steel, malleable scrap and "sprue", that is, gates, runners and defectives from previous melts. The ingredients are so proportioned that when the metal is melted and heated to pouring temperature, it contains as nearly as possible the desired percentage of carbon and contains nearly the percentage of silicon and manganese required in the finished product, but not more. For the content of silicon and manganese, ferro-alloys are used for making final adjustments after chemical analysis of the metal.

It is impracticable to produce from a cupola, metal hot enough to pour castings and as low in carbon as is generally desired. It is therefore common to operate an air furnace with the cupola in a duplex operation. Using charges of pig iron, steel and sprue, the cupola is operated to produce metal of about 2.75 to 3.00% C. The flame conditions and the length of time when the metal is in the air furnace are so arranged as to produce the desired carbon content while the metal is being heated to the temperature needed. Silicon and manganese are added at intervals to make whatever small adjustments are required.

Composition of Malleable Iron. The molten metal must have such a composition that when cast at the desired temperature into castings of the required size, it will be free from graphitic carbon so that flakes will not be present. The metal must also be capable of relatively easy graphitization to convert it into malleable iron. For various purposes the carbon may range from 2 to 3%, and the silicon from 1.50 to 0.80%. By the use of graphite-free melting stock, high melting temperatures and quick freezing, it is possible to increase the silicon in low-carbon iron to as much as 1.50 or 1.60%, or even higher, producing an easily graphitizable iron at some risk of forming primary graphite in large castings or with cold pouring. The manganese is generally held at 1.7 times the sulfur, plus an excess of from 0.10 to 0.15%. As long as this ratio is maintained, the sulfur may be as high as 0.16 or 0.17% without detriment. In much of the metal produced by duplexing, the sulfur content is as high as 0.20% without causing trouble. The phosphorus content may be 0.20% or less. If the percentage of phosphorus is too high, especially in relation to the silicon, the iron will be subject to intergranular embrittlement when cooled quickly from the "blue heat" range near 900 F. The difficulty can be overcome by quenching from 1200 F in water.

Annealing Malleable Iron. The heat treatment of malleable iron is executed either in stationary batch-type furnaces, which are large brick chambers heated by flame passing through them, or in car-bottom furnaces, which resemble the stationary batch type, except that the furnace bottom can be rolled in and out on car wheels, permitting the charging or discharging of a hot furnace.

In such furnaces, the castings are protected from con-

Table I. Classification of Industries, With Condensed List of Products in Which Malleable Castings Are Used[a]

Agricultural Implements	Plows, tractors, harrows, reapers, mowers, binders, cultivators, rakes, spreaders, dairy and poultry equipment, presses, tools, pumps, wagons, fence parts
Automobiles	Parts for frame, wheels, springs, brakes, motor transmission, axles, steering gear, body, accessories
Boilers, Tanks, and Engines	Boilers, tanks, fittings, engine parts, outboard motors, Diesel engines
Building Equipment	Hardware for windows, doors, garage equipment, awning hardware
Conveyer and Elevator Equipment	Chains, buckets, pulleys, rollers, cranes, hoists, fittings
Electrical and Industrial Power Equipment	Motor and generator parts, pumps, stokers, electric locomotives and tractors, steam specialties, outlet and switch boxes
Hardware and Small Tools	Pneumatic and portable tools, miscellaneous tools, saddlery, hardware, table and kitchen utensils
Household Appliances	Stoves, sewing machines, refrigerators, washing and ironing machines, vacuum cleaners, dishwashing machines, oil burners, electric fans and toasters, radios
Machine Tools	Lathes, planers, shapers, grinders, screw machines, gear cutters, drills
Machinery for Special Uses	Textile, cement, rubber, shoe, mining and quarrying, grinding, forging, foundry, bakery, woodworking, bottling, ice, laundry industries
Marine Equipment	Anchors, chains, capstans, fastenings, towing bits, hardware
Metal Furniture and Fixtures	Stoves, beds, desks, filing cabinets, shelving, hotel supply equipment
Municipal, State and Public Service	Manhole covers, posts, guardrail equipment, highway markers, transmission and telephone-line fittings, electric railway fittings
Pipe Fittings and Plumbing Supplies	Elbows, unions, reducers, flanges, valves, bolts, nuts
Railroads	Wide variety of parts for construction of locomotives, freight and passenger cars; guardrails, miscellaneous
Road and Contractor's Machinery	Rollers, excavators, cranes, hoists, tractors, graders, scarifiers, mixers, pavers
Toys and Specialties	Sleds, wagons, automobiles, bicycles, carriages, gun parts

According to the Department of Commerce, there are about 150 plants in the industry, with 1,350,000 tons estimated annual capacity.

(a) Reprinted from the "Symposium on Malleable Iron Castings", published by the AFA and ASTM

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Prepared for the Subcommittee on Malleable Iron, with membership as follows: H. A. Schwartz, *Chairman;* H. Bornstein (Deere & Company) and James H. Lansing (Malleable Founders' Society)

tact with the flame by being packed in cast-iron pots. In order to prevent warpage of castings at high temperature, these box-shaped pots may have the space between the castings filled by some refractory material to furnish support. The packing is apart from the metallurgy except occasionally when decarburization at the surface is desired; then iron oxide is added to the packing. It is also common to anneal large castings in brick muffles, heated externally by flame.

Instead of intermittent or batch-type furnaces, kilns are often employed, through which the stock passes continuously. Such furnaces may be divided into two classes.

In one, a train of cars is pushed through a tunnel in which various sections are kept at various temperatures, so that with a predetermined rate of travel, the time-temperature relations are those desired. No effort is made to control furnace atmospheres; the composition is that of the products of combustion of the fuel (usually oil or gas) diluted with infiltrated air. The castings are packed in pots, as in stationary furnaces. Such units are especially suited for rather large daily production.

Alternatively, castings placed in relatively thin layers in trays, may be passed by a pusher mechanism through a suitably heated tunnel, or may be moved through by the well-known "walking beam" mechanism, which picks up the stock, advances it and sets it down. Another alternative is a furnace with a floor that consists of a traveling conveyer. Castings in such furnaces are usually not packed in containers but the composition of the furnace atmosphere is controlled.

Since the control of atmosphere is not feasible in furnaces through which the products of combustion pass, furnaces of the latter type are heated electrically or by "radiant tubes". These are long tubes made of an alloy that resists oxidation and within which the fuel—usually gas, but sometimes oil—is burned. To be effective in transmitting heat, the radiant tube must be operated at temperatures considerably above those of the metal charge.

In batch-type furnaces, the charge is raised on a car, which seals itself hermetically against the furnace structure. Resistance ribbon heats the units inside the furnace. Batch-type furnaces may also be of the "bell" type, in which a box-shaped furnace heated by resistance coils, or more commonly by radiant tubes, is lowered over a charge placed on a suitable platform. The heat treating time is governed by the composition of the metal and some other details of its manufacture, and still more by the design of the furnace, which determines how fast the furnace temperature can be increased or decreased without producing excessive temperature gradients.

In large stationary batch-type furnaces, it may take 45 hours to heat the metal to 1500 F, 50 hours for higher temperatures, to the maximum of 1650 or 1700 F, and 60 hours to cool. It is desirable to cool the metal through the transformation range at less than 10 °F per hour in the interest of producing pearlite-free material with a minimum cycle of annealing.

The influence of the furnace atmosphere is also connected with annealing time. Atmospheres containing hydrogen should be avoided since they retard annealing. Too much CO in proportion to CO_2 is also objectionable. In practice, the CO should exceed the CO_2 but the amount should not be more than twice that of CO_2, in order to obtain free annealing and to avoid scale. Furnace atmospheres are controlled by introducing partially burned fuel, usually gas, at a rate sufficient to maintain the desired composition against the tendency of the gas to come to equilibrium with the carbon of the metal.

The elements silicon, titanium, aluminum, zirconium, uranium, and especially boron—the last in amounts of 0.001% B—accelerate annealing vigorously. Nickel and copper are slight accelerators. Chromium is an energetic retarder, as is boron in amounts greater than 0.1%. Manganese is also a retarder, and vanadium and molybdenum act similarly. Tungsten is a slight retarder, and the nonmetals sulfur, selenium and tellurium inhibit graphitization by forming films through which carbon cannot migrate.

Especially if packing is not used to support the metal, stationary batch-type furnaces, if not too large, can be operated in a cycle of approximately 70 hours. Furnaces of the continuous type can complete a cycle in approximately 40 hours, and even shorter cycles have been reported. It has been asserted that the high-silicon types of malleable iron can be annealed in 15 to 30 hours. In most instances, furnace design is responsible for these differences.

To permit short annealing times, the furnaces must be small and mechanically operated. Thus the cost may increase, a disadvantage since the annealing cycle is dictated by economic considerations.

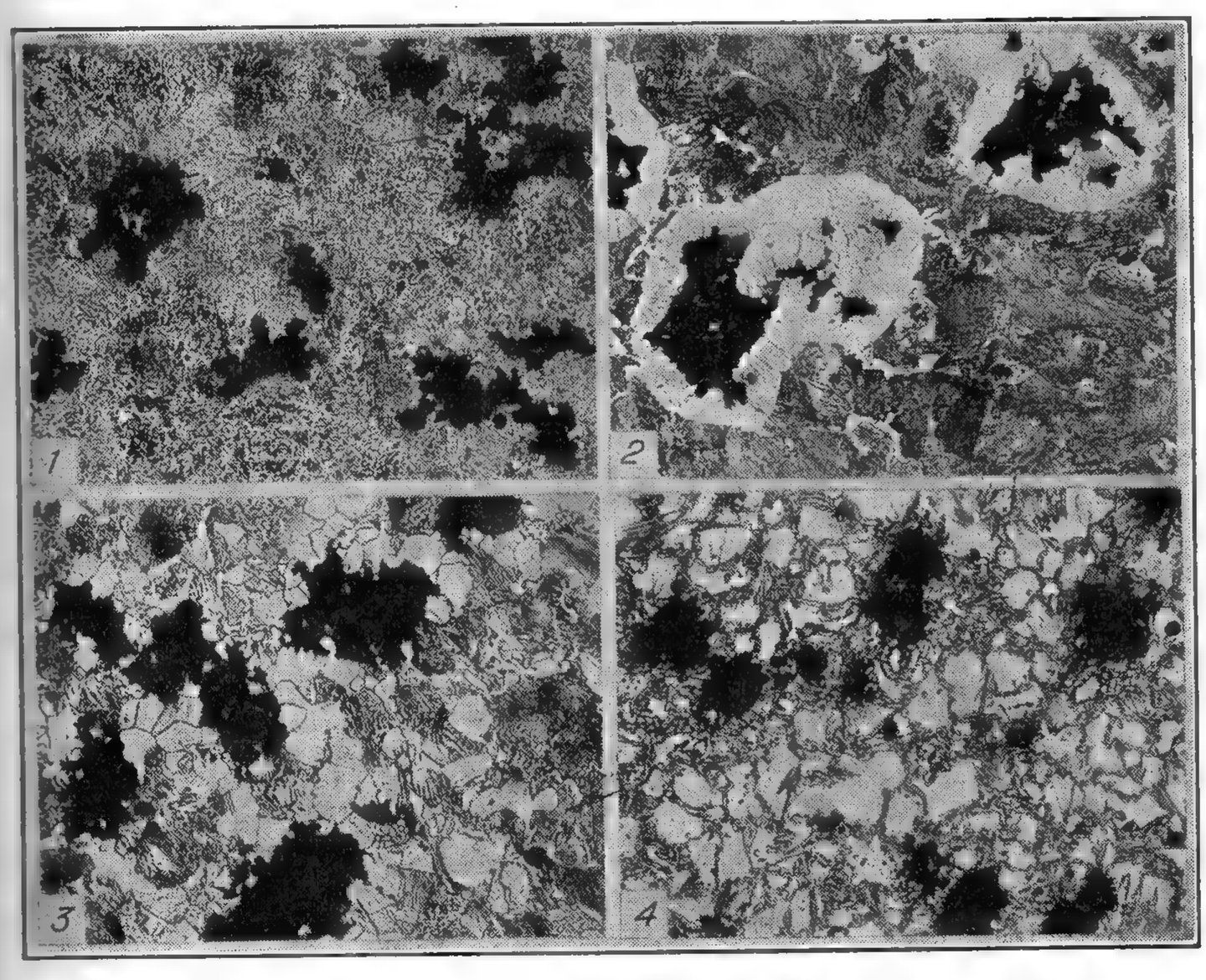

Fig. 1 Temper carbon in spheroidized matrix produced by controlled rapid cooling of high-manganese (about 0.75%) white irons completely graphitized to equilibrium above A_1, followed by spheroidizing (× 100, nital)

Fig. 2 Bull's-eye malleable iron produced by normal graphitizing cycle applied to high-manganese (about 0.70%) hard irons (× 100, nital)

Fig. 3 Granular ferrite and pearlite in high-silicon and chromium white iron with normal graphitizing heat treatment (× 100, nital)

Fig. 4 Sorbitic structure produced at grain boundaries by reheating malleable iron just above A_1, then quenching and tempering (× 100, nital)

Metallurgical Principles. The fundamental purpose in making malleable iron is to produce a casting entirely free from flaky graphite, and having a carbon content high enough for the desired fluidity and machinability, as well as low enough for the desired tensile properties. When once this iron has been produced, the purpose of the annealing cycle is to hold it at a temperature well above the transformation range. At this temperature graphite will crystallize out and cementite will dissolve until nothing remains but graphite and solid solution.

Table II. Physical and Mechanical Properties of Malleable Iron[a]

	For Classes of Iron to Meet ASTM Specification A 47-33, Grade 35018		For Classes of Iron to Meet ASTM Specification A 47-33, Grade 32510	
	Range	Most Probable Value	Range	Most Probable Value
Physical Properties				
Specific gravity	7.20 to 7.45	.....	7.34 to 7.25	.....
Shrinkage allowance, in. per ft	.....	3/16	.....	3/16
Coefficient of thermal expansion, per °C	.....	0.000012	.....	0.000012
per °F	.....	0.0000066	.....	0.0000066
Specific heat, cal per g per °C average between 20 and 100 C	.....	0.122	.....	0.122
Mechanical Properties				
Tensile strength, psi	53,000 to 60,000	55,000	50,000 to 52,000	52,000
Yield point, psi	35,000 to 40,000	36,500	32,500 to 35,000	34,000
Elongation in 2 in., %	18 to 25	20	10 to 18	12½
Modulus of elasticity in tension, psi	.....	25,000,000	.....	25,000,000
Poisson's ratio	.....	0.17	.....	0.17
Ultimate shearing strength, psi	.....	48,000	.....	48,000
Yield point in shear, psi	.....	23,000	.....	23,000
Modulus of elasticity, psi	.....	12,500,000	.....	12,500,000
Modulus of rupture in torsion, psi	.....	58,000	.....	58,000
Brinell hardness number	.....	110 to 145	110 to 135	.....
Charpy impact value, ft-lb ("keyhole" notch 0.04-in. radius at bottom, 0.394-in. sq bar)	.....	.....	.....	7
V-notch, 0.197-in. depth of notch	.....	.....	10 to 14	12
Izod impact value, ft-lb (using V-notch 0.394-in. square bar, 0.079-in. depth of notch)	.....	16	10 to 14	12
Fatigue endurance limit,[b] psi	22,000 to 30,500	27,000	25,000 to 26,500	25,500
Endurance ratio (endurance limit to ultimate strength)[b]	0.43 to 0.54	0.50	.....	0.50
Electrical resistivity, microhm-cm	.....	30	.....	32

(a) Reprinted from "Cast Metals Handbook", published by the American Foundrymen's Association
(b) The longer range of values for grade 35018 material is in part the result of more frequent investigations.
NOTE. Cupola malleable iron, as made to conform with ASTM Specification A 197-39, has a tensile strength of 40,000 psi min, a yield strength of 30,000 psi min, and an elongation in 2 in. of 5% min.

Since gamma iron will dissolve carbon at these temperatures, the process cannot be completed above the transformation range. Pearlite will change into ferrite and graphite by a mechanism the same as that mentioned above, but the reaction by which ferrite and carbon form from austenite in the region between A_1 stable and A_1 metastable is so much faster that it is desirable to hold iron in this range rather than below A_1. This is usually accomplished by slow cooling. Malleable iron is used for castings that are required to withstand shock, to have considerable ductility, and to be easily machinable.

A condensed list of uses is given in Table I.

The properties of two standard grades of malleable iron are shown in Table II. Minimum tensile properties of cupola malleable iron are listed also.

The only alloying elements that are used to a considerable extent in the malleable iron industry are copper and molybdenum, best used together. Copper used alone, especially after precipitation hardening, gives a decided increase in tensile strength—at slight sacrifice of ductility—and seems to be more effective in high-carbon iron than in low-carbon iron. When copper and molybdenum are used together, it is customary to add about 0.50% of each, or perhaps a little more copper. Such additions to malleable iron of the 35018 grade, may increase the tensile strength by as much as 8000 psi while reducing the elongation 5 or 6%.

Table III. Uses of Pearlitic Malleable Iron

Automobiles	Motorcycle parts, axle and differential housings, camshafts and crankshafts
Conveyer equipment	Gears, chain links, sprockets, elevator brackets
Machine parts	Rolls, pumps, nozzles, cams, rocker arms, universal joints
Ordnance	Gun mounts, pistol parts, tank parts
Tools	Wrenches, hammers, clamps, shears

Pearlitic Malleable Iron. This series of alloys contains combined carbon in various forms in the matrix, thus differing from normal malleable iron, in which the matrix is ferritic. Pearlitic malleable iron is produced either by stopping the heat treatment before the combined carbon has all been transformed to graphite or by reheating normal malleable iron above the transformation range. Rather than to stop the heat treatment, it is sometimes more convenient to add a retarding alloy, usually manganese, in an amount about 0.5% greater than that for normal malleable of similar composition, and then to carry on a normal annealing cycle. Especially when a sufficient amount of a retarding element is present to prevent rapid graphitizing, the microstructure of the matrix can be given almost any of the characteristics found in the heat treated steels, by treatments that parallel those for such steels. The pearlitic malleable irons that seem to have been most generally useful, are those in which the cementite is present as spheroids, whether the structure is produced by air-cooling high-manganese alloys or by cooling normal malleable iron more rapidly. In either instance a spheroidizing treatment should follow. Microstructures of various types of pearlitic malleable are shown in the micrographs of Fig. 1 to 4.

Depending on the amount of combined carbon retained and the form of its distribution, the properties of the resulting product will vary. The tensile and yield strengths are always higher than for normal malleable iron, and the ductility and impact resistance are lower. The machinability also is decreased. The fatigue ratio is probably near 0.50. The tensile strength may be as high as 90,000 or 100,000 psi, and the elongation as low as 2 or 3%. As the tensile strength decreases, the elongation increases.

Chromium and aluminum have been added to certain pearlitic malleable irons in order to make nitriding feasible.

Uses of Pearlitic Malleable Iron. The uses of pearlitic malleable iron are manifold, since the material can be made to have a great range of properties. For example, some forms are rigid and resist deformation and others deform considerably before breaking.

Table III gives a summary.

Pearlitic malleable iron is especially well suited to induction hardening. Since temper carbon is rather widely dispersed in malleable iron, an appreciable period of time must be allowed for diffusion to obtain uniform hardness. This difficulty can be overcome when it is possible to use pearlitic malleable iron for the part. The finely laminated, and still more finely spheroidized carbides are dispersed so uniformly that they will dissolve quickly and easily, resulting in a correspondingly rapid saturation of the austenite with carbon. The finely divided carbide of pearlitic malleable iron dissolves readily in gamma iron in the brief periods of time used in local induction hardening, and produces great uniformity of hardness and a very hard surface, since it can be made to contain approximately the amount of combined carbon that will produce martensite of maximum hardness.

Steel Castings

By Charles W. Briggs*

CAST steel is steel that is poured into metal or refractory molds and allowed to solidify. This steel may be used commercially in the cast form (steel castings) or it may be further processed by hot or cold working to become wrought steel. A steel casting is a steel object that has been cast initially into the shape desired for the finished product and does not require mechanical working. The many types of steels produced as wrought steel can all be made as steel castings.

Classes. There are five classes of commercial steel castings:

1 Low-carbon steels (carbon content less than 0.20%)
2 Medium-carbon steels (0.20 to 0.50% C)
3 Higher-carbon steels (carbon content above 0.50%)
4 Low-alloy steels (total alloy content less than 8%)
5 High-alloy steels (total alloy content more than 8%)

Carbon Steel Castings. Carbon steel castings contain less than 1.70% C, along with other elements normally present. These elements vary somewhat but are usually present in amounts ranging as follows: 0.50 to 1.00% Mn, 0.20 to 0.70% Si, 0.05% P max and 0.06% S max. In addition, carbon steel castings contain small percentages of other elements, which are not added but are residual in the scrap steel that constitutes a portion of the melting charge.

The medium-carbon class, comprising the bulk of the steel casting output, is the regular grade product. Low-carbon and high-carbon grades have been developed for steel castings so that useful properties imparted by high and low carbon contents may be available for specialized products and uses.

Alloy Steel Castings. A steel casting is considered to be an alloy steel casting if the alloying elements, either residual or added, are present in quantities greater than those listed as follows: 1.00% Mn, 0.70% Si, 0.50% Ni, 0.50% Cu, 0.25% Cr, 0.10% Mo, 0.05% V, 0.05% W, 0.05% Al, 0.05% Ti. Limitations of phosphorus and sulfur contents apply to cast alloy steels as they do to cast carbon steels, unless they are specified for the purpose of producing an alloying effect.

The low-alloy casting class represents a sizable portion of the total steel casting production. High-alloy steel castings of the types that resist heat and corrosion and of the austenitic manganese type are discussed in detail on pages 549, 570 and 526 of this Handbook.

Distribution of Product. The normal distribution of steel castings by major classification is as follows:

Application	Per Cent
Railroad and transportation castings	35
Machinery castings	25
Rolling mill castings	15
Material handling equipment	8
Valves and pressure fittings	7
Road and building construction	5
Miscellaneous	5

In a normal year the steel casting industry ships approximately a million net tons of castings. In 1943, the peak year for war production, the shipments were 2,700,000 net tons of steel castings.

Range of Weight. Steel castings range from tiny ones weighing only a few ounces to others weighing many tons. The largest steel casting on record had a finished weight of 230 tons. Steel castings are being made in every conceivable size and shape; some have sections 2 ft thick while other measure less than ¼ in.

Manufacture of Steel Castings. Steel castings are being manufactured by approximately 300 companies throughout the United States. In some foundries (for example, in those producing railroad and transportation castings) manufacturing processes are highly mechanized, whereas in jobbing foundries the production scheme is usually fairly flexible and easily adaptable to the requirement of varied products. Since there is considerable diversity in the manufacturing process, it is preferable to describe only those general activities that are common to all steel foundries. It should be pointed out that one method of melting steel, or a particular molding method used by one manufacturer may or may not be duplicated by another manufacturer. These differences in manufacturing processes depend on the nature of the product of each foundry.

Steel Melting Practice. Steel for steel castings is produced commercially by almost all the currently used processes of making steel, namely: open hearth (acid and basic), electric arc (acid and basic), converter (side-blown, acid), and electric induction.

The manufacturing methods used by any one manufacturer depend on certain general conditions and circumstances. The choice of the steelmaking method to be employed depends on the policy of the organization concerning plant capacity, size and intricacy of the castings, type of steel to be produced, operation desired (acid or basic), raw materials available and the prices thereof, fuel costs, and capital to be invested. More than one steelmaking method may be employed in a foundry; in fact, in some foundries as many as four processes are used.

Details concerning the various processes listed above are available in the sections of this Handbook that deal with steelmaking processes, pages 315 to 342. The methods described are based primarily on ingot production, except for the acid electric-arc and high-frequency practices, which apply directly to the production of steel castings. The primary differences in the production of steel for castings and steel for ingots are that steel for castings must always be dead-killed and must have a high degree of fluidity.

A short, fast melting cycle is normally used, since high fluidity has become associated with short refining times, and steel of excellent fluidity is always desired in the running of castings. For information concerning the fluidity of steel, see the article on page 199 in this Handbook.

The steels are deoxidized with ferrosilicon and ferromanganese in such quantities that the residual silicon content will be between 0.35 and 0.60%, and the manganese content will be between 0.60 and 0.85%. If green sand molds are to be used, special deoxidizers are always added to the ladle. The deoxidizers may be aluminum, calcium-silicon, ferrotitanium, or a combination of these or other prepared alloys, added to prevent the evolution of gases during the solidification of the metal in the molds.

Approximately 75 to 100 grades of carbon and alloy cast steels are being made by the industry.

Molding Practice. Most steel castings are produced in synthetic molding sands. These sands are prepared by obtaining a classified silica sand, of either the washed or the crude variety, to which is added a refractory clay such as bentonite or a fire clay, in quantities from 2 to 6%. An addition of an organic binder (approximately 1%) is made in order to assist in developing proper molding qualities and sand properties. These additions are mulled together with water (from 2 to 6%) to obtain the desired plasticity. Sands for cores are prepared in much the same way, except that usually core oil is substituted in part for the clay addition. Most cores are oven-baked or dried; however, a number of green sand cores are used.

Molding practices are classified according to the manner in which the mold is prepared for pouring. These practices are (1) green sand, (2) skin dried, (3) dried, (4) core assembly, (5) Chamotte, (6) cement-sand practice and (7) investment molding. The green sand practice consists of pouring steel into molds shortly after they have been made, with no additional heat processing of the mold except possibly drying in air. The skin-dried practice consists of drying the surface of the mold cavity by flame torches before pouring the mold. The dried-sand practice consists of heating the green sand molds from 200 to 600 F in ovens until the moisture content is low. The molds are then returned to the pouring floor and the steel is poured into them either while they are hot or after they have reached room

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temperature. The practice for core assembly consists of assembling a mold from green or baked cores or both.

The Chamotte practice consists of preparing molds from a ground and classified calcined clay to which is added raw clay and water for bonding purposes. Molds prepared from this mixture are dried by torch or in an oven. The cement-sand practice consists of bonding silica sand with about 10% cement and 5% moisture and permitting the cement to set by drying in air before the mold is poured. In the investment molding process for steel castings, the wax pattern is surrounded with a material consisting of a refractory aggregate (such as silica flour) and a binder. After the investment has hardened, the mold is heated and the wax melts and is poured out. The mold is then ready for the steel to be poured into it.

The molding practice used by a foundry will depend on the shape, size and type of castings to be produced. Selection of a suitable molding practice depends on the experience, equipment and handling methods possessed by the foundry. Molds are rammed either with hand tools or pneumatic rammers, or on various molding machines of the jolt-and-squeeze type as well as with sand slingers. Many kinds of automatic and semiautomatic equipment are used for handling sand and molds while the molds are being prepared and placed in position for pouring.

Gating and Feeding. Considerable importance is attached to the manner in which molten steel enters a mold. Steel foundrymen have long been aware that to be satisfactorily made a casting must be properly gated. The primary purpose of the gate system is to furnish a way for the steel to enter the mold. A gate has other necessary functions also —as a venting system for the removal of gases from the mold and as a riser to furnish liquid metal to the casting.

In pouring a mold, the aims are as follows: (1) to fill the mold cavity completely, (2) to avoid deterioration of the mold by the liquid metal, and (3) to establish proper gradients of temperature in the mold so that the gate will not be responsible for the occurrence of contraction cavities in the casting.

While steel is solidifying, it contracts in volume. If no attention were given to this fundamental characteristic in the process of molding, the casting would be internally defective, because the metal solidifies from the outside inward toward the center of the section. To forestall the formation of cavities, reservoirs of molten metal are provided at suitable locations. These reservoirs, which are not a part of the casting but are essential to the integrity of the casting, are called "risers" or "feed heads". When the casting is cleaned, the risers are removed and the casting is ground smooth to the pattern contour.

The shape, size and position of the riser must be controlled effectively. A riser must meet five primary requirements: (1) It must completely cover the casting section that requires feeding. (2) The volume of the riser must be sufficient to compensate for the contraction of metal within the casting. (3) The fluidity of the metal in the riser must be maintained so that the metal can flow from the riser and penetrate to the last contraction cavity. (4) The riser should be effective in establishing a pronounced temperature gradient within the casting so that the casting will solidify directionally toward the riser. (5) The riser must be the last portion of the casting to solidify.

Finishing Operations. After the steel castings have been poured, have solidified and have been allowed to cool somewhat in the molds, they are shaken out of the molds and the gates and risers are removed by sledging, shearing, torch burning or cold sawing. A grinding operation is then required for the removal of pads, fins, lumps and metal added to make the design castable.

Blast cleaning is performed to remove cores effectively, to clean away adhering sand and scale, and to improve the appearance of the castings. Blasting operations may precede heat treating, follow heat treating, or both.

Heat Treating. Steel castings are heat treated by all the various methods used for wrought steel. Depending on the requirements of service and property specifications, steel castings may be (1) annealed, (2) normalized, (3) normalized and tempered, (4) quenched and tempered, (5) nitrided, (6) carburized, (7) differentially quenched, (8) differentially heated, (9) spheroidized and (10) precipitation hardened. The heat treatment of steel castings is discussed on page 633 in this Handbook.

Welding. The repair of a casting by welding, the joining of one cast part to another, or the joining of a casting to a wrought steel shape, are operations commonly performed in the manufacture and assembly of steel castings. Welding progress in the steel foundry has kept pace with welding developments elsewhere. Qualified welders are employed and careful control is maintained over welding technique and procedures. The welding of cast steel presents the same problems as the welding of rolled steel of similar chemical composition (see page 371 in this Handbook).

Inspection. All steel castings are carefully inspected as to dimensions, conformity with pattern layout, tolerances, surface finish and soundness.

Many castings, depending on service requirements, are subjected to pressure tests, hardness tests, magnetic particle inspection or radiographic examination.

The steel is tested for tensile properties and chemical composition. In some instances, depending on requirements of specification, the steel is tested for notched-bar impact properties and hardenability characteristics, and is inspected for grain size and microstructure.

Centrifugal Casting of Steel. The term "centrifugal casting" is an all-embracing one, referring to any casting that has been rotated during solidification. There are three types of centrifugal steel casting: (1) true centrifugal casting, (2) semicentrifugal casting and (3) centrifuged or pressure casting.

In true centrifugal casting, the steel is poured into a mold that rotates around a horizontal or vertical spindle. The mold may be either a metal die or a sand-lined metal jacket. There are no gates or risers and yields approaching 100% may be obtained.

The molds for semicentrifugal casting may be either dies, sand molds or core assemblies, where the inner surfaces of the castings are formed not by centrifugal force alone but by cores. Gates of various types are employed to act as feed heads. Most molds are produced on the vertical spindle machine.

"Pressure casting" refers to the use of centrifugal action to generate a high pressure to force the molten steel into the mold. This method is used for asymmetrical castings which cannot be spun around their own axes or for castings too small to be spun in that manner. The mold is arranged so that the steel is poured into a gate at the center of rotation. In-gates distribute the steel to mold cavities arranged around the central down-gate.

Design of Steel Castings. Correct design of steel castings is of paramount importance, both for satisfaction in service and for economical production in the foundry.

The purchaser of steel castings is interested in the principles of casting design because of new demands and more exacting engineering requirements, involving either heavier loads or higher pressures. Many of these developments have resulted in a reduction or redistribution of metal in the castings. In some instances sections have been produced that are not only lighter in weight, but are actually stronger than those employed formerly.

Unsatisfactory design is responsible for many defective castings. Co-operation between the steel foundrymen and the purchaser of castings, particularly while the design is in the formative stage, will result in improvements.

Cast steel has certain characteristics that are inherent and must be considered as natural phenomena. The volumetric contraction that takes place when steel transforms from the liquid to the solid state is comparatively high. This means that considerable thought must be given to the casting design so that ■ further supply of liquid metal will compensate for the contraction. Also, steel, in common with other metals, possesses very low strength and ductility at temperatures just lower than the solidification temperature; hence, careful attention must be given to features of design in an effort to reduce stresses that may act upon the casting. Further, in comparison with other common metals, liquid steel has poor fluidity; therefore the designer should not insist on sections so thin as to cause losses from failure to run, or sections that would increase manufacturing costs greatly by impracticably high pouring temperatures.

Unsuitable casting design can cause several types of de-

fects in steel castings. The shape of the casting and drastic variations in section may result in hot tears following solidification and resulting from restricted contraction. Shrinkage cavities result from insufficient feed metal. These cavities are likely to be found in sections designed to be fed through smaller sections that solidify too quickly to be of adequate feeding value.

Rules for Steel Casting Design. The following rules are recommended for the design of steel castings:

1 An attempt should be made to provide uniform thickness, not less than ¼ in., for all sections in a casting.

2 Abrupt changes in sections are not desirable.

3 Sharp corners should be eliminated at adjoining sections.

4 When a design for a cast steel structure becomes very complicated or intricate, it should be divided into parts that can be cast separately and then assembled by welding.

5 In the design of sections that join in L or V shapes, all sharp corners at the junctions should be replaced by radii so that these sections become slightly smaller than those of the arms.

6 In the design of sections that join in an X, two of the arms should be offset considerably.

7 In the design of any joining sections, all sharp corners at the junctions should be replaced by radii. In T and X sections these radii should be ½ to 1 in., regardless of the thickness of the section.

Physical Properties. The physical properties of cast steel are similar to those of wrought steel and are listed for reference.

Elastic Constants. As determined at room temperature, the elastic constants of steel used for steel castings are little affected by composition or structure. The modulus of elasticity is about 30,000,000 psi, Poisson's ratio is 0.3, and the modulus of rigidity is 11,200,000 psi.

Changes in Volume. The changes in volume that take place in steel castings are affected to some extent by the variations in carbon and alloy contents. Average values for medium-carbon steels (about 0.30% C) based on percentage contraction of volume at atmospheric temperature are: liquid contraction, 1.6% per 100° C; solidifying contraction, 3.0%; solid contraction, 7.2%; total contraction from 1600 C, 11.8%..

Density. The density of cast steel is sensitive to changes in composition, structure, temperature and phase. The density decreases with increasing carbon, with quenching and with increasing temperature. The density of medium-carbon cast steel is in the range of 7.835 to 7.845 ■ per cu cm. Steel castings have a weight of 490 lb per cu ft or 0.283 lb per cu in.

Electrical Properties. The resistivity values for various annealed carbon steel castings of 0.07 to 0.20% C are 13 to 14 microhm-cm; for castings of 0.20 to 0.45% C, the resistivity values are 14 to 16 microhm-cm.

Magnetic Properties. Low-carbon dynamo cast steel has excellent magnetic properties and has supplanted other cast metals for use in housings and frames of installations for magnetic circuits. The magnetic properties of low-carbon cast steel are compared with other alloys in the table below.

Material	Coercive Force, oersteds	Residual Induction, gausses	Maximum Permeability	Induction for H = 150	Saturation Magnetization, gausses
Electrolytic iron	0.36	10,800	14,400	18,900	21,630
Low-carbon cast steel, annealed ...	0.37	11,000	14,800	19,100	21,420
Cast iron, annealed ...	4.60	5,350	600	11,000	16,800

Mechanical Properties. The outstanding mechanical properties of cast steel are strength, ductility and resistance to impact. Steel castings possess high rigidity and are capable of withstanding both elevated and low temperatures and high stresses. These properties, in various combinations, have resulted in the use of steel castings for a wide range of exacting engineering applications.

Tensile and Yield Strength. It is well known that if ferritic steels are compared at a given value of hardness or hardenability, the tensile strengths of cast, rolled, wrought, and welded metal are identical regardless of the alloy content; consequently, for purposes of design involving tensile and yield properties, the engineer can interchange rolled, wrought, cast and welded steel with full confidence.

Ductility. Similarly, if the ductility properties of steels are compared in relation to their hardness values, cast, wrought, and rolled steels and welds are almost identical in their properties. The longitudinal properties of the forged and rolled steels are slightly higher than those of cast steel or weld metal; however, the transverse properties are lower, by an amount that depends on the degree of working. Since most service conditions involve several directions of loading, the securing of uniform directional properties in cast steel is sometimes particularly advantageous.

Impact. The notched-bar impact test is often used as a measurement of the toughness of materials. Cast steels have excellent impact resistance at normal and low temperatures. Generally, the properties of wrought steels are listed in the direction of rolling, and show higher impact values than cast steels of similar composition; however, transverse impact values will be 50 to 70% of these values. Cast steels do not show directional properties. If the directional properties are averaged for wrought steels, the values obtained are comparable to the values obtained for cast steels of similar composition.

Specifications for Mechanical Properties. Since there are approximately 75 types of carbon and alloy cast steels, it does not seem advisable to present here the properties of any one or even of several cast steels, or to illustrate the effect of heat treatment on these properties. Some property values of heat treated alloy cast steels are given on page 634 in this Handbook. Most steel castings are purchased according to specifications for mechanical properties rather than according to ranges of chemical composition. These ranges of composition are used as the basis of purchase requirements when the purchaser is considering certain definite engineering properties, such as wear resistance, weldability, service at high temperature and resistance to corrosion.

An indication of the mechanical properties of cast steels can be obtained from the specification requirements for steel castings established by the American Society for Testing Materials. However, it should be pointed out that the values specified are minimum values used as rejection limits. The normal values expected of cast steel meeting these requirements are from 10 to 40% above the minimums specified. (*See* Table I.)

Table I. ASTM Requirements for Steel Castings, Mechanical Properties

Grade	Tensile Strength, min, psi	Yield Point, min, psi	Elongation in 2 in., min, per cent	Reduction of Area, min, per cent
ASTM A 27-46T				
60- 30	60,000	30,000	24	35
65- 35	65,000	35,000	24	35
70- 36	70,000	36,000	22	30
ASTM A 148-46T				
80- 40	80,000	40,000	18	30
80- 50	80,000	50,000	22	35
90- 60	90,000	60,000	20	40
105- 85	105,000	85,000	17	35
120-100	120,000	100,000	14	30
150-125	150,000	125,000	9	22
175-145	175,000	145,000	6	12

Hardenability. The hardenability of cast steels is influenced by composition and other variables in the same manner as the hardenability of wrought steels.

Endurance Properties. The ratio of the endurance limit to the tensile strength for cast steel varies from 0.42 to 0.50, depending somewhat on the composition and heat treatment of the steel.

Engineering Properties. *Resistance to Wear.* In wear testing, cast steels react similarly to rolled steels and give corresponding values, depending on composition, structure and hardness. Cast steels that have given excellent resistance to wear in service are carbon cast steels of approximately 0.50% C, and low-alloy cast steels of the chromium, chromium-molybdenum, nickel-chromium, chromium-vana-

dium and medium-manganese types, all of which contain more than 0.40% C.

Resistance to Corrosion. Cast steel and wrought steel of similar composition and heat treatment appear to be equally resistant to corrosion in the same environments. Small amounts of copper in cast steel increase the resistance of steel to atmospheric attack. High-alloy cast steels of chromium and chromium-nickel types are normally used for resistance to corrosion.

Resistance to Heat. Although not comparable to the high-alloy steels of the nickel-chromium type especially designed for heat resistance, the 4.0 to 6.5% Cr cast steels, particularly with additions of 0.75 to 1.25% W, or 0.40 to 0.70% Mo and 0.75 to 1.00% Ti, show good strength and considerable resistance to scaling at 1000 F and lower.

Machinability. The machinability of carbon and alloy cast steels is similar to that of wrought steels having equivalent strength, ductility and hardness, and similar microstructure. It is well known that the skin on a casting wears cutting tools rapidly. For this reason many manufacturers consider cast steel difficult to machine. However, once the surface skin is removed, the machining of a cast steel product is similar to the machining of a wrought steel product. In order to conserve the life of cutting tools, it is suggested that the first cut be a deep or "hogging" cut to remove the casting skin.

Weldability. The welding of steel castings presents the same problems as the welding of wrought steels.

References

1 "Steel Castings Handbook", Steel Founders' Society, 1941
2 C. W. Briggs, "Metallurgy of Steel Castings", McGraw-Hill, 1946

Austenitic Manganese Steel

By Howard S. Avery* and M. J. Day*

AUSTENITIC MANGANESE STEEL, also called "Hadfield's manganese steel" after its inventor, is an extremely tough nonmagnetic alloy in which the usual hardening transformation has been suppressed by a combination of high manganese content and rapid cooling from a high temperature. This steel is characterized by high strength, high ductility and excellent resistance to wear. In the form of castings or of rolled shapes, it serves many industrial requirements economically and has built up an enviable record as the outstanding material for resisting severe service that combines abrasion and heavy impact.

Manufacture. Present production is confined chiefly to open hearth and electric furnaces, though other methods are possible. Manganese, as either high-manganese scrap, ferromanganese or electrolytic manganese, may be added in the charge or melted separately and mixed before pouring. Basic-lined furnaces are almost necessary if much of the manganese is charged, because manganese oxides dissolve and weaken refractories that contain much silica or alumina. The basic electric-arc furnace is currently preferred for melting in foundries, while the basic open hearth or basic electric furnace, plus a ladle addition of ferromanganese melted in an electric furnace, is favored in melting this steel for the production of ingots that are to be rolled.

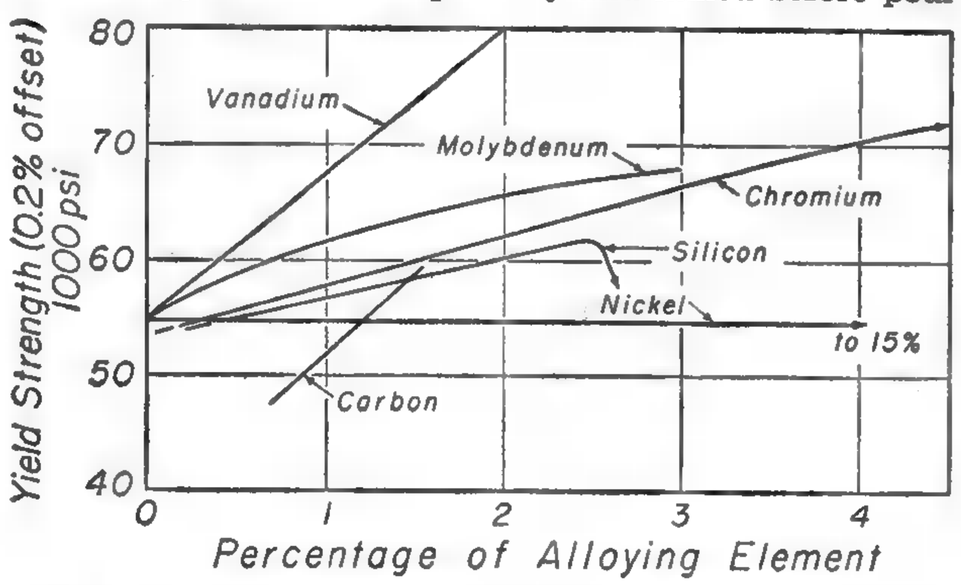

Fig. 1 Effect of alloying elements on the yield strength of toughened austenitic manganese steel (Previously unpublished results, American Brake Shoe Company)

The molten metal freely evolves a reddish brown oxide smoke, which interferes with optical pyrometry. These oxides may also attack mold refractories. In cement-sand molds, manganese has been detected almost half an inch away from the interface between mold and metal.

The alloy is available as castings weighing from a few ounces to several tons, and as sheet, plate and bar stock, wire, rails and the like.

Composition. In the nominal composition, 1.2% C and 12 to 13% Mn are essential elements. Commercial alloys will usually vary within the range 1.0 to 1.4% C and 10 to 14% Mn, as established by ASTM Designation A 128-33 and some other specifications. There is a tendency to operate close to the midpoint of the carbon range and with 12 to 13% Mn, since the lower limit of the composition range is associated with somewhat inferior tensile properties, and the upper extreme provides no economic advantage.

Carbon has a slight but distinct effect on yield strength; reduction in carbon content causes reduction in yield strength (Fig. 1). The effect of carbon content on other tensile properties is overshadowed by variables such as grain size, but there is a suggestive indication of an optimum carbon content around 1.15%. The higher carbon contents may cause trouble in heat treatment or in the foundry. Low carbon content is helpful in avoiding the embrittling effect of carbide precipitation during cooling below the limit of solubility. For this reason, low carbon content is generally employed in alloys to be used for welding-rod and for other modifications where the normal heat treatment, involving a water quench, is impracticable.

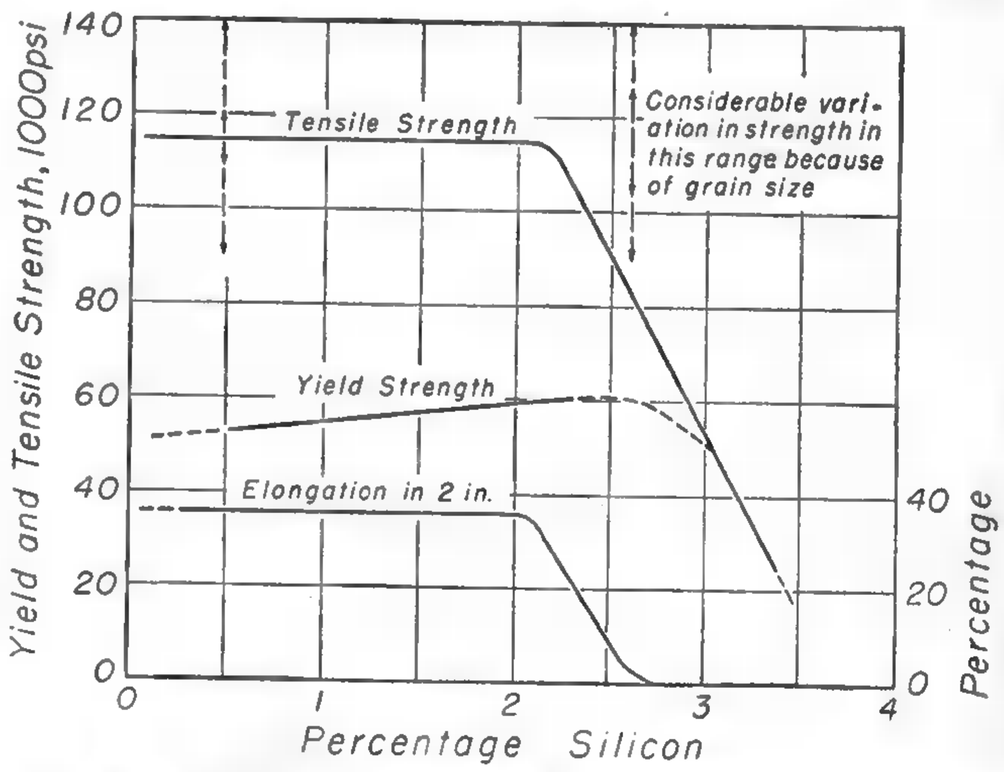

Fig. 2 Effect of silicon content on austenitic manganese steel, water quenched from above A_{cm}, 1.08 to 1.17% C, 11% Mn minimum (Previously unpublished results, American Brake Shoe Company)

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Manganese contributes a vital austenite-stabilizing effect, operating to delay transformation rather than to eliminate it. Thus, with a simple steel that contains 1.1% Mn, the beginning of isothermal transformation at 700 F may occur in about 15 sec, while with 13% Mn, about two days may be required. Below 500 F, phase change and carbide precipitation are so sluggish that for practical purposes they may be neglected, in the absence of deformation, if the manganese content exceeds 10%.

Manganese, within the limits of 10 to 14%, has almost no effect on yield strength, but it does benefit tensile strength and ductility. The difference between 10 and 13% Mn can be demonstrated, though it requires careful control of other variables to make it apparent. Below 10% Mn the tensile properties decline rapidly to perhaps half their normal level at about 8% Mn.

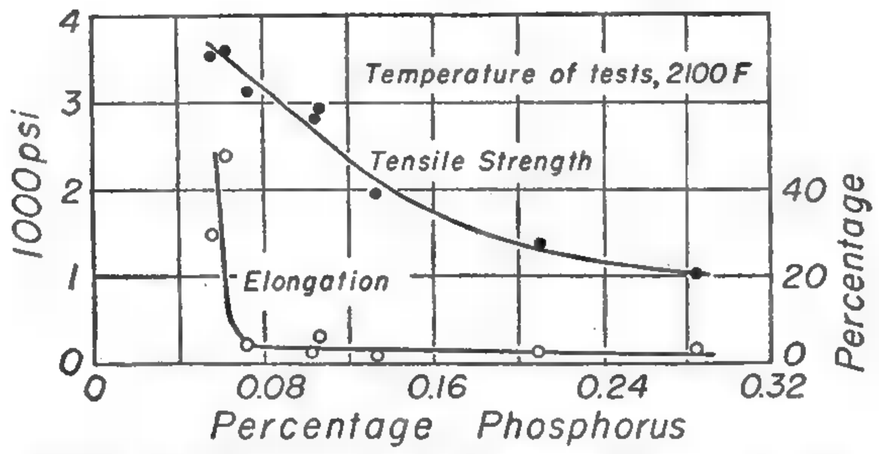


Fig. 3 Effect of phosphorus content on tensile strength and elongation of austenitic manganese steel at 2100 F (Reference 1 and previously unpublished results, American Brake Shoe Company)

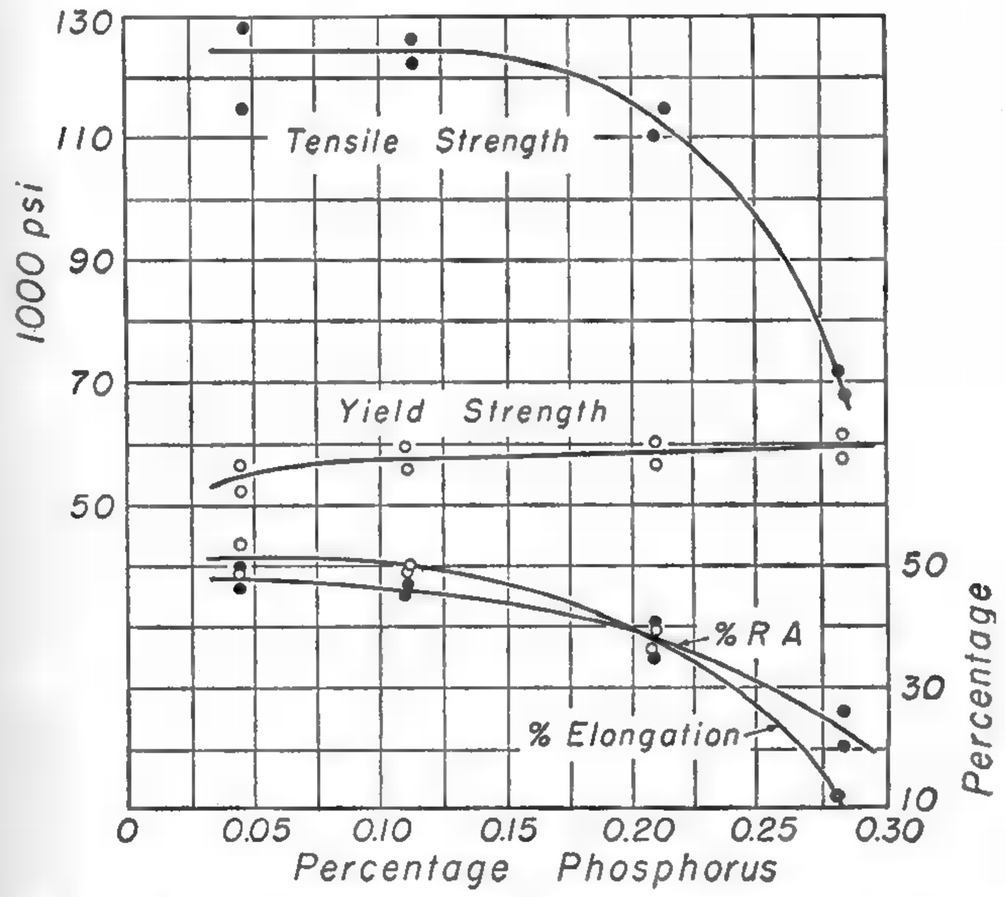


Fig. 4 Effect of phosphorus content on mechanical properties of austenitic manganese steel at room temperature (Previously unpublished results, American Brake Shoe Company)

For critical requirements 11% Mn is desirable as a minimum, though the improvement over 10% is slight. The maximum is rather arbitrary and probably depends more on the cost of the alloy than on metallurgical results, since acceptable properties may be produced up to at least 20% Mn.

Silicon is included chiefly for steelmaking purposes. Although it exceeds 1% infrequently, it may be employed up to about 2% to produce a moderate increase in yield strength and resistance to plastic flow under repeated impact. At about 2.2% a sharp reduction in strength and ductility begins; the range above 2.3% Si is virtually worthless for normal applications (Fig. 2).

Sulfur is seldom a factor in 13% Mn steel, since the scavenging effect of manganese, for which it is customarily added in simple steels, operates to eliminate it by slagging or fixing it in the form of innocuous rounded inclusions of manganese sulfide. Elongation of these inclusions in wrought steels may contribute to directional properties; in cast steel they are considered harmless.

Phosphorus is generally reputed to be harmless below 0.10%. However, this opinion is based on mechanical properties at room temperature. In amounts above 0.06%, phosphorus decreases the strength and ductility at elevated temperature, as determined experimentally by tension tests at 2100 F. This tendency is related to the formation of hot cracks in castings,[1, 2] contributing to the production problems of the foundry. Unless cracked castings escape inspection and go into service, a phosphorus content up to 0.10% is considered acceptable to the user (Fig. 3 and 4).

Other elements, such as nickel, molybdenum, chromium, copper and vanadium, may be added to the standard manganese steel to modify the usual properties.

Heat Treatment. The as-cast or as-rolled structure of manganese steel contains carbides and other transformation products that produce marked brittleness by their continuity. In small test castings, the tensile strength as cast will approximate 60,000 to 70,000 psi, with elongation values down to less than 1%. The standard toughening heat treatment involves austenitizing and water quenching, producing the normal mechanical properties.

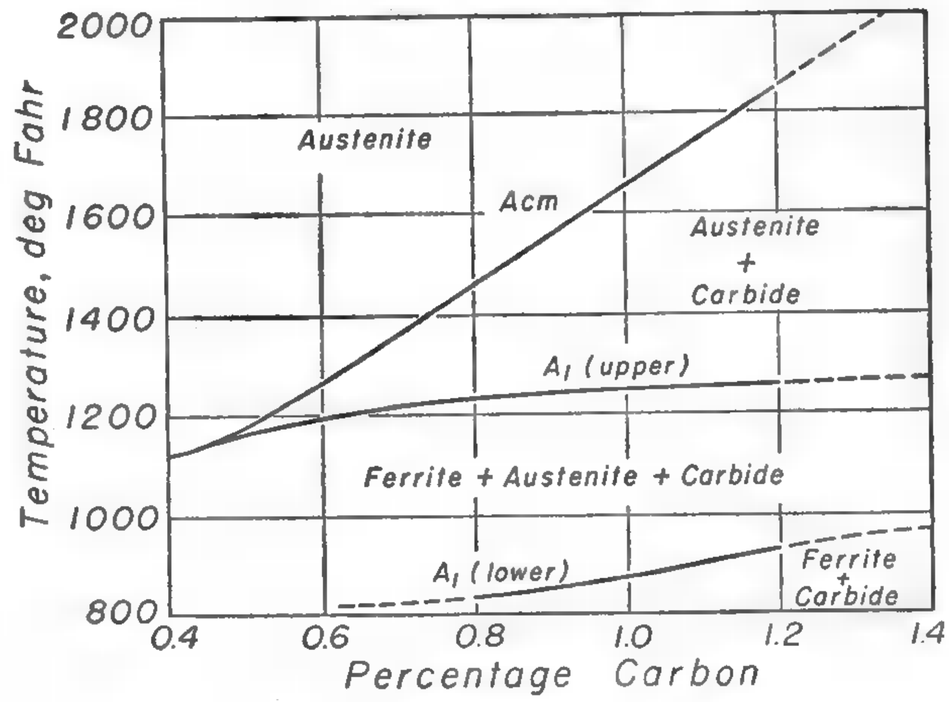


Fig. 5 Effect of heat treatment on 12.5% Mn steel (Modified from Bain, Davenport and Waring[3])

The austenitizing temperature should be high enough to ensure complete solution of carbon. Figure 5 may be used as a guide. The time at temperature is not considered critical, since above 1850 F equilibrium is probably established within 20 to 30 min.[3] An allowance is required, of course, for lag in heat transfer in heavy sections.

The speed of quenching is important, though difficult to accelerate beyond the rate fixed by heat absorption from a surface cooled by agitated water. This results in lower mechanical properties at the center of heavy sections. The effect can be judged quantitatively from the data in Fig. 6 and Table I.

Residual stresses from quenching, coupled with the lower properties of heavy sections, have operated to establish a practical maximum of 5 or 6 in. for the thickness of commercial castings. Stresses that develop during cooling in the mold operate on a much more brittle structure and are likely to produce cracks in heavy castings before heat treatment.

The relatively high austenitizing temperature, in combination with the high carbon content, causes marked surface decarburization and some loss of manganese. The skin may thus be partially martensitic at times, and is usually weaker than the underlying metal. Tensile deformation in service sometimes produces numerous cracks in this inferior skin, which terminate where the tough austenite of normal composition is reached. Service performance is not seriously affected unless critical fatigue conditions or very light sections are involved; in such instances premature failure may result. Under certain conditions, sections such as wrought sheets may be protected

Table I. Effect of Cooling Rate on the Mechanical Properties of Austenitic Manganese Steel[a]

See Fig. 6 for cooling curves of specimens tested

Plate Thickness Corresponding to Cooling Rate Observed, inches	Grain Size	Tensile Strength,[b] psi	Percentage Elongation[b] in 1 in.	Percentage Reduction[b] of Area	Izod V-Notch Test, foot-pounds
2	Coarse	91,700	37.0	35.7	101
2	Fine	118,600	45.5	37.4	99
3¼	Coarse	89,600	25.0	34.5	93
3¼	Fine	111,400	36.0	33.0	85
5½	Coarse	78,800	22.5	25.6	85
5½	Fine	102,000	32.0	28.3	74
7½	Coarse	65,700	18.0	25.1	57
7½	Fine	104,600	33.5	29.2	49

(a) Previously unpublished results, American Brake Shoe Company. Each value is the average of several tests.
(b) Specimens with diam 0.252 in., gage length 1 in.

with covers, metal envelopes, or organic and inorganic coatings, thereby reducing the effect of decarburizing atmospheres used in heat treatment.

Reheating. The reheating of manganese steel parts in the field is much more serious than for ordinary structural steels. Instead of the usual softening and increase in ductility, manganese steel becomes embrittled if heated enough to induce partial transformation of the metastable austenite. As a general rule, manganese steel should never be heated above 500 F, either by accident or by plan, unless the standard toughening treatment is to be applied.

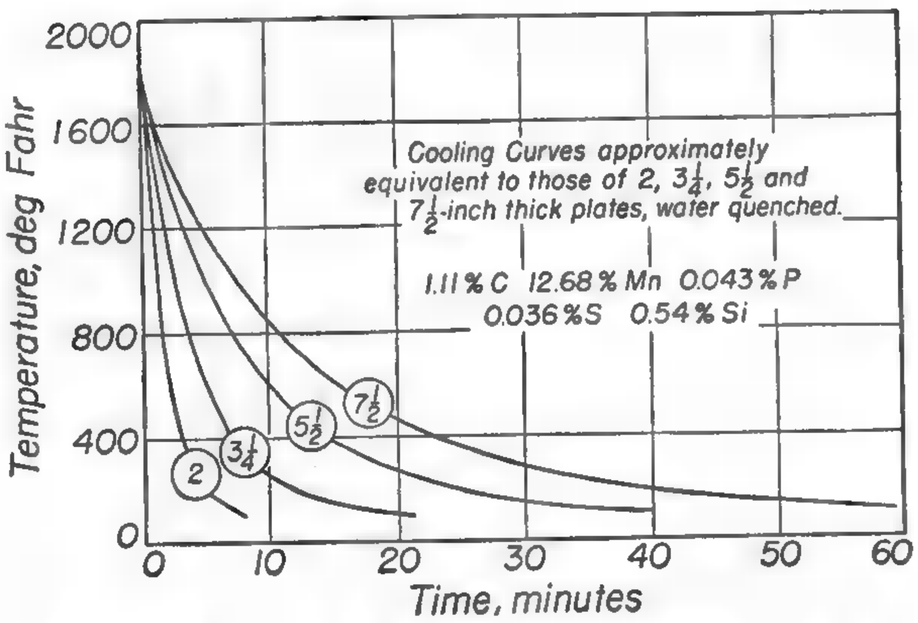


Fig. 6 Cooling curves for water-quenched specimens of which the mechanical properties are presented in Table I.

Both time and temperature are involved; lower temperatures require longer for the impairment to develop. Composition also has an effect. Figure 7 suggests the magnitude of the embrittlement. When large castings are mounted with a backing of molten zinc or lead, temperature should be controlled adequately. However, the most important complication from reheating arises during welding.

Mechanical Properties. The range of tensile properties produced in other alloy steels by heat treatment is developed approximately in manganese steel by work hardening. Thus, yielding signifies the beginning of work hardening and elongation is associated with its progress. There is little or no marked reduction of area by necking, because work hardening is greatest at the point of greatest deformation; the increased strength from working stops

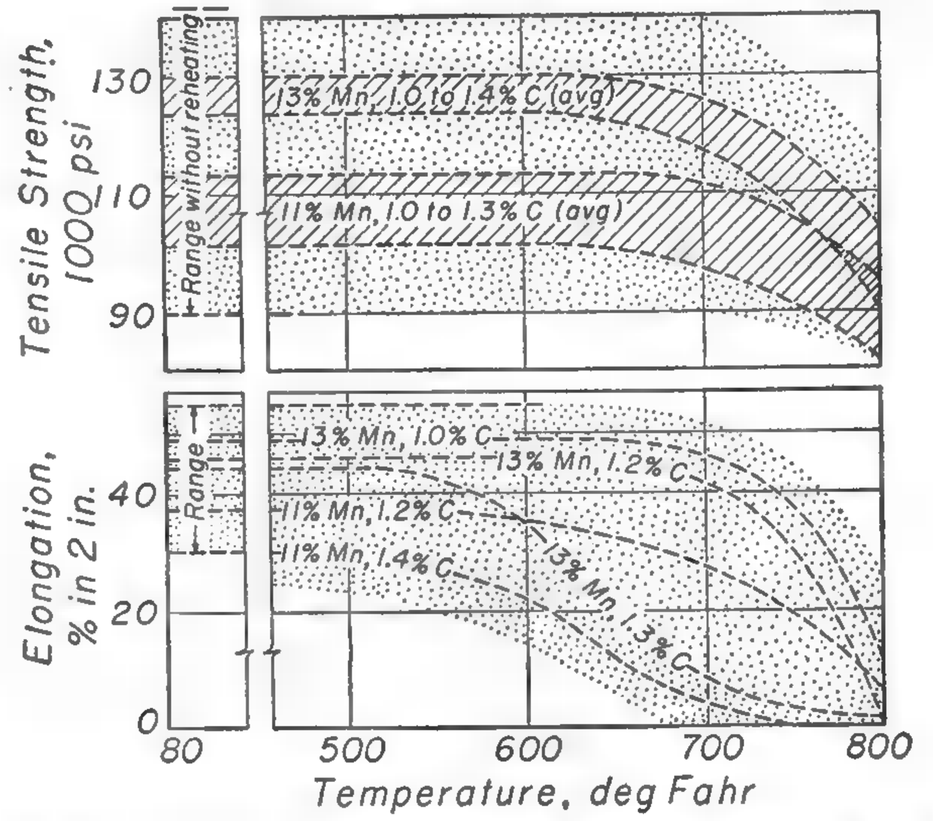


Fig. 7 Embrittlement from reheating austenitic manganese steel. Cast bars (1 in. in diam) reheated 48 hr at temperature indicated, after toughening. [Reference 4(o)]

elongation, and deformation then occurs elsewhere, until the hardening and reduction of area are substantially equalized throughout the specimen.

Representative tensile properties are listed in Table II. The true tensile characteristics of manganese steel are revealed better by the stress-strain curves in Fig. 8, however, which permit a comparison with a tough ferritic steel of about the same nominal tensile strength. The low range of yield strength is significant, and may prevent selection of this alloy where slight or moderate deformation is undesirable, unless the usefulness of the parts in question can be restored by grinding. However, if deformation is immaterial, the low yield values may be considered temporary; that is, deformation will produce a new yield strength, corresponding to the intersection of stress and strain co-ordinates in Fig. 8.

Table II. Mechanical and Physical Properties of Austenitic Manganese Steel

Type	Form (1 in. diam)	Composition, % C	Mn	Si	Ni	Yield Strength, 1000 psi	Tensile Strength, 1000 psi	Elong %	R A %	Brinell Hardness Number	V-Notch Impact: Izod	V-Notch Impact: Charpy
Std[a]	Cast	1.0 to 1.4	10 to 14	0.2 to 1.0	.....	50 to 57	100 to 145	30 to 65	30 to 40	185 to 210	100±	90 to 220
Std[a]	Rolled	1.1 to 1.4	11 to 14	0.2 to 0.6	.....	50 to 60	131 to 142	40 to 60	35 to 50	170 to 200	.....	90 to 150
Ni-Mn[a]	Cast	0.84	12.5	0.48	3.46	.....	105 to 127	45 to 65	35 to 45	170 to 180	.....	95 to 106
Ni-Mn[a]	Cast	1.10 to 1.17	12.5 to 12.7	.....	3.1 to 3.6	.....	113 to 140	44 to 70	35 to 45	150 to 170	.....	105±
Ni-Mn	Rolled	1.1 to 1.4	10 to 14	0.2 to 0.6	3.25 to 3.75	50 to 63	130 to 155	48 to 72	40 to 60	165 to 195	.....	90 to 150

Work hardening capacity. From 170–200 Bhn to 450–550 Bhn
Specific gravity. 7.9 *Density.* 0.286 lb per cu in. = 493 lb per cu ft
Melting point. 2450 F
Electrical resistivity.[c] 70 microhm-cm, about 7 times that of iron
Electrical conductivity.[c] 0.0143 megmho-cm
Specific heat. 0.145 cal per ■
Thermal conductivity. 2.31 against copper at 100[b]
Thermal conductivity (0.8% C, 3% Ni)[c][d] 0.031 cal/cm²/cm/sec/°C = 90 Btu per hr/sq ft/in./deg Fahr
Magnetic permeability. 1.003 to 1.03 (H = 24)
Magnetic permeability without surface preparation. 1.30±
Wet quartz sand abrasion factor. 0.75 to 0.85 (against SAE 1020 as 1.00), see page 220.

Coefficient of Linear Thermal Expansion, in. per in. per °F

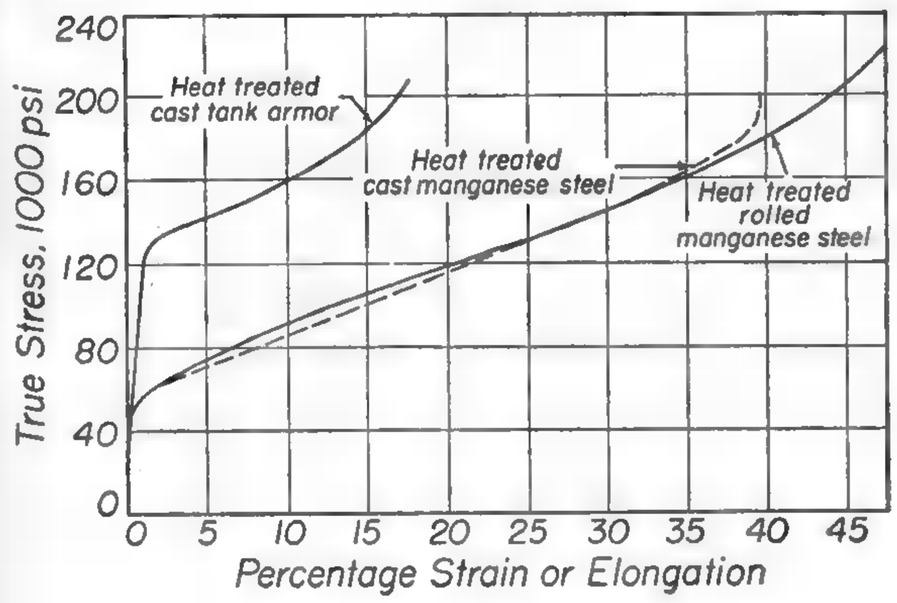
Average		*Instantaneous*	
100 to 300 F	0.0000102	100 F	0.0000102
100 to 500 F	0.0000113	200 F	0.0000106
100 to 700 F	0.0000119	300 F	0.0000111
		400 F	0.0000119
		500 F	0.0000126
		600 F	0.0000134
		700 F	0.0000136

(a) Toughened by water quenching
(b) H. R. Pennington, Engineering and Contracting, February, 1922
(c) Varies considerably with heat treatment. See reference 29.
(d) Swanger, ASTM-ASME Symposium on Effect of Temperature on Metals, 1931, p 732

Tensile strength and ductility are affected somewhat by composition, as outlined above, by heat treatment, and considerably by grain size; the finer-grain specimens exhibit greater strength and elongation. The difference may be as much as 30%. It should be noted that the values sometimes quoted for cast bars may reflect the presence of internal defects, such as shrinkage cavities. The data in this article refer to sound specimens. Aside from the minor influence of directional properties, the chief differences between cast and wrought manganese steel are the result of differences in grain size.

Hardness is about 200 Bhn after toughening, but this value has little significance for estimating machinability or resistance to wear. The hardness will increase so rapidly from deformation that austenitic manganese steel must be evaluated on a distinctive basis.

Notched-bar impact test values are exceptionally high (Table V). Charpy test specimens are sometimes bent and dragged through the machine rather than fractured. Like tensile properties, impact resistance is influenced by grain size and heat treatment. The alloy remains tough at subzero temperatures. The austenitic alloys are apparently immune to hydrogen embrittlement, though with low carbon (0.02% ±) and high manganese contents this embrittlement has been produced.[5]



Conventional Tensile Properties

Heat Treated Steel	Tensile Strength, psi	Yield Strength (0.2% Set), psi	Percentage Elongation in 2 in.	Percentage Reduction of Area
Rolled Mn steel....	140,200	52,200	47.5	36.8
Cast Mn steel.....	132,250	54,200	39.5	33.4
Cast alloy steel.....	138,750	123,000	17.5	50.0

Fig. 8 Comparison of stress-strain characteristics of Hadfield austenitic manganese steel and high-strength heat treated alloy steel (Reference 4c)

NOTE. The true stress indicates that the stress value at every point on the stress-strain curve has been corrected for reduction of area.

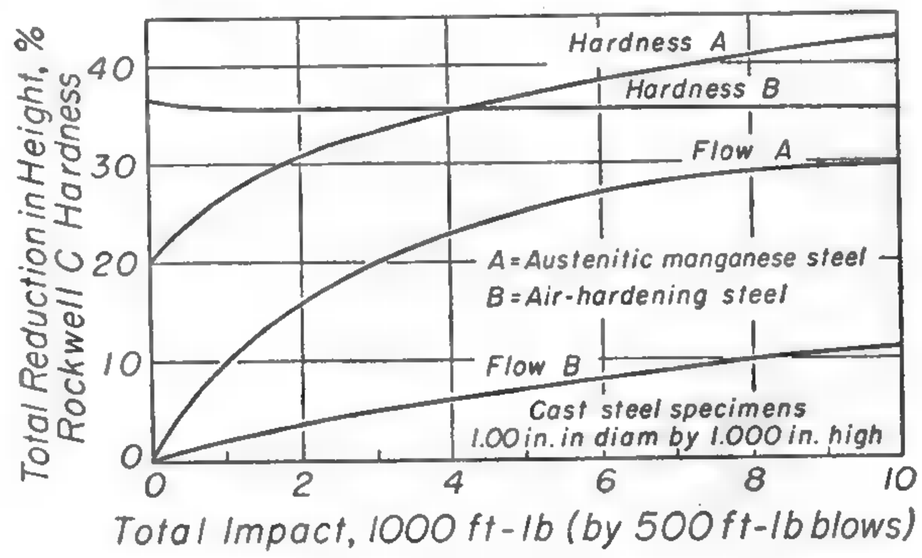
Resistance to crack propagation is high, and is associated with very sluggish progressive failures, permitting periodic observation of fatigue cracks, for example, and removal from service before complete failure occurs. This is a distinct advantage in railway trackwork.

Work Hardening. Manganese steel exceeds even the austenitic stainless steels in ability to work harden, and probably has no equal in this respect. The maximum hardness attainable in practice is about 550 Bhn. Hardness on the wearing surface of a railway frog after service has ranged from 495 to 535 Bhn. Niconoff[6,7] reports a maximum hardness of Rockwell C 49 to 52 after repeated impact on small specimens, while Goss[8] attained Rockwell C 58 after 80% reduction in cold rolling. Niconoff also deduced that a critical unit stress of 35,000 ft-lb per sq in. will be required for maximum hardening.[6] Hardening is produced by *deformation,* and any attempt to harden by working should make appropriate provision for this flow.

Work hardening is usually induced by impact, as from hammer blows. Light blows, even if they are of high velocity, will cause shallow deformation with superficial hardening, though the surface hardness may be high. Heavy impact produces deeper hardening, usually with lower maximum values. The course of flow under impact and the associated increase in hardness are illustrated in Fig. 9. Work hardening on bearing surfaces has been proposed as a substitute for carburized and hardened ferritic steels, to avoid warpage.[9]

Much energy is absorbed by work hardening. Thus sheet manganese steel is an efficient light armor for relatively slow-moving projectiles. If the velocity is high enough, however, to permit the projectile to shear through without some deformation, the protection becomes mediocre, and steels of higher yield strength appear preferable. (This is an effect that is not confined to manganese steel.) In such applications it has been found expedient to preharden by deformation, as in the deep drawing of Army helmets and cold forming of strip for use in body armor. The requirements of these operations necessitate careful control of the martensitic skin formed during the toughening treatment, since tensile deformation may produce cracks that render these thin products unsuitable for the intended use. The skin may not be sufficient to result in a noticeably defective product during manufacture, but may contain minute cracks that lower the subsequent resistance to further deformation. Solution and distribution of carbide is important in such applications. However, most of the impact blows encountered throughout industry are of low velocity, and this material is suitable; it is the preferred choice where high shock resistance, toughness, and absorption of energy are required.

Flow Under Impact. The low yield strength of manganese steel is sometimes a disadvantage. Plastic deformation from impact, as in railway frogs and crossings, increases the yield strength to levels more resistant to flow, but the associated change in dimensions is undesirable. In trackwork, low spots develop at critically pounded locations, resulting in a bumpy roadway and eventually requiring rebuilding with weld deposits. Flow resistance and yield strength are intimately related, and a number of methods for increasing them have been developed.



Steel	Composition, percentage C	Mn	Si	Ni	Cr	Mo	Heat Treatment Deg Fahr	Cooling
A	1.17	12.8	0.46	...	...	...	1850	Water quench
B	0.74	0.88	0.30	0.75	1.40	0.38	1650	Air + 1200, air

Fig. 9 Plastic flow and work hardening characteristics of austenitic manganese steel under repeated impact (with an air-hardening alloy steel for comparison) (Previously unpublished results, American Brake Shoe Company)

Additions of alloying elements and preservice hardening may be employed; the latter is more successful. Additions of vanadium, chromium, silicon and molybdenum are effective; however, vanadium and chromium reduce ductility at the same time (Fig. 1). The relative effects of adding an alloying element in comparison with preharden-ing are shown in Fig. 10. In some applications a dimensional allowance for flow may be required.

Fatigue Strength. The fatigue limit has been reported as 39,000 psi.[10] More recent experiments have provided the data of Table III.

Wear Resistance. Although 12% Mn steel is unquestionably the best metal for resisting certain types of wear,

Table III.
Fatigue Properties of Cast Austenitic Manganese Steel

Composition, percentage C	Mn	Si	P	Tensile Strength, psi	Percentage Elongation in 2 in.	Stress, psi	Cycles at Failure[a]
1.17	12.8	0.34	0.046.....	(Specimen polished)		40,000	4,071,500
1.17	12.8	0.34	0.046..... ..	(Specimen oxidized)		40,000	806,000
1.13	12.8	0.55	0.056..... ..	104,250	34.5	48,500	294,800
1.13	12.8	0.55	0.056.....	102,750	30.0	40,000	853,900
1.13	12.8	0.55	0.056.....	103,500	35.0	38,000	12,663,600
1.13	12.8	0.55	0.056.....	109,000	39.1	36,000	30,600,000 [b]

(a) Rayflex apparatus. Except as indicated, the bars were tested with the oxidized surface characteristic of heat treated specimens.
(b) Endurance Limit = approx 0.34 × tensile strength

it is not universally applicable. When this steel is being considered for abrasive service, the determining factor in selection should be toughness, not resistance to abrasion. If impact and shock are absent, as in a pipe carrying sand-laden water, a martensitic cast iron is a much better choice. If light or moderate impact is involved, the specification of a hardened steel may be justified, but careful judgment is necessary for sacrificing toughness in favor of abrasion resistance. If heavy impact is expected or a large safety factor is required, Hadfield's steel is the logical choice and the large annual tonnage goes chiefly into such applications.

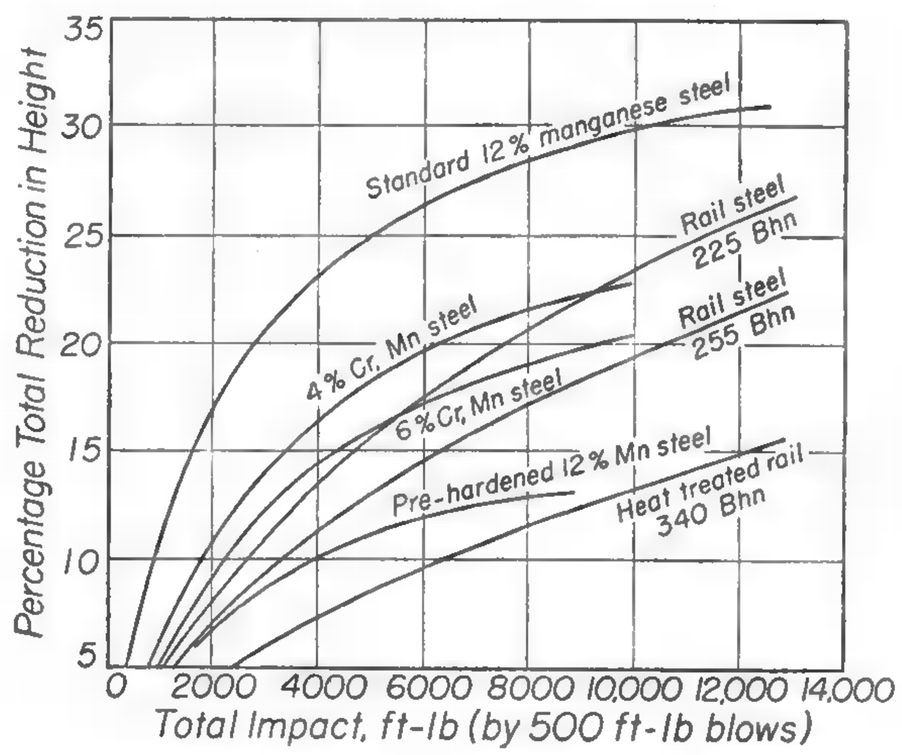


Fig. 10 Flow in austenitic manganese steel under repeated impact; specimens 1 in. in diam and 1 in. high (Previously unpublished results, American Brake Shoe Company)

It is sometimes believed that unless it has been work hardened, manganese steel has poor resistance against wear. This is not a valid generalization. The misunderstanding has probably developed because, where much impact and attendant work hardening are present, 12% Mn steel is so clearly superior to other metals that its performance is attributed to the surface hardening. However, controlled abrasion tests (as described on page 218 of this Handbook) have indicated that there are circumstances where the abrasion resistance of austenitic manganese steel is modified little by work hardening, and others where it will outwear some much harder pearlitic white cast irons in the absence of work hardening.

The relative resistance to abrasion of toughened manganese steel that has not been work hardened is shown in the article entitled "Wear of Metals" in this Handbook. The range of abrasion factors from 0.75 to 0.85 (in comparison with SAE 1020 steel as 1.00) has been established by many tests. If work hardened specimens are tested similarly, the values fall in the lower part of this range, but do not exhibit marked superiority. Some weld deposits of low-carbon manganese steel may give higher factors, though properly balanced weld deposits of nickel-manganese steel will fall within the expected range.

Weiss[11] has employed a similar test to rank many steels. Conversion of his test data to the "abrasion factor" form gives 0.42 for work hardened manganese steel in comparison with SAE 1010 steel as 1.00.

Laboratory wear tests are expected to be better controlled than field tests and to be reported more objectively; however, they seldom can include the full range of variables encountered in service. A summary of reports from practical experience is included below, as a guide to the better understanding of the serviceability of manganese steel. However, it should be recognized that the data are less precise quantitatively than those from rigorously controlled laboratory techniques.

In contrast with the uncomplicated abrasion involved above, a different type of wear is represented by Hall's[12] jaw-crusher tests. The loss in weight of the moving jaw in a machine that crushes about 800 lb of trap rock per day, was used as a criterion of wear resistance, yielding the data in Table IV.

Somewhat similar service is typified by stamp-mill shoes. With operating conditions that include 1550 ft-lb blows at the rate of 100 per min for a total of 21,600,000 times, manganese steel outwore by 25% the next best of 11 cast alloy steels.[4c]

In these applications that involve heavy blows, the very hard and abrasion-resistant, martensitic cast irons may exhibit a slower rate of wear, but early fracture usually terminates their life with a considerable portion of the original cross section unworn, while manganese steel may wear almost to paper thinness without fracture. Pearlitic white cast iron, which is about 400 to 450 Bhn is equally brittle but less resistant to wear. Comparative tests on log washer lugs indicated that the manganese steel was about 25% worn out with no breakage, while white iron lugs in the same period wore to the point of uselessness with 14% breakage.[4c] In clay-crusher rolls, white or chilled iron was outworn from two to three times.[4d] In grinding-barrel liners, cast irons had a life of two to three years as compared with ten years for manganese steel.[4c] Part of this superiority over white cast iron is attributed to greater freedom from breakage and spalling, but some superiority probably results from better intrinsic wear resistance.

Manganese steel chain, with endless links cast in interlocking molds, also provides resistance to wear in other circumstances. Three to nine times the life of heat treated steel chain has been observed.[4b,4c] The alloy is valuable in conveyers as well as in dragline chain subject to abrasion and carrying heavy loads.

Manganese steel is not adequately resistant to wear from an airborne stream of abrasive particles, as in a sandblast; consequently there is no apparent advantage in selecting manganese steel for such service.

In metal-to-metal contact, work hardening is a distinct advantage, decreasing the coefficient of friction and conferring resistance to galling if temperatures are not excessive. Compressive loads, rather than impact, provide the deformation required, and operate to produce a smooth hard surface that has good resistance to wear but does not abrade the contacting part. Sheaves, rails and castings for railway trackwork are common applications of this type. The alloy has also been used successfully in some water-lubricated bearings.

Field tests that involve intermittent metal-to-metal contact provide evidence that manganese steel can render distinctive service in such applications. Locomotive chafing

Table IV. Summary of Wear In Jaw-Crusher Service[12]

Material	Wear of Jaw Surface[a] Fixed Jaws	Moving Jaws
Austenitic Mn Steel (1.21% C, 11.9% Mn)	0.072 to 0.191	0.086 to 0.124
Carbon Steel (0.24% C)	1.26	1.21
Carbon Steel (0.50% C)	0.95	1.07
Chromium Steel (0.26% C, 1.23% Cr) ..	1.19	0.82
Chromium Steel (0.59% C, 0.73% Cr) ..	0.72	0.82
Nickel Steel (0.24% C, 3.63% Ni)	0.58	0.47
Nickel Steel (0.55% C, 3.29% Ni)	0.43	0.48
Nickel Steel (0.46% C, 6.24% Ni)	0.24	0.27
Nickel-Chromium Steel (0.44% C, 1.38% Ni, 0.44% Cr).....	0.41	0.39

(a) Grams per square inch per 1000 lb of stone crushed

irons and plates of manganese steel gave an average mileage of 447,000 versus 84,000 miles for carbon steel parts.[4f] Wheels on a 6-ton gas locomotive were reported to show no appreciable wear after three years, while chilled wheel flanges were about one-third worn through in eight months and also caused more wear on the rails.[4d] A steel mill reports double life from manganese steel crane wheels, with freedom from spalling and from the diametral wear that characterizes carbon steel wheels.[4g] Blooming-mill-housing wearing-plates were in good condition after 16 years, while carbon steel plates required replacement every 2 years.[4g] Wearing-plates on ore-bridge haulage-drums were reported as good as new after 5½ years of service where ordinary cast steel wore about 3 years.[4g] Manganese steel sheave wheels are expected to last about four times as long as cast carbon steel and do not groove and cause excessive rope wear as do wheels of the type that does not work harden.[4c, 4h]

The properties of manganese steel at elevated temperature are inferior to those of Fe-Cr-Ni austenites. This, coupled with the tendency toward embrittlement, does not favor applications where frictional heat causes temperatures above 500 F (Fig. 6).

Since corrosion is a form of wear, it should be considered, because manganese steel is not corrosion-resistant. This type of steel rusts readily and where corrosion and abrasion are combined, as they frequently are in mining and manufacturing environments, the metal may deteriorate or be dissolved at an uneconomical rate.

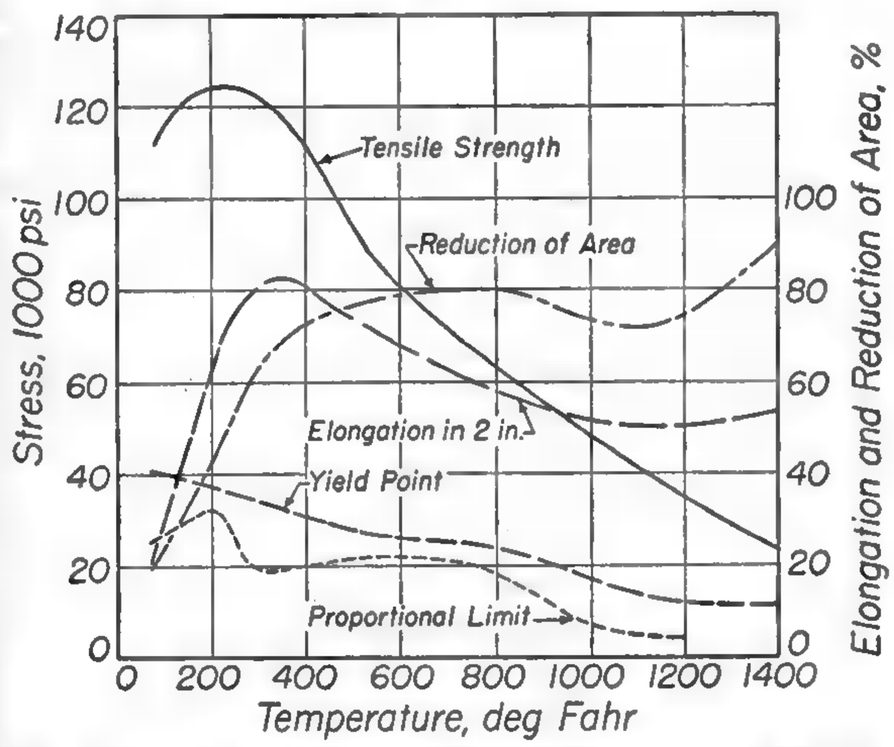


Fig. 11 Results of short-time tests of mechanical properties at elevated temperatures (Reference 13) Composition: 0.47% C, 14.77% Mn, 0.41% Si, 0.040% P, 0.004% ■

Effect of Temperature. The embrittlement produced by heating above 500 F is an argument against operation above this limit. Kanter [13] has reported data obtained from tension tests at elevated temperature on a 0.47% C, 14.8% Mn steel (Fig. 11). These data suggest that austenitic manganese steel has optimum properties between 200 and 400 F. It might be assumed that the nickel-manganese type, as used for welding-rod, would have good high-temperature strength because of its austenitic structure and the decreased tendency to transform. Gillett[14] has demonstrated that the creep rates are relatively high in comparison with the Fe-Cr-Ni austenitic alloys (Fig. 12). The creep rate of 0.0001% per hr at 800 to 950 F and at 2190 psi, is comparable with that of a balanced commercial 26% Cr, 12% Ni heat-resistant alloy at 1800 F.

Like most austenitic structures, manganese steel remains tough at low temperature. At minus 100 F, it retains from 50 to 85% of its room-temperature impact resistance (Table V). There is some evidence that this steel is considerably more brittle at the boiling point of liquid air (minus 300 F) but at all atmospheric temperatures, even in arctic climates, it has outstanding toughness. This provides a valuable safety factor in comparison with ferritic steels, when used in railway trackwork and mining equipment that must serve at subzero temperatures.

Thermal Expansion. The characteristics of expansion are similar to those of other austenitic materials. The expected change in length during heating is about 1½ times that of ferritic steels. A coefficient of linear thermal expansion of 0.000010 in. per in. per °F or 0.000018 in. per in. per °C is generally suitable at room temperature.

Magnetic Properties. The untransformed austenite of 13% Mn steel is virtually nonmagnetic with a permeability of about 1.03 or less (H = 24).[15] This permits use of the material where a strong, tough nonmagnetic metal is required, as in magnet cover plates, traveling crane collector shoes, generator and motor stator core parts, liner plates for storage bins holding materials that are handled by lifting-magnets, magnetic separator parts, instrument-testing devices, and parts in the magnetic field of electric furnaces.

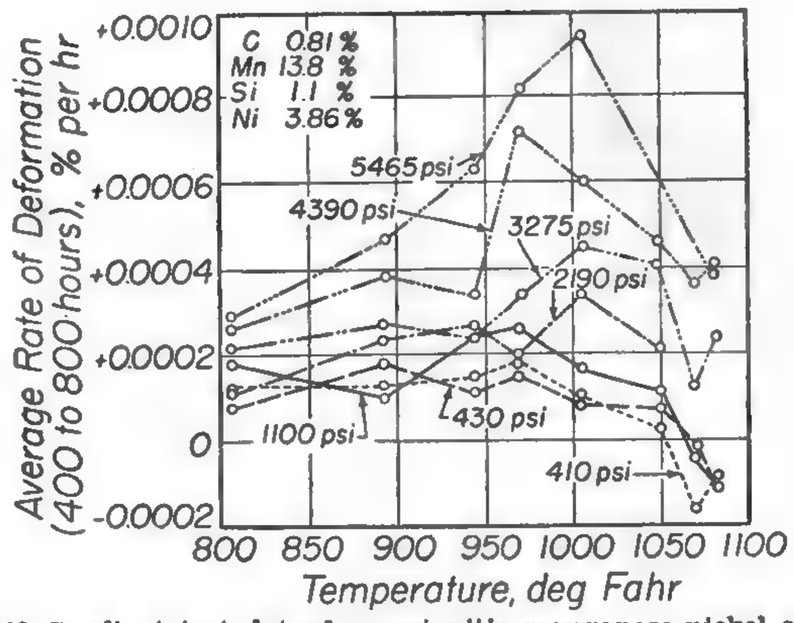


Fig. 12 Gradient test data for austenitic manganese-nickel steel in the form of rods ⅛ in. in diam. The test was carried out in a nitrogen atmosphere to avoid oxidation. (Reference 14)

The changes that occur in composition of the surface during heat treatment, may produce a magnetic skin. Permeability values of 1.3 ± have been obtained on specimens that have this martensitic surface layer. Frequently this layer does no harm, but if necessary it may be removed by grinding or prevented by suitable (although often expensive) measures during heat treatment.

Cast or wrought manganese steel is probably the most economical strong material for nonmagnetic parts if machining is not required. The cost of fabrication and a maximum operating temperature of 500 F should be considered decisive in its selection.

Lack of magnetic attraction is a disadvantage in handling systems that depend on magnetic separators to remove tramp iron ahead of crushers, grinders, or other machinery. To prevent passage by the separator and subsequent damage to the machine, it is advisable to cast soft steel inserts in parts of manganese steel that may be lost from working equipment and carried into the material being processed. The insert is designed to provide enough magnetism for removal by the separator.

Metallography. With its behavior of toughening after a water quench and embrittling after a tempering heat treatment, manganese steel appears as a paradox in contrast with conventional steels. However, an understanding of its sluggish transformation tendencies and of their dependence on temperature, will make apparent the close relationship of this steel with others. Above A_{cm} (Fig. 5) the steel becomes completely austenitic. The austenite is

Table V. Charpy V-Notch Impact Test Values

Composition, percentage				Impact Value, ft-lb			
				at 75 F		at −100 F[a]	
C	Mn	Si	Ni				
1.03	12.9	0.52	...	91	98	46	59
1.18	13.0	0.50	...	105	107	55	62
1.19	14.6	0.50	...	102	106	52	65
0.84	12.5	0.48	3.46	95	106	76	84
1.17	12.7	0.53	3.56	103	106	87	89

Values are from duplicate specimens. Temperature ± 5 °F
V-notches machine ground, to avoid work hardening.
Specimens water quenched from above A_{cm} before machining.
(a) Held in solid CO_2 and acetone until just before testing.

not homogeneous in cast material, because carbon gradients result from the dendritic pattern of solidification. Diffusion during long holding at high temperatures will result in homogenization, accompanied by some improvement of mechanical properties. However, not enough change occurs to make this an addition to commercial practice.

Quenching, as with other steels, tends to suppress austenite transformation, with the difference that the critical cooling velocity is quite low below Ar′. (Grain boundary carbide precipitation between A_{cm} and Ar′ is the primary cause of impaired properties associated with slow cooling.) Isothermal transformation between 500 F and the upper A_1 temperature will develop acicular or pearlite structures, which appear slowly and require very long times for attainment of equilibrium. As with mixed structures in other steels, the mechanical properties of partially transformed austenite are poor—particularly when carbides or other brittle constituents form in large flat plates parallel to crystallographic planes. The mechanical properties are low also when pearlite, which seems to nucleate most readily at grain boundaries, develops in sufficient quantity to form an envelope around each grain. These structures account for the low ductility and reduced strength of austenitic manganese steel after reheating.

Grain refinement, which is suggested as desirable by the difference in properties of fine-grained and coarse-grained specimens, is possible but not feasible. Austenitization, after considerable transformation at subcritical temperature, will produce a fine grain size, but the long time required for producing sufficient transformation usually makes such treatment impractical. (*See* U. S. Patent 1,975,746.)

As the manganese content is lowered, there is an increase in the M_s temperature of initial martensite formation during cooling. M_s reaches room temperature at about 9.2% Mn with 0.5% C; 6.2% Mn with 0.8% C; and 4.6% Mn with 1.0% C. With manganese above 10%, M_s is below 32 F if the carbon content is 0.5% or more, while with the usual 1.10 to 1.20% C, M_s is probably below minus 330 F.[17] Thus, air hardening is possible only when the manganese content is less than 9%[18] and usually less than 7%. The constituents that are present after air cooling or after water quenching are given in the structural diagrams that accompany the article "Manganese in Steel" (page 465 of this Handbook). These represent less stable conditions than are shown in the phase diagrams for the C-Fe-Mn system given in the CONSTITUTION OF ALLOYS section.

Krivobok[15] and Hall[16] have provided excellent examples of the structures that may be encountered.

Preparation of specimens for critical microscopic examination is difficult. Great care is required to avoid cold work and disturbed surface layers. Cold worked scratches from early stages may be flowed over and concealed during fine polishing, only to become pronounced after etching. Similar flow may obscure grain boundaries whose character is an important criterion of the quality of heat treatment. Spurious structures may also result from tarnishing and corrosion caused by the atmosphere.

Nital etching, which reveals structure well, leaves a disturbing dark deposit. An etching cycle that removes this and gives generally satisfactory results is as follows:

> Etch 15 sec in 3% nital, rinse in ethyl alcohol, etch 15 sec in 10% HCl in alcohol, rinse 15 sec in ethyl alcohol. This is usually repeated three times, followed by 15 sec in 2% NH_4OH in alcohol, and rinsing in ethyl alcohol. The polished and etched face must be protected carefully from corrosion, particularly in humid atmospheres.

Transformation of austenite to martensite is apparently produced only by deformation, which results in the characteristic appearance of slip lines. The magnetic nature of these lines can be demonstrated by a special metallographic technique.[20] Transformation may contribute to work hardening; however the mechanism is not clear.

Low-Manganese Steels. As the manganese content is reduced below 10%, transformation occurs at higher temperatures, tensile properties decrease and it becomes increasingly difficult to retain the wholly austenitic structure by quenching. Some of the alloys that contain from 3 to 8% Mn are air hardening and may be utilized where toughness is not required. With about 4% Mn plus 0.5% C and 4% Mn plus 0.8% C the Jominy end-quench hardenability curves[17] are nearly flat at approximately Rockwell C 60 and 56, respectively. These compositions, which merge into the pearlitic steels when the manganese content is further reduced, have received little commercial recognition.

Table VI. Mechanical Properties of Austenitic Manganese Steel with 3% Ni[a]

Cast bars 1 in. in diam, radiographically sound
1.10% C, 12.6% Mn, 0.38% Si, 3.13% Ni

Heat °F	Heat hr	Treatment cooling[b]		Tensile Strength, psi	Percentage Elongation in 2 in.	Percentage Reduction of Area	Brinell Hardness Number
1900	1	WQ	....	136,550	63	43	157
1800	1	WQ	....	128,120	52	38	162
1800	1	WQ	....	133,680	55	38	161
1700	1	WQ	....	126,330	51	38	150
1700	1	WQ	....	128,566	52	■	152
1900	1	AC	....	103,600	29	25	153
1900	1	AC	....	104,200	30	25	142

(a) Previously unpublished data assembled by the American Brake Shoe Company
(b) WQ, water quenched; AC, air cooled

Low-Carbon Manganese Steels. Reduction of carbon, rather than manganese, produces materials that may exhibit satisfactory mechanical properties. The extremes are iron-manganese alloys.[21] They appear to be sensitive to hydrogen embrittlement[5] and, since the attainment of low carbon content is an added expense, they are unlikely substitutes for the 1.15% C, 13% Mn grade. Intermediate carbon contents (0.50 to 0.90%) are employed in welding-rods for austenitic manganese steel, usually with additional alloying elements. A machinable austenite, containing 0.3% C and 17 to 18% Mn, has been advocated in Germany for nonmagnetic parts.[22]

A 16% Mn steel with 0.10 to 0.25% C, 2% Ni, 1% Cu and sometimes chromium, has been suggested for light, high-strength wrought products.

Nickel-Manganese Steels. Additions of nickel to the standard grade of austenitic manganese steel produce no apparent change in yield strength, but there is a distinct trend toward higher tensile elongation (Table VI). The quenching rate is perhaps less critical, but quenching is still necessary in order to obtain the maximum toughness. Such additions of nickel may stabilize the lower-carbon types, and may therefore permit some control of the martensitic skin that sometimes forms during heat treatment.

A lower carbon content is much more effective in conferring toughness without quenching, and since added nickel seems to prevent the lower intrinsic toughness of the straight 12% Mn steels with low carbon content, a group of steels with 0.60 to 0.90% C and about 3% Ni has become popular for welding-rods, for wrought products, and occasionally for castings. Representative properties appear in Table VII. This alloy surpasses the standard grade in resistance to embrittlement that results from reheating up to 800 F.

Table VII.
Properties of 0.84% C Austenitic Nickel-Manganese Steel[a]

12.45% Mn, 0.48% Si, 3.46% Ni, 0.008% Al

Grain Size	Ultimate Tensile Strength, psi	Percentage Elongation in 2 in.	Percentage Reduction of Area	Brinell Hardness Number	Heat °F	Treatment hr
Coarse	106,250[b]	49.5	41.2	...	2000	2[d]
Fine	121,750[c]	60.0	41.5	...	2000	2[d]
Properties After Reheating at Different Temperatures						
					Toughened plus	
Coarse	106,250	49.0	39.4	177	500	48
Coarse	106,500	50.0	42.7	174	600	48
Coarse	105,750	53.0	37.8	165	700	■
Coarse	105,250	47.5	41.5	174	800	48
Fine	123,750	62.5	40.3	174	500	48
Fine	125,000	63.5	39.7	174	600	48
Fine	125,500	61.0	40.0	172	700	48
Fine	127,000	65.0	42.1	179	800	48

(a) Previously unpublished data assembled in the research laboratories of the American Brake Shoe Company
(b) Yield strength, 44,500 psi
(c) Yield strength, 45,700 psi
(d) Quenched in water

Chromium-Manganese Steels. The ability of manganese to stabilize austenite has been utilized in low-carbon modifications of the 18% Cr, 8% Ni stainless steels by substituting manganese for some or all of the nickel. A correlated abstract by Mack[24] is a convenient reference for these alloys, which are reported to have good characteristics in regard to deep drawing, hot working and welding; better machinability than 18% Cr, 8% Ni steel; somewhat lower strength at elevated temperature; lower but generally satisfactory resistance to scaling; and less susceptibility to intergranular corrosion—but also lower resistance to corrosion except in sulfurous mediums.

As the chromium content is decreased and the carbon content is increased, the chromium-manganese steels gradually approach the Hadfield type. The chromium-manganese steels may have higher yield strength and resistance to flow (Fig. 1 and 10), moderately increased resistance to corrosion, and less susceptibility to embrittlement by reheating. The wear resistance is controversial; at present this special modification has no clearly established superiority over the standard grade.

Table VIII. Suitable Current Values for Welding Austenitic Nickel-Manganese Steel

Diam of Rod, in.	Bare Rod, d-c amperes	Coated Rod— d-c amperes	Coated Rod— a-c amperes
1/8	80 to 100	75 to 90	80 to 100
5/32	90 to 125	85 to 110	90 to 125
3/16	110 to 150	100 to 130	110 to 150
1/4	135 to 160	110 to 140	135 to 160

The lowest practical welding current will usually result in the least damage to the parent metal.

Manganese, chromium, nickel and silicon have been used together to produce a heat-resistant alloy suitable for service up to 1400 F.[25] An approximate range of composition is 0.30 to 0.35% C, 4 to 9% Mn, 2% Si, 6 to 9% Ni, and 10 to 12% Cr. This alloy has a limiting creep stress (for 0.0001% per hr minimum creep rate) of 4000 to 7000 psi at 1400 F and 1500 to 3000 psi at 1600 F. The composition must be balanced for maximum strength and structural stability. Above 1400 F the rate of oxidation is rather high.

Copper is sometimes employed in chromium-bearing austenitic manganese steels. Lorig[26] suggests from 1 to 5% Cu, with molybdenum and chromium each up to 3% and manganese between 2 and 9%, in order to obtain strength, toughness, and high sensitivity to work hardening. Experimental compositions near the middle of this range give tensile strength from 68,000 to 88,000 psi with 10 to 16% elongation.* These values are similar to those of 9% Mn steel. Copper and chromium added to the standard composition are reputed to improve yield strength and resistance to flow.[27] It is probable that the chromium is chiefly responsible.

Welding. Manganese steel may be welded with rods that deposit austenitic metal, but several features must be considered carefully. Austenitic stainless steel rods have been used but are not recommended. The best welding alloy is a low-carbon, high-manganese steel, containing enough of an additional alloying element (usually nickel) to compensate for the decreased carbon content, as previously described. Electric welding, with the shortest practical arc, is almost necessary. The primary consideration is minimum heating of the parent metal in order to avoid embrittling transformations or precipitation of carbide. This usually precludes the practice of preheating. Even under the most favorable circumstances some precipitation is expected and the resulting weld zones seldom equal the toughness of the normal parent metal. The weld itself may have good properties; it is the surrounding metal that suffers impairment.

The low heat conductivity and high thermal expansion also contribute to difficulties, combining to produce steep thermal gradients and high residual stresses. Weld metal is subjected to tension as it cools, and in order to minimize cracking, it is desirable to peen the weld while it is hot, thus producing plastic flow and changing the stress to compression. This hammering should be done promptly after a maximum length of 6 to 9 in. of the weld has been deposited.

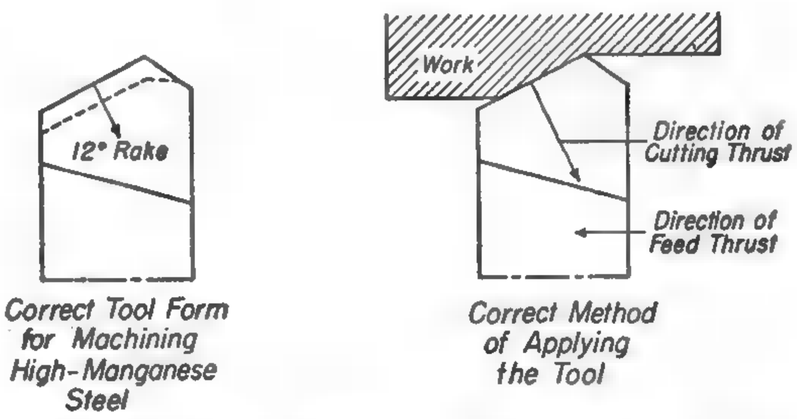
The heat of welding will accentuate the precipitation of carbide if work hardening of the base has preceded welding. For such material as in railway trackwork the cold worked metal should be removed by grinding before the new metal is deposited. A center punch mark provides a crude but convenient index of work hardening; grinding should continue until an indentation is readily produced.

If manganese steel is deposited on carbon or low-alloy steel, the transition zone may be too low in manganese and may develop a martensitic structure which, because of brittleness, may permit spalling of the weld deposit. Such use of an austenitic manganese steel overlay for wear resistance is not recommended; an air-hardening steel or cast iron is generally more satisfactory. However, hard surfacing of manganese steel is practicable if an alloy is employed that is more resistant to abrasion. Such surfacing is useful where the toughness of manganese steel is required only intermittently. Composite structures of this type should follow the principle of using the tougher of the two metals for the base.

Both bare and coated electrodes are used for welding; the conditions listed in Table VIII are suitable.

Machining. Manganese steel is so tough, and work hardens at the point of cutting tools to such an extent that frequently it is typed as commercially unmachinable. However, this steel can be cut with both cemented carbide and cobalt high speed steel tools. A good grade of sulfur-bearing cutting oil is beneficial. Moderately heavy cuts and slow speeds are advisable. Most commercial finishing is by grinding, and foundries specializing in the production of Hadfield steel are equipped to do almost all the required machining operations with grinders.

Machinability is increased by the embrittling that reheating develops between 1000 and 1200 F. Though not usually practicable, such a treatment may be a useful expedient if the part can be properly toughened afterward. Milling is not considered practicable.



Correct Tool Form for Machining High-Manganese Steel

Correct Method of Applying the Tool

Fig. 13 Machining austenitic manganese steel (Lea[28])

British practice is reported to depend less on grinding and to feature the following:[28]

1 Dry machining, with high temperatures at the tip of the cutting tool
2 High-cobalt high speed steel tools
3 Extremely rigid machine tools and chucking, to eliminate chatter
4 Tool design with 7-deg clearance and 12-deg rake (*see* Fig. 13)
5 Cutting speeds of approximately 12 to 14 ft per min, cuts approximately 3/16 in. and feed about 1/32 in. per rpm
6 Tools kept very sharp

Applications. The chief applications of austenitic manganese steel are in the industries of construction, mining, quarrying, oil-well drilling, manufacturing of steel, railroading, manufacturing of cement and clay products, dredging, and lumbering. This steel serves chiefly as parts in equipment for handling materials, rock crushers, grinding mills, dredge buckets, power-shovel buckets and teeth, pumps for handling gravel and rocks, and in a multitude of associated applications. An important use is in railway trackwork, such as frogs, switches and crossings, where the multiple impacts at intersections are especially severe. Austenitic manganese steel resists metal-to-metal wear; therefore it may be used in sprockets, pinions, gears,

*From previously unpublished data assembled at the American Brake Shoe Company

wheels, conveyer chain and various wearing plates, shoes, or other contact members. Nonmagnetic parts, required for lifting-magnets, for induction furnaces and special electrical equipment, represent an expanding field of usefulness.

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High-Strength Low-Alloy Structural Steels

By H. W. Gillett*

IT IS not feasible to quench and temper some large steel structures, for example, bridges, railroad cars and ships. Moreover, steels that harden during quenching present difficulties in welding. The use of ordinary structural steel for making large structures that cannot be heat treated, and for welding, requires that design be based on the low yield strength of the steel (25,000 to 30,000 psi) and on the endurance limit, which for unnotched specimens approaches the yield strength.

There is an obvious need for steels that are stronger in the as-welded or normalized condition so as to allow the saving of weight. Stronger structural steels were at first provided by increasing the percentage of one or more of the three cheap elements—carbon, manganese and silicon. Such steels were used in riveted structures. The cold formability of these strengthened steels was decreased, and their hardenability made them poorly adapted for welding.

To secure freedom from weld hardening, and a better compromise between yield strength and cold formability, it was necessary to decrease the carbon content and to add alloying elements. In the presence of effective amounts of alloying elements, the practical limits of carbon content for normalizing, without production of martensite or bainite, are 0.07 to 0.17%; the usual range is 0.10 to 0.15%. Alloying elements are selected according to the need for making the austenite moderately sluggish during cooling, so that the pearlite transformation, during air cooling, will occur at as low a temperature as possible in order to secure fine pearlite instead of coarse. Yet the steel must not be so sluggish that any austenite is retained to form bainite or martensite at still lower temperatures.

The cementite in the finely distributed pearlite is undoubtedly the major source of strength, since carbon-free ferrite would need to be very highly alloyed if the desired strengths were to be obtained, but the strengthening of the ferrite matrix is an indispensable adjunct. At this low carbon level, carbide-forming elements, such as manganese, chromium and molybdenum, are distributed between the cementite and the ferrite; a considerable proportion of these elements is dissolved in ferrite and strengthens it. Hence these may be used as well as the elements that do not replace iron in cementite in steel. Silicon, copper, nickel and phosphorus are effective in that they strengthen ferrite.

The potency of the elements is in approximately the following order, and the percentages employed are about as shown here:

Carbon	0.10 to 0.13	
Phosphorus	0.03 to 0.12	
Molybdenum	0.10 to 0.25	(when used)
Manganese	0.20 to 1.20	
Silicon	0.05 to 0.75	
Copper	0.10 to 0.90	
Chromium	0 to 0.85	
Nickel	0 to 1.80	

Phosphorus, commonly 0.10%, is used in the compositions that have accounted for the largest tonnages of these "mild alloy" steels made in the U. S. In such an amount phosphorus strengthens steels of this carbon content, without producing the cold brittleness that has barred high phosphorus content in steels of higher carbon content. Because phosphorus may cause a banded structure, with streaks of high phosphorus concentration, when the steel is cast into large ingots, 0.25% C + P is the maximum used. Molybdenum, unusually effective as a strengthener, is recovered quantitatively from remelted scrap, and all that is added to the charge, whether as ferro-alloy or as oxide, is recovered without loss by oxidation.

Manganese may either be kept at the lowest content that will give clean steel or, more commonly, may be raised well above that content. With most furnace practice there is some uncertainty as to the percentage recovery of manganese, and when large amounts are added in

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the cheapest form (high-carbon ferro-alloy) the carbon content of the melt must have been decreased correspondingly. A point of carbon is an important matter in these steels. When more than 1% Mn is employed, few other strengthening elements are added and these other additions are made for control of grain size. About 0.10% V accompanied the high manganese content for this purpose in some of the earlier steels.

Chromium has effects similar to those of manganese in these steels. Chromium is cheaper as high-carbon than as low-carbon ferrochromium. One steel containing about 0.85% Cr, together with 0.40% Cu and about 0.11% P, for resistance to atmospheric corrosion, has been found to produce a particularly adherent type of rust. The chromium content of up to 0.50%, used in some other steels for the strengthening effect, confers no notable corrosion resistance by itself.

Silicon is normally used in amounts sufficient to kill the steel, usually 0.15% or more, though in at least one steel of this class, semikilled to give a high ingot yield, silicon content is kept low. In some other steels, the silicon content is increased considerably beyond that in ordinary killed structural steel, so as to use the strengthening effect of silicon since it is one of the cheapest alloying elements. Objections to high silicon content in basic melting practice, and a tendency toward dirtiness when around 1% Si is present, have operated to keep the silicon at 0.75% or less, though some early foreign steels used it as the major alloying element.

To confer resistance to atmospheric corrosion, copper was used, at about 0.20%, long before it was generally used as a strengthener. Its effect on resistance to corrosion is enhanced when copper is used in conjunction with phosphorus. Like molybdenum, copper is recovered quantitatively from scrap and from additions, since these elements are oxidized less readily than iron. This reluctance to oxidize brings a limitation to the use of copper, since while scaling in the soaking pit or the heating furnace, a steel high in copper forms a film of copper beneath the scale. This film may penetrate into the steel intergranularly and may cause surface checks during hot rolling. Such behavior limits copper additions (for wrought products, not for castings) to from 0.40 to 0.50% unless special precautions are taken in heating, or unless the high copper content is accompanied by at least half as much nickel as copper, preferably more than half.

When the copper content is greater than 0.75%, the copper-containing steels can be precipitation hardened. The copper is retained in solid solution, even at the rate of cooling obtained in normalizing large sections, but is precipitated out when the steel is reheated to about 850 to 950 F, increasing the yield strength considerably and decreasing the ductility slightly. At about 1% Cu the increase in yield strength is 10,000 to 20,000 psi and occurs regardless of what other alloying elements are present.

A steel has been used containing 0.12% C, 0.60% Mn, 0.01% Si, 1.40% Ni, 0.95% Cu and 0.25% Mo. The mechanical properties are:

Condition	Tensile Strength, psi	Yield Strength, psi	Elongation in 2 in., per cent	Reduction of Area, per cent	Bhn
Normalized	73,500	57,000	36	70	155
Normalized plus 4 hr at 1000 F...	84,500	71,500	31	67	185

Since rapid cooling is not necessary to keep the copper in solid solution, ready for precipitation hardening, the increased strength caused by precipitation hardening can be obtained at the center of a large section. Formability in the solution treated condition is better than in the riveting grade of steel not precipitation hardened which has yield strength equal to that produced in this steel by the final precipitation hardening.

Nickel strengthens much as copper does, but causes neither intergranular attack under scale nor precipitation hardening. With regard to atmospheric corrosion, nickel has much the same effect as copper though not so great. Like molybdenum and copper, nickel is recovered quantitatively from scrap and from additions. Next to molybdenum, nickel is the most expensive of the elements used in these steels. Because of its cost, it is seldom used alone, but is commonly accompanied by a considerable copper content, since copper, in permissible amounts, has an approximately equal strengthening effect.

The nickel, copper and molybdenum contained in scrap are retained when remelted. As in the NE steels for heat treatment, the content of these elements in available scrap can be used as the basis on which to build up the composition to the desired level.

Since the mild alloy steels are benefited by fine grain, aluminum, titanium, or zirconium is the final addition to killed steel, especially when low-temperature notched-bar impact resistance is sought. Care is necessary in making such additions, in order to allow separation from the melt of oxides and nitrides that may form clumps and produce laminations during rolling.

With proper choice and suitable amounts of alloying elements, it is possible to produce formable, weldable mild alloy steel that contains 0.10 to 0.15% C, with yield strength 50,000 to 55,000 psi, tensile strength 70,000 to 80,000 psi, and approximately 25% elongation in 8 in. for as-rolled or normalized sections of ½ to ¼ in. In sections of ¾ to 1 in., the yield and tensile strengths are lower.

Table I. Chemical Compositions of High-Strength Low-Alloy Structural Steels

No.	Composition, percentage								
	C	P	Mn	Si	Cu	Ni	Cr	Mo	Others
1.....	0.13	0.03	0.60	0.80	...	...	0.60	...	0.10 Zr
2.....	0.10	0.03	1.20	0.20	0.20	...	...	0.15	0.10 V[a]
3.....	0.10	0.03	0.80	0.15	0.20	...	...	0.25	...
4.....	0.10	0.03	0.35	0.15	0.25	0.35	0.10	...	...
5.....	0.10	0.12	1.10	0.05	0.35	...	...	...	...
6.....	0.10	0.10	0.40	0.55	0.40	...	...	0.20	...
7.....	0.10	0.11	0.35	0.45	0.40	0.40	0.85	...	...
8.....	0.12	0.08	0.75	0.05	0.40	0.60	...	0.08	...
9.....	0.10	0.06	0.60	0.08	0.60	0.75	...	...	0.06 Ti
10.....	0.10	0.06	0.60	0.08	0.60	0.75	...	...	...
11.....	0.10	0.10	0.75	0.30	0.60	0.50	0.75	...	...
12.....	0.13	0.015	0.75	0.005	0.80	1.00	...	0.10	...
13.....	0.11	0.040	0.65	...	0.90	1.80	...	...	...

(a) Or less vanadium, with a low content of titanium

With a few points more carbon or with very low finishing temperatures in rolling, a riveting grade can be obtained with 65,000 to 75,000 psi yield strength and 80,000 to 90,000 psi tensile strength. The elongation is 15 to 20% and there is some sacrifice in cold formability and weldability. The ductility figures given are for longitudinal specimens. Depending on cleanliness and whether or not the steel is cross-rolled, the results of tests made in the transverse direction—and especially in the direction of the plate thickness—may, of course, be lower.

For steels that have a yield strength of about 50,000 psi, the endurance limit and endurance ratio for unnotched specimens are surprisingly high—very close to the yield strength. This is particularly evident in the phosphorus-strengthened steels.

The mild alloy steels that ordinarily contain 0.20% Cu or more—particularly when accompanied by the 0.10% P that is present in many of them—have resistance to atmospheric corrosion superior to that afforded by ordinary structural steels that contain no copper. However, all these steels (including the Cu-P-Cr steel, balanced to secure maximum corrosion resistance) *start* to rust as quickly as ordinary structural steel and, when unsightly rusting must be avoided, all of them require painting.

The modulus of elasticity of these steels is the same as that of ordinary steels. When they are used in the thinner sections made feasible by their yield strength, endurance limit, and resistance to corrosion, whatever stiffness is needed must be engineered into the structure, as by the use of box sections. Table I shows some compositions that have a yield strength of 50,000 psi in the low-carbon (0.10 to 0.15% C) welding grade, and that have been in commercial use or are advocated for such use.

* Properties of some of the high-strength low-alloy steels at low temperature are included in the article on page 204 of this Handbook.

The alloying elements needed for strength, without having to resort to cold finishing, range from a total of about 1%, when the more potent elements are relied upon chiefly, to around 2% or more when less potent elements are used.

While some superficial gradations exist in mechanical properties, formability and weldability among the various compositions, on the whole the series is considered as a unit by the designer and, at least as a first approximation, any steel that meets the mechanical specifications in the section to be used is considered replaceable by any other steel in the series. That is, within the limits of composition favored by the peculiarities of phosphorus, silicon and copper, composition is not an important factor. That each major producer of steel has a pet composition is largely ascribable to the existence of certain patents, familiarity with the processing schedule for one composition, and a desire to be unique.

The availability of scrap that contains copper, nickel and molybdenum, and future changes in the price of these and the other alloying elements, can be expected to direct more attention toward the possibilities of shifting the composition day by day to allow most economical utilization of raw materials and less insistence on a particular chemical composition. The user is concerned with the maintenance of the desired mechanical properties rather than with the composition.

Development of these mild alloy steels so that the static strength and the endurance limit of standard structural steel are doubled, without loss of weldability or much difference in ability to be cold formed, has been no mean accomplishment. The virtues of these steels deserve to be brought more forcefully to the attention of the designer. The saving in weight through the use of these steels justifies the additional cost in many applications. Lighter weight is an advantage in the completed structure, and also reduces the cost of transporting the steel.

Reference. For a more extended discussion, the reader may refer to Materials and Methods, 26, 101 (July 1947).

Cold Finished Carbon Steel Bars and Shafting

By H. W. Graham*

THE cold finishing of steel may be defined as the process of reducing the cross-sectional area of material such as bars and shafting, without the use of heat. There are five cold finishing methods: cold rolling, cold drawing, cold drawing and grinding, turning and polishing, and turning and grinding.

Bars and shafting are cold finished for one or more of the following reasons: special accuracy of size, a smooth or bright finish on the surface, improved mechanical properties and better machinability.

The selection of the method most suitable for cold finishing a specific piece of work depends on the size of section and the physical characteristics desired. For example, the usual practice is to cold draw the smaller round bars, about 3¾ in. in diam or less, and to turn the larger sizes. Whenever a superior finish or more accurate size is required, the material is ground. Turned and polished bars, usually more than 1⅛ in. in diam, are furnished when steel is desired that has mechanical properties characteristic of hot rolled bar stock, plus accuracy of dimensions, and a finish that is reasonably free from the normal surface imperfections of hot rolled bars.

Description of Cold Finishing Processes. Since the surface defects and imperfections present in the hot rolled product are accentuated by cold drawing, it is necessary that the hot rolled material for this purpose be prepared with care, to assure the proper surface quality, size and finish in the cold finished steel. The surface requirements of hot rolled bars for cold finishing are similar to those of forging steel; that is, the surface must be substantially free from seams, pits and excessive scale.

Before cold drawing, the hot rolled material is usually immersed in a bath of 4 to 8% sulfuric acid at about 150 F until the scale is completely removed. The material is then washed and dipped in a lime solution, which neutralizes any acid remaining on the bars and also serves as a rust preventive and a lubricant in the finishing. Drawing through a die, straightening, and cutting to length complete the sequence of operations.

Cold Rolling. Finishing by cold rolling involves passing the cleaned hot rolled bars repeatedly through a set of rolls, thereby subjecting the material to a light reduction during each pass until the final size is obtained. Cold rolling imparts a bright surface finish, accurate size, and an appreciable increase in the tensile strength, with an even greater increase in the yield strength.

Cold Drawing. In this method, a hot rolled bar of virtually any shape, after being cleaned of scale, is pulled cold through a die with bore section generally $\frac{1}{32}$ to $\frac{1}{16}$ in. smaller than the diameter or thickness of the hot rolled stock. The amount of draft, however, may be varied from $\frac{1}{64}$ to ⅛ in., depending on the composition of the material being drawn, the size of the hot rolled bar, and the mechanical properties desired. The effects of cold drawing are similar to those of cold rolling; the final product has a bright surface finish and accurate size, with the tensile strength and particularly the yield strength substantially increased.

Cold Drawing and Grinding. When cold drawing alone or turning and polishing impart inadequate accuracy in size or inadequate surface finish, straightness or concentricity, grinding may follow cold drawing. The mechanical properties of this type of cold finished product remain unchanged from those of the cold drawn bar.

Turning and Polishing. Whereas cold drawing reduces the cross-sectional area by subjecting the bar to compressive and elongating forces, turning and polishing accomplish the same result by removal of metal from the diameter. Usually the bar is finished thereafter in a combination straightening and polishing machine. By this method, close accuracy of dimensions is obtained, similar in degree to that achieved by cold drawing, but the finish of the surface is somewhat brighter. Surface decarburization is removed along with surface seams and other minor defects not affected by the cold drawing operation. Since the steel has not been cold worked in any appreciable manner, the mechanical properties of the hot rolled bar follow through to the turned and polished product.

Turning and Grinding. In this process, after the rough and imperfect surface of the hot rolled bar has been removed by turning, the bar is ground, usually in the centerless type of machine. The resulting product has a finish and characteristics similar to those of cold drawn and ground material, except that the mechanical properties of the hot rolled material have not been changed.

Size and Finish. From the above discussion, the various methods of cold finishing may be grouped as follows, according to superiority of the size and finish produced.

Accuracy of Size	*Finish*
First—Turning and grinding or cold drawing and grinding	Turning and grinding or cold drawing and grinding
Second—Turning and polishing or cold drawing	Turning and polishing
Third—Cold rolling	Cold drawing or cold rolling

One of the outstanding advantages of cold finished steel is the close dimensional tolerance that can be maintained. Cold finished bars are straightened commercially within $\frac{1}{32}$ in. in 5 ft. Rounds for shafting purposes are held considerably closer, and even more exacting requirements of straightness can be met by special processing in straightening.

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Mechanical Properties. Table I gives average mechanical properties of cold drawn, hot rolled steel bars of the various grades listed. The data presented are general in nature and therefore should not be interpreted as values necessarily obtainable for all sizes and conditions. Also the stress-strain diagrams in Fig. 1 give a general idea of the marked increase in tensile strength, and particularly yield strength, that occurs in this process. The tensile strength is increased less than the yield strength; but since permanent distortion is a function of the yield strength rather than of the tensile strength, this effect on cold drawn materials is of vital importance in applications in machinery.

Table I

Average Mechanical Properties of Cold Drawn Steel

Sizes, ⅝ to 2 in. in diam; Test specimens, 2 by 0.505 in.

AISI Steels	Tensile Strength, psi	Yield Strength, psi	Elongation in 2 in. per cent	Reduction of Area, per cent	Brinell Hardness Number
C-1010	67,000	55,000	25.0	57	137
C-1015	71,000	60,300	22.0	55	149
C-1020	75,000	63,700	20.0	52	156
C-1025	80,000	68,000	18.5	50	163
C-1030	87,000	73,900	17.5	48	179
C-1035	92,000	78,200	17.0	45	187
C-1040	97,000	82,400	16.0	40	197
C-1045	102,000	86,700	15.0	35	207
B-1112	87,000	73,900	17.0	45	183
C-1120	78,000	66,300	19.5	49	159
C-1117	80,000	68,000	19.0	51	163
C-1118	82,500	70,100	18.5	50	167
C-1137	105,000	89,200	16.0	35	217
C-1141	112,000	95,200	14.0	30	223

The increase in yield strength is accompanied by a decrease in elongation and in the reduction in area, but not enough to interfere greatly with the use of cold drawn materials where the higher yield strengths are necessary. A cold drawn bar that has properties intermediate between the extremes in yield strength and elongation, can be obtained by annealing or normalizing treatments.

Because of desirable mechanical properties, lower cost and superior machinability, cold drawn bar stock is often used as a substitute for heat treated bars. Also, in applications where other combinations of properties are desired along with the more accurate size tolerances, hot rolled bars may be heat treated in accordance with the requirements, and then turned and ground, or turned and polished.

During the past few years, considerable attention has been given to strain annealing cold drawn bars in the vicinity of 500 to 1100 F. Heating at temperatures between approximately 500 and 600 F increases the tensile and yield strengths slightly without sacrificing ductility. Higher temperatures relieve cold working strains to a limited degree and increase the ductility of the material. Such treatments have virtually no deleterious effect on the accuracy of size or smooth finish of the cold drawn bar, thus preserving intact some of the properties of cold drawn steel and modifying or enhancing other features.

Machinability. Another important advantage of cold finished materials is machinability superior to that of hot rolled products. This superiority comes from several features, including an improved machining quality in the steel itself, resulting from the effect of cold drawing; and if cold finished by any of the standard methods, better machining performance (because of freedom from hot rolled scale), close accuracy of size, and a greater degree of straightness. These advantages are recognized generally by those interested in machining quality, as indicated by the large percentage of cold finished steels used by machine shops, particularly for automatic screw-machine work where the machining requirements are most exacting and severe.

Shafting. It seems appropriate to include in this discussion a brief mention of shafting formulas; more detailed discussions are published in bulletins of the American Standards Association.

Shafts for transmission of power are subjected to transverse and torsional forces. The loads producing these forces are the torque resulting from the resistance offered

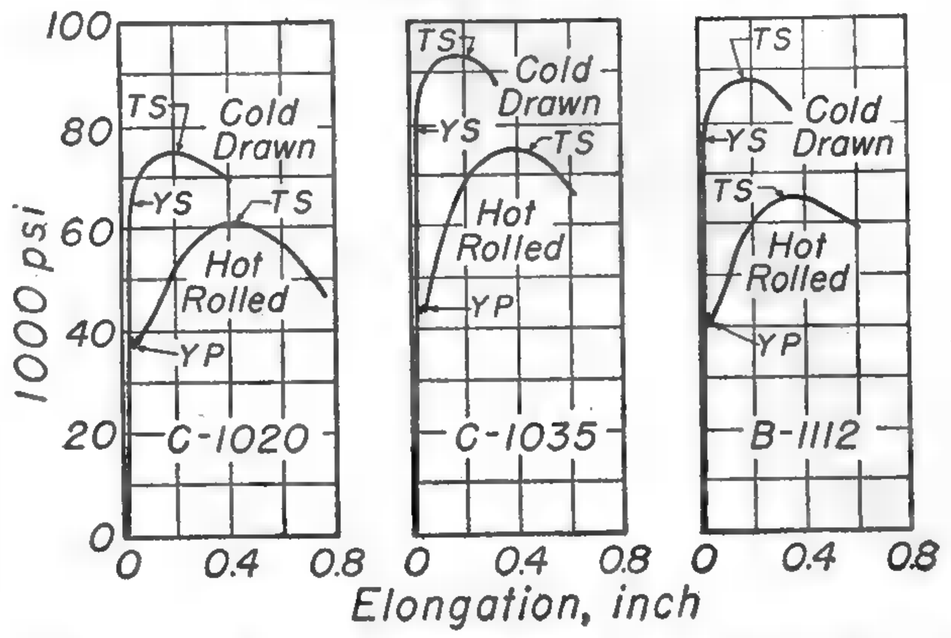

Fig. 1 Typical stress-strain diagrams of hot rolled and of cold drawn steels. (*TS* = tensile strength, *YS* = yield strength, *YP* = yield point)

by the power load to the revolving shaft; the belt pull, the weight of pulleys, gears, sprockets, drums and the weight of the shaft itself. Therefore, in designing a shaft, it is necessary that the stresses to which the shaft is subjected should be within the safe limits of the material used.

For ordinary transmission of power through shafting, experience has shown that when velocity of rotation and spacing of shaft hangers are kept within defined limits, the following formulas fulfill all practical requirements of design. The limitations of these formulas are that the shafts be supported at no greater intervals than 8 ft and that the rpm be no greater than 400.

D = diameter of shaft, in inches
N = number of revolutions per minute
H = horsepower

For head shafts..... $H = \frac{D^3N}{125}$

For line shafts..... $H = \frac{D^3N}{90}$

For short countershafts and single power transmitters ..... $H = \frac{D^3N}{50}$

Conclusion. Because the uses of cold finished steels are numerous, no attempt has been made here to cover them completely. The more common uses include spark plug shells, radio speaker cores, bolts, nuts and screws, gears and pinions, chain pins and rolls for silent chains, motor and transmission power shafting, motorcycle crank axles, oil pump shafts and gears, piston pins, steering gear arms, bushings, pins and worms, tie rods, wringer rolls, gun parts, commutators, and parts for typewriters, sewing machines and cash registers. Particularly large quantities of cold finished steels are used in the manufacture of automobiles, motorcycles, sewing machines, typewriters, adding and calculating machines, textile machinery, shoe machinery, railroad equipment, agricultural implements and electrical equipment.

Wire Rope or Cable

By H. C. Boynton* and A. J. Morgan*

WIRE ROPE is one of the most reliable structural materials. A particular safety feature is that inspection of the surface will indicate when the rope should be replaced. The wear and broken wires disclosed by such inspection, where corrosion is not present, will provide some indication of the remaining strength. Slings made from wire rope, employing proper fittings, furnish the safest method for handling material.

The terms "cable" and "wire rope" are generally considered synonymous. However, when the term "cable" is substituted for "wire rope", it is usually preceded by a descriptive adjective that places it in a more definite class, such as a "track cable" on a cableway, or "bridge cable", as used in suspension bridges.

Five grades of wire rope are used commercially:

Grade	Approximate Carbon Content
Iron	0.05 to 0.15%
Traction Steel	0.20 to 0.50%
Mild Plow Steel	0.40 to 0.70%
Plow Steel	0.65 to 0.80%
Improved Plow Steel	0.70 to 0.85%

There are four standard constructions of wire rope, namely, 6 x 7, 6 x 19, 6 x 37, and 8 x 19. The figures mean that the rope is composed of 6 strands of 7 wires each, 6 strands of 19 wires, and so on. There are, however, many variations in strand construction and the number of wires per strand may vary from 7 to 61, or even more should conditions require more.

To attain the different physical properties required in the various constructions, the individual wires of which a wire rope is composed are specially heat treated and then cold drawn. This sequence of processes produces the necessary toughness and strength. Therefore, any attempt to eliminate the effect of service overstraining by annealing or by any form of further heat treatment, such as is given to chain, would obviously destroy the original properties of the wire, obtained by the cold drawing, and would ruin wire rope.

Qualities of Wire Rope. *Iron Rope (0.05 to 0.15% C).* Iron rope is low in strength and soft compared with steel rope; consequently it will stand little abrasion. Iron rope is pliable and tough, but it is limited to uses where the abrasion is slight and the drums and sheaves are large. It is ordinarily used on drum-type passenger elevators, for compensation and governor ropes, or for transmission of power by wire rope. It is not adapted to general hoisting or to guy ropes. Iron rope is usually furnished only in the 6 x 7 and 6 x 19 standard construction.

Traction Steel Rope (0.20 to 0.50% C). This rope was developed particularly to meet the requirements of traction elevators; that is, high resistance to fatigue, combined with pliability and enough softness to ensure that the rope will not cut the sheaves. Traction Steel rope, therefore, is not so strong as the Mild Plow Steel grade of rope.

Mild Plow Steel Rope (0.40 to 0.70% C). This is a good grade where higher-strength ropes are not required. The most general application is for standard tool drilling in the shallow oil fields and for drilling water wells and blastholes.

Plow Steel Rope (0.65 to 0.80% C). Ropes made from Plow Steel wires are of high strength and unusual toughness, capable of giving good service on many installations where conditions are not unusually severe.

Improved Plow Steel Rope (0.70 to 0.85% C). This grade of rope is generally given a trade name by the manufacturers. It is a high-strength rope recommended instead of the Plow Steel grade where abrasion is severe or the rope is subjected to severe shocks, vibrations, or fatigue stresses. This rope is particularly adapted for severe duty in mines, for logging lines, scraper, dredge and rigging ropes, heavy cranes, ballast unloader ropes and excavating machinery.

Constructions of Wire Rope. *Standard Coarse Laid Rope.* The 6 x 7 wire rope construction called "Standard Coarse Laid Rope", is made of 6 strands of 7 wires each, closed around a fiber core. It is much stiffer than standard hoisting rope and requires larger sheaves. This rope is used for heavy hauling, for wire rope transmissions, tramways, well drilling and sand lines.

*Standard 6 x 19 Construction or Standard Hoisting Rope.** This rope is made of 6 strands, each of which is formed by laying 19 wires together. The strands are finally closed around a fiber core. It is generally accepted that rope made with strands having not less than 16 and not more than 25 wires each, belongs to this general 6 x 19 class. This rope construction, ordinarily

Fig. 1 (Left) Seale construction (6 x 19)
(Right) Filler Wire construction (6 x 25)

considered flexible, is used more generally than all other constructions for hoisting and other rope uses.

Table I gives the important sizes and properties for a Standard Hoisting Rope of 6 x 19 construction made from Mild Plow Steel, Plow Steel and Improved Plow Steel. The two constructions most generally furnished under the 6 x 19 Improved Plow Steel are the 6 x 19 Seale construction and the 6 x 25 Filler Wire construction, as illustrated in Fig. 1.

Table I. Properties of Standard Steel Hoisting Rope (6 x 19 Fiber Core)

Diameter, inches	Approximate Circumference, inches	Approx Weight, lb per ft	Approximate Strength in Tons of 2000 lb — Mild Plow Steel	Plow Steel	Improved Plow Steel
2¾	8⅝	12.10	....	254.0	292.0
2½	7⅞	10.00	....	212.0	244.0
2¼	7⅛	8.10	....	174.0	200.0
2⅛	6⅝	7.23	....	156.0	179.0
2	6¼	6.40	121.0	139.0	160.0
1⅞	5⅞	5.63	107.0	123.0	141.0
1¾	5½	4.90	93.6	108.0	124.0
1⅝	5⅛	4.23	81.2	93.4	107.0
1½	4¾	3.60	69.6	80.0	92.0
1⅜	4⅜	3.03	58.8	67.5	77.7
1¼	3⅞	2.50	48.8	56.2	64.6
1⅛	3½	2.03	39.8	45.7	52.6
1	3⅛	1.60	31.6	36.4	41.8
⅞	2¾	1.23	24.3	28.0	32.2
¾	2⅜	0.90	18.0	20.7	23.8
⅝	2	0.63	12.6	14.5	16.7
9/16	1¾	0.51	10.2	11.8	13.5
½	1⅝	0.40	8.13	9.35	10.7
7/16	1⅜	0.31	6.25	7.19	8.27
⅜	1⅛	0.23	4.62	5.31	6.10
5/16	1	0.16	3.22	3.71	4.26
¼	¾	0.10	2.07	2.39	2.74

6 x 37 Rope Construction. When each of the six strands of the rope is composed of not less than 26 or more than 46 wires, the construction is generally considered in this class. This rope construction is generally known as Extra Flexible Hoisting Rope and is usually recommended instead of Standard Hoisting Rope when the sheaves are found to be too small for Standard Hoisting Rope. The wires in this rope are necessarily much finer than those used in the Standard Hoisting Rope with 19 wires to the

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* The 6 x 19 construction is probably used more often than the others; consequently it is called "Standard".

strand, and consequently are less able to withstand severe abrasion.

8 x 19 Rope Construction. This construction (8 strands of 19 wires each, closed around a fiber core) is generally used where sheaves of small diameter must be employed and where the abrasion is light. This rope construction is generally considered to be an Extra Flexible Hoisting Rope and sometimes may be considered interchangeable with 6 x 37 rope construction. The metallic area of the 8-strand rope is not so great as that of the 6-strand rope, but under severe bending conditions, the decrease in strength is largely offset by the greater pliability. This rope distorts from its circular cross section more readily than a 6-strand rope, so conditions of service that cause crushing require a 6-strand in preference to an 8-strand rope.

Proper Working Loads. It is never advisable for the working load of wire rope, particularly of running ropes, to exceed one-fifth of the breaking strength. This means that the factor of safety should be not less than five. To determine the maximum working load, the breaking strength is divided by the factor of safety. For example, a 1-in. diam 6 x 19 Improved Plow Steel Rope has a breaking strength of 41.8 tons (Table I), and with a factor of safety of five, the working load would not be greater than 8.36 tons.

Factors of safety in excess of five, varying up to eight and even more, are often required for safe and economical operation. The correct factor of safety for a wire rope should be determined by careful and thorough consideration of all pertinent data, including the following: all loads; acceleration; deceleration; rope speed; rope attachments; the number, size and arrangement of all sheaves and drums; existing conditions causing corrosion and abrasion; length of the rope being used; economical rope life; and the possible danger to life and property.

Sizes of Sheaves and Drums. To obtain the most economical service from wire rope, sheaves and drums should be examined carefully for proper size, free running, and suitable groove diameters. It is advisable to design the sheave and drum equipment so that the tread diameters are approximately as follows:

Recommended Average Diameters for Sheaves and Drums

For 6 x 7 rope,	72 times rope diameter	
For 6 x 19 rope,	45 times rope diameter	
For 6 x 30 rope,	45 times rope diameter	(Style G)
For 6 x 37 rope,	27 times rope diameter	
For 8 x 19 rope,	31 times rope diameter	
For 18 x 7 rope,	51 times rope diameter	

For economical service, various conditions allow, and often require, changes from these diameters. For example, on larger hoisting installations, sheaves for use with a 6 x 7 rope are sometimes set at 96 times the rope diameter, and for a 6 x 19 rope, sometimes as high as 90 times the rope diameter.

It is also true that for certain classes of service, ratios smaller than these are possible and economical, although larger diameters give increased life. It is advisable never to allow the sheave and drum diameters to be set below the following:

Minimum Diameters for Sheaves and Drums

For 6 x 7 rope,	42 times rope diameter	
For 6 x 19 rope,	30 times rope diameter	
For 6 x 30 rope,	30 times rope diameter	(Style G)
For 6 x 37 rope,	18 times rope diameter	
For 8 x 19 rope,	21 times rope diameter	
For 18 x 7 rope,	34 times rope diameter	

Rope and cable subjected to intense sheave or drum pressures or operating under conditions of severe heat, are often manufactured with a metallic core instead of the usual fiber core. This core may be in the form of a strand or an independent wire rope. If such a core is used, the rope strength given in Table I may be increased by 7½% and the rope weight by 10%.

Storage. Particular care should be taken to avoid damage of a wire rope while it is in storage. The rope should be stored in a dry place, free from chemicals or gas from chemicals, in order to prevent destructive corrosive action on the steel. Also any exposure to excessive heat may injure the fiber core.

Handling. In handling, care should be taken not to twist or untwist the rope. Kinks of any nature or the pulling down of loops to small diameters should be avoided. The wires are damaged beyond the elastic limit at such points and will break rapidly in subsequent service, producing a condition that is erroneously termed a bad spot in the wire rope. A spot like this is caused by a kink placed in the rope before or during service.

Cutting. Before the actual cutting operation, proper servings* should always be placed on each side of the point where the rope is to be cut. Such a precaution is absolutely necessary in order to prevent the unlaying or the rotating of the strands. It is advisable to use a minimum of three servings on each side of the cut.

Attachments. There are several ways in which the rope ends may be secured. The best one, developing 100% of the rope strength, is a socket connection.

In preparing the wire for socketing, the fiber core is entirely removed and the "brush" of separated wires is dipped in acid. The "brush" should never be dipped beyond three-quarters of its length, so that no trouble from corrosion difficulties may occur later. Moreover, a slight film of hydrochloric acid acts as a flux to assist in the amalgamation of zinc to the wires of the brush.

A thimble spliced in one end of the rope is often used for an attachment. Its efficiency varies between 75 and 90% of the rope strength, depending on the size of the rope. The thimble connection is also used with wire rope clips. This attachment has about the same efficiency as the splice. However, in order to obtain maximum efficiency, it is essential to apply the clips one rope lay apart, to tighten them securely and to place the U-bolts of the clips always on the dead end of the rope. "Rope lay" means the length of rope in which a strand makes one complete revolution about the rope axis. The use of incorrectly designed clips or unsuitable clip attachments results in strengths as low as 60% of the ultimate strength, or less. The thimble is also used with 3-bolt clamps and this efficiency, when the clamps are properly designed, is about the same or is greater than that obtained by using clips. Clips and clamps should be tightened after about an hour of operation and at regular inspection intervals after that. In all these connections employing the thimble it is essential that a proper design of wire rope thimble be used. It should have a large enough eye and should furnish the proper support to the rope.

Lubrication. The subject of lubrication for wire rope should be given careful consideration. Light applications of a comparatively thin oil are usually sufficient for elevator ropes that are not exposed to the elements; the conditions to be met in a mine shaft require a much heavier lubricant and a protector against corrosion.

It is not possible for manufacturers to place sufficient lubrication within a rope to last throughout its entire life. It is essential that a wire rope be lubricated internally as well as externally to reduce internal friction and to provide protection against corrosion. When corrosion starts inside a wire rope, the injurious effect can seldom be seen and cannot be arrested before the service and the safety of the wire rope are affected. It is preferable to use lubricant recommended by the manufacturer of the rope.

When the correct lubricant is applied properly, it will penetrate thoroughly into the rope and, after cooling, will adhere to the wires sufficiently not to drip off, and will form a plastic coating on the wire. The lubricant should also be free from ingredients that would injure the rope. Unsuitable lubricants that harden on the surface will result in more damage than benefit, because while keeping subsequent lubricants out, they let in and keep in moisture, thus accelerating corrosion.

In the American Engineering Standards Committee Paper, dated Feb. 24, 1927, is a set of rules for the selection of lubricants for wire rope.

Sheave and Drum Grooves. Improper sheave or drum grooves are undoubtedly responsible for more damage to wire rope than any other single factor causing ropes to

* Servings, sometimes called "seizings", are soft wire fastening secured around the rope to maintain its manufactured condition.

give irregular and uncertain service. It is essential that the grooves be large enough for operating with new ropes. The grooves are generally worn down by service; the amount of wear depends on the radial pressure and the material of which the sheave is made. The grooves wear to the diameter of the worn rope operated over them and consequently become small for the new rope. This causes the new rope to receive extra abrasion and distortion, both of which are very detrimental. Sheaves and drums should be inspected before the installation of new rope, and where the groove diameters have worn smaller than indicated by the limits given below, the sheaves should be replaced or remachined so that the groove diameter will correspond to the following limits:

Nominal Diameter of Rope, in.	Recommended Clearance, in. — Minimum	Maximum
1/4 to 5/16	1/32	1/32
3/8 to 3/4	3/64	1/16
7/8 to 1 1/8	1/16	3/32
1 3/16 to 1 1/2	1/16	1/8
1 5/16 to 2 1/4	3/32	3/16
2 5/16 and larger	1/8	1/4

Removal of Ropes From Service. It is first necessary to determine the factor of safety to which a rope may deteriorate without danger. This precaution is important. Though in some places the breaking of a rope would not endanger life or property, failure in other types of service would be very dangerous. Consequently the minimum factor of safety must be set. In general, ropes are likely to break rapidly if the outside wires have been reduced 50% of their diameter by abrasion. With some ropes, many wires start breaking before this amount of abrasion is reached. It is, therefore, the number and the distribution of the broken wires, together with the amount of abrasion, that indicate the remaining strength of the wire rope. The correct way to count a rope for broken wires is to count the number of such broken wires by strands per rope lay. Then the worst rope lay counted should be the one on which to base the estimate of remaining strength or on which to base the decision as to whether or not the rope should be removed from service. The rapidity with which broken wires develop indicates the degree of fatigue. Where the broken wires develop rapidly, the rope should be carefully watched, since it will, undoubtedly, have to be removed soon thereafter.

When corrosion occurs in a wire rope, it is impossible to estimate the remaining strength or to state whether or not the rope is safe. Since corrosion causes the wires to become more or less brittle, the reliability of the rope may become seriously impaired because of the rapid accumulation of broken wires. If these are not detected, the rope may fail in subsequent service. Even though a test for ultimate strength is made on a sample representative of the worst-appearing condition, as determined by visual inspection, there is no definite assurance that the sample tested is typical of the worst section in the remainder of the rope. Hence, even if this test proves satisfactory, there is still no positive assurance that the remainder of the rope is in as good or better condition than the piece tested. However, corrosion can be controlled by suitable lubrication.

Long life for wire rope depends on the following factors: use of the proper quality of wires; right construction for the installation at hand; large sheaves, with proper grooves; correct lubricants, applied properly for internal and external lubrication; prevention of corrosion; careful supervision to prevent "kinking" or "looping" in the installation, and overloading in service; a regular count of broken wires, to observe the development of fatigue.

Wire rope is one of the most reliable of structural materials, but it should be realized that a wire rope is essentially a machine, composed of many parts that function as a unit with the individual wires acting as bearing surfaces; and as such the rope is subjected to pressure and wear. It will be readily apparent that the ultimate service of wire rope will depend primarily on maintenance and care.

Sling and Crane Chain

BY THE SUBCOMMITTEE ON CHAIN*

THIS article deals with the care and selection of wrought iron chain, high-test steel chain and alloy steel chain. It does not cover stud-link anchor chain or corrosion-resisting steel, acid-resisting bronze, monel metal or chain larger than 2 in. in section.

Iron chain may be repaired by a competent blacksmith and, with proper equipment, can be satisfactorily annealed. However, steel chain should never be repaired by the user, unless the user is fully equipped for the proper welding, heat treating, proof testing and inspection. It is highly recommended that steel chain be returned to the manufacturer for repairing, since it is very important that all repairs be proof tested and inspected by trained personnel to verify the welding and heat treating.

Chain Dimensions. Table I, showing representative link dimensions and chain weights, is taken from ASTM Specification A 56–39 for Iron Crane Chain. Data for other grades of chain vary somewhat from these, according to the practice of the manufacturer. Where precise dimensions are required, a chain manufacturer should be consulted.

Types of Chains

Wrought Iron. The approximate chemical composition of chain made from this material includes less than 0.06% C and 0.06% max Mn. The average mechanical properties of wrought iron for chain are as follows: tensile strength, 47,000 psi; yield strength, 28,000 psi; elongation, 25%; and reduction of area, 40%. Wrought iron chain has good resistance to impact, to notching or bruising and to corrosion. Iron chain is subject to embrittlement at low temperatures; the impact strength is reduced to one half the normal value at 32 F and to one fifth at minus 4 F. At or below these temperatures, special care should be taken, and if possible the chain should be warmed before use. (Refer to Bureau of Standards Circular C-447, 271, Dec 1, 1943.) Repeated peening of the chain links against one another causes work hardening. Under impact, the hard skin produced by work hardening is broken, localizing the stress and eventually resulting in failure. The work hardened skin may be softened by periodic annealing of the chain.

* The members of this subcommittee are N. J. Gebert, *Chairman* (American Chain Division of American Chain & Cable Company, Inc.), A. D. O'Connor (Sun Shipbuilding & Dry Dock Co.), H. F. Parker (Columbus McKinnon Chain Corporation) and E. W. Taylor (S. G. Taylor Chain Company).

Table I

Link Dimensions and Chain Weights for Iron Crane Chain

Trade Size, inches	Actual Size of Material, inches	Inside Length of Link, inches	Inside Width of Link, inches	Approximate Number of Links per foot	Weight, pounds per 100 feet
3/8	13/32	1 3/32	5/8	11	166
1/2	17/32	1 11/32	3/4	9	275
5/8	21/32	1 11/16	7/8	7	430
3/4	25/32	1 7/8	1	6 1/2	615
7/8	29/32	2 1/4	1 1/4	5 3/8	820
1	1 1/32	2 9/16	1 3/8	4 3/4	1045
1 1/8	1 5/32	2 7/8	1 5/8	4 1/4	1310
1 1/4	1 9/32	3 1/16	1 3/4	3 7/8	1600
1 3/8	1 13/32	3 5/8	1 7/8	3 1/4	1930
1 1/2	1 17/32	3 7/8	2	3 1/8	2335
1 5/8	1 21/32	4 1/4	2 1/8	2 3/4	2740
1 3/4	1 25/32	4 3/4	2 1/4	2 1/2	3180
2	2 1/32	5 3/4	2 5/8	2 1/16	4100

Table II. Breaking, Proof and Safe Working Loads of Wrought Iron Chain

Trade Size, inches	Average Breaking Load, pounds	Minimum Proof Test Load, pounds	Safe Working Load, pounds
3/8	7,950	3,020	2,385
1/2	14,145	5,375	4,240
5/8	22,095	8,395	6,630
3/4	31,800	12,080	9,540
7/8	43,245	16,430	12,960
1	56,550	21,490	16,950
1 1/8	66,800	25,380	20,040
1 1/4	82,500	31,350	24,750
1 3/8	99,800	37,920	29,910
1 1/2	118,700	45,100	35,600
1 5/8	139,500	53,000	41,800
1 3/4	161,600	61,400	48,450
2	211,100	80,200	63,300

The strength properties of wrought iron chain are shown in Table II.

Annealing Treatment of Wrought Iron Chain. The following periodic treatment of wrought iron chain is used generally to remove the effects of work hardening. Unless the treatment is carried out regularly, the chain may fail under impact or repeated loads.

Heating. The chain should be heated to the temperatures given in Table III, and held at temperature for the time specified. The heat should penetrate the work material thoroughly and the top, center and bottom of the charge should reach approximately the same temperature. A sufficient number of thermocouples should be used to assure uniform temperature throughout the charge.

Table III. Annealing Treatment for Wrought Iron Sling and Crane Chains

Diameter of Chain Link, in.	Annealing Temp, deg Fahr	Time of Holding at Temp, hr	Cooling Medium
1/4 to 1/2	1350 to 1375	1/2	Air
5/8 to 1	1350 to 1375	1	Air
1 1/8 to 1 1/2	1350 to 1375	1 1/2	Air
1 5/8 to 2	1350 to 1375	2	Air

Cooling. After the chain has been held at the annealing temperature for the specified time, the charge is pulled onto the cooling platform or onto the floor. The chain should be spread in single layers, with enough space between chains for uniform cooling to room temperature.

After the chain has been annealed, it should be proof tested and reinspected for defective welds and links. By burning off dirt and grease adhering to the chain, the annealing treatment facilitates inspection.

High-Test Steel. The chemical composition of chain made from this material corresponds approximately to SAE 1020. In the heat treated state the average mechanical properties of this material are as follows: tensile strength, 85,000 psi; yield strength, 55,000 psi; elongation, 28%; and reduction of area, 45%. This chain has excellent resistance to impact loading and work hardening, with minimum elongation of 20% at the break. There is no known record of high-test steel chain work hardening to a detrimental degree, so it should never be necessary to heat treat again

Table IV. Breaking, Proof and Safe Working Loads of High-Test Steel Chain

Trade Size, (a) inches	Average Breaking Loads, pounds	Minimum Proof Test Load, pounds	Safe Working Load, pounds
1/4	8,550	4,275	2,150
5/16	12,100	6,050	3,025
3/8	17,100	8,550	4,275
7/16	22,200	11,100	5,550
1/2	28,000	14,000	7,000
9/16	35,000	17,500	8,750
5/8	40,500	20,250	10,125
3/4	56,000	28,000	14,000
7/8	76,500	38,250	19,125
1	97,000	48,500	24,250
1 1/8	121,000	60,500	30,250
1 1/4	150,000	75,000	37,500

(a) Where accurate link dimensions are required, consult the manufacturer.

Table V

Proof and Safe Working Loads of Alloy Steel Chain(a)

Trade Size, inches	Minimum Proof Test Load, pounds	Safe Working Load, pounds
1/4	5,500	2,750
5/16	8,800	4,400
3/8	13,200	6,600
7/16	17,600	8,800
1/2	22,500	11,125
9/16	27,500	13,750
5/8	33,000	16,500
3/4	46,000	23,000
7/8	57,500	28,750
1	77,500	38,750
1 1/8	89,000	44,500
1 1/4	115,000	57,500

(a) Because some manufacturers use material of exact size and some use material 1/32 in. oversize, breaking loads are not given. Where these figures or accurate link dimensions are required, the manufacturer should be consulted.

to remove such effects. Good resistance to low-temperature embrittlement is also characteristic of this chain.

The strength properties of high-test steel chain are shown in Table IV.

Alloy Steel. Material used in the manufacture of this chain is fine-grain alloy steel, and the types in general use contain 0.25% max C.

Exact compositions vary according to the manufacturers' practices, but the types now in use approximate SAE 2320, 4615, 4620 and 8620. When heat treated, these materials develop average mechanical properties, as follows: tensile strength, 125,000 psi; yield strength, 100,000 psi; elongation, 17%; and reduction of area, 60%. Alloy steel chain has excellent resistance to embrittlement at low temperatures.

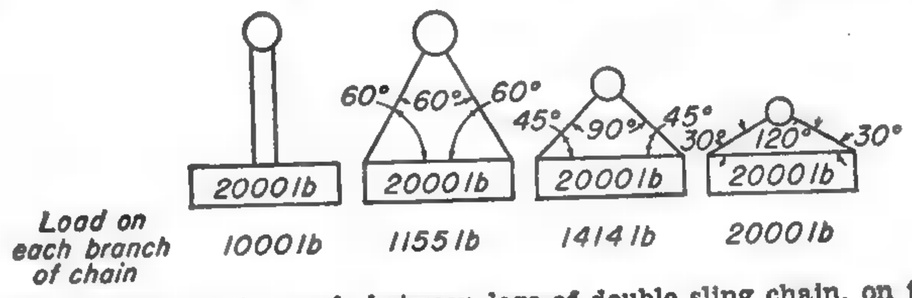


Fig. 1 Effect of the angle between legs of double sling chain, on the load on each branch

This chain also has high resistance to wear because of its hardness, and has a minimum elongation of 15% at break. For all practical purposes this chain is not affected by work hardening.

The proof loads and safe working loads of alloy steel chain are shown in Table V.

General Information

Proof Test. The proof test is the actual load in pounds applied to the complete sling-chain assembly by the manufacturer, before shipment of the chain. This load should not be confused with the safe working load. Usually the proof test is twice the safe working load.

Angle of Sling Chains. The angle between legs or branches of a double sling chain should always be taken into consideration. As this angle increases, the angle decreases between the legs and the piece being lifted. This greatly reduces the safe working load of the chain because, as the angle between the two legs of the chain increases, the tension in each leg is also increased. Thus the tension in each leg varies directly with the sine of the angle between the chain and the horizontal (Fig. 1).

Sling Chain Inspection

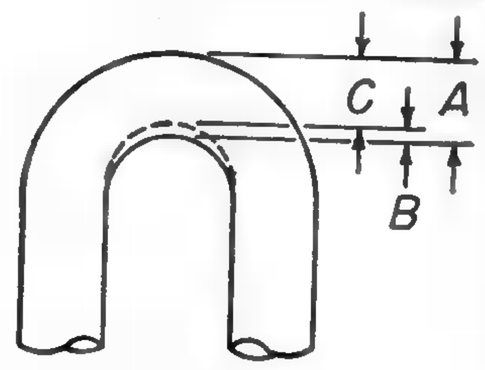
1 For preliminary inspection, hang chain in vertical position, if practical. Chain should hang reasonably straight if links are not distorted.

2 Check for stretch and clearance between the links. Stretch is best indicated by a narrowing of the links. All links should remain entirely free and should have reasonable operating clearance so that the chain remains flexible. If binding or lack of clearance exists, narrow links should be removed. Stretched links are a positive sign that the chain has been overloaded.

3 Check each link for wear by lifting it from its seat and inspecting visually for grooving. If grooving has caused a greater reduction in diameter than that shown in Table VI, the link should be removed.

Table VI. Permissible Wear of Chain

Trade Size, inches	Actual Diameter of New Stock, inches — A	Maximum Permissible Wear, inches — B	Minimum Safe Dimension at Worn Part of Link, inches — C
¼	9/32	1/32	7/32
5/16	11/32	1/32	9/32
3/8	13/32	1/32	11/32
7/16	15/32	1/32	13/32
½	17/32	1/32	15/32
9/16	19/32	1/32	17/32
⅝	21/32	1/32	19/32
¾	25/32	1/32	23/32
⅞	29/32	1/32	27/32
1	1 1/32	1/32	31/32
1⅛	1 5/32	1/32	1 3/32
1¼	1 9/32	1/32	1 7/32



4 Make link-to-link inspection, looking for bent links; cracks in weld areas, shoulders or other sections; scores or markings that would weaken the chain (transverse markings are most dangerous); corrosion pits; lifted fins on either electric or forge welded chain, usually indicating overload; and excessive peening, particularly in iron chain. Check rings and pear-shaped links for all the above faults. Check hooks for opening and for cracks, scores, pits and so on.

5 Unless full and adequate facilities for repair are available, chain showing the above faults should be returned to the manufacturer for reconditioning.

Table VI shows the maximum permissible amount of wear for given sizes of chain.

Care of Sling Chains. A sling chain is one of the most important pieces of equipment in any plant, since it not only lifts and conveys but must also safeguard life and property. Every reasonable care should be taken not to damage, overload or distort the links or attachments. A thorough periodic inspection of sling chains is strongly recommended.

Care should be taken to avoid overloading a sling chain, since the damage caused by this careless operation will greatly shorten the life of the chain and may result in dangerous and costly failure.

It is imperative to avoid impact loading on chains, because great damage to a sling can be done by a relatively small drop of a weight even lighter than the safe working load.

The following precautions should be observed in using sling chains:

1 Take up slack and then start load slowly.
2 Protect sharp corners to prevent damage to chain and load.
3 Keep chain free from twists, knots and kinks.
4 Lift from center of hooks, never from the point.
5 Distribute the load evenly on all legs.
6 Have sling chains inspected and reconditioned regularly.
7 Periodic annealing of iron sling chains has been found beneficial when carefully performed under proper supervision.
8 If iron chain must be used in extremely cold weather, warm it slightly before using.
9 Do not connect two pieces of chain by means of bolts or pins.

Composite Steels

By T. S. Fitch*

A COMPOSITE STEEL has been defined as one that consists of two or more components, of which the smallest comprises at least 3% of the total mass. The components may be joined by casting, welding or other processes.

Characteristics. Using a composite steel may result in one or more of the following advantages: (1) a hard working area with a tough backing, (2) reduction of the cost of material where one of the components is expensive, and the cost of production is not too great, (3) improved resistance to shock, (4) protection against corrosion and oxidation of the surface, (5) special physical properties as a result of combining dissimilar materials—such as thermostatic effect in lead-in wire for electric bulbs, to match the thermal expansion of glass, (6) the possibility of drilling the backing after the article has been hardened, and the possibility of a certain amount of straightening, if warpage has taken place, (7) a damping effect on the vibration of the composite steel as a whole, and therefore less chattering, because each component has a period of vibration of its own.

The chief disadvantage of composite steels, in both production and fabrication, is warpage. This may result from differing expansion characteristics or from an unbalanced arrangement of the components so that the stresses in one section of the piece do not offset those in another section. In many instances the quality of the weld is extremely important, and not all the methods to be described necessarily result in satisfactory welds; the application for which the composite material is to be used, may determine the best method to employ.

Examples of composite steels of various types are shown in Fig. 1 to 6, with typical applications listed.

* President, Washington Steel Corporation, Washington, Pa.

Blacksmith or Forge Weld Method. The "blacksmith's weld" or "forge weld" method is the oldest used for producing composite steels, and is also the simplest, but it is limited to carbon steels and certain low-alloy steels.

The Casting Process. In this method, probably the oldest that has been used for tonnage production, a composite ingot is produced by pouring one metal onto or around another. The technique has many variations, so only the general methods will be mentioned:

1 The earliest application was probably for making "soft-center" plowshares. Molten high-carbon steel is cast about a previously positioned iron insert so that the iron comprises about one-third of the cross section and is located centrally. Since the insert must be reasonably clean, it is usually pickled just before casting. Also the insert should be completely enveloped by the molten metal, because no weld is actually produced in the ingot when one metal is cast around a relatively cold insert. If there is space for air to penetrate between the insert and the cast metal before further working, an excessive amount of oxide will form on the surface of the insert and the cast metal. With carbon steels it is possible to produce a bond even if the insert is not entirely enveloped, but the weld will be somewhat inferior.

In this country, mild steel is cast around cold alloy inserts (particularly stainless steel inserts) as a commercial practice. The process is described in the article entitled "Stainless Clad Steels" on page 545 in this Handbook. It is especially important for the inserts to be as clean as possible when the mild steel is cast and for them to be enveloped completely by the cast steel.

2 There have been attempts to cast metal onto or around a preheated insert. When alloy inserts are heated without some surface protection, in a furnace where gas, coal or oil is burned, a poor weld results.

3 In England, particularly, successful composite steels have been produced by casting one steel into a mold divided by a removable partition. Then the partition is removed and the second steel is cast quickly in the mold. Since both metals are in the fluid or nearly fluid condition, good welds may be produced.

4 It is possible to improve the bonded condition of a composite steel by increasing the surface area of the insert. To accomplish this increase in area, serrations are cut in the insert as shown in Fig. 7.

5 Where the strain on the weld is not great, a satisfactory composite casting can be made by "keying" the insert into the backing. Figure 8 shows how an insert might be cut and held mechanically in the casting.

6 In one of the newest methods the insert is electropickled for removal of all oxide and is then moved wet into a plating bath to obtain a protective coating by electrodeposition. This coating is usually iron because iron is easy to weld onto, produces no zone of weakness as copper would, and also has a high melting point. The electroplated insert is then placed in a mold and the molten metal is cast around it as already described. Excellent welds are produced by this method.

7 In another method, a coating is placed on the side of the mold wall before casting. This coating is composed chiefly of ferroalloy of the desired parent metal plus certain chemicals, so that controlled cladding ($\frac{1}{64}$ to ½ in. thick) results when the molten metal is cast into the mold. This method can also be adapted so that cladding can be placed on previously cast or forged articles.

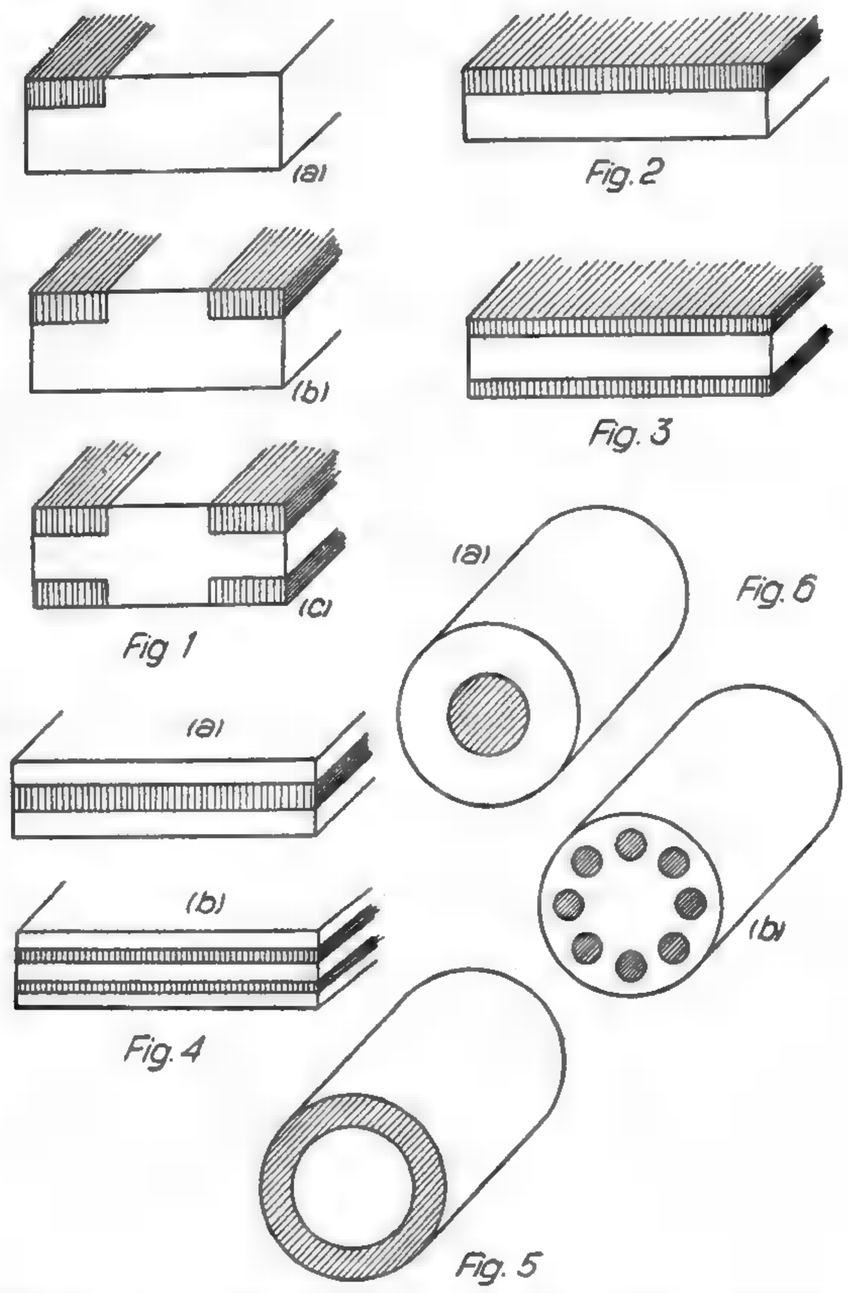


Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 1 Hacksaw blades, shear blades, knives of all types, and lathe tools

Fig. 2 Blanking, piercing, drawing, forming and stamping dies; single-bevel knives, circular knives and cutters, parts that resist abrasion; parts that resist heat and corrosion; and machine ways

Fig. 3 Soft-center plowshares with stainless steel cladding. Applications involving heat conductivity, such as cooking utensils, vats, griddles, electric contacts

Fig. 4 (*a*) Double-bevel knives (*b*) Vault steels

Fig. 5 Reamers, drills, broaches, decorative trim and parts that resist heat and corrosion

Fig. 6 Dies (*a*); punches (*a*); pivots (*a*); jailbar (*b*); stoker bars (*a*) or (*b*); special structural shapes (*a*) *or* (*b*)

The casting method, ordinarily the least costly, is generally convenient for tonnage work and permits production of sections irregular in themselves or containing irregular inserts.

The Cementation Process. The cements used in this process are, in many instances, complicated combinations in which the basic constituents are iron filings, silicomanganese, ferrosilicon, nickel and borax. Some of these cements are so effective that it is necessary merely to squeeze out the excess, and after the cement has hardened, a good bond results. For large sections, a heavy press is advisable, but for small tools (such as tool bits for lathes) the components may be squeezed with a pair of tongs and held until cold. These cements require temperatures in the vicinity of 2300 F. The producers recommend that the surfaces be machined before cementation.

One of the latest refinements of this general process has been applied for combining nonmetallic material with metallic claddings; for example, wallboard is made with a thin cladding of stainless steel by putting a special cement on the nonmetallic surface, placing the stainless steel sheet thereon and then sending the cemented materials through rolls to bond the two components together.

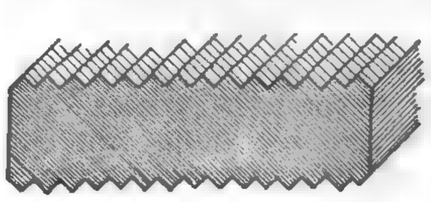


Fig. 7

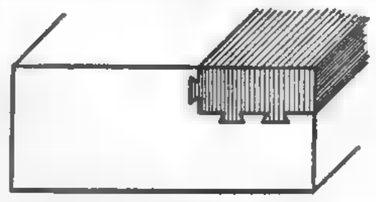


Fig. 8

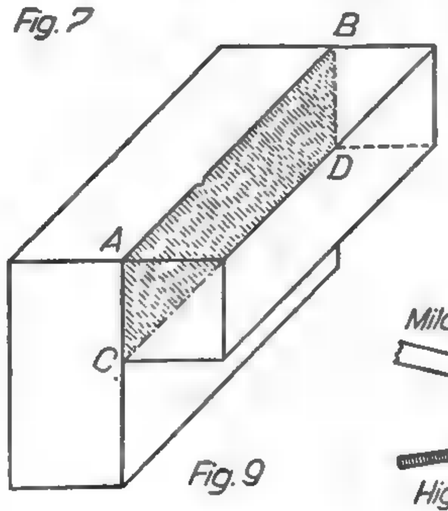


Fig. 9

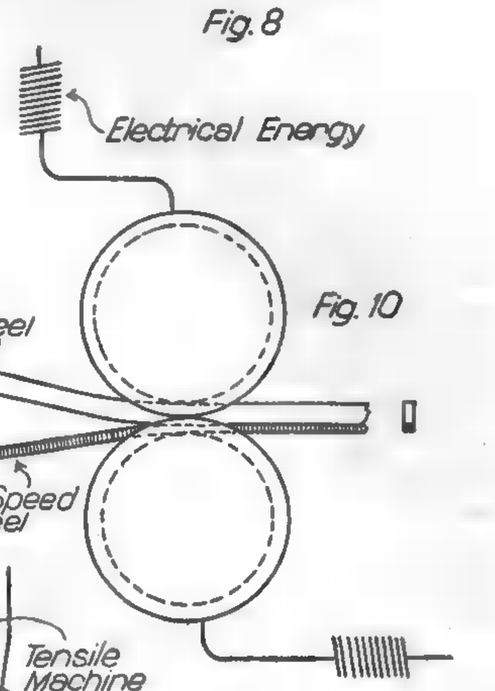


Fig. 10

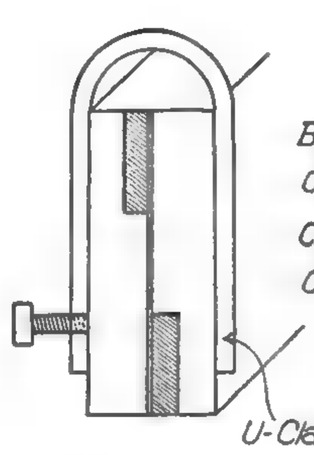


Fig. 11

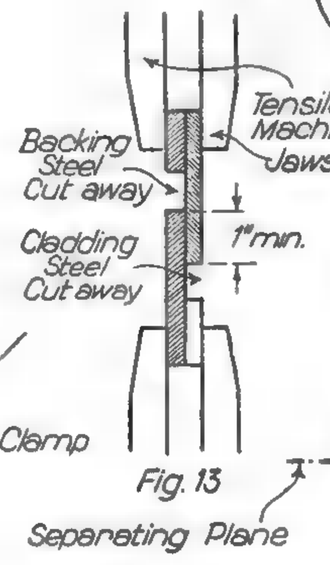


Fig. 13

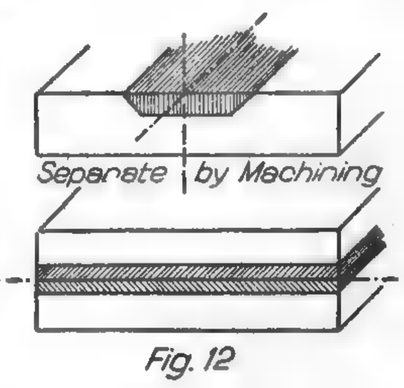


Fig. 12

Fig. 7 Bond improved by cutting serrations in the insert

Fig. 8 Method of keying insert into the backing material

Fig. 9 Composite die section made by welding insert

Fig. 10 Composite hacksaw strips made by electric resistance welding

Fig. 11 Multiple heat treatment in clamps to offset stresses

Fig. 12 Assembly or ingot made double the desired size so that stresses are partially offset

Fig. 13 Tension test of composite steel in the welded condition

Fusion Welding Processes. Whenever more than about 3% of one metal is deposited on the surface of a steel base metal by fusion welding, the resulting article is a composite steel. Certain types of articles that are made in this way are described under the title "Facing or Surfacing by Welding", in this Handbook; production of other composite steels by fusion welding is discussed below.

When the components are small enough, the penetration of the welding heat may be sufficient to produce a strong joint between them. For example, in the making of composite die sections it may be desirable to weld a piece of steel 1 by 1 in. to a section of mild steel 1⅛ by 2¼ in., as indicated in Fig. 9. The welds are made along the lines *AB* and *CD* and, with proper control of the arc, good fusion may be effected to a depth of ½ *AC* during each welding operation; thus the finished section will be completely fused throughout the weldable plane *ABCD*.

Electric resistance welding has been adapted successfully to the making of composite hacksaw strips. Low-voltage, high-amperage current is conducted through rolls to the mild steel strip and the high speed steel strip, which are held firmly together by the rolls (Fig. 10).

For applications in which a cheap steel is faced with an expensive alloy that resists corrosion or heat, such composite steels are often produced by "spot welding" one to the other. The result is a large number of welded spots

surrounded by nonwelded areas; consequently the material is held together less securely than a composite sheet or plate having a homogeneous welded condition.

The Assembly Process. This method consists in joining together prefabricated bars or plates and then subsequently reworking the assembly to the desired finished form. For a complete description of this process, the reader may refer to the article entitled "Stainless Clad Steels" on page 545. This method is advantageous in many instances because of greater flexibility, when used for small quantities, than with any of the casting methods; also the relative proportions of the components can be controlled more accurately. Generally the assembly process is somewhat more costly than the casting process.

Backings. Only recently has special consideration been given to the backing materials used in the production of composite steels. The problem is complicated by conflicting requirements, especially where the insert is placed so that it is likely to pull the bar out of shape. An important consideration is the desired mechanical characteristics of the backing material in the finished article; for example, a composite hacksaw steel should have a backing component that is as tough as possible without becoming too hard during the hardening of the blade; whereas a composite stainless plate should ordinarily have a soft back that may be readily formed. For an article that is to be heat treated, it would be ideal for the two alloys of the composite to have the same coefficient of thermal expansion, in order to eliminate warpage. From the producer's viewpoint it would be ideal if the two metals had equal rates of elongation so that the composite product could be worked similarly to solid steels.

SAE 1020 is the steel most often used for backing. This alloy is relatively inexpensive, easily obtained, readily formed even after hardening, and comparatively simple to weld. However, if a fairly tough backing steel is preferred, then SAE 1020 is not the best type. Its coefficient of expansion differs appreciably from that of the alloys customarily used for inserts, which means difficulty in any heating or cooling operation; the rate of elongation is more rapid than that of the usual insert alloys; and enlarged grains develop when the composite product must be annealed after working. In spite of these drawbacks, SAE 1020 has been and probably will continue to be the usual commercial backing for most applications.

In instances where the comparative coefficients of expansion are most important, a silicomolybdenum steel (0.10% C, 0.20% Mn, 1.50% Si, 0.50% Mo) has proved satisfactory. Also SAE 2340 has given good results. The coefficients of expansion of these steels are more like the coefficients of tool steels, particularly high speed steels, than are the coefficients of any other relatively inexpensive steels that have been tried.

For applications such as chipper knives when the knife must have a tough backing component to absorb severe shocks, the following composition has proved excellent: 0.28 to 0.34% C; 0.45 to 0.65% Mn; 0.35 to 0.55% Si; 0.020% S and P max; 0.85 to 0.95% Cr; and 0.20 to 0.25% V.

For applications such as hacksaw blades, where it is desirable to produce some hardening effect in the backing steel, the following composition has proved satisfactory: 0.42 to 0.50% C; 0.50 to 0.65% Mn; 0.20 to 0.40% Si; 0.020% S and P max; 1.25 to 1.45% Ni; and 0.50 to 0.65% Cr. After proper hardening, this alloy affords a backing that has springiness and superior resistance to abrasion. It is somewhat more difficult to weld properly, but this disadvantage can be overcome by the proper choice and adaptation of method.

Heat Treatment. The difficulties in the heat treatment of composite steels depend on where the inserts are located, relative proportion of inserts to backing component, relative composition, and suitability of equipment. Considerable experience is usually necessary before fully satisfactory results are obtained, but a composite steel can usually be straightened somewhat after hardening and tempering.

Design. The location of the inserts is important only when the coefficients of expansion differ. If a tool steel and backing steel had the same expansion rate, the warpage would be no worse than on a solid piece of either steel. When the insert is placed symmetrically within the mass of the composite cross section, there is no abnormal warpage, because the deformational stresses offset one another; for example, a composite bar that has a high-carbon, high-chromium alloy steel center uniformly surrounded with SAE 1020, will not pull out of shape during heat treatment. When the insert is along one edge or covers one flat surface entirely, the composite steel may bow; when the insert is in one corner, the bar may be pulled out of shape in two directions, so this form is the most difficult to heat treat.

Relative Proportions. The smaller the amount of tool steel in comparison with the amount of backing, the less will be the likelihood of warpage.

Relative Compositions. The greater the difference in the thermal properties of the component metals, the greater will be the warpage during heat treatment. Since the thermal properties are determined primarily by the composition and also depend somewhat on grain size, it is obvious that the relative compositions are important.

Air Cooling. Any composite steel made of materials that can be cooled in air, may be held straight in a press after being removed from the furnace. In some instances, particularly where the insert is in one corner, a special die with a groove is made for the press so that the bar is sure to be straight lengthwise as well as flatwise.

Multiple Heat Treatment. Small composite sections are heat treated best in pairs. About the maximum convenient size is ⅝ by 6 in. Bars larger than this have too much distortional strength. To hold them, such large clamps would be required that handling would be inconvenient, and unless the clamps were carefully designed, nonuniform heating might result. The intention of this multiple heat treating method is to arrange the bars within the group in such a way that the stresses will offset one another. A typical example is shown in Fig. 11.

Presetting Method. In this method considerable experience is required in learning precisely how much and in what direction to deform the bar before heat treatment, so that the stresses during treatment will cause the bar to return to adequate straightness. This method is not recommended when the insert comprises 40 to 60% of the mass.

The section should be treated so that, after tempering, the insert will be convex. The material may be straightened when the tool steel is under compression because the backing steel will elongate readily.

Annealing and Normalizing. The simplest method of producing composite steels in which the insert mass is unsymmetrically arranged in the backing, is to make the assembly or ingot twice the size of the finished form so that the stresses will offset one another at least partially. Two typical forms are shown in Fig. 12.

Testing. Because of the presence of materials with dissimilar characteristics, composite steels present a peculiar and often difficult testing problem. It is not feasible to prescribe testing methods that will apply in all instances, because of the numerous modifications in composite steels. The following comments are intended to be helpful in establishing and interpreting tests.

The simplest method of testing the welded condition is the bend test. For material clad on one side it is recommended that one piece be bent with the cladding on the outside and a second piece with the cladding on the inside of the bend. It is advisable to bend every piece back again, because an improperly welded composite steel may bend one way without showing a fracture at the weld.

A more severe and reliable test of the welded condition may be made by pulling a specimen that has been prepared as shown in Fig. 13, in a tension-testing machine.

Welded flat specimens for the tension test may be pulled satisfactorily and the results will usually be found reasonably accurate. In round specimens that are machined from bar stock, the proportion of inserted material to backing material may be changed by machining. Allowance should be made for this in evaluating results.

The reliability of the various methods of hardness testing depends chiefly on the thickness of the piece to be tested. Samples $\frac{3}{16}$ in. or thicker may be tested safely by Rockwell hardness-testing devices or by any of the testing machines that incorporate the drop-and-rebound principle, such as the scleroscope. Samples thinner than 0.0625 in.

are tested best on machines of the drop-and-rebound type. Actually the surest practice is to grind or otherwise remove all the steel except where the hardness is to be tested.

In making cup tests on specimens of clad sheet and strip, there will be some variation, depending on the direction in which the cup is drawn; if the insert material is on the inside of the cup, the draw tends to be better. The reason for this is that the soft backing material supports the harder insert material during the draw. Users who wish to determine the drawing properties, should draw the material so that the stainless steel is on the same side as in the finished product. When reporting cup tests, it should be stated whether the cladding was inside or outside.

General. Two methods are in common use for indicating the location and extent of the insert in a composite steel—acid etching and heat coloring. A warm 50% nitric acid solution will reveal the insert in approximately 30 sec. The acid may be washed off with warm water; and lacquer, oil or vaseline may then be put on the etched plane to protect it from subsequent corrosion. Heat coloring is often used when the insert is a tool steel or SAE steel that can be turned straw-color or light blue if the end is exposed to a temperature that does not affect adversely the structure of any of the components. The colored plane should be protected with lacquer, oil or vaseline. Heat coloring renders the insert more readily visible but is not so fast as the acid-etch method.

When any machine work is done on a composite tool steel before heat treatment, a hardening effect results and thus a strain is set up. This strain is relieved preferably by normalizing before the hardening process. The warpage during hardening and tempering may thus be reduced. This machine strain is not a serious factor on short sections. 18 in. or less.

During fabrication, composite steels have decided advantages. For example, a tool steel composite bar may be 25% tool steel, and the remainder soft steel that can be machined more quickly. Composite steels in which the inserted material is symmetrically arranged, may be cold drawn faster. Clad plates can be bent or formed more readily than solid material of the same composition.

The fusion welding of composite steels (not referring to the production of the composite steel itself) requires special precautions:

1 Because of the tendency of the alloying elements in the insert to migrate into the unalloyed steel, it is well to select a welding rod that has higher alloy content than the insert steel; this tends to replenish any loss resulting from migration.

2 In electric-arc welding, the amperage should be maintained as low as efficient because excessive heat may admix the backing and insert steels. In high-alloy composite steels, the carbon in the tool steel might be reduced sufficiently to impair the desirable properties; also the backing might be embrittled locally by carbon enrichment.

3 Thick composite steels (⅜ in. or more) should be beveled away from the insert; then a small bead is laid down along the abutting insert edges, the two plates are turned over, and the back is filled in with whatever rod suits the conditions.

4 In the stainless clad steels a stabilizing element such as titanium or columbium should be added to the stainless composition to avoid intergranular corrosion in subsequent welding; thus annealing can be eliminated after welding.

5 High-grade electrodes of the shielded-arc type, or gas filler rods are recommended.

A skilled operator with suitable equipment can soon learn to weld composite steels satisfactorily.

Stainless Clad Steels

By L. C. Grimshaw*

PLATES and sheets of mild steel faced with stainless steel have been produced commercially for about ten years. The layer of stainless steel usually constitutes 10 to 20% of the thickness of the plate or sheet; either one or both sides may be coated. Such clad steels have been developed largely to reduce the cost of stainless plates, particularly for the many applications where only one side of the plate needs to be stainless.

Strength of Bond. The bond between the mild steel and the stainless "cladding" must be strong enough to withstand stresses incident to fabrication into the finished product. Stainless clad steels are produced that can be bent, spun into deep heads, and deep drawn without damage. Often the bond must be strong enough to withstand great stresses caused by a difference of expansion between the stainless facing and the backing when the material is heated and cooled repeatedly.

Methods of Bonding. Two clean pieces of mild steel will weld together readily if hammered while being heated. High-carbon steel and mild steel can be welded similarly though less easily, and usually with the aid of a flux. Indeed, the first commercial use of laminated steel was probably such a combination used for turning plows, manufactured by John Lane in 1868.

Nickel and mild steel, and copper and mild steel, can be welded together by heat and pressure alone. High-alloy steels cannot be successfully welded to mild steel by this method without considerable modification; they were first successfully welded by "casting on", a method relatively old, and often referred to in technical publications at the turn of the century.

Casting. Stainless clad sheets and plates are produced successfully by casting methods. In one casting method, two cleaned sheets of stainless steel are placed face to face with a separating material between them, and are fusion welded together around the edges. These two sheets are then set upright in a mold, and mild steel is poured all around them. The composite ingot is hot rolled until it has received the desired amount of reduction; the edges of the rolled composite plate are trimmed off and it separates into two sheets, each clad on one face with stainless steel.

Temperature control during casting is important. Since there is oxide on the surface of the stainless steel insert in the ingot, no effective weld can be made until this oxide is broken up by elongation into small islands.

Because of the fusion weld required in their fabrication, it is important from an economic standpoint that the clad plates be made large in size. There is a limit to the amount of reduction that can be given by hot rolling before the material between the two stainless sheets fails to separate them because of thinning out. The above method has been used to produce plates as thick as 1¼ in., but only of small size (1500 to 2000 lb) and not thinner than 18 gage.

A different method for producing stainless clad plates by casting is said to be used successfully in England. Grooves are cut in opposite sides of a mold, in such a position that a spacer plate slid down in these grooves divides the mold in a ratio of about 3 to 1. Mild steel is cast into the larger space. After a short time the spacer plate is withdrawn and stainless steel is cast into the remaining space. After cooling, two such ingots are surface ground, and their stainless faces are placed face to face with separating material between them. "Straps" of mild steel are then fusion welded all around the sides to hold the two-high assembly together. The assembly is then heated, rolled, and separated into two clad plates by shearing off the edges.

This method would seem to be subject to all the limitations of the first casting method described above.

Facing With Weld Metal. A method now in the early stages of development appears to be especially suitable for the production of thick plates in which the stainless steel may well be much less than 10% of the plate thickness. The stainless steel (usually 18–8) is deposited on

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the mild steel slab from electrodes. This forms a good weld, and only enough hot rolling need be given to the slab to eliminate the cast structure of the stainless steel; to facilitate discovery and elimination of pinholes in the deposit; and to smooth the surface.

Other Welding Methods. In another method of bonding, a thin sheet of iron, placed between the stainless and the mild steel, is fusion welded around the edges to prevent scaling, and is then heated and hot rolled. The thin sheet of iron is said to have a beneficial cushioning effect, and after a great deal of elongation by rolling, a satisfactory weld can be made. Oxides are troublesome, and the results are too uncertain for this method to be used commercially. No matter how carefully stainless steel is cleaned, it becomes covered with an invisible oxide film as soon as it is exposed to air, and before a weld can be made, the oxide thus formed must be broken into small islands by elongation during rolling. It is undoubtedly easier to weld stainless steel to iron of low carbon content than to iron of high carbon content. A variation of the method above would be to decarburize the surface of the mild steel before attempting to make the weld, and to leave out the thin piece of sheet iron. A zone of pure iron in the weld is a zone of weakness, and should be reduced as much as possible.

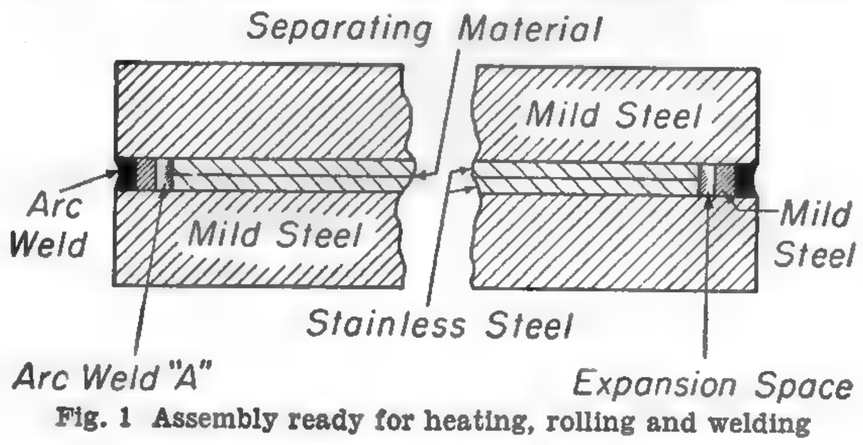

Fig. 1 Assembly ready for heating, rolling and welding

A commercial method that is used increasingly, produces a good weld after the invisible oxide film has been removed from the stainless steel by anodic pickling in hydrochloric acid. Electrolytic iron is then deposited on a chemically clean surface. Iron plating is begun while the stainless steel is still wet with acid and free from oxide film. The iron plating is usually about 0.012 in. thick. Any kind of steel plated in this manner with electrolytic iron will weld to mild steel if heated and rolled. When stainless clad plates are produced commercially by this method, "separating material" is placed between the juxtaposed faces of two sheets of stainless steel, and a watertight fusion weld is made around the edges of the sheet. The unit is then pickled, iron plated and placed between two thick plates of mild steel. This assembly is fusion welded together around the edges, both to hold it together as a unit during hot rolling and to exclude air that would cause scaling on the surfaces to be welded. It is then heated and hot rolled. During the first pass a weld is made; then rolling is continued to produce plates of the desired size. The composite assembly behaves like mild steel, and may be cross rolled if necessary to increase the width. When the edges are trimmed off, the composite plate separates into two plates, each clad on one face with stainless steel.

If the stainless steel is austenitic (the 18–8 variety) it will expand a great deal more than the mild steel when it is heated for rolling, and so must be left free to expand laterally between the mild steel plates. Such an assembly ready for heating, rolling and welding, is shown in Fig. 1. No expansion space is needed for martensitic or ferritic stainless steels.

During hot rolling, even with little reduction, an excellent, oxide-free weld is made. Diffusion soon eliminates the zone of electrolytic iron in the welded plate, since this zone is less than 0.002 in. after 12 to 1 reduction of the two-high assembly. Diffusion is rapid while the plate is hot. Such plates may be spun readily into deep heads, or may be drawn.

Stainless clad plates are produced successfully also by iron-plating stainless steel in the above manner, and casting mild steel around it. The surface of the stainless steel is as free from oxide as in the assembly method, and it is more satisfactory to cast mild steel against the iron plating than against the stainless steel itself.

Separating Material. In most of these methods, whether by casting or assembling, it is common practice to prepare a "sandwich" with mild steel outside, stainless sheets inside, and separating material in the center. The "sandwich" is held together as a unit either by an excess of cast metal or by fusion welding the edges. The difference in the hot working properties and in expansion of the stainless and mild steel tends to produce curled plates. By rolling as a "sandwich", curling is prevented. Hot rolling of single clad sheets is not done unless the finished sheet can be straightened cold. Hot straightening is impracticable, since the straightened sheet curls again when cooling, particularly if clad with 18–8 stainless steel.

The separating material used in two-high assembles is commonly a mixture of aluminum oxide and lacquer, spread like paint thinly and evenly over the steel surface. The lacquer dries in a short time, leaving the fine oxide powder adhering to the steel. Any inert oxide can be used, but sodium silicate should not be substituted for lacquer unless all moisture is driven off at a high temperature before the sheets are assembled for rolling.

Resistance Welding. Another commercial method of making stainless clad plates is to bond a stainless sheet to a mild steel plate by a special method of resistance welding. The electric current does not pass through the thickness of the mild steel plate; instead it passes from one spot on the stainless sheet through the surface of the mild steel to another spot on the stainless sheet only a short distance away. This method bonds by means of a great number of resistance welds, placed close to one another all over the sheet. Such a sheet is never rolled except in forming rolls. The bond, though discontinuous, is strong enough to withstand the stresses incident to heat treatment and to fabricating into spun heads. By this method composite plates of any convenient size are produced, and thick plates are covered with a protecting sheet of stainless steel, far less than 10% of the plate thickness. Many large tanks, cracking vessels and chemical towers have been made in this way.

Uses of Stainless Clad Steels. Stainless clad steel may be useful either because of lowered cost (in comparison with solid stainless steel), improvement of physical properties, or both. Lowered cost seems obvious, but is actually difficult to attain. The stainless sheets used for cladding must have at least one perfect surface and must be flat. The mild steel plates must also be flat if the assembly method is used. The fusion welding of an assembly is expensive, and stainless rod must be used for weld *A* (Fig. 1). If casting is used, there is waste by trimming.

Since clad plates are rolled in pairs, one clad plate is always left over when only a single clad plate is desired.

However, many clad sheets are used because of the physical properties obtained. If the weld is a good one, cooking vessels such as those used in the varnish, canning, and soap industries are best when made of stainless clad steels; for although the inside of such vessels is required to be stainless, a solid stainless steel vessel is subject to hot spots and low heat conductivity. The clad vessel combines the stainless surface with the excellent heat conductivity of mild steel.

The 12 or 28% Cr ferritic stainless irons are often desired for use, but they are difficult to fusion weld. This problem is solved by substituting ferritic stainless iron as cladding on mild steel, and such clad steels are finding increasing applications.

Austenitic steels, such as 18-8, have a coefficient of expansion greater than that of mild steel, so for stainless clad plates used at elevated temperatures the bond must be good. The high quality of many commercial bonds is proved by the wide use of such material at elevated temperatures. If the fabrication of the steel vessel requires fusion welding, and intergranular corrosion is feared, an 18-8 steel that contains a stabilizing element is advisable, because a stabilizing heat treatment at 2000 F is undesirable when applied to the mild steel backing, and would also probably warp the vessel.

Nickel and Nickel-Alloy Clad Steels

By W. G. Theisinger* and F. P. Huston*

NICKEL-CLAD steels are composite materials consisting of a base of open hearth steel that has a layer of pure nickel or an alloy of nickel and chromium bonded to it on one or both surfaces.

The composite plate is formed by pressure-welding the clad material to the steel slab in a rolling mill at a temperature of about 2200 F. Thorough cleaning and protection of the bonding surfaces during heating insures an intimate bond between the cladding and the base plate. A reduction ratio ranging between 8 to 1 and 16 to 1 is generally used. A solid solution of nickel and iron is formed at the junction of the two metals.

The ratio of the cladding material to the base plate is usually expressed as a percentage of the total thickness of the composite plate. For example, a ½-in. plate clad 10% on one side only, consists of about 0.45 in. of steel and about 0.05 in. of pure nickel; a ½-in. plate with 20% cladding, consists of about 0.10 in. of pure nickel and 0.40 in. of steel. The same order of thicknesses of cladding is produced for plates clad on both sides. It is the usual practice when cladding both sides to use an equal thickness of either nickel or the nickel-chromium alloy, although different thicknesses may be applied. For special purposes plates may be obtained that are clad on one side with nickel and on the other side with the nickel alloy. Nickel-clad steels are regularly supplied with standard claddings of 5, 10, 15 and 20%, with flange-quality steel that has a minimum tensile strength of 55,000 psi, as the standard base metal.

Properties of Pure Nickel for Cladding. The modulus of elasticity of commercially pure nickel is 29,000,000 to 30,000,000 psi, which is essentially the same as for steel, and the hot working range is likewise similar to that of steel. The coefficient of expansion of nickel is close to that of steel.

The fact that the modulus of elasticity of nickel is the same as that of steel is important in a composite material such as nickel-clad steel plate and insures equal distribution of stress across the section of the plate with no sudden change at the interface between nickel and steel.

Properties of Nickel-Clad Steel. Results obtained from an 8-in. tensile test specimen of nickel-clad steel ½ in. thick and with 10% cladding are as follows:

	Tensile Strength, psi	Yield Point, psi	Elongation, % in 8 in.	Reduction in Area, %
Clad	60,600	40,400	30.0	57.2
Plate	60,800	40,200	30.5	59.0

To determine the value of bond between the nickel and steel, a clad surface was placed at right angles to the striking face and with one blow of a power hammer a 1-in. cube, with one face clad 20%, was flattened cold to ⅜ in. in thickness without rupturing the bond. To test the strength of the bond after sudden changes of temperature, a 10% clad plate (18 by 9 by ½ in.) with stiffeners welded to the steel side was heated to 900 F and quenched in water at room temperature. No separation of the nickel layer occurred after quenching 30 times.

Treatments for Nickel-Clad Steel. Cold bending, flanging, forming, beveling and the like, can be carried out readily on nickel-clad steel. Ordinarily, and especially when shearing and punching, the nickel side should be up so as to prevent damaging the surface and to throw the burr on the steel side.

Annealing. Annealed plate is required for severe cold working operations; for example, in pressing heads and die work. To anneal, heat the plate between 1650 and 1750 F, hold at temperature from 1 to 3 min, and allow the plate to cool in the air.

A fuel of low sulfur content (not more than 0.5%) should be used to prevent embrittlement of the nickel layer. A covering of lime on the nickel surface is helpful.

Heating. When nickel-clad steel is heated, either for annealing or for hot working, the plate is charged into the furnace, which is at temperature. The atmosphere should be reducing and the flame should not strike the surface.

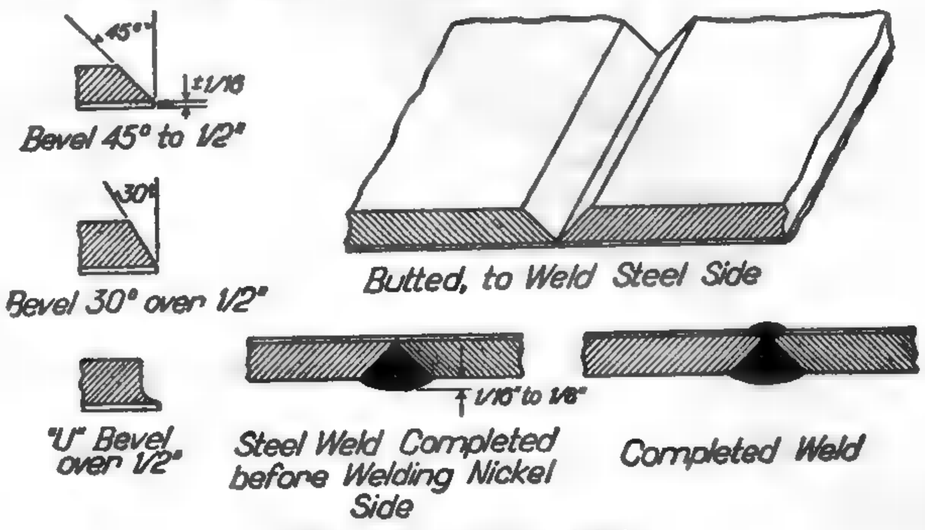

Fig. 1 Beveled butt joints

Hot Working. The hot working of nickel-clad steel entails no unusual difficulties if the proper conditions for heating are maintained. No change need be made from the usual practice for steel, in regard to temperatures, amount of work done on each heat, or the general methods used in performing the work.

Joining. Nickel-clad steel plates and heads may be joined to form pressure vessels and tanks by gas or electric welding, or riveting and calk welding. With all methods, the nickel surface should be made continuous by welding all junctions in the nickel side of the joint with nickel filler metal. In general, the resistance of such welds to corrosion is not inferior to that of the nickel surface.

Table I. Tension and Bend Tests of Welds

	Tensile Strength, psi	Yield Point, psi	Elongation, % in 2 in.
Full section	65,300	40,700	25.0
Reduced section	59,800	40,300	22.2
Bend Tests			
Steel weld, outside surface	31.0% elongation in 1 in.		
Nickel weld, outside surface	37.0% elongation in 1 in.		

Metal-arc welding is the method generally used. The plates are beveled as shown in Fig. 1, and the vessel is assembled by "tacking" on the steel side. The weld on the steel side is then made with a covered steel electrode; no change from standard practice for welding plain steel is required. A narrow groove on the nickel side is then chipped to a depth at which the chip no longer shows parting. The width and depth of the groove vary with the thickness of the cladding layer, but should be kept to a minimum. The width is usually ¼ in. and should never exceed ⅜ in., even in 1-in. plate. The welding on the nickel side is done with coated nickel electrodes. If two beads are required, the slag should be completely removed from the surface of the first bead before the second is deposited. Butt welding is most commonly used, though the lap and the butt-and-strap joint are also used.

Because carbon-arc welding is necessarily slow, this method is used only occasionally for welding nickel-clad steel, but it yields strong, dense welds of high ductility.

Acetylene welding gives satisfactory joints in nickel-clad steel and no change from regular procedure is needed in welding the steel side. However, in welding the nickel side it is important to maintain a slightly reducing flame, since the intense flame that yields entirely satisfactory welds in steel gives brittle and spongy welds in nickel. Bare nickel wire for gas welding is used without flux.

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* Development and Research Division, The International Nickel Company, Inc., New York.

Nickel-clad steel may be welded in all positions encountered in erection work by any of the methods mentioned. In vertical welding it is advisable to start the weld at the top and work toward the bottom rather than the reverse.

Welds in nickel-clad plate meet the requirements of the ASME Boiler Code. Samples of plates welded as described above were stress relieved at 1150 to 1200 F and gave the results shown in Table I.

Design. A continuous nickel surface should be maintained in the fabrication of pressure vessels and other equipment. Jackets are welded or riveted to clad vessels and any type of bottom outlet, either in solid nickel or nickel-clad steel, may be attached. Forged, tapped welding flanges in solid nickel are used. Virtually any formed shape obtainable in steel is obtainable also in the nickel-clad material. The material responds readily to hot spinning, hot and cold pressing, and hand shaping.

Nickel-Chromium Clad Steel. The alloy containing 78 to 80% Ni, 12 to 14% Cr, and 6 to 8% Fe, combines a high degree of resistance to corrosion with high strength and good working properties.

Nickel-chromium clad steel and nickel-clad steel are manufactured similarly, can be fabricated with the same facility and can be welded by similar procedures. In welding the clad surface of the plate, a covered electrode containing 80% Ni and 20% Cr is used. This insures deposited metal of approximately the same composition and resistance to corrosion as the cladding.

Nickel-Copper Clad Steel. The alloy containing 67% Ni, 30% Cu and 1 to 2% Fe, combines several desirable features of both nickel and copper under corrosive attack.

Nickel-copper clad steel and nickel-chromium clad steel are manufactured similarly, can be fabricated with the same facility and welded by comparable procedures. In welding the clad surface of the plate, a covered electrode of approximately the same composition as the cladding is used.

Copper-Covered Steel Wire

By L. C. Whitney*

ENGINEERING requirements often demand a combination of properties in a material that is not found in any single common metal or alloy. Copper-covered steel wire is an example of this. The copper exterior provides high electrical conductivity and good resistance to corrosion, and the steel core allows the development of tensile strengths considerably above those attainable in hard drawn copper and bronze wires.

To produce this material, a round steel billet with its surfaces properly prepared is preheated in a mold, and molten copper is poured around it. After solidification, the composite billet is hot rolled to a rod, which is then heat treated or annealed and drawn into wire of the desired size.

The casting of molten copper around a heated steel billet with properly prepared surfaces produces a weld between the two metals. This weld withstands subsequent heating, hot rolling, and cold drawing; the finished wire may be bent, twisted or deformed without causing a separation of the two metals.

This composite wire is produced commercially in two grades based on the electrical conductivity of the material. They are the 30% and 40% grades, a designation which indicates the electrical conductivity as a percentage of that of a solid copper wire of the same cross-sectional area. The electrical resistance, measured on each coil, is less than the limits shown in Table I.

* Chief Metallurgist, Copperweld Steel Co., Glassport, Pa.

Table I. Electrical Resistance of Copper-Covered Steel Wire

Rated Conductivity	Max Average Resistance for Entire Coil, ohms per cir mil-ft at 68 F	Max Resistance for Any Part of Coil, ohms per cir mil-ft at 68 F
30%	35.26	39.18
40%	26.45	28.59

In addition to the two grades having specified conductivities, two other grades are based on the tensile strength of the wire. These are designated as "high-strength" and "extra high-strength" grades. Detailed information on the properties of individual wire sizes is given in Table II.

To insure a uniform coating of copper of the desired thickness on the wire, all coils are tested with a magnetic testing device which measures the thickness of copper accurately at any given point. By means of such equipment, it is possible to guarantee a minimum thickness of copper at any point around the circumference of the wire.

Physical and electrical constants and specifications for copper-covered wire are as follows:

Average weight of wire. 8.15 ■ per cu cm at ■ F. (Equivalent values are 3.533 lb per in.-ft and 0.002775 lb per cir mil-1000 ft)

Coefficient of linear expansion. 0.0000072 per ° F

Temperature coefficient of electrical resistance for wire. 0.0021 per ° F

Modulus of elasticity. 24,000,000 psi

Table II. Properties of Copper-Covered Steel Wire

Diam, in.	Breaking Load, lb: High Strength 40% cond	Breaking Load, lb: High Strength 30% cond	Breaking Load, lb: Extra High Strength, 30% cond	Weights(a): lb per 1000 ft	Weights(a): lb per mile	Resistance, ohms per 1000 ft at 68 F: 40% cond	Resistance, ohms per 1000 ft at 68 F: 30% cond	Cross Section: cir mils	Cross Section: sq in.
0.4600	13,300	14,960	....	587.2	3100	0.1250	0.1666	211,600	0.1662
0.4096	10,540	11,860	....	465.7	2459	0.1576	0.2101	167,800	0.1318
0.3648	8,361	9,407	....	369.3	1950	0.1988	0.2650	133,100	0.1045
0.3249	6,797	7,791	....	292.9	1546	0.2506	0.3341	105,500	0.08289
0.2893	5,916	6,705	....	232.2	1226	0.3160	0.4213	83,690	0.06573
0.2576	5,056	5,682	6,412	184.2	972.5	0.3985	0.5313	66,370	0.05213
0.2294	4,258	4,754	5,519	146.1	771.2	0.5025	0.6699	52,630	0.04134
0.2043	3,541	3,934	4,672	115.8	611.6	0.6337	0.8447	41,740	0.03278
0.1819	2,938	3,250	3,913	91.86	485.0	0.7990	1.065	33,100	0.02600
0.1620	2,433	2,680	3,247	72.85	384.6	1.008	1.343	26,250	0.02062
0.1443	2,011	2,207	2,681	57.77	305.0	1.270	1.694	20,820	0.01635
0.1285	1,660	1,815	2,204	45.81	241.9	1.602	2.136	16,510	0.01297
0.1144	1,368	1,491	....	36.33	191.8	2.020	2.693	13,090	0.01028
0.1019	1,130	1,231	....	28.81	152.1	2.547	3.396	10,380	0.008155
0.09074	896	....	....	22.85	120.6	3.212	....	8,234	0.006467
0.08081	785	....	....	18.12	95.68	4.051	....	6,530	0.005129

(a) There is a slight difference between the weights of 30% and 40% conductivity wire. These figures represent the average for both.

STAINLESS STEELS AND HEAT-RESISTING ALLOYS

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Corrosion-Resistant Castings

By E. A. Schoefer*

CASTINGS are classed as corrosion-resistant if they are capable of sustained operation when exposed to attack by corrosive agents at operating temperatures that create metal temperatures lower than 900 F. Ferrous alloy castings for such service fall into the following groups: iron-chromium ("straight chromium" alloys); iron-chromium-nickel (chromium in excess of nickel); and iron-nickel-chromium (nickel in excess of chromium).

Nickel-base and other nonferrous alloys also employed for their resistance to corrosion, are discussed elsewhere in this Handbook. The ferrous castings used for corrosion resistance include many alloys of the same general type as those used for their resistance to corrosion or structural damage at elevated temperatures above 900 F. As a rule, such heat-resistant alloys contain considerably more carbon than the corrosion-resistant grades, but the distinction between the classes is rather vague and there is overlapping in the temperature range from 900 to 1200 F. Thus, the terms "corrosion-resistant" and "heat-resistant" are relative and are arbitrarily differentiated by the operating temperature of the material.

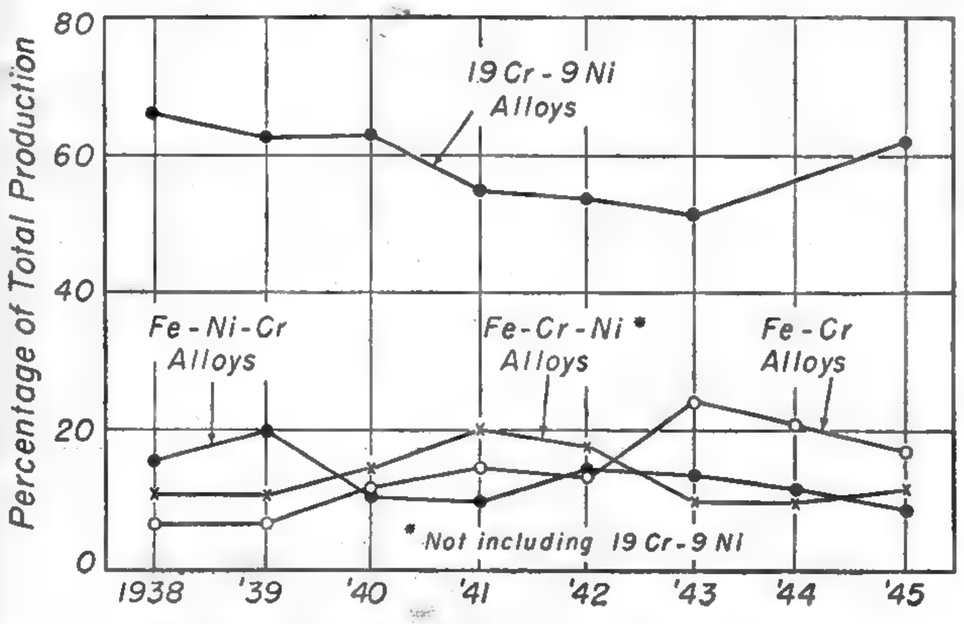

Fig. 1 Production of corrosion-resistant castings (Alloy Casting Institute)

Corrosion-resistant castings, as defined, are used in equipment for chemical plants, food processing, oil refineries, textile mills, pulp and paper mills, sanitation, building construction, transportation, and miscellaneous services that involve handling corrosive substances.

Alloys that contain from 18 to 22% Cr and 8 to 12% Ni are by far the largest group of corrosion-resistant castings. The straight chromium compositions are also produced in considerable quantities, particularly the hardenable alloys that contain from 11.5 to 14.0% Cr. Other alloys with chromium in excess of the nickel content are used for special service conditions, as are the alloys that contain nickel in greater amounts than chromium. A summary by percentage of total production for each of these groups in recent years is shown in Fig. 1.

Table I. Physical Properties of Corrosion-Resistant Castings

ACI Type	Mean Composition, % Ni	Mean Composition, % Cr	Mean Coefficient of Linear Thermal Expansion, Range, deg Fahr	Mean Coefficient of Linear Thermal Expansion, Per deg Fahr	Density, pounds per cubic in.	Modulus of Elasticity in Tension, million psi
CA	1 max	12	32 to 1300	0.0000067	0.275	29
CB	2 max	20	32 to 212	0.0000057	0.272	29
			32 to 1300	0.0000067		
CC	4 max	28	32 to 212	0.0000059	0.272	29
			32 to 1000	0.0000063		
CE	9	29	32 to 1600	0.0000105	0.277	22
CF	9	19	32 to 212	0.0000096	0.280	28
			32 to 1100	0.0000104		
CG	11	21	32 to 212	0.0000090	0.281	28
			32 to 950	0.0000099		
CH	13	24	32 to 212	0.0000083	0.279	28
			32 to 950	0.0000096		
CK	20	25	32 to 212	0.0000080	0.280	29
			32 to 950	0.0000092		

General Physical Properties. Mechanical properties are given in the descriptions of the individual alloy types. Table I shows mean coefficients of thermal expansion, moduli of elasticity in tension, and densities.

Manufacture. Castings produced in the various compositions for resistance to corrosion, may be made from heats melted in electric-arc furnaces with either acid or basic linings; or in high-frequency induction furnaces with acid, basic or amphoteric linings. The production of sound, satisfactory castings requires care, especially when the

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castings are to be used under pressure, and foundries producing such castings have developed special techniques for this work. Castings may be made by the static method, by centrifugal pouring, or by precision casting (*see* article entitled "Precision Casting", page 54).

Heat Treatment. Castings used for their resistance to corrosion are almost always subjected to heat treatment. For the hardenable ferritic-martensitic straight chromium compositions, the heat treatment is primarily for the purpose of obtaining desired mechanical properties. Austenitic alloys, such as the 19% Cr, 9% Ni type, on the other hand, are heat treated to increase their resistance to corrosion. These latter alloys are usually heated to a temperature of 1900 to 2100 F and are quenched rapidly in air, water or oil in order to ensure the solution of carbides. When the alloys are quenched from 1900 F or higher, it is most important that a rapid cooling rate be maintained through the range 1600 to 1000 F, since in this range carbides may precipitate along the grain boundaries, thus making the alloy subject to intergranular corrosion.

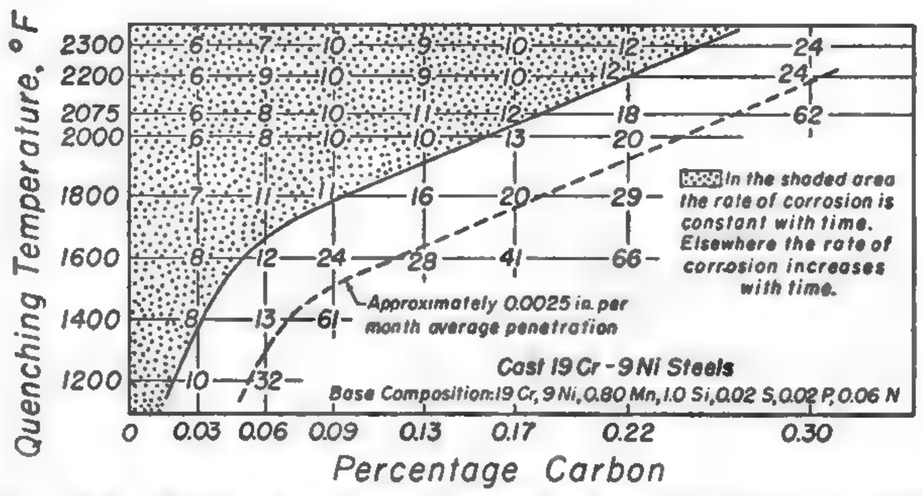

Fig. 2 Effect of carbon content on resistance to corrosion in boiling 65% nitric acid. Specimens were quenched in water after ½ hr at the temperatures indicated. Numbers on the graph indicate the penetration in ten-thousandths of an inch per month, calculated from the average loss in weight during five 48-hr periods in boiling nitric acid. (See Reference 1 for details, including micrographs of the alloys.)

Heat treatment for the 12% Cr alloy castings usually consists of air cooling or oil quenching from about 1800 F, and then tempering between 600 and 1400 F, depending on the final properties desired. Tempering at about 900 F results in a marked loss of impact resistance.

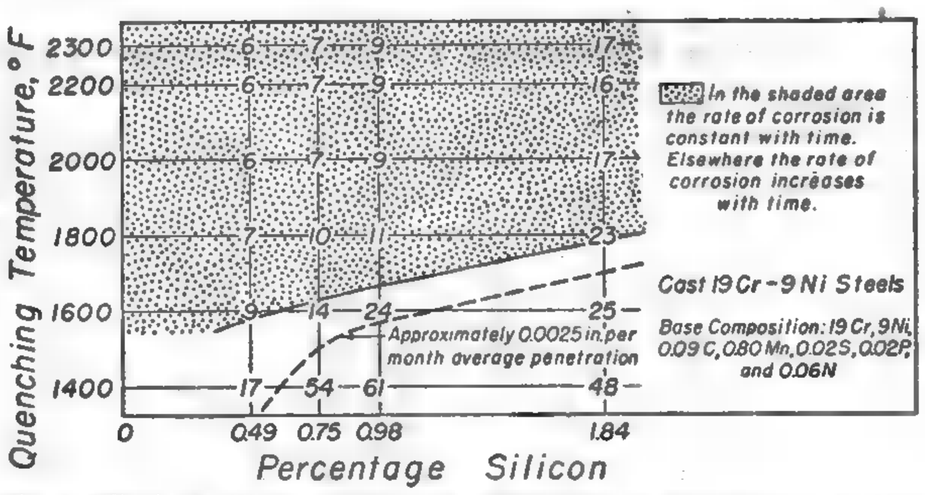

Fig. 3 Effect of silicon content on resistance to corrosion in boiling 65% nitric acid. (See caption for Fig. 2.)

Proper quench-annealing of the 19% Cr, 9% Ni alloys produces desirable carbide-free structures. Such structures render the alloys immune to intergranular attack as long as the metal is not exposed to temperatures in the carbide precipitation range from 800 to 1600 F. The quenching temperatures required depend on the carbon and silicon contents of the alloy. If molybdenum is present, it must also be considered in determining the quenching temperature that will result in a carbide-free material. Figures 2, 3 and 4 show the relations between rates of corrosion in 65% boiling nitric acid, the microstructures, the quenching temperatures, and the carbon, silicon and molybdenum contents, respectively, of a series of 19% Cr, 9% Ni alloys. The solid curves on these charts form the boundary between alloys with constant rates of corrosion and those with rates that increase with time. All alloys to the left and above the broken curves have average rates of corrosion slower than 0.0025 in. per month, as measured by five 48-hr test periods in boiling nitric acid. In general, it is advisable to select a quenching temperature that is somewhat higher than indicated by the solid line for the composition under consideration.

Where castings are to be welded without subsequent heat treatment, the injurious effect of carbide precipitation that results from the heat of welding, can be eliminated by the addition of columbium to the alloy. The carbon in the alloy combines preferentially with the columbium, so columbium carbides rather than chromium carbides are precipitated. Depletion of chromium at the grain boundaries is prevented by this action; therefore intergranular corrosion does not occur.

Columbium-containing alloys that have been heated to sensitizing temperatures around 1200 F, although not subject to intergranular corrosion, have over-all corrosion rates, when tested in nitric acid, somewhat greater than those for columbium-free, quench-annealed alloys of the same nickel, chromium and carbon content. For columbium-containing alloys in the sensitized condition, rates of corrosion comparable with the rates for quenched alloys, can be obtained by balancing properly the chromium, carbon, manganese and silicon.

Where the usual quench-annealing practice is difficult or impossible, a 24 to 48-hr heat treatment at 1600 to 1800 F is helpful in improving the resistance of castings to intergranular corrosion. Except for alloys of very low carbon content, however, this treatment fails to produce material with as good resistance to intergranular corrosion as properly quench-annealed material. The effect of extended heating at various temperatures is shown in Fig. 5 and 6 for alloys that contain 0.06 and 0.12% C.

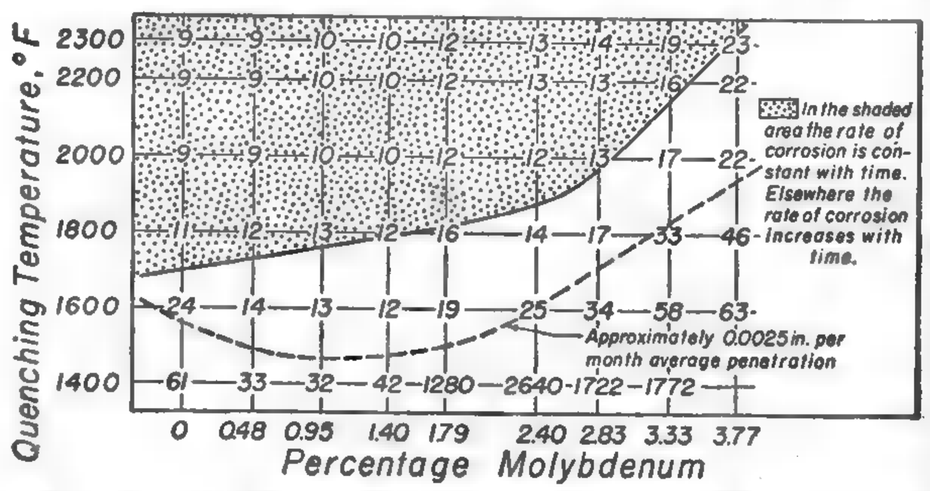

Fig. 4 Effect of molybdenum content on resistance to corrosion in boiling 65% nitric acid. (See caption for Fig. 2.)

Iron-Chromium Alloys. The so-called straight chromium alloys are made in the compositions listed in Table II.

Table II. Composition Limits of Iron-Chromium Corrosion-Resistant Castings

ACI Type	Composition, percentage — Carbon	Manganese	Silicon	Chromium	Nickel
CA-15	0.15 max	1.00 max	1.50 max	11.5 to 14	1.00 max
CA-40	0.20 to 0.40	1.00 max	1.50 max	11.5 to 14	1.00 max
CB-30	0.30 max	1.00 max	1.00 max	18 to 22	2.00 max
CC-50	0.50 max	1.00 max	1.00 max	26 to 30	4.00 max

Type CA. Castings made from this alloy are used extensively for applications that require high resistance to oxidation and also resistance to erosion. A considerable tonnage is utilized for valve trim. Castings are made from two alloy grades: 0.15% C max, and 0.20 to 0.40% C. Of the two, the low-carbon grade is the more popular. The mechanical properties of the alloy can be altered by heat treatment. Figure 7 shows typical values obtained, after various treatments, for an alloy containing 0.14% C and 0.56% Ni. As the nickel content is increased in these alloys, there is an increased tendency for the material to air harden when air cooled from 1500 F. This is an important consideration when the alloy is softened before machining.

Type CB-30. The 20% Cr alloy has greater resistance to corrosion than the CA type, but the material is only slightly hardenable by heat treatment. Castings of this alloy are used for valve bodies and trim, and for contain-

ers for nitric acid. When the 20% Cr alloy is used for service in contact with nitric acid, the carbon content is customarily limited to 0.20% max. Because of difficulty in casting low-carbon alloys of the CB type, the carbon content is usually from 0.20 to 0.30%. As carbon content is increased, however, the corrosion resistance is impaired. In recent years the CF type (19% Cr, 9% Ni) has replaced

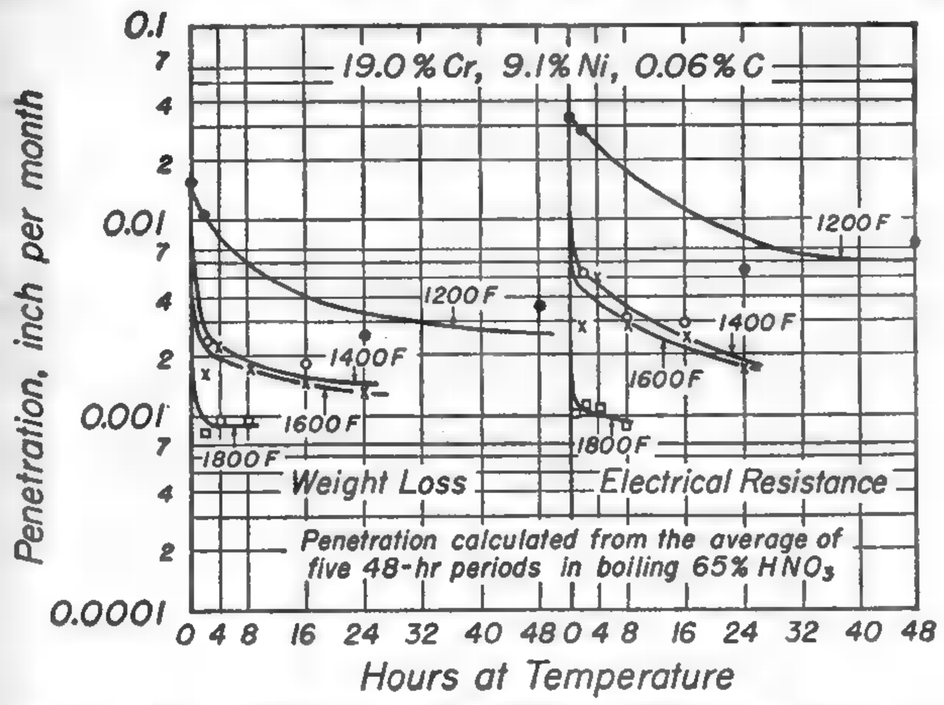

Fig. 5 Effect of holding at temperatures of 1200 to 1800 F for 2 to 48 hr on corrosion rate in nitric acid. Alloy composition: 0.06% C, 19.0% Cr, 9.1% Ni. As cast, heat treated in muffle furnace. Penetration average, five 48-hr periods in boiling 65% nitric acid (Reference 2)

the CB grade in many applications, and production of the straight chromium type has consequently declined.

Typical mechanical properties of a 20% Cr alloy, oil-quenched from 1850 F and tempered at 1400 F, are:

Tensile strength, psi	75,000
Yield strength, psi	50,000
Elongation, per cent in 2 in	15
Brinell hardness number	170

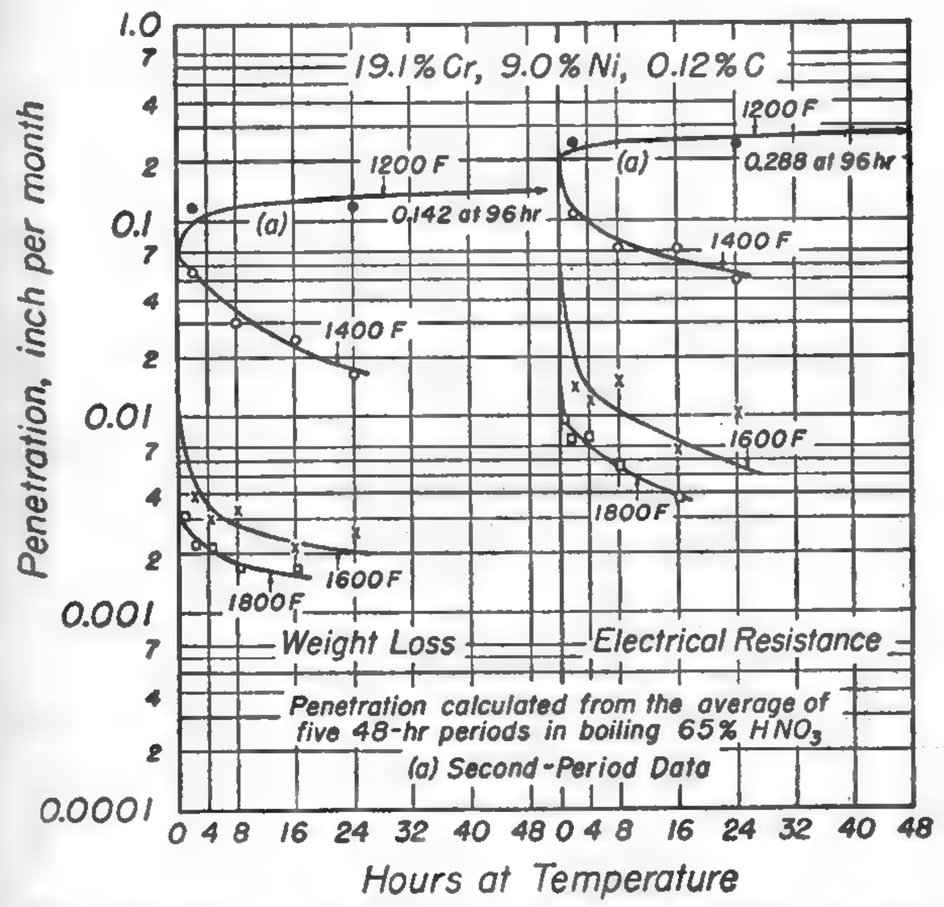

Fig. 6 Same as Fig. 5 except that this alloy contained 0.12% C, 19.1% Cr, 9.0% Ni (Reference 2)

Type CC-50. Alloys that contain about 28% Cr and up to 4% Ni are resistant to oxidizing corrodents and have been used extensively in contact with acid mine waters. Castings may be used in the as-cast condition without heat treatment. Typical mechanical properties of the CC-50 type are:

Tensile strength, psi	65,000
Elongation, per cent in 2 in	2
Brinell hardness number	212

In the CC type of alloy containing more than 2% Ni, strength and ductility are improved by increasing the nitrogen content to 0.15% or more.

Machinability of all the straight chromium alloys is as good or better than that of annealed 19% Cr, 9% Ni type alloys. Weldability is fair. Castings made of these compositions are usually preheated between 400 and 800 F before

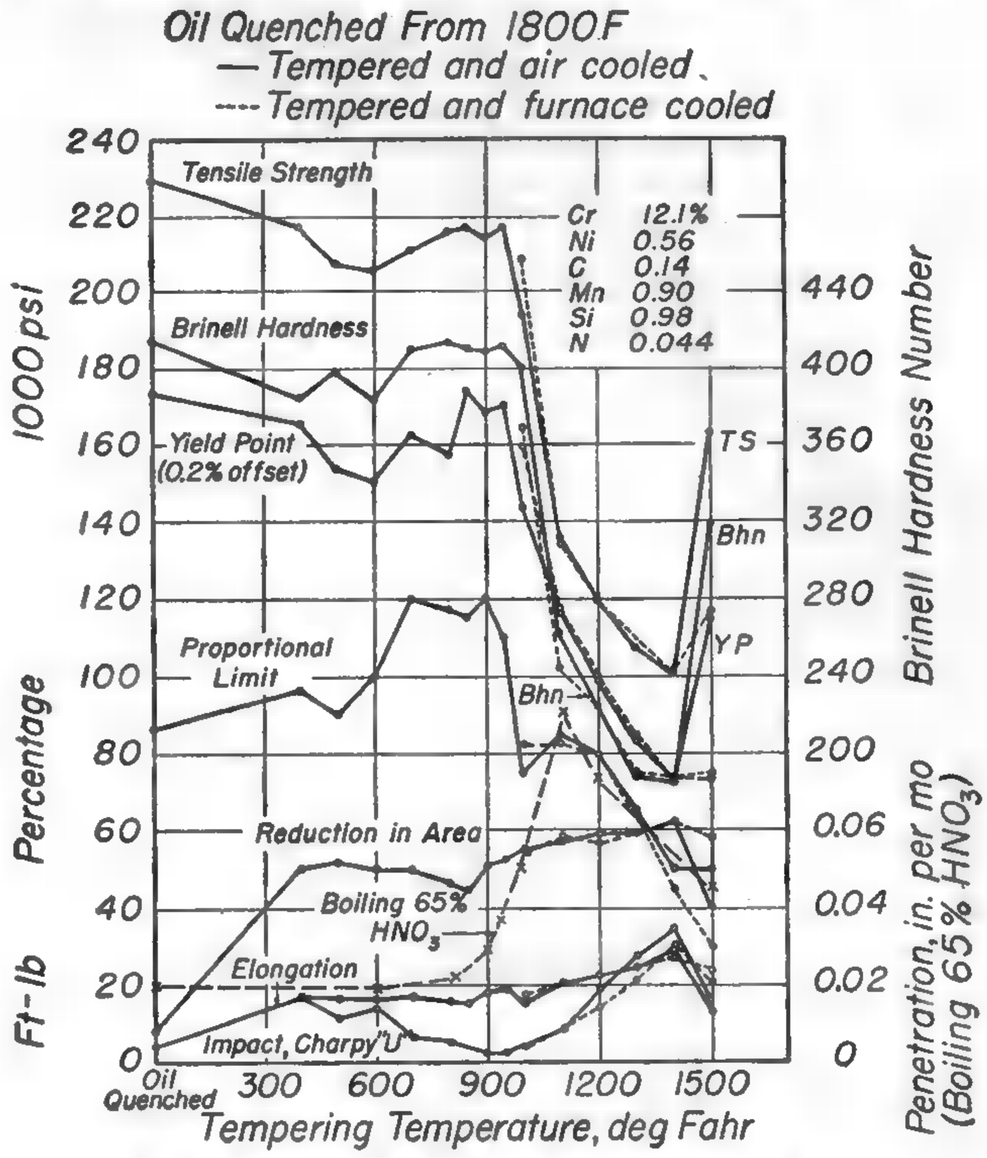

Fig. 7 Mechanical properties of 12% Cr steel casting (Alloy Casting Institute, previously unpublished data)

being welded. After welding, the alloys are heated between 1100 and 1400 F and are then cooled in air.

Iron-Chromium-Nickel Alloys. Ferrous alloys in which the chromium content exceeds the nickel content are made in the compositions listed in Table III.

Table III. Composition Limits of Iron-Chromium-Nickel Corrosion-Resistant Castings

ACI Type	Composition, percentage				
	Carbon (max)	Manganese	Silicon	Chromium	Nickel
CE-30	0.30	1.50 max	2.00 max	26 to 30	8 to 11
CF-*	0.07; 0.10 0.16; 0.20	1.50 max	2.00 max	18 to 20	8 to 10
CG-12	0.07; 0.10 0.16	1.50 max	2.00 max	20 to 22	10 to 12
CH-*	0.10; 0.20	1.50 max	2.00 max	22 to 26	12 to 15
CK-25	0.25	2.00 max	2.00 max	23 to 27	19 to 22

* These alloys are made in several carbon grades, designated CF-8, CF-16 F (free-machining), CF-20, CH-10, CH-20.

Type CE-30. This alloy has been used in considerable quantities for valves, fittings and pumps handling sulfite liquor in the paper industry. Type CE alloys can be made with a higher carbon content than the CF type composition, without suffering the injurious effects of carbide precipitation. In the as-cast condition the CE alloys have a structure consisting of austenite, ferrite and carbides; because of this structure the metal is less susceptible to intergranular corrosion than alloys of the CF type. For this reason, type CE alloys are useful where castings cannot be heat treated effectively or where they must be welded without subsequent heat treatment.

Although the CE alloys are often used in the as-cast condition, the ductility and resistance to corrosion may be improved somewhat by quenching the material from about

2000 F. Nominal mechanical properties of the as-cast alloy are as follows:

Tensile strength, psi	90,000
Yield strength, psi	50,000
Elongation, per cent in 2 in.	15
Brinell hardness number	197

Type CF. Alloys with about 19% Cr, 9% Ni and less than 0.20% C constitute the most widely used group of corrosion-resistant alloys. When properly heat treated, the alloy is resistant to a great variety of corrodents, and is usually considered the best general-purpose alloy. Structurally, the alloys are austenitic and nonmagnetic, although the low-carbon grade shows slight magnetic permeability. By proper balance of the nickel, manganese and nitrogen

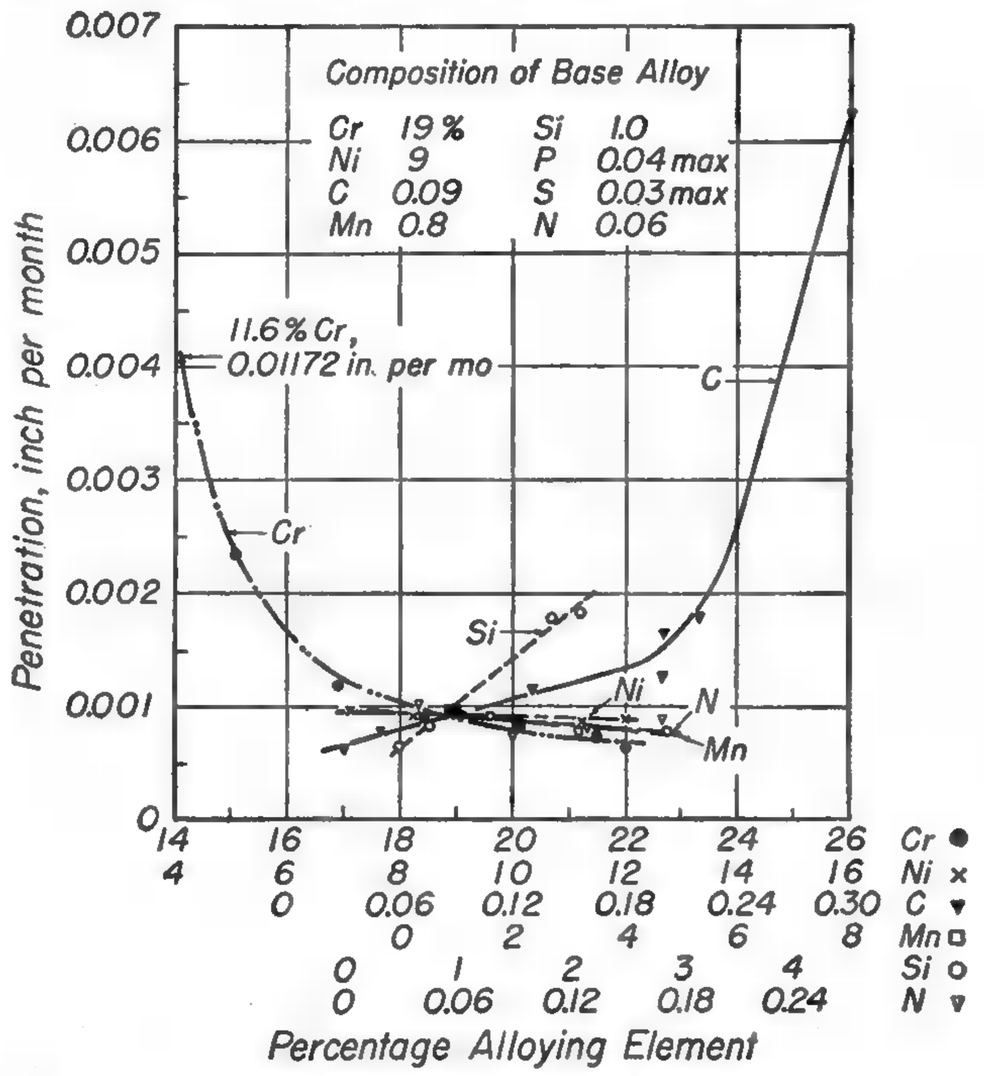

Fig. 8 Effect of composition on rate of corrosion penetration as determined from quench-annealed specimens in boiling 65% nitric acid (Reference 3)

contents, the low-carbon grade also may be made completely nonmagnetic. Because of their austenitic structure, CF type castings are not hardenable, but they have excellent ductility and toughness with fairly high tensile strength.

Table IV. Mechanical Properties of Type CF Alloys (19% Cr, 9% Ni)

Property	ACI Type CF-8	CF-20	CF-8M[a] CF-12M[a]	CF-8C[b]
Tensile strength, psi	80,000	83,000	88,000	85,000
Yield strength, psi	40,000	42,000	45,000	44,000
Elongation, per cent in 2 in.	55	55	50	45
Brinell hardness number	140	163	156 to 170	149

(a) Containing 2 to 3% Mo
(b) Containing columbium eight times the carbon content, 1% Cb max

For best resistance to corrosion, this type of material is made in the low-carbon grade, designated CF-8, containing 0.08% C max. The medium-carbon grade, CF-20, with 0.20% C max, is used satisfactorily under less corrosive conditions than those where the low-carbon type is employed.

Where the intended service will involve contact with dilute sulfuric acid the resistance of the alloy can be improved by the addition of 2 to 3% Mo. Higher molybdenum content is sometimes specified for special conditions of corrosion, but such alloys are less resistant to corrosion in nitric acid than the molybdenum-free material.

Columbium and selenium are also used as special additions to the normal CF composition—columbium as a stabilizing element to avoid intergranular attack, and selenium to improve machinability.

Typical mechanical properties for CF alloys water quenched from about 2000 F are listed in Table IV.

Type CG. This alloy is nearly the same as the CF composition in corrosion resistance and mechanical properties. The nickel and chromium contents are higher than in the CF type, thereby allowing somewhat higher carbon content without loss of resistance to corrosion. CG alloys are made in low-carbon and medium-carbon grades and with molybdenum, columbium and selenium additions. Castings of this composition are heat treated by quenching from about 2000 F.

Type CH. The 25% Cr, 12% Ni alloy with less than 0.20% C is similar to the CE composition. It is used for specialized applications in the chemical and paper industries. The CH type is made in two carbon grades: 0.10%

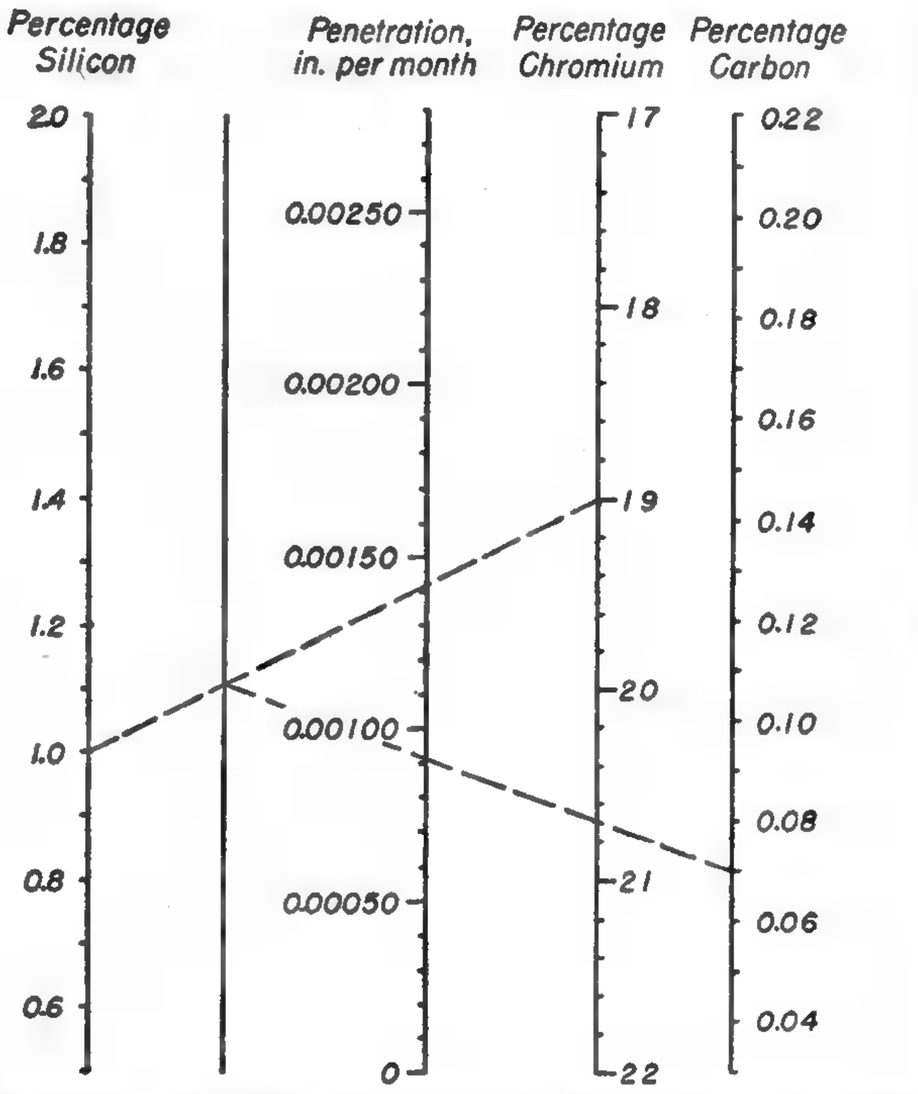

Fig. 9 Nomograph for determining rate of penetration in 65% boiling nitric acid for quench-annealed CF and CG type alloys (Reference 3)

and 0.20% C max. For resistance to reducing chemicals, molybdenum is added to the low-carbon type. Typical mechanical properties for alloys water quenched from 2000 F are shown in Table V.

Table V. Mechanical Properties of Type CH Alloys (25% Cr, 12% Ni)

Property	CH-10	CH-20	CH-10M[a]
Tensile strength, psi	82,000	88,000	90,000
Yield strength, psi	44,000	50,000	66,000
Elongation, per cent in 2 in.	38	38	15
Brinell hardness number	170	180	180

(a) Containing molybdenum

Type CK. This alloy is used extensively in the pulp and paper industry. It is similar to the CE and CH compositions, but has considerably higher nickel content. The CK type is sometimes made with a columbium addition to minimize the effect of carbide precipitation. Typical mechanical properties of an alloy quenched from 2000 F are as follows:

Tensile strength, psi	75,000
Yield strength, psi	45,000
Elongation, per cent in 2 in.	20
Brinell hardness number	180

Machinability characteristics of all the iron-chromium-nickel type alloys (chromium in excess of nickel) are about on ■ par with the quench-annealed CF type composition. The CE-30 type and the alloys that contain columbium are somewhat easier to machine; the alloys that contain selenium also have improved machinability; the CH type is slightly less machinable than the CF type.

All these alloys are readily weldable but, with the exception of the CE type (as previously discussed) and the stabilized compositions that contain columbium, all must be heat treated again after welding. It is advisable to preheat the molybdenum-containing CH type alloys at 600 to 1000 F before welding.

Iron-Nickel-Chromium Alloys. Alloys in which the nickel content exceeds the chromium content are made in the compositions listed in Table VI.

Table VI. Composition Limits of Iron-Nickel-Chromium Corrosion-Resistant Castings

ACI Type	Composition, percentage				
	Carbon	Manganese	Silicon	Chromium	Nickel
CM-25	0.25 max	1.50 max	2.00 max	8 to 11	19 to 22
CN-7	0.07 max	1.50 max	2.00 max	18 to 22	20 to 30
CT-7	0.07 max	1.50 max	2.00 max	13 to 17	34 to 37

Type CM-25. This composition is used in equipment for oil refineries and in special applications where dilute sulfuric acid is encountered. Typical mechanical properties are as follows:

Tensile strength, psi	71,000
Yield strength, psi	34,000
Elongation, per cent in 2 in.	38
Brinell hardness number	128

Types CN-7 and CT-7. These alloys are used for resistance to various concentrations of hot sulfuric acid and for specialized applications of severely corrosive nature. The compositions usually contain molybdenum and other alloying elements. Within the broad ranges of nickel and chromium are several proprietary, patented alloys. The iron-nickel-chromium alloys are machinable and weldable to about the same extent as the more widely used iron-chromium-nickel alloy types.

Influence of Composition on Resistance to Corrosion. Corrosion-resistant alloys may be exposed to five types of corrosive attack, namely: (1) *general attack,* in which the entire surface is corroded at an approximately uniform rate; (2) *intergranular attack,* in which corrosion proceeds along the grain boundaries, causing disintegration of the metal; (3) *contact corrosion,* in which the products of corrosion are concentrated at the point of contact of the alloy with another body, causing localized attack; (4) *pitting corrosion,* in which the general surface remains relatively unattacked, but severe corrosion occurs at some points; and (5) *erosion-corrosion,* in which erosive action continuously removes the passive film on the surface of the metal, causing active corrosion at a rate higher than ordinary, along the path of erosion.

In alloys of the CF and CG types, the influence of composition on the rates of corrosion caused by *general attack* has been studied at Battelle Memorial Institute for the Alloy Casting Institute, and certain definite relationships have been established. Through use of the Huey test (average rates of corrosion determined from specimens immersed in boiling 65% nitric acid for five 48-hr test periods) it has been shown that in this standardized environment, carbide-free, quench-annealed alloys of varying nickel, chromium, silicon, carbon and manganese contents, have corrosion rates directly related to the amounts of the elements present in the composition. Figure 8 shows the influence of each of the elements on the corrosion rate. Variations within the normal ranges of nickel, manganese and nitrogen contents have relatively little effect on the rate, but chromium, carbon and silicon have a marked influence on resistance to corrosion. The corrosion rate for a given composition depends on the actual analysis. However, the effect of each element remains the same, regardless of the amounts of the other elements present. The relationship of composition to corrosion rates for properly heat treated CF alloys in boiling 65% nitric acid, is summarized in the nomograph of Fig. 9.

Intergranular attack may be avoided in the CF and CG alloys by the two following methods: (1) by the addition of the stabilizing element columbium, or (2) by the formation of an austenite-ferrite structure obtained through the addition of molybdenum or through changes in the silicon and chromium contents. The addition of columbium to molybdenum-containing alloys of the normal CF and CG compositions has been found unsatisfactory for castings. If the addition of these two elements to the same alloy is desired, a special composition must be employed, containing amounts of nickel considerably higher than normal. In general, intergranular corrosion is of less concern in alloys that contain 25% Cr or more, than in the lower-chromium alloys.

Corrosion Testing. Accelerated corrosion tests, although useful for laboratory study of corrosion-resistant alloys, should not be considered valid criteria in determining the suitability of alloys for castings in service installations. It is virtually impossible to duplicate service conditions in any laboratory test; for this reason, experience in similar applications is a better guide for selection of compositions.

Casting Design. In this article no comments have been made concerning comparative serviceability of the different alloys, because such comparisons are more likely to be misleading than helpful. All the alloy compositions have individual peculiarities as far as foundry practice is concerned, and the experience of the foundryman should be relied on in determining casting designs.

References

1 Effect of Heat Treatment on Corrosion Resistance, Part I, Alloy Casting Bull No. 6, Jan 1946

2 Effect of Heat Treatment on Corrosion Resistance, Part II, Alloy Casting Bull No. 7, April 1946

3 Effect of Composition on Corrosion Resistance, Alloy Casting Bull No. 3, Nov 1944

Wrought Stainless Steels

By Owen K. Parmiter*

THE WROUGHT stainless steels in common use are of three principal types: austenitic, martensitic, and ferritic. Some of these steels are used extensively where strength or resistance to scaling at elevated temperatures is required; such grades are discussed in the article on "Wrought Heat-Resisting Alloys", page 562. The properties of corrosion-resistant steel castings are given in the article on page 549.

Austenitic Stainless Steels. The stainless steels that are austenitic (and not ferromagnetic) contain both chromium and nickel; as shown in Table I the total content of these elements is at least 23%; the minimum content of chromium is 16% and of nickel, 7%. Types 302, 303, 304 and 316 are probably the most extensively used alloys of this class. Austenitic stainless steels work harden readily. They are extremely shock-resistant and difficult to machine unless they contain sulfur or selenium. They can be hot worked readily, and can be cold worked when proper allowance is made for their rapid work hardening. These steels can be welded without difficulty and, if the welding operation is controlled properly, the resistance to corrosion is not impaired. These steels have the best high-temperature

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Table I. Composition Limits of Austenitic Stainless Steels

AISI Type No.	Composition, percentage: Carbon	Chromium	Nickel	Other Elements	General Properties and Uses
301	0.08 to 0.20	16.0 to 18.0	6.00 to 8.00	Mn 2.00 max	A general-utility stainless steel, easily worked; for trim, household utensils, structural purposes
302	0.08 to 0.20	17.0 to 19.0	8.00 to 10.00	Mn 2.00 max	A readily fabricated stainless steel for decorative or corrosion-resistant use
302B	0.08 to 0.20	17.0 to 19.0	8.00 to 10.00	Si 2.00 to 3.00 Mn 2.00 max	Silicon added to increase resistance to scaling at high temperatures
303	0.15 max	17.0 to 19.0	8.00 to 10.00	P, S, Se 0.07 min Zr, Mo 0.60 max	A free-machining grade 18-8 stainless steel
304	0.08 max	18.0 to 20.0	8.00 to 11.00	Mn 2.00 max	A low-carbon 18-8 steel, weldable with less danger of intercrystalline corrosion
308	0.08 max	19.0 to 21.0	10.00 to 12.00	Mn 2.00 max	For use when corrosion resistance greater than that of 18-8 is needed
309	0.20 max	22.0 to 24.0	12.00 to 15.00	Mn 2.00 max	For use at elevated temperature, combining high scaling resistance and good strength
309S	0.08 max	22.0 to 24.0	12.00 to 15.00	Mn 2.00 max	Low carbon permits welded fabrication with a minimum of carbide precipitation
310	0.25 max	24.0 to 26.0	19.0 to 22.0	Mn 2.00 max	Similar to 25-12 stainless, with higher nickel content for greater stability at welding temperatures
316	0.10 max	16.0 to 18.0	10.0 to 14.0	Mo 2.00 to 3.00	Superior resistance to chemical corrosion
317	0.10 max	18.0 to 20.0	11.0 to 14.0	Mo 3.00 to 4.00	Higher alloy content than 316 for increased corrosion resistance
321	0.08 max	17.0 to 19.0	8.0 to 11.0	Ti min 5 times C	An 18-8 type, stabilized against intercrystalline corrosion at elevated temperatures
347	0.08 max	17.0 to 19.0	9.00 to 12.00	Cb 10 times C	A stabilized 18-8 steel for service at elevated temperatures

Table II. Composition Limits of Martensitic Stainless Steels

AISI Type No.	Composition, percentage: Carbon	Chromium	Nickel	Other Elements	General Properties and Uses
403	0.15 max	11.5 to 13.0	.....	.....	Widely used for forged turbine blades
410	0.15 max	11.5 to 13.5	.....	.....	A low-priced general-purpose heat treatable stainless steel
414	0.15 max	11.5 to 13.5	1.25 to 2.50	.....	For springs, knife blades, tempered rules
416	0.15 max	12.0 to 14.0	.....	P, S, Se 0.07 min Zr, Mo 0.60 max	A free-machining grade
420	more than 0.15	12.0 to 14.0	.....	.....	For cutlery, surgical instruments, valves, ball bearings, magnets
420F	more than 0.15	12.0 to 14.0	.....	P, S, Se 0.07 min Zr, Mo 0.60 max	A free-machining variation of 420
431	0.20 max	15.0 to 17.0	1.25 to 2.50	.....	For high mechanical properties
440A	0.60 to 0.75	16.0 to 18.0	.....	Mo 0.75 max	For instruments, cutlery, valves; high hardness obtainable in high-carbon grades
440B	0.75 to 0.95	16.0 to 18.0	.....	Mo 0.75 max	
440C	0.95 to 1.20	16.0 to 18.0	.....	Mo 0.75 max	
501	more than 0.10	4.00 to 6.00	.....	.....	Corrosion-resistant rather than stainless; good strength at elevated temperatures
502	0.10 max	4.00 to 6.00	.....	.....	Corrosion-resistant rather than stainless; good strength at elevated temperatures

strength and resistance to scaling of the stainless steels; however, they are subject to intercrystalline corrosion at temperatures between 800 and 1600 F unless the structure is "stabilized" to prevent the presence of carbide at or near the grain boundaries. The corrosion resistance of the austenitic stainless steels is usually better than that of the martensitic or ferritic steels.

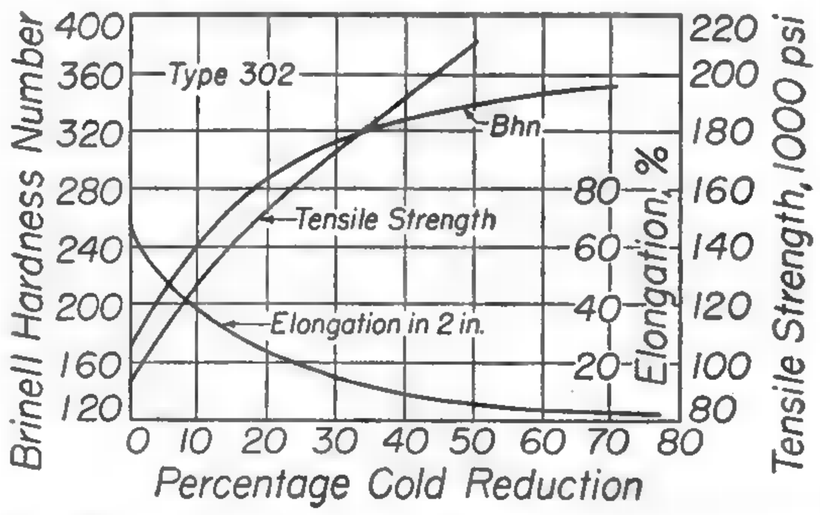

Fig. 1 Influence of cold work on a typical 18-8 stainless steel containing 0.11% C, 18.47% Cr, 8.20% Ni. Stainless steels of lower carbon content will work harden more rapidly; with carbon content higher than 0.11%, the rate of work hardening will be somewhat less than indicated.

Martensitic Stainless Steels. The steels that can be hardened by heat treatment are primarily straight chromium steels of the compositions shown in Table II. Types 410 and 416 are probably the most commonly used alloys of this class. The martensitic types of stainless steel are ferromagnetic; can be cold worked without difficulty, especially when the carbon content is low; show satisfactory resistance to weather, to water and to some chemicals; can be machined satisfactorily; have good toughness; and are easily forged or otherwise hot worked. The corrosion resistance is usually increased by hardening, but to obtain best resistance to corrosion it is important to quench from the recommended temperatures, especially for the high-carbon grades. The martensitic types of stainless steels

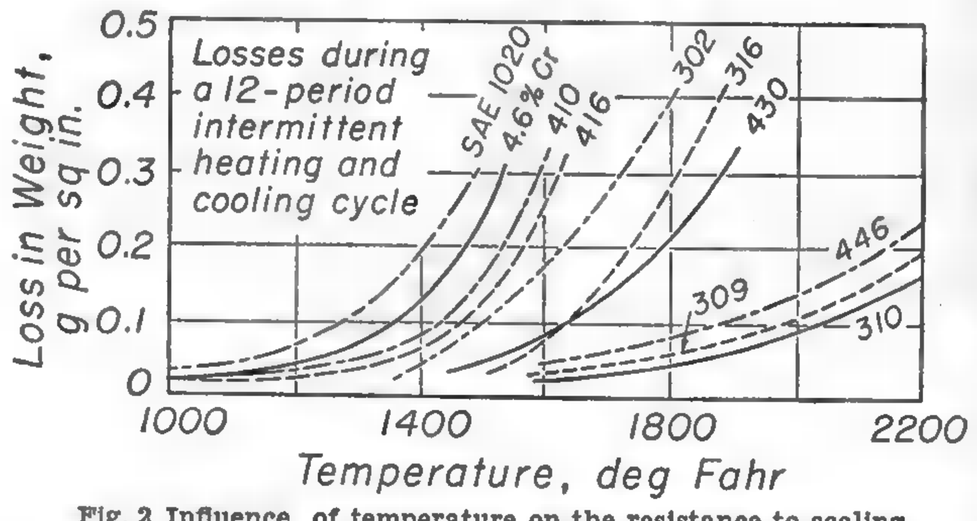

Fig. 2 Influence of temperature on the resistance to scaling of nine stainless steels and SAE 1020

tend to harden when cooled in air from above 1500 F; welds made by the electric-arc, resistance, or gas methods will consequently contain some martensite after cooling to atmospheric temperature. At temperatures below 1200 F the strength is greater than that of carbon steel.

Ferritic Stainless Steels. These alloys are chromium steels that are not hardenable by heat treatment (Table III). They can be cold worked or hot worked, are ferromagnetic, usually undergo excessive grain growth during prolonged exposure to elevated temperatures and may develop brittleness after electric-arc, resistance, or gas welding. These steels have lower strength at elevated temperatures than the martensitic type. However, resistance to scaling and to corrosion are generally better. Machinability

Table III. Composition Limits of Ferritic Stainless Steels

AISI Type No.	Composition, percentage: Carbon	Chromium	Nickel	Other Elements	General Properties and Uses
405	0.08 max	11.5 to 13.5	.....	Al 0.10 to 0.30	Nonhardening when air cooled from high temperatures
406	0.15 max	12.0 to 14.0	.....	Al 3.50 to 4.50	For electrical resistances; aluminum also reduces air hardening
430	0.12 max	14.0 to 18.0	.....	.....	An easily formed stainless alloy, much used for automobile trim and chemical equipment
430F	0.12 max	14.0 to 18.0	.....	P, S, Se 0.07 min Zr, Mo 0.60 max	A free-machining variety of 430
442	0.20 max	18.0 to 23.0	.....	.....	For high-temperature service when ease of fabrication is not required
443	0.20 max	18.0 to 23.0	.....	Cu 0.90 to 1.25	An easily worked steel of high corrosion resistance, for chemical equipment, and use at elevated temperatures.
446	0.35 max	23.0 to 27.0	.....	.....	High resistance to corrosion and scaling resistance up to 2150 F

Table IV. Physical Properties of Wrought Stainless Steels

Type[a]	Density: g/cm³	Density: lb/in.³	Coeff. Expansion, microinches/in./°F: 0 to 200 F	0 to 600 F	0 to 1000 F	0 to 1500 F	Thermal Conductivity: cal/cm/sec/°C: RT	100 C	500 C	Thermal Conductivity: Btu/sq ft/hr/°F/in.: 200 F	1000 F	Specific Heat, cal per g at 100 C	Modulus of Elasticity, million psi	Structure	Melting Range, deg Fahr
302	7.93	0.286	9.0	9.5	10.1	11.1	0.052	0.050	0.0515	110	150	0.118	29	Austenitic	2550–2600
303	7.93	0.286	9.0	9.5	10.1	11.1	0.052	0.050	.....	110	148	0.118	29	Austenitic	2550–2600
309	7.98	0.288	8.0	8.6	9.5	10.8	0.045	0.040	.....	92.5	113	0.118	30	Austenitic	2500–2550
310	7.98	0.288	8.0	8.5	9.4	10.0	....	0.039	.....	...	...	0.118	30.5	Austenitic	2500–2600
316	7.98	0.288	8.4	9.0	9.7	11.0	....	0.050	.....	108	147	0.118	28.5	Austenitic	2500–2550
321	8.02	0.290	8.8	9.2	10.2	11.3	....	0.052	.....	110	150	0.118	29	Austenitic	2550–2600
345	7.98	0.288	8.8	9.4	10.2	11.3	....	....	.....	110	150	0.118	29	Austenitic	2500–2550
SAE[b] 1020	7.85	0.284	6.5	8.0	9.8	...	....	0.1436	.....	335	...	....	30	Pearlitic Ferritic	.....
403															
410	7.75	0.279	5.7	6.1	6.7	7.0	0.096	0.060	0.0686	160	184	0.154	28	Martensitic Ferritic	2700–2750
416	7.73	0.278	5.7	6.1	6.7	7.0	0.096	0.060	.....	160	183	0.154	28	Martensitic Pearlitic	2700–2750
420	7.70	0.277	..	6.0	...	...	0.080	0.070	.....	...	...	....	28	Martensitic	2700–2750
430	7.70	0.277	5.4	5.6	6.1	6.3	0.072	0.0583	0.0624	156	170	0.152	29	Ferritic Pearlitic	2650–2700
440	7.68	0.277	..	5.9	...	...	0.060	0.070	.....	...	...	....	29	Martensitic	2650–2700
446	7.60	0.273	5.3	5.5	6.0	6.2	....	0.050	.....	140	162	0.144	29	Ferritic	2650–2700

(a) Data apply also to close modifications of these steels. (b) For comparison

Table V. Typical Mechanical Properties of Austenitic Stainless Steels

Properties	Steel: 302	303	309	310	316	321	345
Brinell hardness number							
Annealed	135 to 185	130 to 150	140 to 185	145 to 210	135 to 185	135 to 185	135 to 185
Cold Rolled	190 to 330	.....	.....	.....	180 to 300	180 to 300	.....
Rockwell Hardness, B Scale							
Annealed	75 to 90	72 to 80	78 to 90	80 to 95	75 to 90	75 to 90	75 to 90
Cold Rolled	92 to 109	.....	.....	.....	92 to 105	92 to 105	.....
Tensile Strength, 1000 psi							
Annealed	80 to 90	80 to 90	90 to 110	90 to 110	80 to 90	80 to 90	80 to 90
Cold Rolled	100 to 180	.....	.....	.....	100 to 150	100 to 180	.....
Yield Point, 1000 psi							
Annealed	35 to 45	35 to 45	40 to 60	40 to 60	35 to 55	35 to 45	35 to 45
Cold Rolled	50 to 150	.....	.....	.....	50 to 125	50 to 150	.....
Elongation, % in 2 in.							
Annealed	60 to 55	60 to 50	65 to 50	55 to 45	70 to 60	60 to 55	60 to 55
Cold Rolled	50 to 10	.....	.....	.....	50 to 15	50 to 10	.....
Reduction of Area, %							
Annealed	65 to 55	70 to 55	65 to 50	60 to 50	75 to 60	65 to 55	65 to 55
Izod Impact, ft-lb							
Annealed	110 to 70	110 to 70	.....	.....	120 to 70	.....	.....

Table VI. Typical Mechanical Properties of Ferritic and Martensitic Types of Wrought Stainless Steel

Properties	Steel: 403 410	416	420	430	440C	446	SAE 1020
Brinell Hardness Number							
Annealed	160 to 190	145 to 185	200 to 230	145 to 185	220 to 260	140 to 185	120 to 140
Heat Treated	200 to 375	180 to 300	275 to 500	.....	550 to 600	.....	.....
Cold Rolled	350 to 450	.....	.....	185 to 250	.....	.....	.....
Rockwell Hardness Number							
Annealed	78 to 88B	79 to 90B	93 to 98B	79 to 90B	98 to 104B	78 to 90B	53 to 78B
Heat Treated	12 to 40C	88 to 107B	30 to 52C	.....	55 to 59C	.....	.....
Cold Rolled	38 to 46C	.....	.....	90 to 104B	.....	.....	.....
Tensile Strength, 1000 psi							
Annealed	65 to 85	60 to 80	90 to 110	70 to 80	100 to 125	75 to 95	55 to 65
Heat Treated	100 to 200	90 to 160	150 to 250	.....	Too hard	.....	.....
Cold Rolled	170 to 220	.....	.....	90 to 120	.....	.....	.....
Yield Point, 1000 psi							
Annealed	40 to 60	40 to 50	50 to 60	40 to 55	50 to 70	45 to 60	35 to 45
Heat Treated	80 to 180	60 to 130	120 to 220	.....	Too hard	.....	.....
Elongation, % in 2 in.							
Annealed	35 to 25	30 to 20	25 to 20	30 to 20	12 to 8	30 to 20	40 to 30
Heat Treated	25 to 15	20 to 10	12 to 2	.....	Too hard	.....	.....
Reduction of Area, %							
Annealed	75 to 60	60 to 50	50 to 40	55 to 40	20 to 10	50 to 40	70 to 60
Heat Treated	70 to 60	55 to 35	40 to 4	.....	Too hard	.....	.....
Izod Impact, ft-lb							
Annealed	110 to 60	50 to 30	.....	45 to 30	.....	.....	70 to 40
Heat Treated	100 to 25	35 to 25	25 to 10	.....	Too hard	.....	.....

Table VII. Some General Properties of Wrought Stainless Steels

Type	Magnetic Permeability Annealed	Electrical Resistivity, microhms/in.,[2] 70 F	Scaling Temperature, °F: Continuous Service	Scaling Temperature, °F: Intermittent Service	Welding Properties	Machining Properties	Drawing or Stamping
302	1.003	27.6	1600	1450	Very good; tough welds	Fair, tough	Very good
303	1.003	27.6	1600	1450	Fairly good. May crack; not recommended	Good, about 65% of screw stock	Fairly good
309	1.003	30.0	2000	1800	Good	Fair, tough	Good
310	1.001	30.5	2000	1900	Good	Fair, tough	Good
316	1.003	28.5	1650	1500	Very good	Fair, tough	Good
321	1.003	28.0	1600	1450	Very good	Fair, tough	Good
347	1.001	28.0	1600	1450	Very good	Fair, tough	Good
SAE 1020	Ferromagnetic	4.32	800	1000	Good	Good	Good
410	Ferromagnetic	22.5	1250	1400	Fair. Small welds can be annealed.	Fair	Fair
416	Ferromagnetic	22.7	1250	1400	Poor. Small welds likely to crack; not recommended	Good, about 80% of screw stock	Poor
420	Ferromagnetic	23.0	....	....	Fair. Brittle welds can be annealed.	Fair	Poor
430	Ferromagnetic	23.5	1500	1600	Fair. Brittle welds have slight response to anneal.	Fair	Good
440	Ferromagnetic	24.0	....	....	Not recommended generally	Fair	Poor
446	Ferromagnetic	26.5	1900	2000	Fair. Brittle welds have slight response to anneal.	Fair	Poor

is good and can be improved by adding sulfur or selenium. There is no tendency toward intercrystalline corrosion.

Physical and Mechanical Properties. The physical and mechanical properties of typical stainless steels of the three principal types are listed in Tables IV, V, VI, and VII. Figure 1 shows the influence of cold work on a type 302 (18-8) stainless steel.

Heat Treatment. Forging, annealing, hardening and tempering treatments are given in Table VIII. During heat treatment, carburizing conditions should be avoided because an increase in the carbon content of the surface of the steel will lower the resistance to corrosion. For stress relieving after hardening, the martensitic steels may be heated to temperatures between 300 and 700 F. The austenitic alloys are annealed in order to soften after cold working or to dissolve carbides.

Mechanical Properties at Elevated Temperatures. The tensile strength, rupture strength, creep strength and fatigue strength of typical stainless steels at elevated temperatures are given in the article on "Wrought Heat-Resisting Alloys", page 562.

Mechanical Properties at Low Temperatures. See the article on "The Properties of Metals at Low Temperatures", page 204.

Resistance to Scaling. The resistance of several grades to scaling is given in Fig. 2 and Table VII. The article on "Wrought Heat-Resisting Alloys" lists the normal operating ranges of temperature for 14 of the standard alloys.

Corrosion Resistance. The article on "Resistance of Stainless Steels to Corrosion", discusses the effect of various corrosive environments, of cold work, heat treatment and microstructure on the corrosion properties of stainless steel. *See also* "Stress Corrosion of Metals", page 227.

References

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"Steel Products Manual", Section 24, Stainless and Heat-Resisting Steels, American Iron and Steel Institute, May 1946

ASTM Specifications for Corrosion-Resisting Steel

Table VIII. Forging and Heat Treating of Wrought Stainless Steels

Type	Forging Temperature, °F: Start	Forging Temperature, °F: Finish	Annealing[a] Temperature, °F	Hardening[b] Temperature, °F	Tempering Temperature, °F
302	2100	1700	1850 to 1950	Nonhardening[c]	Nonhardening
303	2100	1700	1900 to 1950	Nonhardening[c]	Nonhardening
309	2150	1800	1900 to 2050	Nonhardening[c]	Nonhardening
310	2150	1800	1900 to 2050	Nonhardening[c]	Nonhardening
316	2200	1700	1950 to 2050	Nonhardening[c]	Nonhardening
321	2100	1700	1950 to 2050	Nonhardening[c]	Nonhardening
347	2250	1800	1950 to 2050	Nonhardening[c]	Nonhardening
SAE 1020	2300	1400	Cool slowly 1600 FC 1450 to 1100	WQ 1650 to 1700	250 to 325
410	2000	1650	AC 1200 to 1250	OQ 1750 to 1825	400 to 1200
416	2150	1700	FC 1450 to 1100	OQ 1800 to 1850	Up to 1200
420	2000	1650	FC 1450 to 1100	OQ 1775 to 1850	350 to 800
430	1950	1500	FC 1450 FC 1650 to 1100	Nonhardening	Nonhardening
440	2000	1650	AC 1400	OQ 1825 to 1925	350 to 800
446	2000	1500	AC 1450 to 1550	Nonhardening	Nonhardening

(a) Quench in water unless otherwise noted. FC = furnace cool; AC = air cool

(b) WQ = water quench; OQ = oil quench

(c) Except by cold working. The free-machining types (303, 416, 430F) are designed for machining applications and are not recommended for cold shaping or hot forging operations that require severe deformations.

The Resistance of Wrought Stainless Steels to Corrosion

By W. O. Binder*

STAINLESS steels are corrosion-resistant materials that rely mainly on surface passivity for resistance to attack. The use of these steels is governed by the oxidizing characteristics of the environment. For strongly oxidizing conditions, stainless steels are superior to the more noble metals and alloys.

The stainless steels may be grouped according to chemical composition and response to heat treatment, as follows: (a) martensitic steels, containing 11.5 to 18% Cr, (b) ferritic nonhardenable steels, containing 15 to 30% Cr, and (c) austenitic steels, containing 16 to 26% Cr and 6 to 22% Ni. All these steels are produced in the form of castings and wrought materials, which have been used extensively in industry because of their strength, toughness, good fabricating characteristics, and resistance to heat as well as to chemical and atmospheric corrosion.

The martensitic steels have chromium (11.5 to 18%) as the principal alloying element, and may contain from 0.08 to 1.10% C. The steels in this group respond to heat treatment in much the same manner as plain carbon and low-alloy steels. Further details in connection with the heat treatment may be found in the article on page 553 in this Handbook. Because of relatively low chromium content, the martensitic steels are used principally for resistance to atmospheric oxidation and to mildly corrosive chemicals. One of the earliest and best known applications of this type of steel is in cutlery.

Because they contain more chromium than the martensitic steels, the steels in group *b* have a stable ferritic structure, and they do not harden to any appreciable extent when quenched from high temperatures. The nonhardenable steels are extremely resistant to oxidation and to strongly oxidizing solutions. In addition to applications in chemical plants, these steels are widely employed in the form ot sheet and strip for structural purposes.

The addition of 6 to 22% Ni to low-carbon steels that contain 16 to 25% Cr, retards the transformation of austenite to ferrite so that austenite is retained at atmospheric temperatures when the steels are cooled from elevated temperatures. As indicated in the articles on cast and wrought stainless steels, the austenitic steels have greater strength at elevated temperatures than the plain chromium steels; they cannot be hardened except by cold work; and they are adaptable to cold forming operations. Because of the ease of fabricating them by welding and because they resist corrision in various mediums, the austenitic steels have been used more extensively than any plain chromium steel.

Nature of Passivity in Stainless Steels.[1-6] It is believed, although not by all investigators, that the resistance to corrosion of the stainless steels results from the presence of a thin oxide or hydrate film on the surface of the metal, which is stabilized by chromium and protects the metal from attack. The film is considered insoluble, nonporous and self-healing. If broken, the film will repair itself when re-exposed to an oxidizing agent.

Investigators generally concede that passivation is not a constant state and that it exists only in certain environments or under certain conditions. In some instances, the range over which these steels exhibit passivity is relatively broad, but in others the range is narrow and passivity may be destroyed by slight changes in conditions. Under circumstances favorable to passivity, the stainless steels have a solution potential between the potentials of copper and silver. When passivity is destroyed, the potential is equal to that of ordinary iron. Passivity has a greater influence on the resistance to corrosion of the stainless steels than on the resistance of any other metal. For this reason the metal and environment factors affecting passivity will be discussed next.

Effect of Composition on Resistance to Corrosion.* The chromium steels derive their remarkable resistance to corrosion from the presence of chromium. Although additions of 1 to 12% Cr to steel enhance progressively the resistance to oxidation at elevated temperatures and to rusting in the atmosphere, the resistance to corrosion of these steels is ordinarily insufficient for successful chemical service until the chromium content reaches about 12%. The application of the chromium steels in the chemical industry is chiefly for resistance to oxidizing conditions. The data in Table I illustrate the effectiveness of chromium in developing passivity, and show that the steels become more resistant to oxidizing conditions as the chromium content is increased. The rate at which the steels develop passivity depends on their chromium content; steels that contain more than about 20% Cr become passive in the atmosphere without developing even a slight film of rust.

Table I. Influence of Chromium Content on the Resistance of Low-Carbon Steel to Boiling 65% Nitric Acid

Chromium, percentage	Average Rate of Corrosion, inches penetration per month
4.5	12.900
8.0	0.144
12.0	0.010
18.0	0.0025
25.0	0.00063

Silicon and aluminum further improve the resistance of the chromium steels to direct oxidation at elevated temperatures. Silicon in excess of the percentage required for deoxidizing the steels, reduces their resistance to hot concentrated solutions of nitric acid. In commercial grades of stainless steel, the use of aluminum is restricted to the 12% Cr steel (types 405 and 406†). Aluminum is employed in these steels to prevent air-hardening and to increase electrical resistivity.

The presence of nickel in the high-chromium steels decreases attack by nonoxidizing corrosives. Nickel increases somewhat the tendency of the chromium steels to become passive, but in strongly oxidizing conditions, nickel adds little to the passivity of steels that contain more than about 22% Cr.

Manganese has a beneficial effect on the hot workability of these steels, without reducing their resistance to corrosion. Manganese has been used to replace all or part of the nickel in the austenitic chromium steels,[7] but the chromium-manganese and chromium-manganese-nickel steels are less resistant than the fully austenitic steels that contain 18% Cr, 8% Ni.

The presence of molybdenum in the chromium steels and the austenitic 18% Cr — 8% Ni steels (type 316) improves their resistance to sulfuric, sulfurous and organic acids, halogen salts, and sea water. Additions of molybdenum strengthen the passive film under conditions in which it is likely to fail, but such additions lessen the resistance of the steels to corrosion in strongly oxidizing environments, if the amount of molybdenum present exceeds 3%. The action of molybdenum produces increased nobility as well as passivity. The addition of molybdenum greatly improves the resistance to pitting of the 18% Cr — 8% Ni steels. This type of corrosion will develop under foreign deposits that prevent access of oxygen to the surface of the steel. Pitting may also occur in environments that are oxidizing and free of foreign deposits. The mechanism by which steels corrode after a pit has formed has been described by Uhlig.[8]

Effect of Heat Treatment on Resistance to Corrosion.‡ The changes in microstructure produced by different heat treatments have considerable influence on the resistance to corrosion of the stainless steels. These steels exhibit greater resistance when carbon is completely dissolved, producing a homogeneous single-phase structure, than when the carbon is partially or completely divorced from solid solution.

* Metallurgist, Union Carbide and Carbon Research Laboratories, Inc., Niagara Falls, N. Y.

* For data concerning the effect of composition on the resistance of stainless steel castings to corrosion, see page 549.

† AISI type numbers and compositions of stainless steels are listed on pages 554 and 555.

‡ *See also* the article "Corrosion-Resistant Castings", page 549.

The martensitic steels must be properly heat treated to exhibit good resistance to corrosion, and although normally they show maximum resistance in the fully hardened condition, relief of quenching stresses, coupled with greatly improved ductility and toughness, may be obtained by tempering these steels at temperatures of 400 C (750 F) or less without seriously reducing their resistance to corrosion. However, tempering between 400 and 600 C (750 and 1110 F) should be avoided, particularly when the carbon content is high, since this range of temperature imparts low toughness as well as low resistance to corrosion.[9] Tempering temperatures higher than 600 C (1110 F) coagulate the precipitated carbides and offset the detrimental influence of the carbides on resistance to corrosion. Although in low-carbon ferritic nonhardenable chromium steels and in low-carbon steels that contain 12 to 14% Cr, the general resistance to corrosion is not affected noticeably by any form of heat treatment, it is advisable to anneal the nonhardenable steels after welding, in order to obtain maximum resistance to corrosion and to obtain ductility in the heat-affected zones adjacent to the weld.

When austenitic chromium-nickel steels are properly heat treated, they exhibit a wide range of passivity in corrosive solutions. These steels resist corrosion most effectively when they are heated to temperatures within the range from 1050 to 1100 C (1920 to 2010 F) and cooled rapidly, because this heat treatment produces a homogeneous austenitic structure. Rapid cooling from the heat treating temperature is essential in order to keep the carbides in solution. Very small parts may be air-cooled but larger parts must be water-quenched. These steels, however, are subject to severe attack at the grain boundaries by even relatively mild corrosive mediums after exposure to temperatures in the range from 400 to 900 C (750 to 1650 F). This attack is known as "intergranular corrosion". The cause of intergranular attack has been the subject of considerable research. Some investigators believe that this kind of attack results from precipitation of chromium carbide and consequent depletion of chromium in the area adjacent to the grain boundaries. Decreasing carbon content decreases susceptibility of the steel to intergranular attack.[10,12]

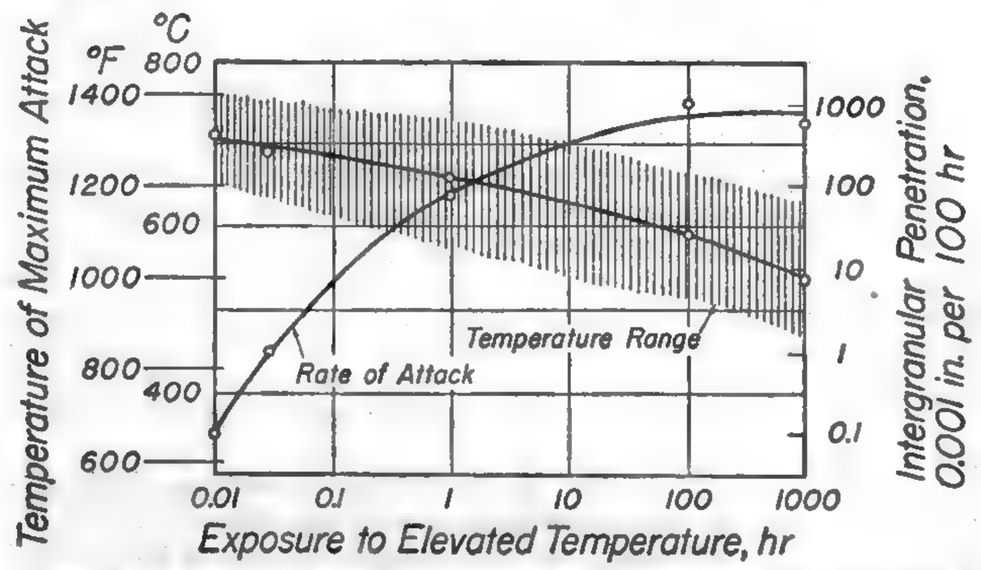

Fig. 1 Effect of time and temperature on the maximum sensitivity to intergranular attack of low-carbon steel containing 18% Cr, 8% Ni[12]

Besides carbon, the important factors are time, temperature and corrodent. The data shown in Fig. 1[12] illustrate the influence of time and temperature on sensitivity to intergranular attack. It should be emphasized that the precipitation of carbides at the grain boundaries may take place very rapidly. For example, after welding, the metal adjacent to the weld is subject to intergranular attack, whereas the weld metal itself and the base metal outside the heat-affected zone are virtually free from attack. The intergranular weakness may be removed by annealing the steel properly or may be avoided by using stabilized compositions (types 321 and 347).

The desire to use welded equipment of any size and to avoid inconvenience, distortion, and residual stresses caused by heat treatment and rapid cooling, led to the development of austenitic steels free from intergranular susceptibility.[11,13,14,21,25] The loss of resistance to corrosion because of carbide precipitation at grain boundaries, is eliminated by adding small amounts of titanium (type 321) or columbium (type 347). For complete immunity, the titanium content must be at least four to six times the carbon content; the columbium content must be eight to ten times the carbon content. Precipitation of carbide, detrimental to corrosion resistance, does not occur in the stabilized steels that contain 18% Cr, 8% Ni, when they are welded or stress-relieved. The steels that contain columbium (type 347) are suitable for welding rods, since nearly all the columbium in the rod is transferred to the weld.

As with other metals and alloys, the stainless steels sometimes show lower resistance to corrosion after cold work. This effect is rather specific and depends on the composition of the steel, the extent and uniformity of cold work, and particularly on the nature of the environment. For example, local cold work has a greater effect on the corrosion resistance of the steel than uniform cold work. In general, the greater the resistance to corrosion of the steel, the less likely that the steel will be attacked when it is cold worked locally.

Effect of Surface Condition. The stainless steels usually operate under severely corrosive conditions. To insure satisfactory service life the surface condition of the steel must be given careful attention, because smooth surfaces, freedom from defects and from all traces of scale, oil, and other foreign material, reduce the probability of corrosion. Generally the smoother the surface, the greater the resistance to corrosion. Oil and grease can be removed by either hydrocarbon solvents or alkaline cleaners, but care must be taken to remove these cleaners before heat treating the steels. Surface contamination may be caused by machining, shearing and drawing operations. Small particles of metals from the tools become embedded in the steel surface and, unless removed, may cause corrosion. These particles are removed best by immersing the surface in a solution containing approximately 20% nitric acid heated to a temperature between 50 and 60 C (122 and 140 F). This treatment also hastens the development of passivity.

Environment Factors Affecting Resistance to Corrosion. The important factors concerned with the corrosive environment are oxidizing characteristics, acidity, velocity and temperature.

Stainless steels are normally passive but, when exposed to corrosive solutions that are nonoxidizing, these steels become active. It is necessary, then, that oxidizers be present in solution to maintain passivity. The oxidizing agent producing passivity should be replenished constantly. Localized corrosion frequently results from depletion of the oxidizing agent. Pitting beneath a barnacle, in sea water, is a typical example of localized corrosion from depletion of oxygen.

In reducing or weakly oxidizing conditions, the resistance of stainless steels in dilute acids is increased by reducing the concentration of the acid. Because of decreased ionization, the corrosion rate of the steels may be less in concentrated acid than in dilute, when other factors are the same—for example, temperature. In highly concentrated acid—for example, in fuming sulfuric acid—corrosion is more severe because of changes in the chemical behavior of the acid itself; the rate of corrosion rises rapidly also with increasing temperature.

An increase in velocity of the corrosive solution increases the rate at which the oxidizing agent is brought in contact with the steel and, hence, does not normally reduce the resistance to corrosion of stainless steels unless the increased velocity is accompanied by abrasion. The effect of abrasion is to inhibit the formation of a passive film.

The rate of corrosion increases with rising temperatures, as a result of increased ionization, rate of diffusion, and mobility of the reactants. In weakly oxidizing conditions, a rise in temperature may increase the rate of corrosion by decreasing the amount of oxygen dissolved in the solution.

The above statements indicate the reason for the complex behavior of the stainless steels under corrosive conditions. The characteristics of both the steel and the corrosive environment must be fully recognized in order to apply these steels successfully to specific purposes. Since ordinarily not all the facts are known, it is frequently necessary to test the steels under operating conditions before any accurate selection can be made.

Galvanic and Concentration-Cell Corrosion. The factors influencing galvanic corrosion include conductivity of the

circuit, potential between anode and cathode, polarization, relative areas of cathode and anode, geometrical relationship between dissimilar metal surfaces, and contact between metals. Of these, the influence of relative areas of anodic and cathodic surfaces has the most pronounced effect on the degree of damage produced by galvanic action, since a small anode and a large cathode result in an increase in current density at the anode with a great consequent increase in the rate of corrosion. Thus, small differences in potential under these conditions may produce extensive corrosion because of increased current density in the anodic areas.

As shown in Table II,[15] the stainless steels will form galvanic couples when used in contact with other metals in the presence of an electrolyte. If the solution produces an active condition, metals like copper and bronze will accelerate the corrosion of stainless steel, particularly if the area of steel is small in comparison with the area of copper or bronze; but when the steels are passive, they are extremely stable in contact with these metals. In the passive condition the stainless steels are strongly cathodic; hence they will damage other metals, such as carbon steel, cast iron, and aluminum alloy, especially when the area of stainless steel is large in comparison with the other metal in the couple.

Table II. Galvanic Series of Metals and Alloys

Corroded end (anodic, or least noble)	
Magnesium	Hastelloy A
Magnesium alloys	Hastelloy B
Zinc	Brasses
Aluminum 2 S	Copper
Cadmium	Bronzes
Aluminum 24 S-T	Copper-nickel alloys
Steel or iron	Monel
Cast iron	Silver solder
13%-Cr iron (active)	Nickel (passive)
Ni-Resist	Inconel (passive)
18% Cr — 8% Ni steel (active)	13%-Cr iron (passive)
18% Cr — 8% Ni — 3% Mo steel (active)	18% Cr — 8% Ni steel (passive)
Hastelloy C	18% Cr — 8% Ni — 3% Mo steel (passive)
Lead-tin solders	Silver
Lead	Graphite
Tin	Gold
Nickel (active)	Platinum
Inconel (active)	
	Protected end (cathodic, or most noble)

The type of corrosion associated with surface crevices, scale, and other surface deposits, is known as "concentration-cell corrosion". The types of cells most frequently encountered in the stainless steels are the oxygen and active: passive cells.[16] Oxygen cells will develop into active: passive cells when the re-establishment of passivity in the anodic area becomes impossible. Because of the large areas of passive metal that normally surround the anodic areas, the active:passive cells are extremely energetic, since the surrounding oxygen serves as a depolarizer by reacting with the hydrogen from the reaction. Solutions that contain chlorides are most active in promoting these cells, and severe pitting may develop from their action.

In order to prevent these cells from forming, cracks and crevices should be avoided in equipment that must resist corrosion. Concentration-cell corrosion is particularly troublesome at joints made with gaskets, so tight dry joints are essential for optimum service.

Effect of Stress.[17–20,22,29–32]* Stress-corrosion failures in stainless steels have been reported in solutions that contain chlorides, but the occasions of such failures have been relatively few, and the residual stresses have undoubtedly been high. Solutions of magnesium, zinc or lithium chlorides, and moist ethyl chloride in combination with a high stress, cause stress-corrosion cracking. Of these, a boiling concentrated solution of magnesium chloride is the most corrosive and will cause the austenitic steels to fail in short periods of time when the applied stress is near the yield strength of the steel. The corrosive environments causing stress-corrosion cracking, which have been encountered in the chemical industry, are rather specific and are limited to certain chloride solutions.

* *See also* the article "Stress Corrosion of Metals", page 227.

The 18% Cr — 8% Ni steel, having a tensile strength as high as 200,000 psi, has been used extensively for lightweight structures with no failures from stress-corrosion cracking, although exposed to all kinds of atmospheric conditions. Cold drawn articles made of this steel may crack as a result of high residual stresses introduced during fabrication. Such cracking does not require the presence of a corrosive atmosphere or solution and can be avoided by thermal stress-relieving of the metal after drawing. Optimum deep-drawing conditions are obtained with a steel containing 18% Cr and 10 to 12% Ni, which work hardens at a slow rate.

Corrosive Effects of Various Mediums.[6,7,9,26] Since the corrosion resistance of a material depends largely on the

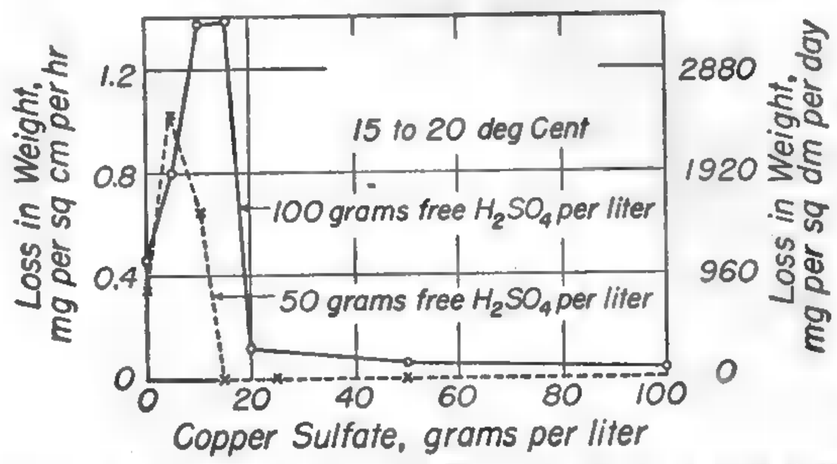

Fig. 2 Effect of copper sulfate on the corrosion of 12 to 14% Cr steel in sulfuric acid at 15 to 20 C[4]

nature of the corrosive condition, only broad general statements can be made; therefore the information given in this section should be used only as a preliminary guide. Whenever possible, specific tests or consultation with the manufacturer are advisable.

The resistance to corrosion of the stainless steels in acid solutions depends greatly on the oxidizing capacity of the solution. These steels are extremely resistant to acids, such as nitric acid, that have a high hydrogen-ion concentration and are strongly oxidizing in character. The presence of oxidizers like ferric and cupric sulfates in acid solutions permits the stainless steels to resist dilute

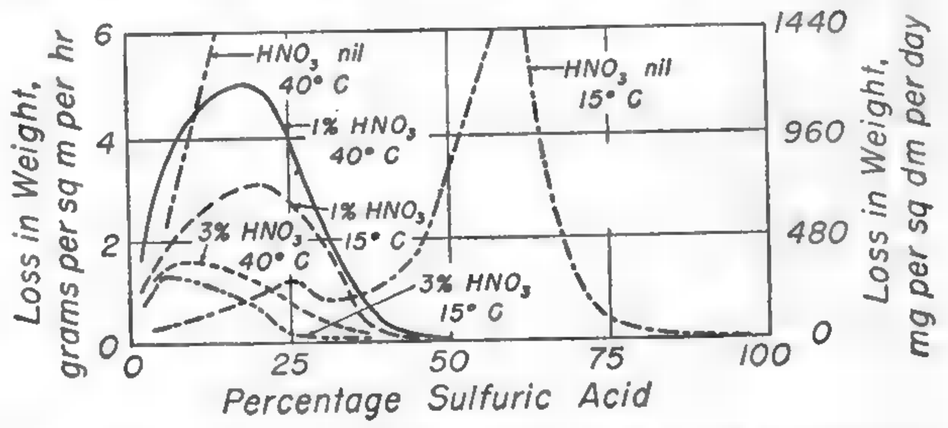

Fig. 3 Effect of a small addition of nitric acid on the corrosion of 15% Cr — 11% Ni steel in sulfuric acid[4]

acid solutions that exhibit high acidity and relatively low oxidizing power. These salts are more favorable to passivity than dissolved oxygen. Hydrochloric acid differs somewhat from the other acids in its action on the stainless steels, and it is difficult to render them passive in this acid. An increase in temperature increases the corrosion rate of the stainless steels in acids, particularly when the effect of raising temperature is to alter the oxidizing capacity of the solution.

Since the stainless steels that contain more than 16% Cr resist nitric acid solutions satisfactorily under most conditions of concentration and temperature, steels of this composition are used widely in equipment for resisting nitric acid. Typical corrosion rates of the stainless steels in boiling 65% nitric acid solution are given in Table III to illustrate the degree of passivity of these steels in a strongly oxidizing acid.

Sulfuric acid solutions, as already indicated, may or may not attack the stainless steels, depending on the concentration, temperature and oxidizing capacity of the

solution. When air or strong oxidizers are present, like nitric acid or cupric sulfate, the stainless steels exhibit a high degree of passivity (Fig. 2 and 3).

Cold concentrated sulfuric acid does not corrode the stainless steels, because of its greater oxidizing power and lower degree of ionization than cold dilute sulfuric acid solution; but hot concentrated solutions attack stainless steels. Molybdenum greatly improves the resistance of the 18% Cr — 8% Ni steels to sulfuric acid solutions, and considerable quantities of type 316 stainless steel are used in the textile industry, in which sulfuric acid solutions of various concentrations are employed.

Table III. Results of Tests on Chromium Steels and Austenitic Chromium-Nickel Steels in Boiling 65% Nitric Acid

Steel	Composition, percentage Cr	Ni	C	Mo	Cb	No. of Periods[a]	Penetration, inch per month
410	12.0	...	0.08	...	...	1	0.0108
						2	0.0099
						3	0.0097
430	18.0	...	0.08	...	...	1	0.0022
						2	0.0023
						3	0.0026
446	25.0	...	0.08	...	...	1	0.00065
						2	0.00058
						3	0.00065
304	19.04	9.24	0.06	...	...	1	0.00063
						2	0.00048
						3	0.00046
310	25.70	20.34	0.09	...	...	1	0.00040
						2	0.00030
						3	0.00030
347	18.16	11.12	0.06	...	0.82	1	0.00095
						2	0.00060
						3	0.00054
316	18.38	12.08	0.07	2.00	...	1	0.00070
						2	0.00060
						3	0.00060

(a) The duration of each period was 48 hr.

Provided their chromium content exceeds 12 to 15%, the stainless steels resist attack by pure sulfurous acids. The austenitic stainless steels are subject to intergranular attack in sulfurous acid solutions after welding, unless they are properly heat treated or fully stabilized. Large amounts of 18% Cr — 8% Ni steel—particularly steels containing molybdenum (type 316)—are used in the paper industry to resist the impure sulfurous acid solutions of the sulfite digesters.

The austenitic stainless steels are passive in all concentrations of acetic acid at temperatures as high as the boiling point. In hot acid, the resistance to corrosion of the 18% Cr — 8% Ni steels is improved by the addition of molybdenum, as shown in Table IV.

Under many conditions too numerous to mention specifically in this article, the stainless steels resist satisfactorily solutions of phosphoric acid, chromic acid, hydrogen sulfide and many organic acids. The degree of passivity in these acids is governed by the factors of concentration, temperature, and alloy content of the steel. Nickel and molybdenum help to enhance passivity, whereas increasing the temperature of the solution decreases passivity.

The stainless steels have been found satisfactory for handling weak and strong alkaline solutions at both room and elevated temperatures; for example, they are completely resistant to ammonia solutions.

Salt solutions usually contain sufficient amounts of dissolved oxygen to maintain passivity, and ordinarily they do not corrode the stainless steels. When acid chloride salts are present, however, attack may occur because the protective film is susceptible to penetration by the acid chloride solutions resulting from the hydrolysis of these salts. Oxidizing acid chloride salts are extremely corrosive; for instance, chlorides of copper, chromium, iron, tin, and mercury. Nonchloride oxidizing acid salts, such as dichromates, chromates, nitrates, and persulfates, do not attack the stainless steels. Oxidizing alkaline chloride salts liberate free chlorine as well as the chloride; hence in concentrated form they are corrosive, but in dilute form they are much less corrosive. The attack by dilute solutions is generally localized in the form of pits. Molybdenum additions increase the resistance of the 18% Cr — 8% Ni steels in salt solutions. Oxidizing alkaline solutions, such as solutions of sodium peroxide, are effectively resisted by the stainless steels, particularly the austenitic steels that contain 18% Cr, 8% Ni, with or without molybdenum. Because the austenitic stainless steels do not catalyze excessively the decomposition of peroxide solutions, they are used successfully in peroxide bleaching equipment.

Table IV

Results of Tests in Condensate of Boiling Acetic Acid

Steel	Corrosion Rate, inch penetration per month 80% acid	Glacial acid
304	0.0310 to 0.0378	0.0060 to 0.0088
347	0.0208 to 0.0230	0.0046 to 0.0056
316	0.00016 to 0.00028	0.00026 to 0.00030
309	0.00845 to 0.0103	0.0024 to 0.0051
310	0.00615 to 0.0074	0.00282 to 0.00305

Under some conditions, the steels are subject to pitting in dilute solutions of neutral salts. External conditions, such as adhering deposits, heat effects from welding, and surface imperfections, are troublesome because they greatly influence the attack. Continued exposure to sea water, as shown in Table V, may cause plain chromium steels, 18% Cr — 8% Ni steel, and other austenitic steels to pit, although general corrosion of the steel is virtually nil. The addition of molybdenum increases the resistance of these steels to pitting. The steels resist the action of sea water if oxygen is available to the metal surface.

Corrosion rates of the stainless steels in contact with food products are usually negligibly low, as shown in Table VI. In boiling fruit juices, which are acid in nature, the behavior of stainless steels is unlike that of the same steels when exposed to the pure forms of the organic acids, since the concentration of acids in fruit juices is low. For resisting excessively acid fruits, austenitic stainless steels of higher alloy content are preferred. For all practical purposes the stainless steels resist natural fresh waters, mine waters, boiler waters, and high-pressure steam at elevated temperatures. The austenitic stainless steels resist the action of a number of nonaqueous corroding liquids and gaseous corrodents, but are badly attacked by others. Data concerning several such mediums are listed in Tables VII and VIII.

Table V. Results of Exposure of Stainless Steels to Flowing Sea Water at Wilmington, N. C.[a]

Steel	Composition, percentage Cr	Ni	Mo	C	Size of Sample, inches	Condition of Metal	Period of Exposure, days	Loss in Weight, grams	Depth of Pitting, inch
410	13.15	...	...	0.08	12 by 12 by ¼	Hot rolled, pickled	568	134	0.057
430	17.28	...	...	0.10	12 by 12 by ¼	Hot rolled, pickled	568	102	0.107
446	25.50	...	...	0.08	12 by 12 by ¼	Hot rolled, annealed, pickled	322	60	0.064
304	18.16	9.23	...	0.08	12 by 12 by ¼	Hot rolled, pickled, No. 1 finish	667	49	0.040
304	18.43	9.41	...	0.07	12 by 12 by 0.063	2B finish	438	14	Perforated
316	17.80	12.15	2.90	0.06	12 by 12 by 0.063	2B finish	438	4	0.047
316	18.78	10.20	2.74	0.05	12 by 12 by ¼	Hot rolled and pickled	1923	13	0.042
310	24.03	20.95	...	0.12	12 by 12 by 0.024	HNO_3-HF, pickled	643	4	0.006
310	24.03	20.95	...	0.12	12 by 12 by 0.024	HNO_3-HF, pickled	988	15	Perforated

(a) Unpublished data, The International Nickel Company, Inc.

Table VI. Corrosion of Stainless Steels in Food Products[a]

Substance	Condition, or Temp, deg Fahr	Steel 18-8	18-8 Mo	17 Cr	12 Cr
Beer	....	A	A	...	...
Blood (meat juices)	Cold	A	A	A	...
Buttermilk	70°	A*	A	A	B
Carbonated water	....	A	A	A	...
Cider	70°	A	A	...	...
Coca-Cola syrup (pure)	70°	A	A	A	...
Coffee	Boiling	A	A	A	...
Fruit juices	70°	A	A	A	A
Ketchup	70°	A*	A	A*	A*
Lard	70°	A	A	A	...
Mayonnaise	70°	A*	A	...	...
Milk, fresh or sour	Hot or Cold	A	A	A	B
Molasses	....	A	A	A	...
Mustard	....	A*	A*	C*	...
Vegetable oils	Hot or Cold	A‡	A	A‡	...
Sugar juices	....	A	A	A	...
Vegetable juices	....	A	A	...	...

(a) Laboratory test data from various manufacturers of steel
* Subject to pitting at air line or when allowed to dry
‡ May attack when sulfuric acid is present

Symbol	*Description*	*Gram Lost per Sq Meter per Hr*	*Theoretical Penetration in Inch per Month*
A	Fully resistant	Less than 0.1	Less than 0.00035
B	Satisfactorily resistant	0.1 to 1.0	0.00035 to 0.0035
C	Fairly resistant	1.0 to 3.0	0.0035 to 0.01

Moist chlorine and hydrochloric acid gases seriously attack the stainless steels at room temperature. The dry gases are not injurious to the austenitic steels at temperatures as high as 370 C (700 F).[27] When air is present, there is a possibility of more severe attack, and caution should be used in applying these limits. Sulfur dioxide is not active unless moist. The steels that contain 25% Cr, 12% Ni; 25% Cr, 20% Ni; and 18% Cr, 8% Ni, 2% Mo are more effective in resisting moist sulfur dioxide than is the 18% Cr — 8% Ni steel.

Stainless steels containing more than 18% Cr are extremely resistant to rural, industrial and marine atmospheres.[24,28] Wide use is made of these steels in architectural designs, for example in the Chrysler and Empire State buildings. It is necessary that the steel surface be free from scale and iron contamination; but if the surfaces are kept reasonably clean, they maintain their brightness indefinitely. The importance of cleaning frequently should be emphasized strongly, since dust and dirt act as contact corrodents, and may cause superficial rust spots.

Resistance to Corrosion at High Temperatures.* The chromium content influences the resistance of the stainless steels to atmospheres of oxidizing gas without sulfur, at elevated temperatures. A general view of the influence of chromium on the resistance of steel to oxidation may be gained from Fig. 4,[23] which indicates graphically that with ordinary steel, scaling begins at about 538 C (1000 F), and that additions of chromium increase progressively the resistance of steel to scaling. When 25% Cr is present, the steels resist scaling at temperatures as high as 1100 C (2010 F). The stainless steels most frequently used at high temperatures are those containing 25% Cr, 12% Ni (type 309), 25% Cr, 20% Ni (type 310), and 25 to 30% Cr (type 446), since these steels exhibit maximum resistance to oxidation. The steels that contain less chromium are also used at elevated temperatures, but the useful range is limited to temperatures below about 815 C (1500 F).

The presence of sulfur in hot oxidizing gases is not seriously harmful as long as the chromium content is high enough. When nickel is present in steel that is to be used in such an atmosphere, the chromium content should be at least 25%. Attack by sulfur is more severe in reducing gases than in oxidizing gases since sulfide corrosion products are less protective than oxides. However, the extent of the corrosive attack by hot sulfur compounds depends on the concentration of the sulfur compounds, the temperature, and the oxidizing power of the atmosphere. Practical observations indicate that the higher the chromium content of the steel, the more severe are the sulfur conditions that can be tolerated.

Under conditions that prevail in the manufacture of ammonia, the stainless steels show considerable resistance to attack, since the presence of chromium greatly retards the penetration of the hydrogen into steel.

Table VII. Corrosion of Stainless Steels in Some Nonaqueous Substances[a]

Substance	Condition, or Temp, deg Fahr	Steel 18-8	18-8 Mo	17 Cr	12 Cr
Acetone	Boiling	A	A	...	...
Ethyl alcohol	70°	A	A	A	...
Ethyl alcohol	Boiling	A	A	A	...
Methyl alcohol	70°	A	A	A	...
Methyl alcohol	150°	C*	B	C	...
Benzene	70°	A	A	A	...
Carbon tetrachloride, pure	70°	A	A	A	A
Chloroform	70°	A	A	A	...
Creosote (coal tar)	Hot	A	A	...	...
Creosote oil	Hot	A	A	...	...
Ether	70°	A	A	A	...
Ethyl chloride	70°	A	A	A	...
Ethylene chloride	70°	A	A	...	...
Fuel oil	Hot	A	A	...	...
Gasoline	70°	A	A	A	A
Glue, dry	70°	A	A	A	...
Glue Sol-acid	70°	B*	A	...	...
Glue Sol-acid	140°	B*	A	...	...
Glycerin	70°	A	A	A	...
Kerosene	70°	A	A	A	...
Linseed oil	70°	A	A	A	...
Naphtha	70°	A	A	A	...
Naphtha crude	70°	A	A	...	...
Crude oil	Hot	A‡	A‡	A‡	...
Crude oil	Cold	A‡	A‡	A‡	...
Paraffin	Hot	A	A	A	A
Paraffin	Cold	A	A	A	A
Petroleum ether	...	A	A	A	A
Rosin	Molten	A	A	A	...
Soap	70°	A	A	A	...

(a) Laboratory test data from various manufacturers of steel
* Subject to pitting at air line or when allowed to dry
‡ May attack when sulfuric acid is present

Symbol	*Description*	*Gram Lost per Sq Meter per Hr*	*Theoretical Penetration in Inch per Month*
A	Fully resistant	Less than 0.1	Less than 0.00035
B	Satisfactorily resistant	0.1 to 1.0	0.00035 to 0.0035
C	Fairly resistant	1.0 to 3.0	0.0035 to 0.01

Table VIII

Corrosion of Stainless Steels in Some Gaseous Corrodents[a]

Substance	Condition, or Temp, deg Fahr	Steel 18-8	18-8 Mo	17 Cr	12 Cr
Acetic acid vapors					
100%	Hot	E	C	...	...
30%	Hot	C	B	...	...
Ammonia					
all concentrations	70°	A	A	A	...
Ammonia gas	Hot	E	...	D	...
Carbon monoxide	1600°	A	A	A	...
Carbon monoxide	1400°	A	A	A	A
Carbon bisulfide	70°	C	C	C	...
Cyanogen	70°	A	A	...	...
Fluorine	70°	E	E	E	E
Hydrogen sulfide	Dry	A	A	A‡	...
Hydrogen sulfide	Wet	B‡	A‡	C‡	...
Steam	...	A	A	A	A
Sulfur dioxide	Moist, 70°	B	A	C	...
Sulfur dioxide gas	575°	A	A	A	...
Vinegar fumes	...	A	A	...	...

(a) Laboratory test data from various manufacturers of steel
‡ May attack when sulfuric acid is present

Symbol	*Description*	*Grams Lost per Sq Meter per Hr*	*Theoretical Penetration in Inch per Month*
A	Fully resistant	Less than 0.1	Less than 0.00035
B	Satisfactorily resistant	0.1 to 1.0	0.00035 to 0.0035
C	Fairly resistant	1.0 to 3.0	0.0035 to 0.01
D	Slightly resistant	3.0 to 10.0	0.01 to 0.035
E	Not resistant	More than 10.0	More than 0.035

* *See also* "Resistance of Metals to Oxidation", page 223.

The stainless steels carburize under reducing conditions, but their carburizing tendency decreases as the chromium content increases. Steels that contain 25% Cr with or without nickel, have been used in retorts for gas carburizing, and in seamless tubes for treating hydrocarbon gases at elevated temperatures. In steel used for treating hydrocarbon gases the nickel content is kept low in many instances to prevent unwanted catalytic reactions.

Austenitic steels that contain 18% Cr, 8% Ni as well as titanium or columbium (types 321 and 347) are extremely resistant to exhaust gases from internal combustion engines and are used widely in exhaust manifolds. Condensing flue gases usually contain small amounts of sulfuric acid, and the solution that condenses when the dew point is reached is extremely corrosive. However, the stainless steels that contain 18% Cr, 8% Ni, 2% Mo (type 316) have been found exceptionally resistant under such conditions and are used successfully in contact with flue gases.

Ordinarily the stainless steels are not used in contact with molten metals such as zinc, copper, brass, aluminum, and babbitt, because these metals attack the steels intergranularly. Fused compounds that may revert to caustic are also corrosive and, in general, the stainless steels are not suited for continuous exposure to molten chlorides or cyanides.

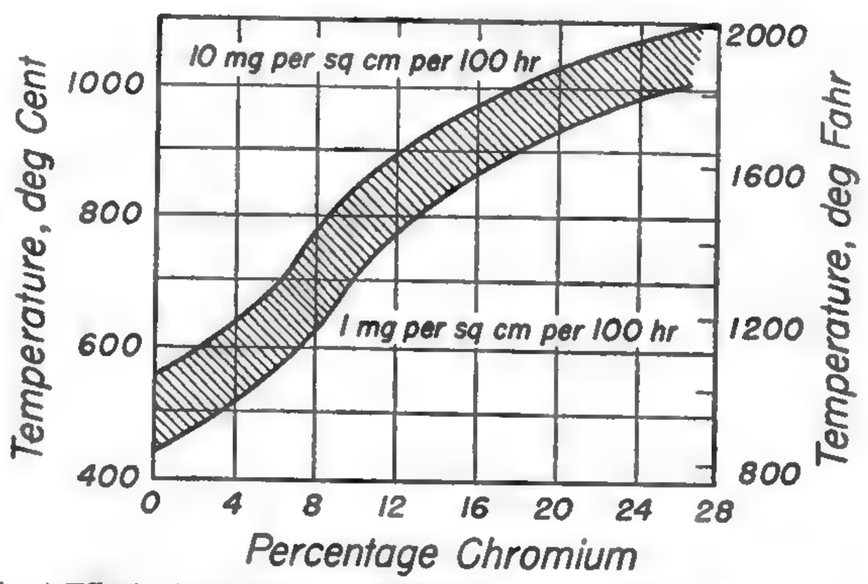

Fig. 4 Effect of increasing chromium content on the resistance of steel to oxidation[23]

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Wrought Heat-Resisting Alloys

BY THE SUBCOMMITTEE ON WROUGHT HEAT-RESISTING ALLOYS*

THE USEFUL APPLICATION of wrought heat-resisting steels and alloys is becoming increasingly important in apparatus, parts and equipment required for high-pressure processes in chemical plants, for conversion of hydrocarbons, for generation of power, and in other structures or appliances that operate at elevated temperatures. Primary requirements include resistance to creep or rupture, resistance to oxidation and corrosion, sufficient ductility and workability for fabricating operations, and reasonable stability of structure so as to avoid detrimental changes in properties during exposure in service. These requirements are met in greater or lesser degree by the wrought heat-resisting steels now available to industry.

Recent developments in jet-propulsion engines, turbochargers and gas turbines, have been possible because of new wrought materials even stronger than those formerly available. These new materials are described briefly in following paragraphs. In addition, there are other, more specialized fields of application for high-temperature steels —for example, bolting steels and valve materials for internal-combustion engines. Because of their limited field of application in general construction, bolting materials will not be considered here. Although numerous low-alloy steels may properly be designated as high-temperature steels, this chapter defines heat-resisting steels as those containing 4% Cr or more, in accord with the present AISI commercial designation for such materials. In Table I are listed the compositions of the more important and most widely used wrought heat-resisting steels. These materials are available in all the usual commercial forms, such as plate, sheet,

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The section on Superstrength Wrought Heat-Resisting Alloys was prepared by H. C. Cross.

Table I. Composition Limits of Wrought Heat-Resisting Steels[a] [b]

Type No. (AISI)	Composition, percentage: Carbon	Manganese (max)	Silicon (max)	Phosphorus (max)	Sulfur (max)	Chromium	Nickel	Other Elements
Wrought Chromium Steels								
501	0.10 min	1.00	1.00	0.040	0.030	4.00 to 6.00	.....	.....
7 Cr	0.15 max	0.60	0.50 to 1.00	0.030	0.030	6.00 to 8.00	.....	Mo 0.45 to 0.65
9 Cr	0.15 max	0.60	1.00	0.030	0.030	8.00 to 10.00	.....	Mo 0.90 to 1.10
403	0.15 max	1.00	0.50	0.040	0.030	11.50 to 13.00	.....	.....
410	0.15 max	1.00	1.00	0.040	0.030	11.50 to 13.50	.....	.....
430	0.12 max	1.00	1.00	0.040	0.030	14.00 to 18.00	.....	.....
442	0.25 max	1.00	1.00	0.040	0.030	18.00 to 23.00	.....	.....
446	0.35 max	1.50	1.00	0.040	0.030	23.00 to 27.00	.....	N 0.25 max
Wrought Chromium-Nickel Steels								
302	0.08 to 0.20	2.00	1.00	0.040	0.030	17.00 to 19.00	8.00 to 10.00	.....
302B	0.08 to 0.20	2.00	2.00 to 3.00	0.040	0.030	17.00 to 19.00	8.00 to 10.00	.....
304	0.08 max	2.00	1.00	0.040	0.030	18.00 to 20.00	8.00 to 11.00	.....
309	0.20 max	2.00	1.00	0.040	0.030	22.00 to 24.00	12.00 to 15.00	.....
310[c]	0.25 max	2.00	1.50	0.040	0.030	24.00 to 26.00	19.00 to 22.00	.....
316	0.10 max	2.00	1.00	0.040	0.030	16.00 to 18.00	10.00 to 14.00	Mo 2.00 to 3.00
321	0.08 max	2.00	1.00	0.040	0.030	17.00 to 19.00	8.00 to 11.00	Ti 5 × C min
347	0.08 max	2.00	1.00	0.040	0.030	17.00 to 19.00	9.00 to 12.00	Cb 10 × C min
330[d]	0.25 max	2.00	1.00	0.040	0.030	14.00 to 16.00	33.00 to 36.00	.....

(a) AISI Steel Products Manual, Section 24, Part 10

(b) Not all the compositions in this table conform strictly with those established for seamless tubing. Composition ranges for tubing are listed in AISI Steel Products Manual, Section 18, and in the following ASTM specifications: A 158, A 213, A268, A 269 and A 271.

(c) A modification of this type, known as 310B, contains 2.0 to 2.5% Si and is used to a considerable extent for carburizing boxes and furnace parts.

(d) This material is not listed as a standard AISI grade, but it has been used to some extent in wrought form.

strip, forgings, bars, rod, tubing and wire. Table II gives the nominal compositions of heat-resisting steels that have been used in making exhaust valves for internal-combustion engines.

General Requirements. Heat-resisting steels must meet two basic requirements: they should provide satisfactory resistance to oxidation or other chemical attack at the temperature and in the atmosphere of the intended service, and should provide sufficient strength to withstand loads that are either imposed by the structure itself or applied externally. The steel selected for use should meet these conditions without an excessive amount of stretch or flow.

All heat-resisting steels contain chromium in varying amounts, since their resistance to oxidation is obtained chiefly from chromium and ordinarily depends on the chromium content. Other metallic elements, such as silicon and aluminum, act similarly and are often added to chromium steels to obtain enhanced resistance.

Table II. Nominal Compositions of Wrought Heat-Resisting Steels for Exhaust Valves in Internal-Combustion Engines

No.	Composition, percentage: C	Si	Cr	Ni	W	Mo	Other
1	0.40	4.0	2.9	....	....	....	....
2	0.60	....	3.5	....	14.0	....	....
3	0.50	1.5	8.0	....	....	7.5	....
4	0.45	3.25	8.5	....	....	....	....
5	0.50	0.2	11.0	1.5	....	....	1.8 Al
6	1.10	0.50	13.0	....	....	....	....
7	1.35	0.65	13.3	....	....	0.7	2.5 Co
8	1.05	1.90	13.5	0.9	3.5	0.6	....
9	0.80	2.0	19.5	1.50	....	....	....
10	0.55	0.5	3.5	12.0	....	....	5.0 Mn
11	1.10	2.00	15.5	14.0	....	....	....
12	0.45	0.55	14.0	14.0	2.4	0.35	....
13	0.45	3.00	14.0	14.0	2.4	0.5	....
14	0.50	1.25	14.0	86.0	3.5	....	....
15	0.38	2.9	19.0	8.0	....	....	....
16	0.50	1.0	20.0	32.0	....	....	....
17	0.25	0.85	21.5	11.5	....	....	....
18	0.25	2.80	21.5	11.5	....	....	....
19	0.45	0.55	25.0	14.0	....	2.5	....
20	0.30	2.50	12.8	7.4	....	....	....
21	0.45	0.45	23.8	4.8	....	2.75	....

NOTE. Alloys 1 to 9 are hardenable steels for use in automobiles and depend on chromium or chromium plus silicon or aluminum for resistance to oxidation. As the chromium content is increased, particularly with high silicon, it becomes necessary to increase the carbon content in order to maintain hardenability. The 19.5% Cr alloy 9 was devised for better resistance to gases that contain lead compounds. Alloys 10 to 19 are nonhardenable austenitic types designed for greater strength than the hardenable plain chromium types. Most of these are for high-duty and airplane engines.

Steels 20 and 21 are not hardenable by ordinary quenching. No. 20 is austenitic when quenched from a relatively high temperature and hardens during reheating. Alloy 21 ages to a hardness of about Rockwell C 40 while heating for a number of hours at 1400 F. This hardening is attributed to the formation of sigma phase. Alloy 21 has high resistance to attack by leaded gasolines.

Strength at elevated temperatures is obtained by the addition of metallic elements. At room temperature or at slightly elevated temperatures, carbon serves admirably, in conjunction with proper heat treatment, to increase the strength of steels; but where higher temperatures are involved, carbon is less effective. In most of the common constructional steels, the strength obtained by tempering is lowered drastically by prolonged heating at temperatures as low as 700 F. Additions of molybdenum, tungsten, or columbium are effective in increasing the strength of chromium steels at high temperature. However, at temperatures somewhat above 1000 F, no marked advantage is derived from these additions. To obtain increased strength within this higher temperature range it is necessary to use steels of an austenitic type. Nickel is added in appreciable amounts to accomplish this purpose. In some steels, manganese and nitrogen may be used in conjunction with nickel to promote formation of an austenitic structure. The strength of these austenitic steels may be increased further by addition of small amounts of molybdenum, tungsten, or columbium.

Many steels of both the ferritic and austenitic types are not structurally stable throughout the entire temperature range in which they may be used. Thus, when held in or slowly cooled through the range between 800 and 1000 F, ferritic 27% Cr steel loses in ductility and becomes somewhat less resistant to impact at room temperature because of the so-called "475 C brittleness". The formation of a constituent known as "sigma phase", which occurs at higher temperature (950 to about 1300 F) also has a serious embrittling effect. Heating to above 1200 F and cooling rapidly from that temperature alleviates the effect of the "475 C brittleness" and restores the original ductility; a temperature above 1500 F is required for the solution of sigma phase in the 27% Cr alloy. The plain chromium steels, down to about 15.5% Cr, lose some of their notch-impact toughness and ductility after prolonged heating within this range (800 to 1000 F); however, the original ductility is restored by heating above 1200 F, and then cooling rapidly.

Sigma phase, which is related to composition, may develop in austenitic steels during exposure to certain temperatures within the range from about 1100 to 1700 F. This transformation occurs most readily when the compositions are balanced so that high-temperature ferrite coexists with austenite in the annealed steel. Serious embrittling effects may occur in Types 309, 316 and 347, and sigma may also form in Types 309 and 310 even though the original structure is austenitic, especially if silicon is on the high side of the range. The precipitation of this phase may alter mechanical properties to a minor extent

Table III. Comparative Maximum Temperatures for Satisfactory Operation of Wrought Heat-Resisting Steels Without Excessive Scaling

No.	Material	Maximum Temperature,[a] deg Fahr
501	5 Cr-Mo	1150
...	7 Cr-Mo	1200
...	9 Cr-Mo	1250
403, 410	12 Cr	1300
430	17 Cr	1550
442	21 Cr	1750
446	27 Cr	2000
302, 304	18-8	1650
302 B	18-8 Si	1800
309	24-12	2000
310	25-20	2100
316	18-8 Mo	1650
321	18-8 Ti	1650
347	18-8 Cb	1650

(a) Maximum temperature in oxidizing atmospheres without excessive scaling.

or to a marked extent, depending on the amount of sigma precipitated.

Since austenitic alloys that have been cooled rapidly from 1800 F and higher are supersaturated with carbon, chromium carbide is precipitated at the grain boundaries if the alloys are used within the range from about 900 to 1500 F, or if they are cooled slowly through this range. When these steels are tested at room temperature, lower ductility and higher tensile strength may result, after holding for extended periods of time in the range of carbide precipitation. However, short periods of time will not usually affect the mechanical properties to any measurable extent. In atmospheres that do not contain corrosive agents, the presence of the carbide phase has little effect on the performance of the steel. In the presence of corrosive gases, the carbide phase or areas at the grain boundaries may become susceptible to selective and rapid attack. The addition of appropriate amounts of columbium or titanium renders these alloys immune to attack of this nature. When the metal is in contact with hydrocarbon gases, carburization may influence the serviceability, especially at temperatures higher than about 1400 F. Even so, the austenitic alloys are used for the construction of carburizing furnaces and are often used for equipment to handle hydrocarbon fluids.

In order to meet the more exacting service requirements of gas turbines, a number of high-strength alloys have been developed. In some instances, less than 5% Fe is present. These new alloys have even greater strength at high temperature than the better known austenitic steels mentioned in the preceding paragraphs. These high-strength alloys contain enough chromium to ensure adequate resistance to oxidation, and have an iron and nickel or nickel and cobalt base, together with smaller amounts of columbium, molybdenum, tungsten or titanium to increase the strength at high temperature. Information concerning these special high-strength alloys is given in a later section of this article.

Table IV. Results of Scaling Test of Five Wrought Heat-Resisting Steels[a]

Test Conditions	Steels: 12 Cr	17 Cr	27 Cr	18-8	25-12
	Gain in Weight, mg per sq cm				
50 hr 1650 F in air	0.7	0.7	..	...	...
50 hr 2010 F in air	250.0	7.0	2.5	15.0	9.0
50 hr 1800 F in hydrogen sulfide	1000.0	930.0	820.0	...	...

(a) More detailed information is included in Chapter 17 of "The Book of Stainless Steels", American Society for Metals, 1935

Resistance to Oxidation. Table III gives a suggested limit of operating temperature for ordinary use, which may require modification, depending on the severity of the oxidation rate as influenced by the type of atmosphere, amount of sulfur compounds present, or other factors that tend to increase the loss of metal. The scaling temperature or operating temperature limit given is based on arbitrary standards and indicates approximately the temperature at which, after prolonged heating in a strongly oxidizing atmosphere, a scale will form of sufficient thickness to cause flaking or spalling. The heat-resisting steels oxidize superficially at lower temperatures, forming a series of temper colors, until a thin, more or less adherent layer of scale is formed. This action proceeds very slowly until the scaling temperature is reached, whereupon progressive thickening of the scale layer, with spalling, causes much more rapid deterioration of the metal, thus reducing the service life or making mandatory the selection of a more highly alloyed material for economical and continued operation.

Modification of composition, by the addition of aluminum or silicon, affects the scaling temperature by changing the nature of the scale layer. A similar effect, also related to the nature of the scale, concerns the type of atmosphere in which the metal is tested. Table IV presents the results of scaling tests conducted in a highly oxidizing atmosphere and, for comparison, similar tests conducted in an atmosphere of hydrogen sulfide are cited also. At 1650 to 2010 F the chromium-rich oxide is refractory and

Table V. Tensile Strength (psi) of Annealed Wrought Heat-Resisting Steels at Various Temperatures

Temp, deg Fahr	½ Cr[a] Type 501	7 Cr[b]	9 Cr[c]	12 Cr Type 410	17 Cr Type 430	27 Cr Type 446	18-8 Type 304	18-8 Ti Type 321	18-8 Cb Type 347	18-8 Mo Type 316	24-12 Type 309	25-20 Type 310
RT	76,500	72,500	75,500	89,000	74,500	83,000	87,000	83,500	90,000	82,500	91,000	96,000
200	63,000	70,000	.....	83,000	69,000	78,000	78,500	73,500	79,000	77,000	84,500	93,000
300	62,000	.....	.....	79,000	66,000	75,000	75,500	68,000	75,000	75,000	81,000	90,500
400	60,000	67,000	.....	76,000	64,000	73,500	74,000	64,000	71,500	74,000	79,000	88,000
500	58,500	.....	.....	74,500	62,500	72,500	73,500	62,000	69,500	73,500	77,000	86,000
600	58,000	65,500	.....	73,000	60,500	71,500	73,000	61,000	68,000	73,000	75,500	85,000
700	57,000	.....	.....	71,000	57,500	70,500	71,500	60,000	67,000	72,500	74,000	85,000
800	56,000	54,000	.....	66,000	54,000	68,500	69,000	59,000	66,000	71,500	72,000	84,500
900	52,500	45,000	61,000	55,500	48,000	66,000	65,000	58,000	64,500	70,000	69,000	83,500
1000	44,000	43,000	53,500	44,500	39,000	61,000	58,000	54,000	61,500	67,500	65,500	80,500
1100	32,500	34,000	41,500	33,000	29,000	43,500	51,500	50,000	57,000	63,000	61,000	72,000
1200	24,000	23,500	30,000	22,000	20,500	24,000	44,500	44,500	50,000	56,500	55,000	61,500
1300	17,500	17,000	19,000	13,500	14,000	17,000	37,500	36,500	40,500	46,500	45,000	50,500
1400	12,000	11,000	13,000	9,000	9,500	12,000	29,500	28,500	31,500	35,000	34,000	41,000
1500	9,500	8,000	10,000	9,000	6,500	8,000	22,000	22,000	24,000	27,000	25,500	32,500
1600	.....	9,000[d]	14,000[d]	9,500[d]	4,500	5,500	16,000	17,500	18,500	22,000	19,500	25,000
1700	.....	.....	.....	9,000	3,500	4,000	12,000	15,000	14,500	18,500	15,000	18,500
1800	.....	.....	.....	7,000	....	3,000	8,500	....	12,000	.....	11,500	13,500
1900	.....	.....	.....	5,500	....	2,500	6,500	....	10,000	.....	8,500	10,000
2000	.....	.....	.....	4,500	....	2,000	5,500	....	8,500	.....	6,500	8,000
2100	.....	.....	.....	3,000	....	1,500	....	....	7,000	.....	4,500	6,500
2200	.....	.....	.....	2,500	....	1,250	....	....	5,500	.....	3,500	5,000
2300	.....	.....	.....	1,500	....	1,000	....	....	4,000	.....	2,500	4,000
2400	.....	.....	.....	500	....	....	....	....	.....	.....	2,000	3,500

(a) 0.50% Mo (b) 0.50% Mo (c) 1.00% Mo
(d) Reversal caused by the transformation of ferrite to austenite

Table VI. Rupture Strength of Heat-Resisting Steels at Various Temperatures

Temp, deg Fahr	5 Cr[a] Type 501	7 Cr[b]	9 Cr[c]	27 Cr Type 446	18-8 Type 304	18-8 Ti Type 321	18-8 Cb Type 347	18-8 Mo Type 316	24-12 Type 309	25-20 Type 310
				Stress (psi) for Rupture in 1000 hr						
1000	19,000	....	....	....	....	....	....	....	....	32,000
1100	11,000	14,000	18,000	6000	28,000	27,000	30,000	33,000	....	24,000
1200	6,000	6,500	8,300	4000	15,000	17,500	17,000	25,000	20,500	17,000
1300	3,300	3,400	3,800	2800	9,000	10,000	11,200	17,000	11,700	11,000
1400	2,000	....	....	1700	6,000	5,500	7,500	11,000	....	7,000
1500	1,500	1,000	1,250	1100	3,700	3,700	4,400	7,000	4,800	4,500
1600	....	....	....	....	....	2,750	....	4,000	2,750	3,000
1800	....	....	....	....	....	....	....	1,300	1,025	1,950
				Stress (psi) for Rupture in 100,000 hr (Extrapolated)						
1000	14,500	....	....	....	....	....	....	....	....	16,000
1100	7,000	8,400	11,800	....	....	....	16,500	....	....	13,000
1200	2,500	3,200	3,500	2000	8,500	....	11,000	12,500	11,250	8,000
1300	1,200	1,300	1,600	1500	4,000	....	4,500	9,000	3,725	4,600
1400	....	....	....	900	3,000	....	....	4,200	....	2,600
1500	....	....	....	500	1,500	....	....	1,500	....	1,200

(a) 0.5% Mo (b) 0.5% Mo (c) 1.0% Mo

minimizes further chemical reaction, while the complex sulfides formed are liquid and promote interaction between the gas and metal phases. In reducing atmospheres where quantities of carbon monoxide are present, the scale formed is lower in chromium and therefore offers less protection. Furthermore, if carburization occurs, since carbon combines preferentially with chromium, the surface of the metal is depleted in effective chromium content—or, in other words, loses its "stainlessness" and forms scale more rapidly. During repeated heating and cooling, the ferritic stainless steels may scale less than austenitic steels because of their lower coefficient of thermal expansion. Numerous data concerning the resistance to oxidation of the heat-resisting steels under various conditions of exposure, are available in technical publications.

Mechanical Properties. Mechanical properties at ordinary temperature have no particular significance for heat-resisting steels, except as the data relate to fabrication of the part or to shock resistance at ambient temperature. In general, the plain chromium steels that contain more than about 15% Cr are notch-sensitive and are subject to grain growth during heating to high temperatures. Consequently, the plain chromium steels have a more limited field of application than the chromium-nickel austenitic steels. They also have less load-carrying ability when under stress at elevated temperatures.

In American practice, three types of tests are commonly employed to determine the high-temperature properties of metals; namely, short-time tension tests, rupture tests and creep tests (tensile or relaxation). Further information about the testing of metals at elevated temperature appears in the MECHANICAL TESTING section of this Handbook. The departure from room-temperature testing technique is necessitated by the fact that at temperatures higher than about 700 F a new phenomenon of flow becomes operative, which requires study on the basis of stress-strain-time factors at each temperature. The short-time tension test is similar in procedure to the ordinary tension test (*see* page 105) except that the specimen is enclosed in a furnace designed to ensure a uniform temperature over the specimen. The specimen is held at the designated testing temperature for a period of 30 min to one hour and is then pulled to fracture while still at temperature. Table V contains a compilation of data on tensile strength obtained by this type of test.

Short-time tensile, creep and rupture properties of metals are affected by the grain size, heat treatment, presence of cold work and the like, aside from the direct effect of composition. These factors are responsible for some of the divergencies in the data reported in various publications for given types of alloys. The wrought heat-resisting steels are usually applied in the annealed or softened condition. The data cited here concerning high-temperature properties, relate to annealed metal. The user of the data in this article should note that the specific heat treatment influences grain size; this may result in wide variation in high-temperature properties of the austenitic steels. In general, the coarse-grained steels have better resistance to creep or rupture than fine-grained steels but have poorer ability to elongate under stress.

Rupture Strength. The widely used stress-rupture test indicates the time required for fracture at a given temperature, under various constant loads. The data obtained by this method of testing are particularly useful for parts that have relatively short life in service, or where considerable uncertainty exists in regard to the temperature of the metal in service as, for example, in fired equipment. The stress-rupture test is similar to a creep test except that in the former, precise measurements of strain

Table VII. Creep Strength of Wrought Heat-Resisting Steels

Material		1000 F	1100 F	1200 F	1300 F	1400 F	1500 F
				Stress (psi) for 1% creep in 10,000 hours			
501	5 Cr, 0.5 Mo	9,000	5,000	2,000	1500	....	....
...	7 Cr, 0.5 Mo	8,000	4,200	2,300	1400	....	....
...	9 Cr, 1 Mo.	12,000	6,700	2,600	1500	....	....
410	12 Cr	11,000	4,500	2,000	1300	....	....
430	17 Cr	8,500	5,000	2,200	1200	800	....
442	21 Cr	8,500	5,000	1,600	1000	....	600
446	27 Cr	6,000	3,000	1,500	600	300	....
302, 304	18-8	17,500	12,000	7,000	4000	2500	1000
302 B	18-8 Si.....	....	....	7,000	4500	....	1000
321	18-8 Ti	18,000	13,000	8,000	4500	2000	850
347	18-8 Cb	19,000	15,000	9,500	5000	2500	1100
309	24-12	17,000	13,000	8,500	4500	2000	1000
310	25-20	20,000	15,000	9,000	5000	2300	1000
316	18-8 Mo.....	24,000	18,000	11,000	7000	4500	2000
				Stress (psi) for 1% creep in 100,000 hours			
501	5 Cr, 0.5 Mo	7,200	2,500	900	....	....	....
...	7 Cr, 0.5 Mo	5,000	2,500	1,300	....	....	....
...	9 Cr, 1 Mo..	8,500	3,000	1,600	....	....	....
410	[redacted] Cr	10,000	3,700	1,300	800	....	....
430	17 Cr	7,000	4,500	1,600	900	....	....
446	27 Cr	4,200	2,300	1,000	250	100	....
304	18-8	11,300	7,500	4,100	2200	1200	700
310	25-20	13,000	8,700	5,800	3600	2200	800
316	18-8 Mo	14,800	10,000	6,000	3800	2300	900

Table VIII. Fatigue Strength of Heat-Resisting Steels at Elevated Temperatures[5, 13]

Composition, %:
C 0.10, Mn 0.29, P 0.014, S 0.019, Si 0.31, Ni 0.38, Cr 12.30
Condition:
Annealed, 5 hr 1175 F, furnace cooled to 570 F, then air cooled

Mechanical Properties at Room Temperature

Tensile strength, psi	111,700
Yield strength, psi	80,000
Elongation, % in 2 in.	23.5
Reduction of area, %	67.9

Temperature, deg Fahr[a]	Room	700	850	1000
Endurance limit, psi at 10^7 cycles	58,000	49,000	43,500	27,200

Steel Type	Composition, % C	Cr	Ni	N	Treatment	Test Temperature, deg Fahr: Room	800	1000	1200
						1000 psi			
304	0.067	18.21	9.56	0.056	WQ 2000 F*	40	32	32	30
302	0.125	18.50	9.67	0.035	.....	42	37	38	[redacted]

* WQ, water-quenched
(a) There seems to be no real endurance limit at elevated temperatures, as at room temperature, but rather the S-N curve slopes downward at all reversals investigated.

Table IX. Physical Constants of Annealed Heat-Resisting Steels

Steel	501	7 Cr[a]	9 Cr[b]	403 410	430	442	446	304 302	302B	321	347	309	310	316
Modulus of elasticity, 10^6 psi	29.0	29.0	29.0	29.0	29.0	29.0	29.0	28.0	28.0	28.0	28.0	29.0	29.0	28.0
Density, lb per cu in	0.28	0.28	0.28	0.28	0.28	0.28	0.27	0.29	0.29	0.29	0.29	0.29	0.29	0.29
Specific resistance, 70 F, microhms per cu cm	40	45	53	57	60	64	67	72	72	72	73	78	78	74
Specific heat (32 to 212 F) Btu/lb/°F	0.11	0.11	0.11	0.11	0.11	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Ferromagnetic	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No
Structure (annealed)	α	α	α	α	α	α	α	γ	γ	γ	γ	γ	γ	γ
Thermal conductivity, Btu/hr/sq ft/ft/°F														
At 212 F	21.2	...	...	14.4	15.1	12.5	12.1	9.4	9.2	9.3	9.3	8.0	8.0	9.4
At 932 F	19.5	...	...	16.6	15.2	14.2	14.1	12.4	12.5	12.8	12.8	10.8	10.8	12.4
Mean Coefficient of Expansion, millionths per deg Fahr														
32 to 212 F	6.2	6.2	6.2	5.5	5.0	4.9	5.9	9.6	9.0	9.3	9.3	8.3	8.0	8.9
32 to 600 F	6.8	6.5	6.67	5.6	5.8	5.7	6.2	9.9	10.0	9.5	9.5	9.3	9.0	9.0
32 to 1000 F	7.2	7.0	7.1	6.4	6.2	6.4	6.4	10.2	10.8	10.3	10.3	9.6	9.4	9.7
32 to 1200 F	7.3	7.2	7.3	6.5	6.3	6.7	6.7	10.4	11.2	10.7	10.6	10.0	9.7	10.3
32 to 1500 F	...	...	...	...	6.9	...	...	...	...	11.2	11.1	...	...	11.1
32 to 1800 F	...	...	...	...	...	...	...	...	...	...	...	11.5	10.6	...
Melting Range, °F														
Solidus	2700	...	...	2700	2600	2600	2550	2600	2550	2550	2550	2550	2550	2500
Liquidus	2800	...	...	2790	2750	2750	2750	2750	2650	2600	2600	2650	2650	2550

(a) 0.5% Mo (b) 1.0% Mo

are not usually required and higher stresses are employed. A series of tests is made at each temperature under several loads and the time for fracture is noted. These data may then be plotted on logarithmic co-ordinates to determine the fracture time in 100, 1000, 10,000 or more hours, and from these graphs, service stresses or operating temperatures may be selected in accordance with the life or performance desired. Since the part seldom ruptures in actual practice except in instances of inadvertent overheating or overstressing, proper allowance is made for dimensional changes of considerable magnitude. Table VI gives rupture-strength data for a number of the heat-resisting steels. The short-time tensile strengths given in Table V correspond to the first point on a stress-rupture curve.

Rupture testing is useful for evaluating the strength properties of steels, aside from the usefulness of data so derived for the engineering design of structures that are to be used at high temperature. In the longer stress-rupture tests, which ordinarily do not exceed about 2000 hours, continuous strain measurements may be taken so that accelerated creep data may be obtained. It is common practice to extrapolate stress-to-rupture data in order to give theoretical values for rupture at 10,000 and 100,000 hours. This can be a dangerous practice because many metals used at high temperature tend to become brittle under load and to change in microstructure with the passage of time; consequently, premature failure may result. Also the full extent of progressive oxidation or corrosion may not be detected in these relatively short-time tests. Changes in the slope of the stress-rupture curve indicate either surface instability (oxidation) or structural instability (carbide precipitation, grain growth, phase change). When such changes are detected in tests that last up to 1000 hours or slightly more, proper warning is given but there is no guarantee that the slope of the curve will remain constant during longer periods. Consequently the engineer must select suitable factors of safety and incorporate them in the design values. Ferritic alloys usually exhibit greater ability to elongate under stress than do alloys of austenitic structure, which may break short under stress at temperatures higher than about 1000 F.

Creep Strength. The creep test is well known and numerous data exist on steels and other metals. In the tensile creep test, specimens are maintained under precise temperature control and under constant load; the strain is measured and recorded at regular time intervals throughout the test, which is conducted under several stresses at each temperature for periods of at least 1000 hours, and in many tests 5000 to 10,000 hours. Individual specimens are used for each set of stress-temperature conditions. Some few tests have been extended to 100,000 hours. The secondary rate of creep is ascertained from the slope of the time-elongation curves, and the rate of creep at various stresses can be determined by log-log plotting versus stress. Commonly used values correspond to 0.10%, 0.01% and 0.001% creep per 1000 hours. These values are usually considered in terms of 1% elongation in 10,000 hours, 1% in 100,000 hours and 1% in 1,000,000 hours respectively, and are used in design after proper allowances have been made, in accordance with the specific service requirements and permissible deformation.

The carbon steels are satisfactory for service under low stresses at 800 F, and in some instances up to 1000 F; low-alloy steels are commonly used between 800 and 1100 F. Above 1100 F the extra strength and resistance to corrosion of the heat-resisting stainless steels generally become necessary. Table VII, which concerns the heat-resisting steels, contains averaged values of creep strength from several sources, for 1% elongation in 10,000 hours. This table includes typical supplementary data on stresses for 1% elongation in 100,000 hours. The stress required for producing a flow rate of 1% in 10,000 hours is greater

Table X. Chemical Compositions of Wrought Heat-Resisting Alloys

Alloy	C	Mn	Si	Cr	Ni	Co	Mo	W	Cb	Ti	N	Fe	Other
19-9 W-Mo	0.12 max	0.50	0.60	19.00	8.50	....	0.35	1.25	0.50	0.35	....	Rem	....
19-9 DL	0.25	0.50	0.60	19.00	9.00	....	1.25	1.20	0.30	0.20	....	Rem	....
234-A-5	0.38	4.17	0.30	18.52	4.55	....	1.35	1.34	0.57	....	....	Rem	....
Timken 16-25-6	0.10	1.35	0.70	16.72	25.23	....	6.25	....	....	....	0.147	Rem	....
Low-carbon N-155	0.15	1.50	0.50	21.3	20.0	20.0	3.0	2.0	1.0	....	0.15	Rem	....
N-155	0.36	1.54	0.59	21.08	20.8	20.54	3.0	2.18	0.98	....	0.11	Rem	....
S-495	0.40–0.50	1.0 max	1.0 max	13.0–15.0	19.0–21.0	....	3.50–4.50	3.50–4.50	3.50–4.50	....	....	Rem	....
S-497	0.40–0.50	...	...	....	....	19.0–21.0	....	....	....	....	....	Rem	....
S-590	0.40–0.50	2.0 max	1.0 max	18.50–20.5	19.0–21.0	19.0–21.0	3.50–4.00	3.50–4.00	3.50–4.00	....	....	Rem	....
S-816	0.35–0.45	1.0 max	1.0 max	18.50–20.50	19.0–21.0	42.0–44.0	3.50–4.00	3.50–4.00	3.50–4.00	....	....	Rem	....
Inconel "X"	0.04	0.50	0.40	15.0	73.0	....	....	....	1.0	2.5	....	7.0	Al 0.7
K-42-B (Type 5)	0.06	0.70	0.34	18.0	42.0	22.0	....	....	....	2.56	....	13.0	Al 0.59
Refractaloy 26	0.03	0.70	0.65	17.9	37.0	20.0	3.03	....	....	2.99	....	Rem	Al 0.25
Hastelloy B	0.05	0.59	0.19		65.10	....	28.63	....	....	....	....	4.71	....
Vitallium	0.22	0.66	0.53	27.42	2.84	62.20	5.53	....	....	....	....	0.70	....
25 Cr - 20 Ni - 1.5 Si (Type 310)	0.25	2.0 max	1.5 max	24.0–26.0	19.0–22.0	....	....	....	....	....	....	Rem	....

Table XI. Stress-Rupture Data for Wrought Heat-Resisting Alloys

Condition As Tested	Stress (psi) for Rupture in 100 and 1000 Hours											
	1200 F		1350 F		1500 F		1600 F		1700 F		1800 F	
	100 hr	1000 hr	100 hr	1000 hr	100 hr	1000 hr	100 hr	1000 hr	100 hr	1000 hr	100 hr	1000 hr
19-9 W-Mo												
Forged bar stock reduced 26% at 1200 F by rolling[b]	54,500	42,000	28,500	.....	.....	.....	.....	.....	.....	.....	.....	.....
19-9 DL												
Hot rolled	43,000	36,000	.....	.....	11,000[a]	.....	.....	.....	.....	.....	.....	.....
Annealed 2100 F, air cooled	42,000	34,500	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Forged bar stock reduced 21% at 1200 F by rolling	62,000	50,000	35,000	20,500	.....	.....	.....	.....	.....	.....	.....	.....
234-A-5												
Hot forged	50,000	39,000	22,500	12,500	.....	.....	.....	.....	.....	.....	.....	.....
Hot rolled	48,000	37,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Annealed 2050 F, water quenched	47,500	37,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Annealed 2050 F, water quenched and reduced 20% at 1200 F[b]	53,000	32,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Timken 16-25-6												
Hot rolled[b]	52,000	39,000	28,500	.....	.....	.....	.....	.....	.....	.....	.....	.....
Annealed 2100 F, air cooled	49,000	35,000	25,500	.....	12,900[d]	< 10,000[d]	.....	.....	.....	.....	.....	.....
Annealed 2100 F, air cooled and reduced 22.5% at 1200 F by rolling[b]	57,000	42,000	28,000	19,000	.....	.....	.....	.....	.....	.....	.....	.....
Low-carbon N-155												
Hot forged	58,000	48,000	36,000	27,500	20,000	12,500	.....	.....	.....	.....	.....	.....
Hot rolled	49,000	38,000	.....	.....	.....	.....	.....	.....	5100[b]	2500[b]	.....	.....
Annealed 2200 F, water quenched, aged 50 hr at 1350 F	47,000	37,000	30,000	22,500	18,800	.....	.....	.....	7600[c]	4800[c]	4900[c]	2800[c]
Rolled bar stock reduced 20% at 1200 F[b]	61,000	46,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
N-155												
Hot rolled[b]	59,000	46,000	28,000	20,000	.....	.....	.....	.....	.....	.....	.....	.....
Annealed 2100 F, air cooled	52,000	39,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Annealed 2200 F, water quenched, aged 50 hr at 1500 F	.....	.....	.....	.....	21,500	16,500	.....	.....	.....	.....	.....	.....
S-495												
Hot worked	35,000	26,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Annealed 2250 F, water quenched, aged 16 hr at 1400 F	.....	36,000	.....	.....	18,000[d]	14,000[d]	13,300[d]	9200[d]	.....	.....	.....	.....
S-497												
Hot worked	45,000	33,500	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Annealed 2250 F, water quenched	.....	.....	.....	.....	18,000[d]	14,500[d]	11,500[d]	8600[d]	.....	.....	.....	.....
S-590												
Annealed 2300 F, water quenched	.....	.....	32,000[e]	26,000[e]	19,000–21,000[f]	14,000–15,500[f]	12,500[g]	9000[g]	9400[g]	6600[g]	5600[g]	3500[g]
S-816												
Annealed 2300 F, water quenched	.....	.....	35,000[h]	30,000[h]	24,000–25,000[f]	17,000–18,000[f]	14,000[g]	9500[g]	9500[g]	6100[g]	5300[g]	3000[g]
Inconel "X"												
Annealed 2100 F, air cooled, aged 24 hr at 1550 F plus 20 hr at 1300 F	80,000	69,000	58,000	42,000	28,000	18,000	.....	.....	.....	.....	.....	.....
K-42-B (Type 5)												
Annealed 2100 F, oil quenched[d]	.....	.....	.....	.....	23,500	.....	.....	.....	.....	.....	.....	.....
Refractaloy 26												
Annealed 2100 F, oil quenched[i]	.....	.....	.....	.....	28,500	18,000	.....	.....	.....	.....	.....	.....
Hastelloy B												
Annealed 1900 F, air cooled 24 hr	.....	.....	.....	.....	17,000	.....	.....	.....	.....	.....	.....	.....

(a) Hot worked and aged at 1500 F
(b) Stress relieved at 1200 F
(c) Annealed 2280 F, air cooled
(d) Aged 50 hr at test temperature
(e) Annealed 2270 F, water quenched, aged 16 hr at 1400 F
(f) Range for material aged 50 hr at 1350 or 1500 F
(g) Aged 16 hr at test temperature before testing
(h) Aged 16 hr at 1400 F
(i) Aged 20 hr at 1500 F, air cooled, then aged 20 hr at 1350 F

than, but not in direct proportion to, the stress required for 1% in 100,000 hours. Although frequently practiced, the extrapolation of these data to different temperature ranges, flow rates or compositions, is not recommended. Furthermore, the engineer should consider the heat treatment given and the grain size of the steel, in order to assay its specific creep properties.

The superior creep resistance of the austenitic steels indicates the advantage of this type of alloy for service at temperatures above 1000 F. Lighter weight structures, higher stresses, higher temperatures and, in general, more adequate factors of safety, are made possible through the use of such austenitic materials. Composition has an important influence and relatively small additions of such elements as molybdenum, aluminum and silicon have been observed to alter considerably the creep strength of the various chromium-nickel alloy steels. In the marginal austenitic alloys, this may be caused by ferrite formed as a result of the additional element. The unexpected decrease in creep resistance of the higher-chromium ferritic alloys at 1100 F and higher, is probably related to the peculiar aging phenomenon that occurs in this range, promoting the formation of sigma phase. It is generally believed that structural instability lowers creep resistance, although high recrystallization temperature and certain types of precipitation have a strengthening effect. However, it appears that fundamentally, the body-centered cubic crystal structure (ferrite or alpha) is less resistant to creep than the face-centered cubic structure (austenite or gamma). The austenitic heat-resisting steels are greatly superior, therefore, in load-carrying ability.

Fatigue Stresses. Alternating stresses and fluctuations of temperature accelerate creep in metals at high temperature. Similarly, rapid intermittent stresses (fatigue stresses) may have a detrimental effect at elevated temperature, especially in the range where the steels are relatively rigid and stress is not relieved quickly by plastic flow. Since pulsating or alternating stresses occur at elevated temperature in some types of service, further research on this subject appears advisable. Information about the subject is relatively scanty. The data given in Table VIII indicate the effect of temperature on endurance properties.

Physical Properties and Characteristics. Relevant data concerning the physical properties and characteristics of annealed heat-resisting steels are listed in Table IX.

Although the useful life of the heat-resisting steels may be judged on the basis of their oxidation resistance and properties of rupture strength and creep strength at high temperatures, nevertheless other characteristics also must be considered in order to estimate correctly the behavior of these steels at elevated temperatures. The expansion characteristics and magnetic properties may be altered to some extent by cold working, especially in borderline austenitic steels, although, as previously stated, these steels are generally used in the annealed condition. The thermal conductivity of the more highly alloyed steels varies with

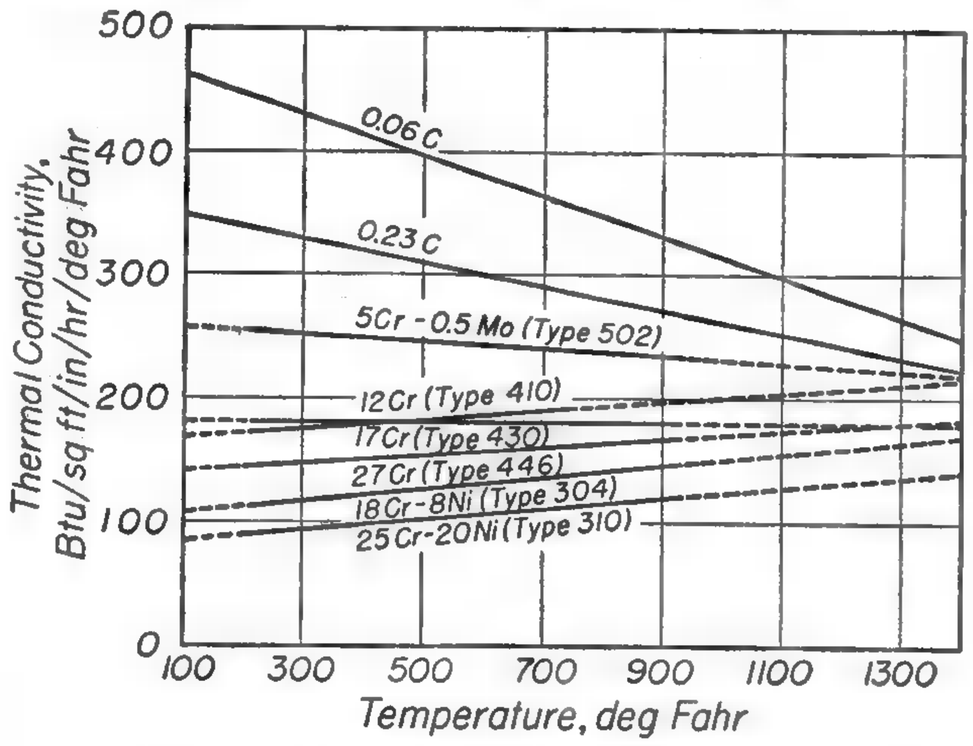

Fig. 1 Influence of temperature on the thermal conductivity of heat-resisting steels

temperature in approximately the manner shown in Fig. 1, where the conductivity of carbon steels is shown for comparison.

Design. In view of the variety of design problems involved in the application of these heat-resisting steels to structures and parts of high-temperature equipment, and because of the lack of uniform methods for applying safe stress values, it is obvious that each application is a problem in itself with regard to the selection of material for the particular service conditions and proper design for the expected life of the equipment.

The properties, behavior and application of the heat-resisting steels are becoming fairly well known and their utility and limitations are recognized. Applications in industry are made accordingly. For more detailed information, the reader may refer to the selected references listed at the end of this article.

Superstrength Wrought Heat-Resisting Alloys. Wartime requirements greatly accelerated the development and evaluation of heat-resisting alloys. These alloys have found their greatest use in rotors and buckets for turbosuperchargers and jet aircraft engines, but are also being used in the fabrication of gas turbines for marine power plants. In aircraft applications, the expected service life was short, and the alloys were evaluated principally on the basis of the stresses that produce rupture in 1000 hours. For longer service life, and particularly in those instances in which the allowable total deformation was limited to relatively low values, the alloys were evaluated by creep tests that lasted from 2000 to 2500 hours. The temperature range studied was from 1200 to 1800 F. High yield strength at room temperature was also needed in rotor materials, to withstand the high stresses produced in an overspeed inspection test.

A large number of alloys were supplied for test by industry, but only a few have received attention for commercial use. Many alloys not now in use varied little in composition. The data presented here are for a selected group of these heat-resisting alloys and serve to indicate both the alloys commanding the most attention and the range of properties available.

Table X shows the chemical compositions of the alloys for which the available stress-rupture and creep data are presented in Tables XI and XII. Except for alloy 19-9W-Mo these alloys are wholly austenitic.

All the alloys except Inconel "X" and Hastelloy B contain 18% Cr or more, with sufficient nickel to make the metal austenitic and to show adequate surface stability. The addition of cobalt appears necessary for the best strength in the higher temperature ranges. Molybdenum, tungsten and columbium are added singly or together to increase the strength of the alloys at high temperature. Three of the alloys—Inconel "X", K-42-B, and Refractaloy 26—are strengthened by precipitated phases produced by additions of titanium and aluminum. Hastelloy B contains no chromium and its use is restricted to about 1400 F. Vitallium, plain Inconel, and 25 Cr–20 Ni–1.5 Si (type 310) have been used in sheet form for combustion chambers and tail pipes on jet aircraft engines. The test data presented here were taken largely from the wartime research reported by J. W. Freeman, E. E. Reynolds, and A. E. White; and by Howard C. Cross and Ward F. Simmons; also from data in the files of the producers of heat-resisting alloys.

Space does not permit presentation of all the data obtained. The above-noted reports include short-time high-temperature tension test data for many of the alloys, as well as stress-rupture and creep data for the alloys in conditions not shown in Tables X, XI and XII.

The test data have shown that chemical composition alone does not determine the properties, but that fabrication procedure and heat treatment also are potent factors. For this reason many of the alloys were studied in several conditions of heat treatment and fabrication.

High yield strengths at room temperature were obtained only by so-called "hot cold working" the alloys about 20% or more at temperatures below 1700 F (usually near 1200 F) except in age hardening alloys of the Inconel "X" type. The best combination of strength and ductility both at room temperature and at 1200 F was generally

Table XII. Creep Test Data for Wrought Heat-Resisting Alloys

Alloy	Condition As Tested	Stress (psi) for Minimum Creep Rates of 0.0001 and 0.00001% per Hour: 1200 F, 0.0001% per hr	1200 F, 0.00001% per hr	1350 F, 0.0001% per hr	1350 F, 0.00001% per hr	1500 F, 0.0001% per hr	1500 F, 0.00001% per hr	1600 F, 0.0001% per hr	1600 F, 0.00001% per hr
19-9 W-Mo	Hot rolled[a]	.....	6,600	.....	.....	.....	....	....	....
19-9 DL	Annealed 2250 F, oil quenched[b]	.....	.....	13,000	.....	6,500	<5000	....	....
Timken 16-25-6	Annealed 2150 F, water quenched	20,000	12,800	.....	.....	6,600–7,000[b]	4500–5000[b]	....	....
Low-carbon N-155	Annealed 2200 F, water quenched[b]	.....	.....	16,000	12,500	9,000	6500	....	....
N-155	Annealed 2200 F, water quenched[b]	.....	.....	16,000	12,500	8,500–10,000	7000	....	....
S-495	Annealed 2250 F, water quenched[b]	.....	.....	15,500	.....	10,000	7500	<6500	....
S-497	Annealed 2250 F, water quenched[b]	.....	.....	15,500	12,000	10,500	8500	....	....
S-590	Annealed 2300 F, water quenched	.....	.....	20,000[b]	13,500[b]	11,000[c]	9000[c]	7400[b]	5500[b]
S-816	Annealed 2300 F, water quenched	.....	.....	>20,000[b]	14,000[b]	>10,000[d]	8000[d]	6500[d]	5000[d]
Inconel "X"	Annealed, air cooled and aged[f]	60,000	48,000	37,000	30,000	18,000	15,000		
K-42-B (Type 5)	Annealed 2100 F, oil quenched[b]	.....	.....	.....	.....	< 9,500	<7000 (see text)	....	....
Refractaloy 26	Annealed 2100 F, oil quenched[e]	.....	.....	>20,000	>20,000	....	.... (see text)	....	....
Hastelloy B	Annealed 1900 F, 24 hr air cooled	.....	.....	<12,000	.....	< 8,000	....	....	....

(a) Stress-relieved at 1200 F
(b) Aged 50 hr at test temperature
(c) Aged 50 hr at 1350 F
(d) Aged 16 hr at 1400 F
(e) Aged 20 hr at 1500 F, air cooled, then aged 20 hr at 1350 F
(f) Aged 24 hr at 1550 F plus 20 hr at 1300 F

found in alloys forged or rolled down to temperatures between 1700 and 1200 F. Superior rupture strengths at 1200 F can be imparted by hot cold working after a solution treatment, but this procedure generally causes low ductility in the rupture tests. Hot cold worked materials have better load-carrying ability under high stresses and for short periods, while annealed or solution treated materials are better under low stresses for long periods.

At about 1350 F alloys that have been given a solution treatment, with or without aging treatments, usually develop the best properties. At 1500 and 1600 F, either hot or hot cold work develops properties inferior to those obtained from solution treated and aged alloys. The

Table XIII. Endurance Properties of Wrought Heat-Resisting Alloys[a]

Alloy	Condition as Tested	Test Temp, °F	Endurance Strength, psi 10^8 cycles	Endurance Strength, psi 2.5×10^8 cycles
19-9 W-Mo	2000 F, water quenched, aged 4 hr at 1200 F	1200	37,000	35,000
19-9 DL	2100 F 1 hr, air cooled, cold worked 15% at 1200 F, aged 4 hr at 1200 F	1200	43,000	.....
19-9 DL disk	2100 F 1 hr, air cooled, cold worked 15% at 1200 F, aged 4 hr at 1200 F	1500	17,000	.....
Timken 16-25-6	2000 F, water quenched, aged 4 hr at 1200 F	1200	46,000	.....
	2150 F ¾ hr, water quenched, aged 50 hr at 1500 F	1500	19,000	18,000
N-155 Low-Carbon	Aged 50 hr at 1200 F	1200	66,000	.....
	Aged 50 hr at 1500 F	1500	33,000	32,000
S-495	2000 F 1 hr, water quenched, aged 16 hr at 1300 F	1200	42,000	41,000
S-497	2000 F 1 hr, water quenched, aged 16 hr at 1300 F	1200	50,000	49,000
S-816	2350 F 1 hr, water quenched, aged 16 hr at 1500 F	1200	69,000	.....
Inconel "X"	2100 F 4 hr, air cooled, aged 24 hr at 1550 F plus 20 hr at 1300 F	1200	53,000	.....
		1350	48,000	.....
		1500	35,000	.....
K-42-B Type 5	2100 F 1 hr, water quenched, aged 20 hr at 1350 F	1200	54,000	48,000
	2100 F 1 hr, water quenched, aged 20 hr at 1500 F	1350	48,000	.....
Hastelloy B	2000 F, water quenched, aged 4 hr at 1200 F	1200	66,000	64,000
	2050 F, air cooled, aged 24 hr at 1900 F	1500	34,000	.....

(a) Data supplied by Research Laboratories of the Westinghouse Electric and Manufacturing Company

available data concerning large forged disks of several alloys, indicate that the properties of bar stock are virtually duplicated in large forgings when the processing and heat treatments are equivalent.

Comparison of properties of wrought and cast alloys indicates that above approximately 1350 F the alloys have better rupture strengths cast than forged.

These wrought heat-resisting alloys are much more difficult to machine and weld than either ferritic steels or the plain 18 Cr – 8 Ni steels.

The mechanism by which the various alloy compositions produce usable properties at high temperatures is not understood. Aging at temperatures of 1200 F or higher causes precipitation of phases whose identification is unknown except in a few alloys. Processing and fabricating procedures and heat treatment have been shown to influence the precipitation of these phases both before and during service at elevated temperature and under stress. Considerable experience has been acquired in producing most of the alloys for which data are shown, but it should be realized that the data presented are for the particular heats processed and heat treated as indicated.

Alloys K-42-B and Refractaloy 26 are strengthened by precipitation of phases produced by additions of titanium and aluminum. These alloys are among the strongest at 1350 F, and under high stresses at 1500 F. Under low stresses at 1500 F, they enter third-stage creep relatively early in a creep test, and the values shown for stresses for 0.0001 and 0.00001% per hour apply only to short-time service and should be used with caution.

Table XIII lists the high-temperature reversed-bending fatigue test data for many of the superstrength wrought heat-resisting alloys, as determined by the Research Laboratories of the Westinghouse Electric Company. Data are included for tests at 1200 and 1500 F on alloys heat treated as indicated in the table. It should be noted that for many of these alloys, the endurance strengths exceed the tension stresses that will produce rupture in 1000 hours at the same temperatures.

Research is continuing on these superstrength alloys, and as more fundamental information about their behavior is obtained, the alloys known at present may be improved by better techniques for processing or heat treatment, and still better new alloys may be developed.

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Heat-Resistant Castings

BY THE SUBCOMMITTEE ON HEAT-RESISTANT CASTINGS*

CASTINGS are classed as heat-resistant if they are capable of sustained operation when exposed, either continuously or intermittently, to operating temperatures that create metal temperatures in excess of 900 F. Alloys used in castings for such service may be considered in the following groups: iron-chromium ("straight chromium" alloys), iron-chromium-nickel, nickel-chromium base, nickel-molybdenum base, cobalt base, and chromium base.

Many alloys of the same general type are used also for their resistance to corrosive mediums at temperatures below 900 F, and castings intended for such service are

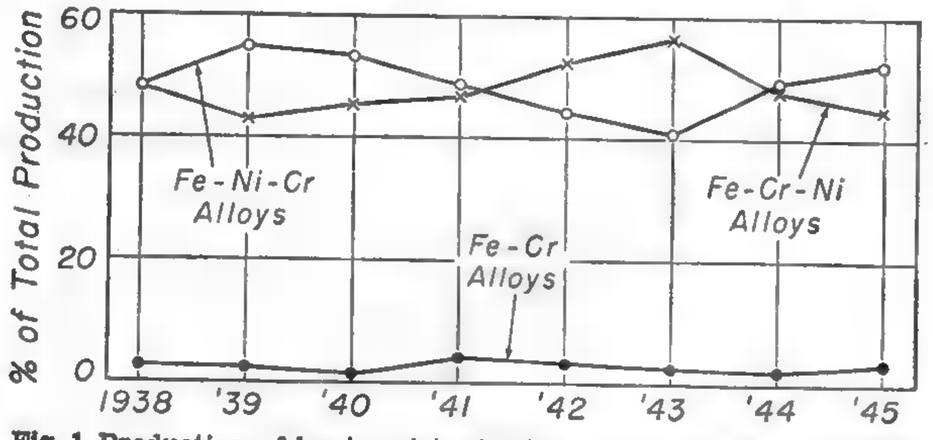

Fig. 1 Production of heat-resistant alloys (Alloy Casting Institute)

classed as corrosion-resistant. Although there is usually a distinction between the alloys of the two classes, based on carbon content, the line of demarcation is rather vague, particularly in the range from 900 to 1200 F. Thus the terms "heat-resistant" and "corrosion-resistant" are relative and are differentiated arbitrarily by the operating temperature of the material.

Heat-resistant castings, as defined, are used in metallurgical furnaces, oil-refinery furnaces, cement-mill furnaces, power-plant equipment, turbosuperchargers, gas turbines, and the manufacture of synthetic rubber.

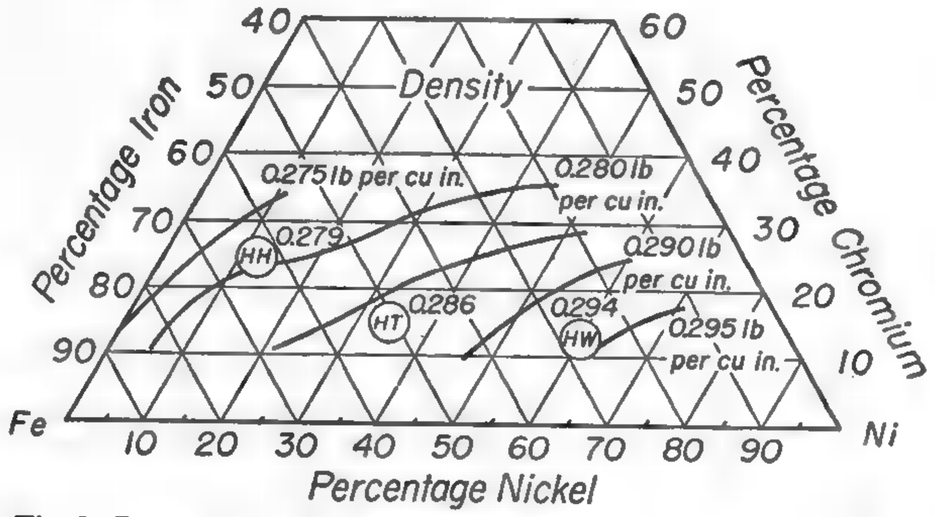

Fig. 2 Density of Fe-Cr-Ni alloys in pounds per cubic inch. Alloys also contained about 0.45% C, 1.25% Si and 0.80% Mn (Alloy Casting Institute)

During World War II special heat-resistant alloys were developed and produced in large quantities for use in military equipment, but the major commercial application is in furnaces for the treatment of metals. Alloys of the iron-chromium and iron-chromium-nickel groups are of the greatest commercial importance; these divide into three general categories, according to the major alloying element. The percentage of total production of these alloys accounted for by each group in recent years is shown in Fig. 1.

General Properties of Iron-Chromium and Iron-Chromium-Nickel Alloys. The general characteristics of the three types of heat-resistant iron-chromium and iron-chromium-nickel alloys are as follows:

1 Iron-chromium alloy castings that contain from 10 to 30% Cr and little or no nickel.

These alloys are useful chiefly for resistance to oxidation. They have low strength at elevated temperatures. The use of these alloys is dictated by conditions, either oxidizing or reducing, that involve low static loads and uniform heating. The chromium content depends on the temperature to which the alloys are to be exposed in service.

2 Austenitic alloys that contain more than 18% Cr and more than 5% Ni—always more chromium than nickel.

These alloys are used ordinarily under oxidizing or reducing conditions similar to those withstood by the iron-chromium alloys, but in service they have greater strength and ductility than the straight chromium alloys. They are used, therefore, to withstand greater loads and moderate changes of temperature. These alloys are also used in the presence of reducing gases that contain sulfur.

3 Austenitic alloys that contain more than 10% Cr and more than 25% Ni—always more nickel than chromium.

These alloys are used for withstanding a reducing as well as an oxidizing atmosphere, except where sulfur content is appreciable (for example, 0.05% H_2S or more). In such atmospheres the iron-chromium-nickel alloys of type 2 are recommended. The type 3 alloys do not carburize rapidly or become brittle and do not take up nitrogen in a nitriding atmosphere, in contrast with type 2 alloys. These properties become enhanced as the nickel content increases, and in carburizing and nitriding atmospheres the life of the casting increases with the nickel content. Austenitic ferrous alloys are used extensively under conditions of severe temperature fluctuations like those encountered by fixtures used in quenching and by parts that are not heated uniformly or that are heated and cooled intermittently. In addition these alloys have characteristics of electrical resistance that make them suitable for electrical resistor heating elements.

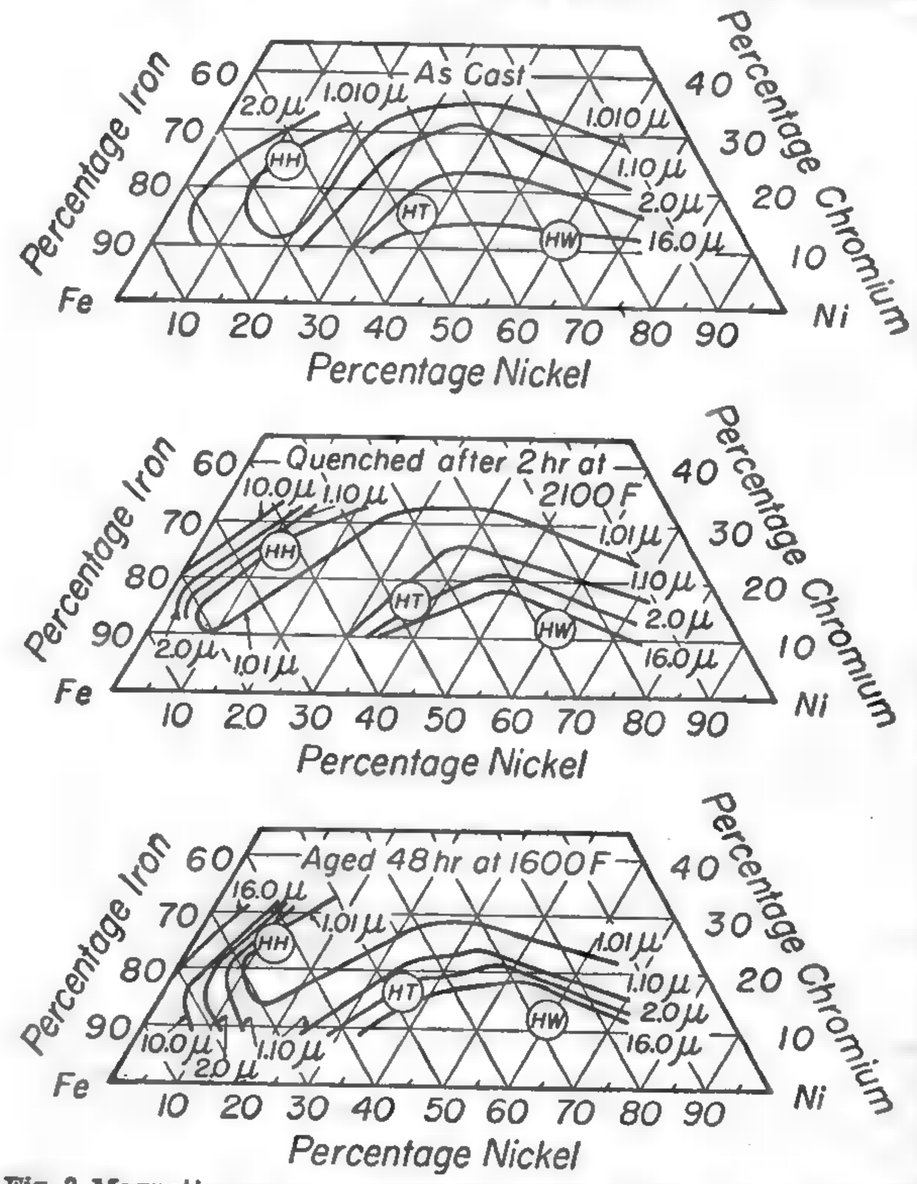

Fig. 3 Magnetic permeability of Fe-Cr-Ni alloys. Alloys also contained about 0.4% C, 1.25% Si and 0.80% Mn (Alloy Casting Institute)

Figures 2 and 3, showing density and magnetic permeability, have been plotted from data obtained in an extensive investigation of these alloys, sponsored by the Alloy Casting Institute. The approximate rates of corrosion in Table I were determined in the same research program. Table II gives mean coefficients of thermal expansion for the more commonly used alloys.

Manufacture. Castings produced in these several compositions may be made from heats melted in an electric-arc

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Table I. Approximate Rates of Corrosion of Commercial Heat-Resistant Castings in Air and in Flue Gas[a]

Data, based on 100-hour tests, expressed in inches penetration per year

Alloy	% Ni	% Cr	Oxidation in Air: 1600 F in./yr	1800 F in./yr	2000 F in./yr	Sulfur-Containing Gas at 1800 F: Oxidizing[b] 5 gS in./yr	Oxidizing[b] 100 gS in./yr	Reducing[b] 5 gS in./yr	Reducing[b] 100 gS in./yr
HB	(2)	20	0.025—	0.250—	0.500—	0.100+	0.250—	0.500—	0.500
HC	(4)	29	0.010	0.050	0.050	0.025—	0.025	0.025+	0.025—
HD	5	29	0.010—	0.050—	0.050—	0.025—	0.025—	0.025—	0.025—
HE	10	29	0.005—	0.025—	0.035—	0.025—	0.025—	0.025—	0.025—
HF	10	20	0.005—	0.050+	0.100	0.050+	0.050+	0.100+	0.250—
HH	12	25	0.005—	0.025—	0.050	0.025—	0.025	0.025	0.025—
HI	15	28	0.005—	0.010+	0.035—	0.025—	0.025—	0.025—	0.025—
HK	20	25	0.010—	0.010—	0.035—	0.025—	0.025—	0.025—	0.025—
HL	20	30	0.010+	0.025—	0.035	0.025—	0.025—	0.025—	0.025—
HN	25	20	0.005	0.010+	0.050—	0.025—	0.025	0.025	0.025
HP	30	30	0.025—	0.025+	0.050—	0.025—	0.025—	0.025—	0.025—
HS	30	10	0.100	0.250	1.000+	0.250	0.500—	0.160	0.500+
HT	36	15	0.005—	0.010+	0.050	0.025	0.025	0.025—	0.100
HU	39	19	0.005—	0.010—	0.035—	0.025—	0.025—	0.025—	0.025
HW	61	12	0.005—	0.010—	0.035	0.025	0.050—	0.025—	0.250
HX	67	17	0.005—	0.010—	0.035—	0.025—	0.025—	0.025—	0.025—

(a) From Alloy Casting Institute, and A. Brasunas, J. T. Gow and O. E. Harder, Resistance of Fe-Ni-Cr Alloys to Corrosion in Air at 1600 to 2200 F, ASTM Symposium on Materials for Gas Turbines, June 1946, p 129–52

(b) gS, grains of sulfur per 100 cu ft of flue gas

furnace that has either an acid or a basic lining; or in a high-frequency induction furnace. Care must be used in producing sound, satisfactory castings; foundries producing such castings have developed special techniques for this work. Castings may be made by the static method, by centrifugal pouring or by the precision casting practice (*see* page 54). The centrifugal method is used extensively in the production of tubes for radiant heating furnaces and for other tubular parts.

With the exception of a small tonnage of iron-chromium alloys, the heat-resistant castings are not usually heat

Table II. Thermal Expansion of Commercial Heat-Resistant Castings

ACI Type	Mean Composition % Ni	% Cr	Mean Coefficient of Linear Thermal Expansion: Temp, °F	Per °F
HC	4 max	28	32 to 1000	0.0000063
			32 to 1850	0.0000076
HE	10	29	120 to 1650	0.0000105
HF	10	20	80 to 1600	0.0000104
HH	12	25	70 to 1300	0.0000099
			70 to 1650	0.0000101
			70 to 1850	0.0000110
HK	20	25	32 to 950	0.0000092
			32 to 1850	0.0000106
HT	36	15	70 to 1850	0.0000097
HU	39	19	32 to 1850	0.0000095
HW	61	12	32 to 1850	0.0000090
HX	67	17	32 to 1850	0.0000085

treated before shipment. When the 12 and 18% Cr alloys are used, it is sometimes necessary to give the castings a full annealing treatment to remove casting stresses, because these two alloy grades are hardenable.

Properties of Iron-Chromium Alloys. "Straight chromium" alloys are made in the compositions listed in Table III.

Type CA (12% Cr). This alloy is a heat treatable ferritic-martensitic material used in considerable tonnage in corrosion-resistant applications, but to only a minor extent for heat-resistant castings. This alloy, however, contains enough chromium to make it suitable for applications at temperatures as high as 1250 F providing stresses are low. The mechanical properties of the alloy

Table III. Composition Limits of Iron-Chromium Heat-Resistant Castings

ACI Type	Composition, percentage: Carbon	Manganese	Silicon	Chromium	Nickel
CA	0.15 max	1.00 max	1.5 max	11.5 to 14	1.0 max
HB	0.30 max	1.00 max	2.0 max	18 to 22	2.0 max
HC	0.50 max	1.00 max	2.0 max	26 to 30	4.0 max
HD	0.50 max	1.50 max	2.0 max	26 to 30	4 to 7

at room temperature depend on the heat treatment. For high-temperature service, castings are given ■ full anneal.

Nominal values for the mechanical properties of annealed castings at room temperature are as follows:

Tensile strength	95,000 psi
Yield point	65,000 psi
Elongation in 2 in.	25%
Brinell hardness number	170

Type HB (18% Cr). This alloy is only slightly hardenable and is ferritic. It contains enough chromium to make it suitable for castings that are to resist oxidation up to temperatures of 1500 F. Castings are usually air-cooled from a temperature between 1400 and 1500 F and are

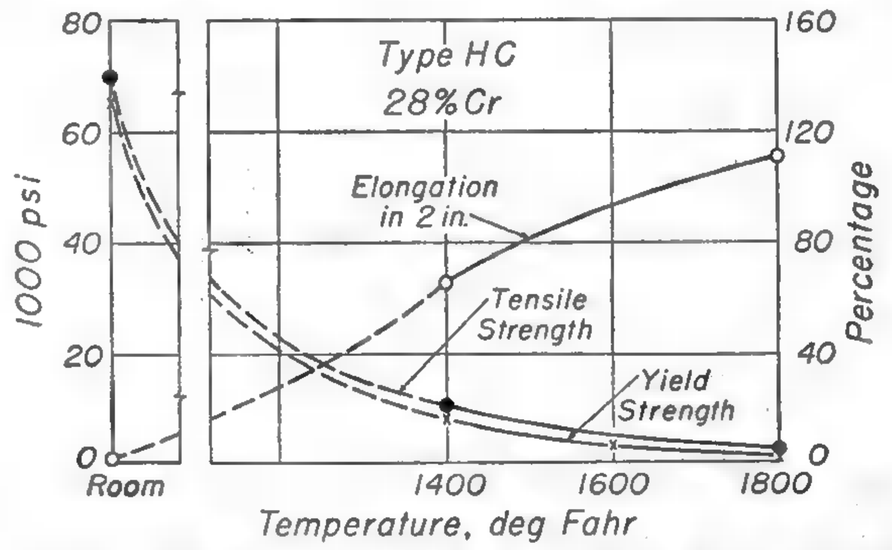

Fig. 4 Influence of temperature on the tensile strength, yield strength and elongation of Type HC (28% Cr) alloys

furnished in the annealed condition. Nominal mechanical properties at room temperature are as follows:

Tensile strength	75,000 psi
Yield point	50,000 psi
Elongation in 2 in.	25%
Brinell hardness number	170

Type HC (28% Cr). This alloy is used primarily for heat-resistant applications where strength is not a consideration, in high-sulfur atmospheres, and in some services where the presence of nickel cannot be tolerated. This alloy resists oxidation up to 2000 F. Castings are supplied in two carbon ranges: (1) 0.50% C max, used

Table IV. Mechanical Properties of Type HC Alloys (28% Cr, 0.50% C max)

Property	Normal Nitrogen	High Nitrogen
Tensile strength, psi	70,000	110,000
Yield strength, psi	65,000	75,000
Elongation, % in 2 in.	2	19
Brinell hardness number	179	223

Table V. Composition Limits of Iron-Chromium-Nickel Heat-Resistant Castings Containing More Chromium than Nickel

ACI Type	Composition, percentage				
	Carbon	Manganese	Silicon	Chromium	Nickel
HF	0.20 to 0.40	2.0 max	2.0 max	18 to 23	8 to 12
HE	0.20 to 0.50	2.0 max	2.0 max	26 to 30	8 to 11
HH	0.20 to 0.50	2.0 max	2.0 max	24 to 28	11 to 14
HI	0.20 to 0.50	2.0 max	2.0 max	26 to 30	14 to 18
HK	0.20 to 0.60	2.0 max	3.0 max	24 to 28	18 to 22
HL	0.20 to 0.60	2.0 max	3.0 max	28 to 32	18 to 22

for normal high-temperature service; and (2) 3.00% C max, used where a hard material resistant to abrasion is required for high-temperature service.

The nominal mechanical properties at room temperature of the 28% Cr alloy containing 0.50% C max are shown in Table IV. The ductility and ultimate strength of this alloy are improved by the addition of nitrogen in excess of 0.15%, when more than 2% Ni is present.

The high-nitrogen alloy differs from the normal-nitrogen alloy in Table IV, in that the nickel content is higher than 2% and the nitrogen content is higher than 0.15%.

The Type HC alloys, when heated for prolonged periods in the range of temperatures from 750 to 1025 F, are embrittled and show low resistance to impact.

The curves in Fig. 4 show the nominal properties of the alloy as determined from short-time tests at elevated temperatures.

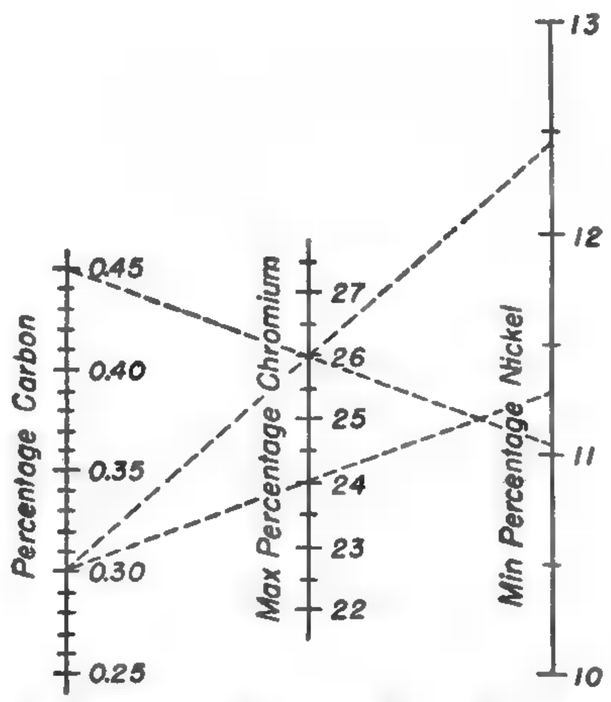

Fig. 5 Nomographic chart of chromium, nickel and carbon contents for wholly austenitic Type HH (25% Cr, 12% Ni) alloys (Gow and Harder[2])

Type HD (28% Cr, 5% Ni). This alloy is similar to the HC grade, except that the higher nickel content imparts somewhat greater strength at high temperatures.

Properties of Iron-Chromium-Nickel Alloys. Ferrous alloys in which the chromium content exceeds the nickel content are made in the compositions shown in Table V.

Type HF (20% Cr, 10% Ni). This alloy is essentially the same as the well-known 18% Cr, 8% Ni composition widely selected for its resistance to corrosion. The type HF alloy is also suitable for use at temperatures up to 1600 F. When used for resistance to oxidation at elevated temperatures, it is not necessary to keep the carbon content at the low level specified for corrosion-resistant castings. The nominal mechanical properties of the material at room temperature, without special additions of alloying elements, are given in Table VI. Molybdenum, tungsten, columbium and titanium are sometimes added to the normal type HF composition to impart greater strength at elevated temperatures.

Table VI. Mechanical Properties of Type HF Alloys (20% Cr, 10% Ni)

Property	As Cast	After 24 hr at 1400 F, Furnace Cooled
Tensile strength, psi	80,000	100,000
Yield strength, psi	45,000	50,000
Elongation, % in 2 in.	35	25
Brinell hardness number	170	192

Type HE (29% Cr, 10% Ni). This alloy has excellent resistance to corrosion at elevated temperatures. Because of the higher chromium content, this alloy can be used at higher temperatures than the HF type and is suitable for applications up to 2000 F. The material is stronger and more ductile at room temperatures than the straight-chromium types. Nominal mechanical properties at room temperature in the as-cast condition are as follows:

Tensile strength	85,000 psi
Yield strength	45,000 psi
Elongation in 2 in.	10%
Brinell hardness number	201

In recent years, as described hereafter, a great deal of work on the HH type alloy has provided a basis for evaluating the effect of variations in composition within the group of Fe-Cr-Ni alloys similar to type HH. Type HE belongs to this group.

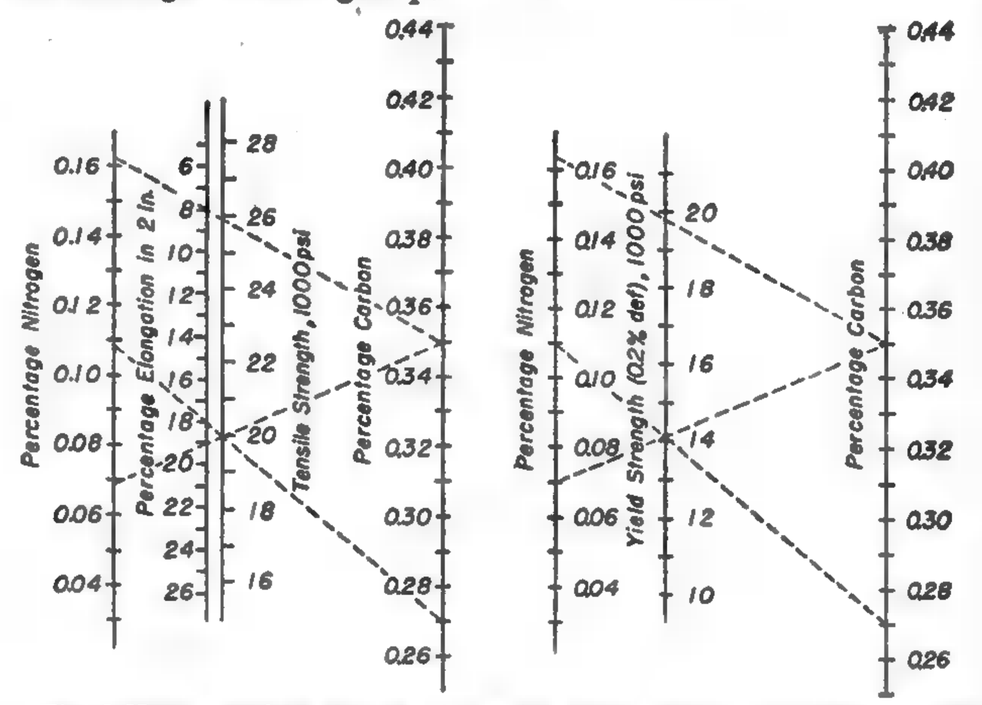

Fig. 6 Nomographic charts of results from short-time tension tests at 1600 F, showing elongation, tensile strength and yield strength in relation to carbon and nitrogen contents of Type HH (25% Cr, 12% Ni) alloys (Gow and Harder[2])

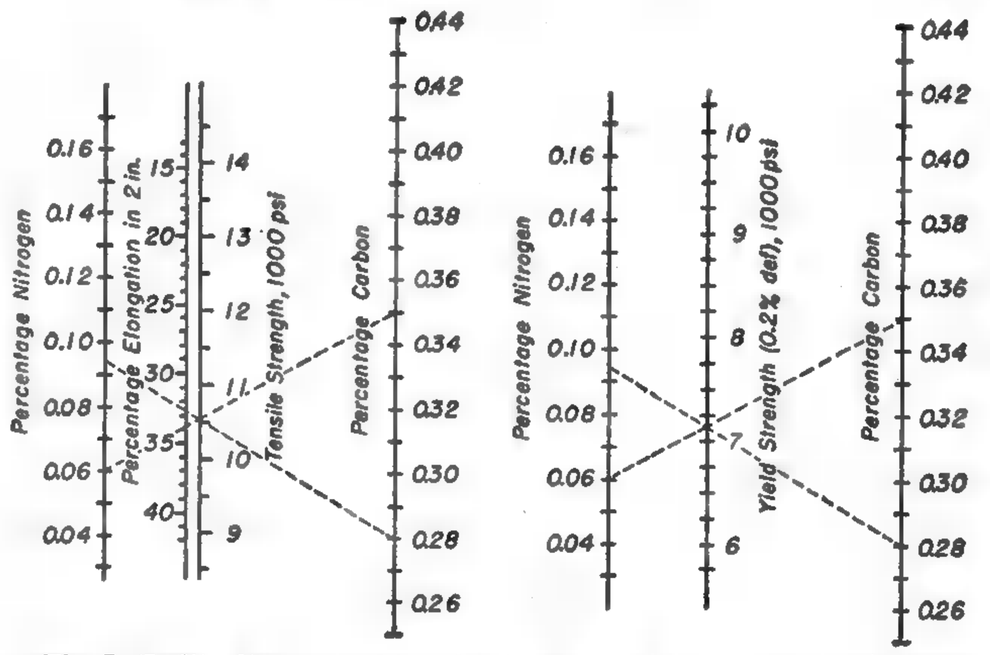

Fig. 7 (Left) Nomographic chart of the elongation and tensile strength at 1800 F in relation to carbon and nitrogen contents of Type HH (25% Cr, 12% Ni) alloys (Gow and Harder[2])

(Right) Nomographic chart of the yield point at 1800 F in relation to carbon and nitrogen contents of Type HH (25% Cr, 12% Ni) alloys (Gow and Harder[2])

Type HH (25% Cr, 12% Ni). Alloys of the nominal composition 25% Cr, 12% Ni, comprise about one third of the total production of heat-resistant castings. This material is used extensively in high-temperature applications, because of its strength and its resistance to oxidation at temperatures up to 2000 F.

Balancing the Composition of Type HH Alloys. The composition of this type of alloy is critical. As pointed out by Foley,[1] the range of nickel and chromium contents lies at the junction of the alpha plus gamma, the gamma, and the gamma plus sigma regions of the Fe-Cr-Ni sys-

Table VII. Mechanical Properties of Type HH Alloys (25% Cr, 12% Ni)

Property	As Cast	After 24 hr at 1400 F, Furnace Cooled
Tensile strength, psi	70,000 to 95,000	80,000 to 100,000
Yield strength, psi	35,000 to 50,000	40,000 to 55,000
Elongation, % in 2 in	15 to 30	4 to 20
Brinell hardness number	150 to 210	180 to 250

tem at 1650 F. Consequently, relatively large amounts of ferrite-promoting elements, in comparison with the amounts of austenite-promoting elements, may result in the presence of substantial amounts of ferrite in the metal. The presence of ferrite decreases the strength at high temperatures, and if the ferrite transforms to sigma at intermediate temperatures, castings may suffer from brittleness or cracking when held within certain temperature ranges or when heated and cooled repeatedly through these ranges.

To achieve maximum strength at high temperatures and good retained ductility, it is necessary that this alloy be essentially austenitic. If a balance is maintained between ferrite-promoting elements, such as chromium and silicon, and austenite-promoting elements, such as nickel and carbon, the desirable austenitic structure can be obtained. In commercial alloys of the HH type, with the usual carbon, nitrogen, manganese and silicon contents, Gow and Harder[2] found that the ratio of chromium to nickel necessary to ensure a stable austenitic alloy is expressed by the formula:

$$\frac{\text{Cr (\%)} - 16\ \text{C (\%)}}{\text{Ni (\%)}} = \text{less than } 1.7$$

The work of Gow and Harder provides strong evidence of the effect of silicon and molybdenum on the presence of sigma. Silicon in excess of 1% has the effect on structure of three times its weight in chromium, and molybdenum has the effect of four times its weight in chromium.

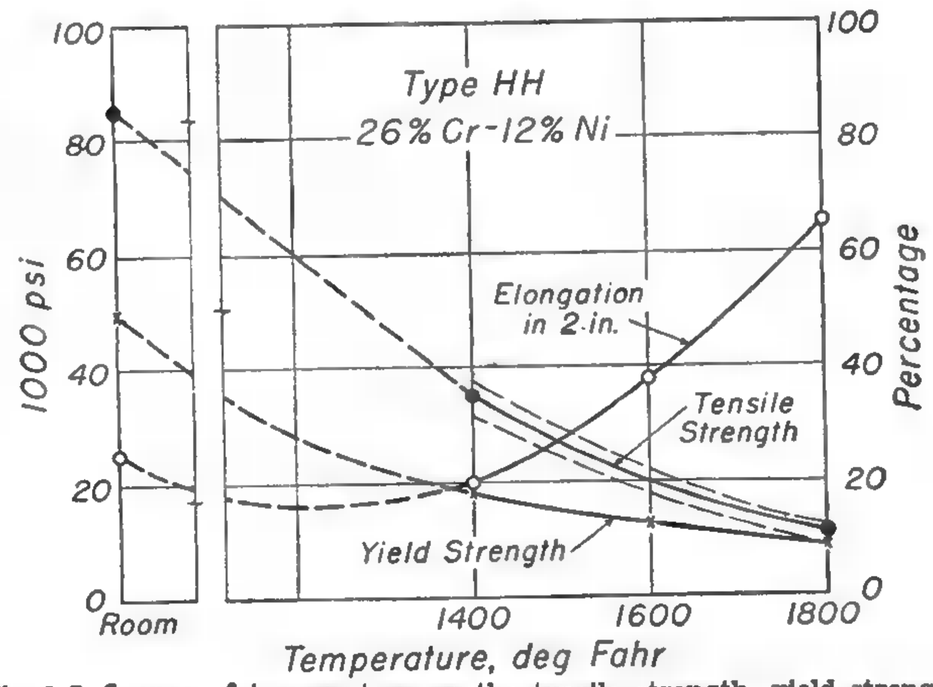

Fig. 8 Influence of temperature on the tensile strength, yield strength and elongation of Type HH (26% Cr, 12% Ni) alloys

After the metal has been heated between 1200 and 1600 F, loss in ductility results from two changes within the alloy: (1) precipitation of carbides and (2) transformation of ferrite to sigma. Obviously, when the composition of the alloy is balanced so that the structure is wholly austenitic, only the carbide precipitation occurs. In partially ferritic alloys, both carbides and sigma phase may form.

Figure 5, showing the relationship of carbon, chromium and nickel in the wholly austenitic HH type alloy, will be found useful in balancing the composition to obtain an austenitic structure.

Before selecting the HH type alloy as material for heat-resistant castings, it is advisable to consider the relation between the chemical composition and the temperature range in which the castings must operate. If castings are to operate continuously at a temperature appreciably above 1600 F, there is little danger of serious embrittlement from either carbide precipitation or sigma phase. In this instance the composition of the alloy may be 0.50% C max (0.35 to 0.40% preferred), 10 to 12% Ni and 24 to 27% Cr. On the other hand, if the operating temperature is to be from 1200 to 1600 F, the composition should be 0.40% C max, 11 to 14% Ni and 23 to 27% Cr. In all alloys, the composition should be balanced to provide an austenitic alloy; for instance, for the 1200 to 1600 F application, the use of 11% Ni with 27% Cr is likely to produce sigma phase and its associated embrittlement, which occurs most rapidly around 1600 F. It is better,

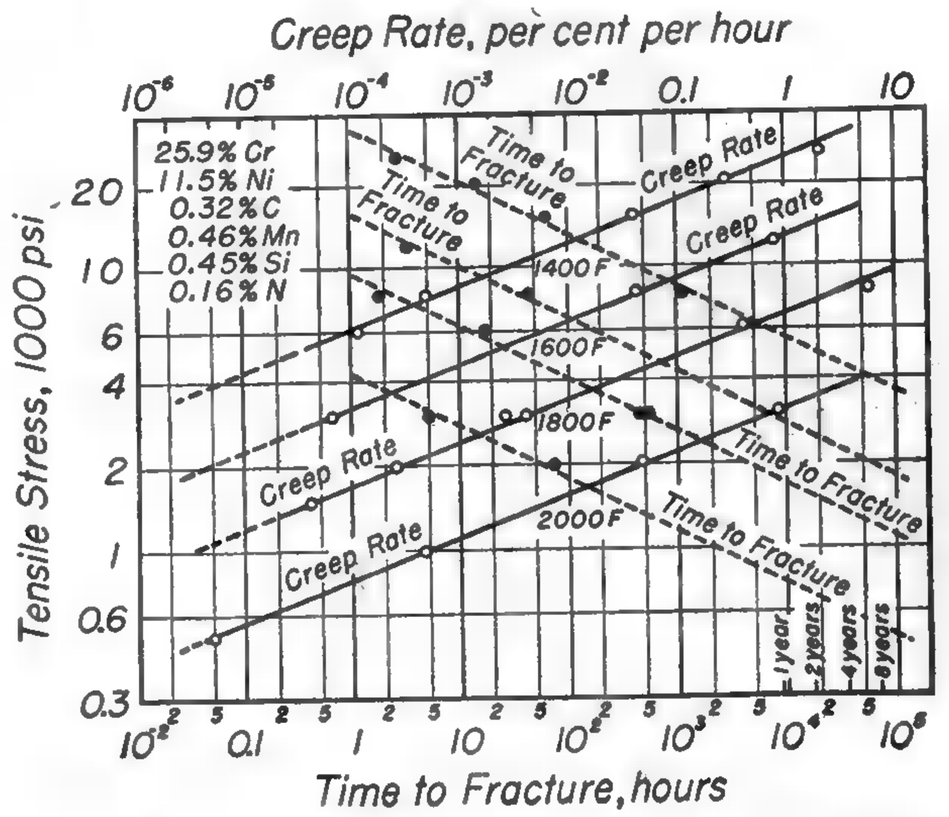

Fig. 9 Creep and rupture characteristics from 1400 to 2000 F of a Type HH (26% Cr, 12% Ni) alloy (Avery, Cook and Fellows[3])

therefore, not to use the maximum chromium content with the minimum nickel content.

Mechanical Properties of Type HH Alloys. The mechanical properties of the HH type alloy at room temperature vary considerably with the composition (Table VII).

Short-time tests of properties of austenitic HH type alloys at elevated temperatures, show that the tensile strength and elongation depend on the carbon and nitrogen contents. The nomographic charts in Fig. 6 and 7 may be used to determine the properties of these alloys at 1600 and 1800 F. Figure 8 shows curves of nominal mechanical properties for this alloy, as determined from short-time tests at elevated temperatures.

Table VIII. Chemical Compositions of Type HH Alloys Tested in Creep (Gow and Harder[2])

For results of creep tests of these alloys, see Tables IX, X and XI.

Alloy No.	Composition, percentage C	N	Cr	Ni	Si	Mn	Other Elements	Ratio Factor*
AD	0.41	0.119	25.48	12.57	0.92	0.68	....	1.51 A
AE	0.44	0.023	25.18	11.96	1.04	1.05	....	1.52 A
AS1	0.33	0.032	24.18	12.36	0.83	0.96	....	1.54 A
AS2	0.33	0.087	24.57	12.48	0.84	0.97	....	1.54 A
AS4	0.31	0.15	25.30	11.97	0.91	0.99	....	1.70 A
AU2	0.30	0.086	22.95	12.66	0.87	0.78	....	1.43 A
AX1	0.31	0.096	27.17	11.84	0.95	0.98	....	1.87 PF
AN2	0.37	0.040	24.94	10.20	0.80	0.59	Mo 0.96	PF(a)
AQ	0.38	0.073	23.84	11.98	0.85	1.04	Cb 0.96	A
AQ2	0.35	0.086	24.40	11.96	0.98	1.00	Cb 0.51	A
AS5	0.30	0.204	24.41	12.14	1.09	1.02	Zr 1.36, Al 0.30	PF(b)
AS5-3	0.31	0.072	23.8	13.0	1.07	1.04	Zr 0.14, Al 0.11	A
AT2	0.30	0.136	24.26	9.15	1.07	5.71	....	PF(c)

* A = Austenite, PF = Partially Ferritic

(a) Calculated ratio factor from $\frac{\text{Cr} + 4\ \text{Mo} - 16\ \text{C}}{\text{Ni}} = 2.24$

(b) Microstructure indicated less ferrite than AX1

(c) Calculated ratio factor from $\frac{\text{Cr} - 16\ \text{C}}{\text{Ni} + \frac{\text{Mn}-1}{3}} = 1.81$

Table IX. Results of Creep Tests on Type HH Alloys (Gow and Harder[2])

See Table VIII for chemical compositions of alloys

Temperature of Test, deg Fahr	Load, psi	Specimen No.	Ratio Factor*	Duration of Test, hours	Initial Deformation, per cent	Rate of Deformation per cent per hour × 1000 at 500 hr	1000 hr	1500 hr	Total Deformation In Test, per cent
1400	5,000	AD-5B	1.51	1510	0.028	0.040	0.035	0.020	0.176
1400	8,000	AD-7D	1.51	1508	0.051	0.160	0.075	0.065	0.364
1400	8,000	AE-2C	1.51	1466	0.051	0.110	0.075	0.050	0.407
1400	8,000	AS2-3C	1.54	1055	0.065	0.170	0.125	....	0.329
1400	10,000	AE-4A	1.51	1502	0.062	0.200	0.120	0.125	0.535
1400	10,000	AS2-3D	1.54	1031	0.078	0.260	0.230	....	0.577
1600	3,000	AD-5C	1.51	1531	0.024	....	....	0.010	0.061
1600	4,000	AD-8A	1.51	1595	0.026	0.045	0.048	0.050	0.238
1600	4,000	AE-4B	1.51	1510	0.029	0.035	0.035	0.030	0.161
1600	4,000	AX1-3C	1.87PF	730	0.053		1.25 at 730 hr		1.357
1600	5,000	AD-7C	1.51	1521	0.036	0.130	0.110	0.220	0.402
1600	5,000	AE-4C	1.51	1514	0.036	0.150	0.142	0.220	0.374
1600	5,000	AS2-3A	1.54	1031	0.039	0.095	0.100	....	0.241
1800	2,000	AD-5A	1.51	1505	0.032	0.090	0.050	0.045	0.165
1800	2,000	AE-2B	1.51	1512	0.012	0.075	0.035	0.035	0.131
1800	2,000	AS1-2D	1.54	505	0.020	0.030	....	....	0.084
1800	2,000	AS2-2D	1.54	1079	0.020	0.050	0.025	....	0.098
1800	2,000	AS4-2D	1.70	505	0.032	0.020	....	....	0.091
1800	2,000	AU2-3A	1.43	1004	0.020	0.035	0.020	....	0.092
1800	2,000	AX1-3A	1.87PF	742	0.038	0.220	0.310 at 742 hr		0.193
1800	2,000	AQ-2D	A	505	0.010	0.010	....	....	0.024
1800	2,000	AQ2-2D	A	580	0.018	0.010	....	....	0.050
1800	2,000	AS5-2D	PF	505	0.019	0.230	....	....	0.172
1800	2,000	AS5-3-2A	A	520	0.026	0.010	....	....	0.043
1800	2,000	AT2-3D	1.81PF	594	0.020	0.130	....	....	0.106
1800	2,000	AN2-1D	2.24PF	742	0.023	0.520	0.660 at 740 hr		0.578
1800	2,400	AE-2A	1.51	1901	0.021	0.120	0.001	0.130	0.337
1800	2,500	AD-7B	1.51	1507	0.026	0.110	0.230	0.240	0.316
1800	2,500	AS2-3B	1.54	1540	0.025	0.050	0.078	0.200	0.170
1800	2,500	AQ2-2D	A	475	0.057	0.010	....	....	0.071
1800	3,000	AD-7A	1.51	1090	0.023	0.380	0.540	(a)	1.120
1800	3,000	AE-2D	1.51	1374	0.026	0.120	0.400	....	1.300

* A = Austenite, PF = Partially Ferritic

(a) AD showed a minimum creep rate of 0.15 between 100 and 300 hr

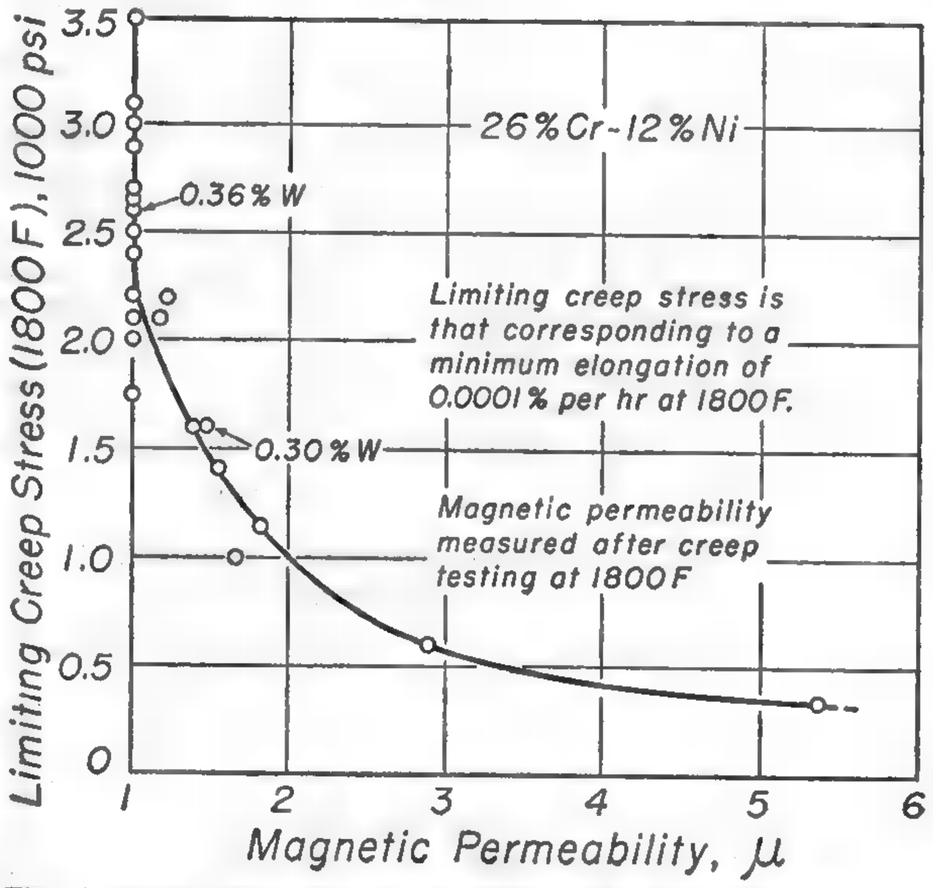

Fig. 10 Correlation of creep strength with magnetic permeability after creep testing of a Type HH (26% Cr, 12% Ni) alloy (Avery, Cook and Fellows[3])

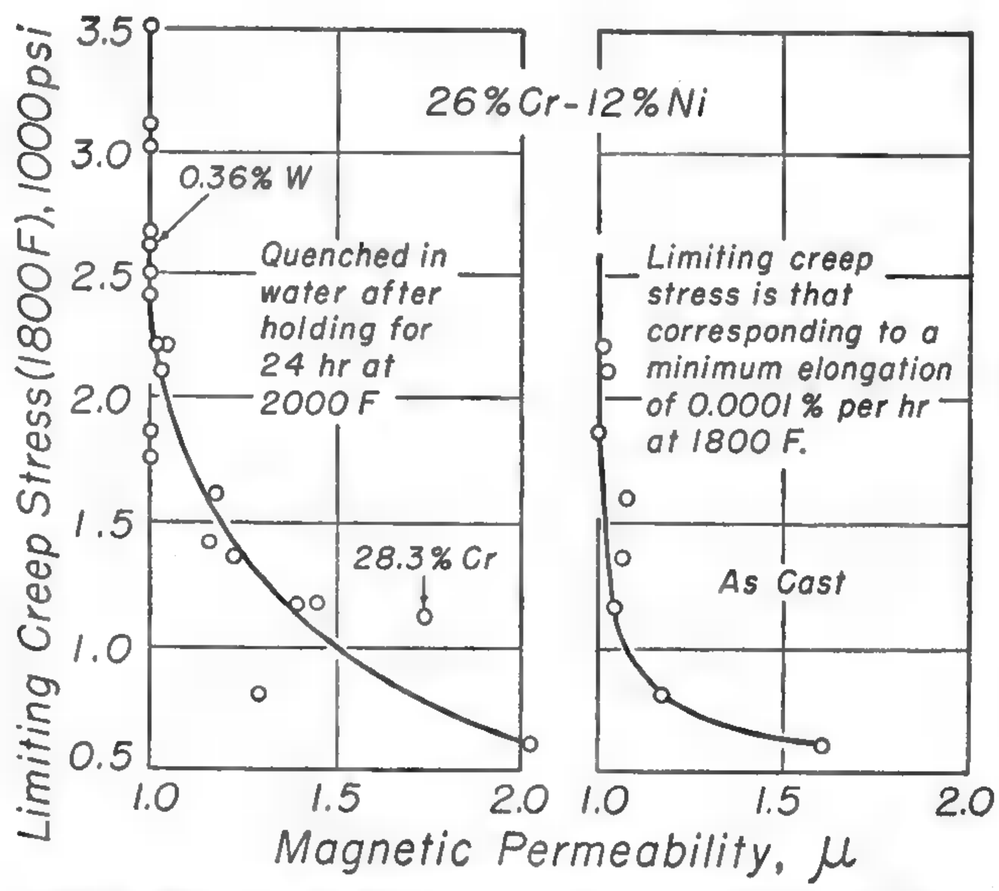

Fig. 11 Correlation of creep strength with permeability of unstressed specimens of a Type HH (26% Cr, 12% Ni) alloy (Avery, Cook and Fellows[3])

In the application of heat-resistant alloys, the considerations include (1) resistance of the alloy to corrosion at elevated temperature; (2) the stability of the alloy—that is, its resistance to warping, cracking or thermal fatigue; (3) the resistance of the alloy to plastic flow—that is, its creep strength. Research conducted at Battelle Memorial Institute for the Alloy Casting Institute, has indicated that for maximum creep strength the HH type alloy should be essentially austenitic in structure. Tables VIII to XI contain creep data for a number of alloys.

In the design of load-carrying castings, data concerning creep stresses should be used with an understanding of the limitations of these data. Avery, Cook and Fellows[3] have pointed out: "There is danger in assuming that an extrapolated L.C.S. (Limiting Creep Stress) for 1% elongation in 10,000 hours can necessarily be sustained for that length of time without structural damage." These authors suggest that stress-rupture tests are a valuable adjunct to creep tests and are useful in the selection of suitable design stresses. A comparison of creep rates and fracture times at various stresses and temperatures is shown in Fig. 9 for a wholly austenitic alloy.

As pointed out before, HH type alloys of wholly austenitic structure have greater strength at high temperatures than alloys of similar composition but of a partially ferritic structure. Although a ratio factor of less than 1.7,

Table X. Comparison of Creep Rates of Wholly Austenitic and Partially Ferritic Type HH Alloys at 1800 F Under a Load of 2000 psi (Gow and Harder[2])

See Table VIII for chemical compositions of alloys

Alloy No.	Microstructure	Min Creep Rate, per cent per hour × 1000
AD	Austenitic	0.045
AE	Austenitic	0.035
AS1	Austenitic	0.030
AS2	Austenitic	0.025
AS4	Austenitic	0.020
AU2	Austenitic	0.020
AS53	Austenitic	0.010
AQ	Austenitic	0.010
AQ2	Austenitic	0.010 avg 0.023
AX1	Partially ferritic	0.220
AS5	Partially ferritic	0.230
AT2	Partially ferritic	0.100
AN2	Partially ferritic	0.667 avg 0.304

calculated from the nickel, chromium and carbon contents, is an indication of a wholly austenitic material, ratio factors greater than 1.7 do not give a quantitative indication of the amount of ferrite present. It is possible, however, to measure the amount of ferrite in the material by magnetic analysis, after quenching the alloy from about 2000 F.

The magnetic permeability of HH type alloys increases with the amount of the ferrite phase. Thus, preferably after holding the alloy 24 hours at 2000 F and then quenching it in water, measurement of magnetic permeability can be related to the creep strength of the alloy, since this property depends also on the structure of the material. Figures 10 and 11 show the correlation between limiting creep stress and magnetic permeability.

The curves in Fig. 12 show the limiting creep stress for 0.0001% per hour minimum rate for alloys that have magnetic permeabilities between 1.00 and 1.70μ.

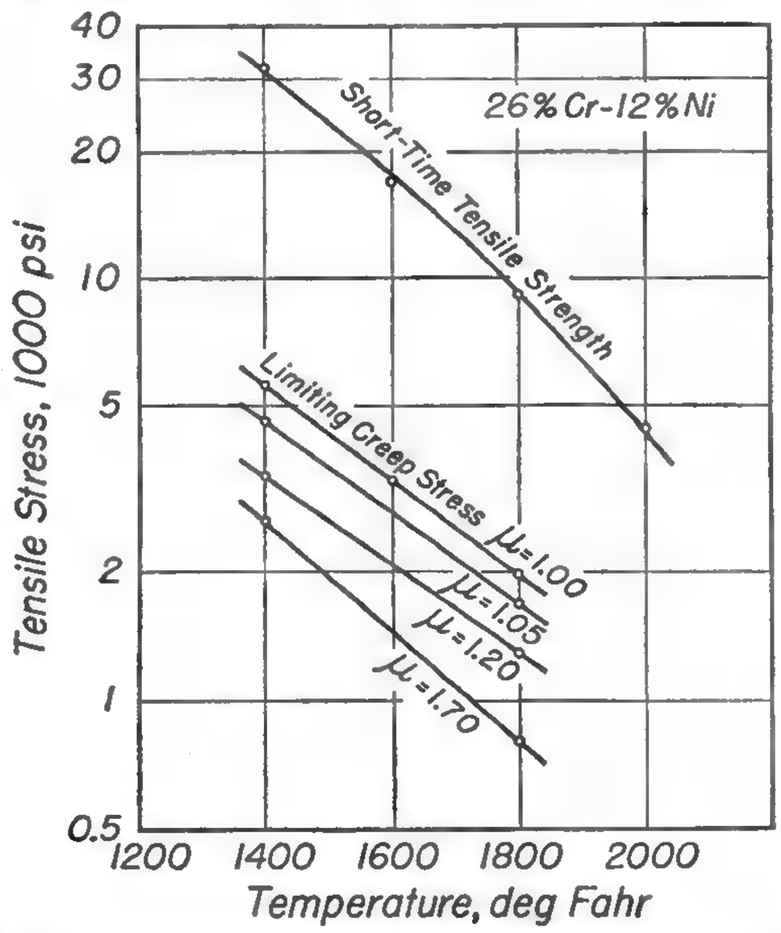

Fig. 12 Limiting creep stress for 0.0001% per hr minimum rate for Type HH (26% Cr, 12% Ni) alloys having magnetic permeabilities between 1.00 and 1.70 μ (American Brake Shoe Company)

Table XI. Comparison of Creep Rates of Wholly Austenitic and Partially Ferritic Type HH Alloys at 1600 F Under a Load of 4000 psi (Gow and Harder[2])

See Table VIII for chemical compositions of alloys

Alloy No.	Microstructure	Min Creep Rate, per cent per hour × 1000
AD	Austenitic	0.045
AE	Austenitic	0.030
AS2	Austenitic (5000 psi)	0.100
AX1	Partially ferritic	1.25

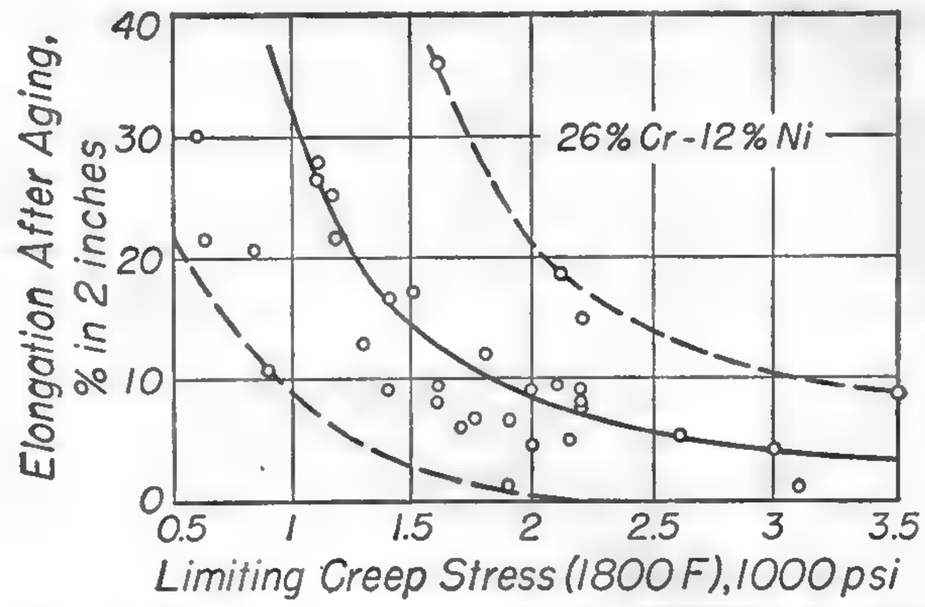

Fig. 13 Inverse relationship between creep strength and ductility after aging of Type HH (26% Cr, 12% Ni) alloy (Avery, Cook and Fellows[3]). Limiting creep stress is that corresponding to a minimum elongation of 0.0001% per hr. Elongation after aging was measured on specimens furnace cooled after being held for 24 hr at 1400 F.

Alloys of the HH type are often evaluated by comparing the percentage elongation of sample bars in a tension test at room temperature after the bars have been held 24 hours at 1400 F. Such a test may be misleading, since there is a tendency to favor compositions that produce the greatest elongation after this particular heat treatment. Avery, Cook and Fellows show that high ductility values are likely to be related to low creep resistance, as indicated in Fig. 13.

Type HI (28% Cr, 15% Ni). This alloy is similar to the HH type composition as far as mechanical properties and sensitivity of composition are concerned. However, the higher nickel and chromium contents increase the resistance of the material to oxidation. This alloy has been employed successfully at temperatures up to 2150 F.

Table XII. Comparison of Physical and Mechanical Properties of Type HH (26% Cr, 12% Ni) and Type HK (26% Cr, 20% Ni) Alloys[a][b]

Property	HH-32	HK-30
Nominal composition	26% Cr 12% Ni	26% Cr 20% Ni
Yield strength, as cast, psi	49,000	42,500
Tensile strength, as cast, psi	82,000	71,750
Elongation, as cast, % in 2 in.	18	16
Reduction of area, as cast, %	23.7	30.5
Brinell hardness number, as cast	156	170
Modulus of elasticity (room temp), psi	23,500,000	23,000,000
Density, g per cu cm	7.72	7.75
Density, lb per cu in.	0.279	0.280
Aged 1400 F, 24 hr, furnace cooled		
Yield strength, psi	50,000	51,250
Tensile strength, psi	86,000	78,000
Elongation, % in 2 in.	6.5	7.5
Reduction of area, %	8.0	10.4
Brinell hardness number	202	205
Thermal expansion		
Temperature Range, deg Fahr	*Total Expansion, per cent*	
80 to 1200	1.09	1.05
80 to 1400	1.30	1.26
80 to 1600	1.53	1.48
80 to 1800	1.78	1.72
80 to 2000	2.03	1.94
	Average Coefficient of Expansion, microinches per inch per °F	
80 to 1200	9.7	9.4
80 to 1400	9.9	9.6
80 to 1600	10.1	9.7
80 to 1800	10.4	10.0
80 to 2000	10.6	10.1
Stress for 100-hr rupture, psi		
1400 F	13,000	14,500
1600 F	6,800	7,800
Limiting creep stress (0.001% per hr min rate) psi		
1400 F	8,400	8,500
1600 F	4,600	5,100
Limiting creep stress (0.0001% per hr min rate) psi		
1400 F	5,900	5,800
1600 F	3,200	3,800
Recommended max tensile working stress, psi		
1400 F	2,900	2,900
1600 F	1,600	1,900

(a) Previously unpublished data, American Brake Shoe Company

(b) Both of these alloys are wholly austenitic, that is, they are free from ferrite and sigma.

Table XIII. Composition Limits of Iron-Nickel-Chromium and Nickel-Chromium-Base Heat-Resistant Castings

ACI Type	Composition, percentage				
	Carbon	Manganese	Silicon	Chromium	Nickel
HT	0.35 to 0.75	2.00 max	2.50 max	13 to 17	33 to 37
HU	0.35 to 0.75	2.00 max	2.50 max	17 to 21	37 to 41
HW	0.35 to 0.75	2.00 max	2.50 max	10 to 14	58 to 62
HX	0.35 to 0.75	2.00 max	2.50 max	15 to 19	64 to 68

Type HK (25% Cr, 20% Ni). The HK type alloy may be considered similar to a balanced HH type in general characteristics and mechanical behavior. The higher nickel content, strongly effective in the stabilization of austenite, removes the likelihood that either ferrite or sigma phase will develop at service temperatures, provided the carbon content exceeds 0.20%. Some low-carbon grades, similar to ranges characteristic of wrought products of this nominal composition, are subject to sigma embrittlement at certain temperatures around 1600 F.

Resistance of HK alloys to corrosion by hot gas is generally greater than that of the HH type, and in atmospheres containing 100 grains or more of sulfur per 100 cu ft of gas (0.016% SO_2), the HK compositions are superior to the high-nickel types HT and HW. Type HK thus appears as the most economical alloy for high resistance to oxidation and relative insensitivity to changes in alloy content. It is an excellent alloy for general structural applications at temperatures as high as 2100 F, and has substantial interchangeability with balanced HH alloys in design calculations. An extended comparison of properties of the HK and HH types is given in Table XII.

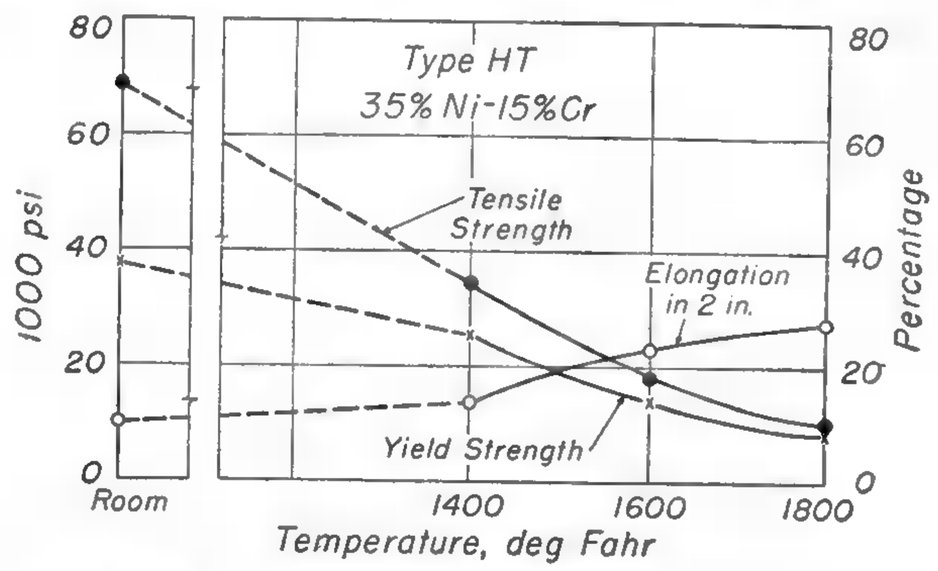

Fig. 14 Influence of temperature on the tensile strength, yield strength and elongation of Type HT (35% Ni, 15% Cr) alloys

Type HL (30% Cr, 20% Ni). This alloy is very similar to the HK type, except that the increase of chromium content to about 30%, places the composition in the alloy range indicated to be most resistant to corrosion at temperatures above 1800 F in atmospheres high in sulfur.

Properties of Iron-Nickel-Chromium and Nickel-Chromium-Base Alloys. Heat-resistant alloys in which nickel is either the predominant alloying element or actually the base material, form an important class of castings essential in equipment for the heat treating industry. Four types are of paramount importance. The composition ranges are indicated in Table XIII.

In general these alloys have a more stable structure than the compositions in which chromium is the predominant alloying element. There is no evidence of a phase change that would cause brittleness within certain ranges of temperature. Experimental data indicate that the composition limits are not critical, and for this reason the production of castings in these alloys does not require such close control with respect to composition as when alloys in the preceding Fe-Cr-Ni group are used.

Table XIV. Mechanical Properties of Type HT Alloys (35% Ni, 15% Cr)

Property	As Cast	After 48 hr at 1800 F, Air Cooled
Tensile strength, psi	69,000	75,000
Yield strength, psi	37,500	45,000
Elongation, % in 2 in	10	5
Brinell hardness number	192	197

Table XV. Mechanical Properties of Type HW Alloys (60% Ni, 12% Cr)

Property	As Cast	After 48 hr at 1800 F, Air Cooled
Tensile strength, psi	68,000	75,000
Yield strength, psi	36,000	38,000
Elongation, % in 2 in	4	4
Brinell hardness number	179	205

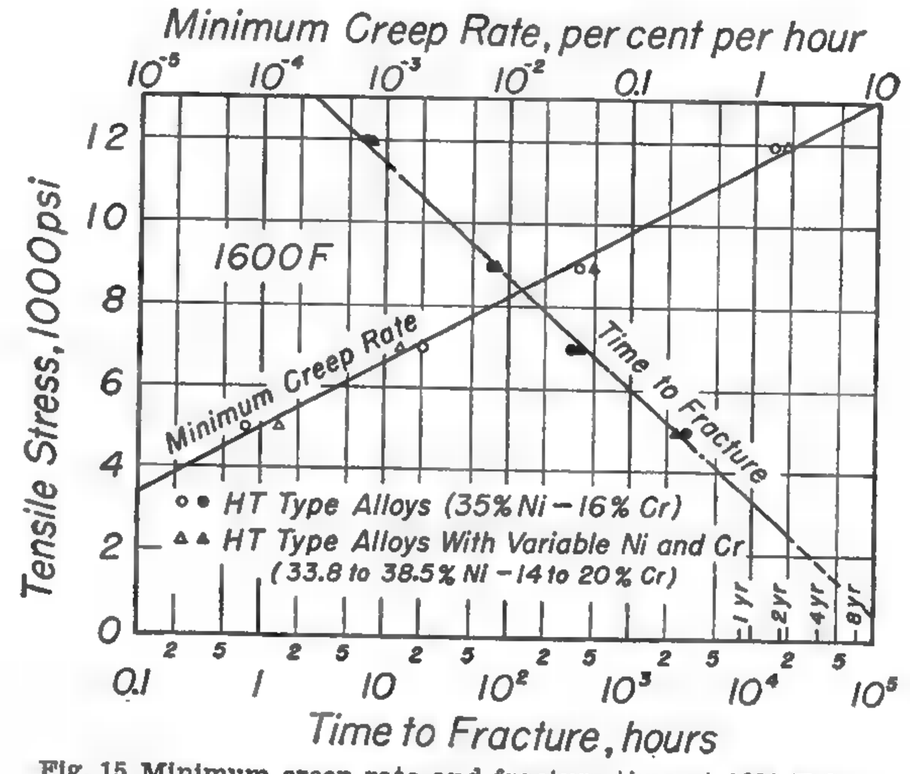

Fig. 15 Minimum creep rate and fracture time at 1600 F for Type HT (35% Ni, 16% Cr) alloys (Avery[4])

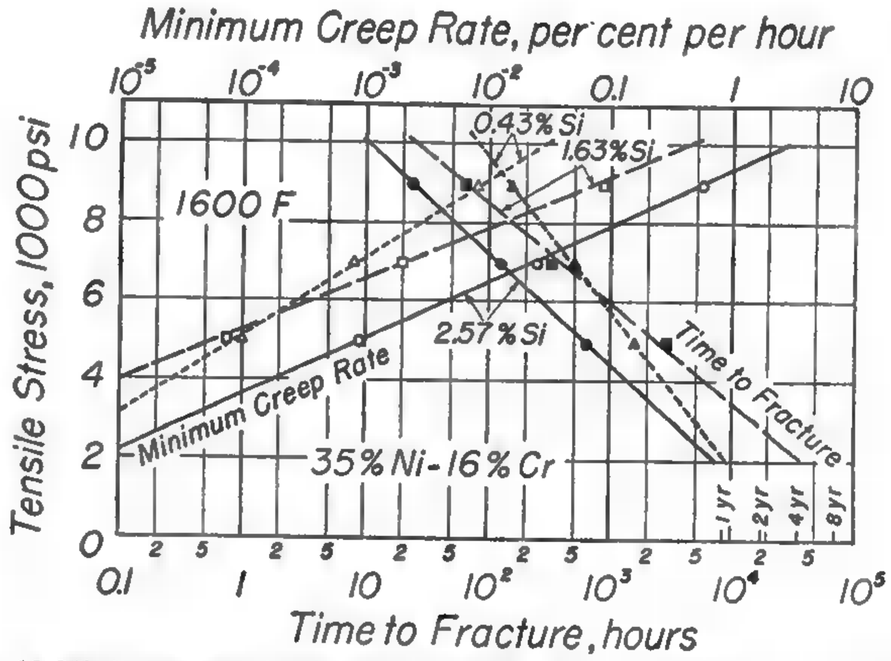

Fig. 16 Minimum creep rate and fracture time at 1600 F for Type HT (35% Ni, 16% Cr) alloys of three silicon contents (Avery[4])

Alloy types HT, HU, HW and HX as a group normally constitute more than 50% of the total production of heat-resistant alloys. These four alloys have given excellent service life in fixtures and trays for heat treating furnaces, where the castings are subjected to rapid heating or cooling.

Table XVI. Mechanical Properties of Type HX Alloys (67% Ni, 17% Cr)

Property	As Cast	After 48 hr at 1800 F, Air Cooled
Tensile strength, psi	75,000	82,000
Yield strength, psi	40,000	42,000
Elongation, % in 2 in	9	9
Brinell hardness number	170	183

Since these compositions carburize less readily than the Fe-Cr-Ni types, they are used extensively for parts in carburizing furnaces. Because they form an adherent scale that does not tend to fleck off, castings of high-nickel alloys are also made for the enameling industry, for applications where loose scale would be detrimental to the process.

In many respects there is no sharp line of demarcation between the HT, HU, HW and HX alloys as far as service applications are concerned. The following general observations, however, should be considered when the most suitable alloy is being selected for any given service.

1 As the nickel content is increased, the tendency for the alloys to carburize is decreased.
2 As the nickel content is increased, the tensile strength of the alloys at elevated temperatures is decreased somewhat, but the alloys are more resistant to thermal shock.
3 As the chromium content is increased, the alloys become more resistant to corrosion and oxidation.
4 As the carbon content is increased, the tensile strength of the alloys at elevated temperatures is increased.
5 As the silicon content is increased, the tensile strength of the alloys at elevated temperatures is decreased, but the resistance to carburization is increased somewhat.

Type HT (35% Ni, 15% Cr). This alloy is used far more widely than the others in which nickel and chromium are the dominant elements. The HT type is used for more than one-third of all the heat-resistant castings that are produced, and it is employed satisfactorily at temperatures up to 2100 F in oxidizing atmospheres and up to 2000 F in reducing atmospheres. Castings of this type are used in many heat treating furnace applications.

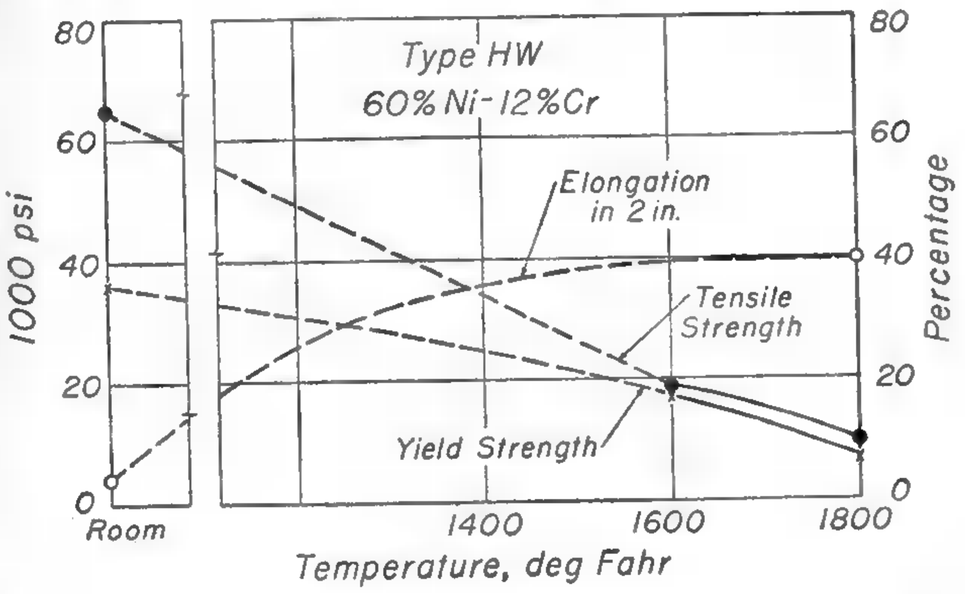

Fig. 17 Influence of temperature on the tensile strength, yield strength and elongation of Type HW (60% Ni, 12% Cr) alloys

Nominal mechanical properties of the HT type alloys at room temperature are listed in Table XIV.

Figure 14 presents a summary of the strength of the HT type alloys at elevated temperatures, as determined from short-time tension tests. Comparison of creep rates and fracture times,[4] are shown in Fig. 15 for alloys of the HT composition at 1600 F. The curves in Fig. 16 indicate the effect of silicon content in HT alloys on rate of creep and time to fracture.

Studies made with pack carburizing compounds indicate that HT type alloys may carburize rather rapidly as the silicon content is decreased below 1.5%. If carburization is to be kept at a minimum, the silicon should be not less than 1.25%.

Type HU (39% Ni, 19% Cr). This alloy is substantially the same as the HT composition with regard to mechanical properties. The increased chromium content, however, increases the strength somewhat at elevated temperatures. Under severe service conditions, this alloy is often recommended instead of the HT type, because the higher alloy content increases the resistance of castings to corrosive attack, as indicated in Table I.

Type HW (60% Ni, 12% Cr). Alloys of high nickel content, such as the HW type, are used extensively for retorts and furnace parts that require resistance to oxidation, carburization, nitriding and thermal shock. Because of their electrical resistivity, these compositions are also used for cast electrical heating elements. Although generally considered not quite so strong as the HT type alloys at elevated temperatures, the alloys of the HW type may be used in applications at temperatures up to 2050 F in oxidizing and up to 1900 F in reducing atmospheres.

Where hot gases have a high sulfur content, as in the products of combustion of high-sulfur fuels, the HW composition is likely to be attacked too severely, and alloys of the Fe-Cr-Ni type, such as HH or HL, are usually substituted. However, an increase in the chromium content to about 17%, increases the resistance of the high-nickel alloys to corrosion by sulfur-bearing gases, as stated in discussion of the HX type material, below.

Nominal properties of HW alloys at room temperature are presented in Table XV. Approximate properties, determined from short-time tests at elevated temperatures, are shown in Fig. 17.

Type HX (67% Ni, 17% Cr). This alloy is comparable in most respects with the HW type, but the higher nickel and chromium contents make the material more resistant to corrosion at elevated temperatures. As shown in Table I, the HX alloy is considerably better than the HW type in resistance to reducing gases that contain up to 100 grains of sulfur per 100 cu ft at 1800 F.

The mechanical properties of this alloy at room temperature are shown in Table XVI. Properties of the HX type at elevated temperature correspond to those given for the HW composition.

Alloys of both the HW and HX types are particularly useful because of their ability to withstand repeated heating and cooling without cracking or warping. For this reason they are employed extensively in severe service—for example, in quenching fixtures. The HW and HX alloys are highly resistant to carbon penetration in carburizing applications, and also have excellent resistance to corrosion when in contact with tempering salts and cyaniding salts. The HW and HX alloys are not recommended, however, for use in contact with the so-called "neutral" salts or with the salts used for heating high speed steel for hardening. Pots cast from these alloys have proved satisfactory as containers for molten lead.

General Remarks About Mechanical Properties. The properties shown for the various alloys are not necessarily indicative of the behavior of castings at elevated temperature. First, room-temperature data, either for the material in the as-cast condition or after exposure of the alloy to a high temperature for a short time, are only an indication of the soundness of the metal. Tests of a particular composition at room temperature are valuable, therefore, merely as confirmation that the alloy will behave at elevated temperatures in the same way that the *same composition* has behaved previously in the *same application.* Furthermore, short-time tests at elevated temperatures do not indicate the extent of the plastic deformation (creep) to which castings are subject in service; and for this reason, the values of stress shown by such tests could not be sustained by the materials for a prolonged time. Therefore, stresses used in designing castings for service at high temperature should be selected with due regard to the creep-strength characteristics of the material employed.

In the design of castings and in the selection of alloys, the safest course for the user is to consult the manufacturers of the alloys in order to obtain the benefit of their experience with similar applications. Faulty design, overloading or uneven heating are often factors of greater importance than alloy composition in determining the life of castings in service. It is most important that heat-resistant castings be designed to provide free expansion of the parts. Overlooking this point will inevitably result in the imposition of extremely high stresses that may crack or distort the structure.

Ni-Mo-Fe and Ni-Mo-Cr-Fe Alloys. The nickel-base alloys that contain high percentages of molybdenum as a primary alloying element were developed for their resistance to chemical corrosion. (*See* data in the NICKEL SECTION, pages 1054 to 1057.) However, these alloys also have good mechanical properties at high temperature and are used in the form of castings for certain high-temperature applications that warrant the cost of the alloys—higher than that of iron-base heat-resistant alloys. In regard to both cost and resistance to the effects of heat, these alloys

are intermediate between the iron-base and the cobalt-base heat-resistant alloys.

Table XVII. Composition Limits of Nickel-Molybdenum-Base Alloys

Alloy Designation	Composition, percentage				
	Ni	Mo	C	Fe	Other
Hastelloy A.....	55.5–59.5	18–22	0.04–0.15	18–22	.....
Hastelloy B.....	62.5–66.5	26–30	0.04–0.15	4–7	.....
Hastelloy C.....	54.5–59.5	15–19	0.04–0.15	4–7	13-16 Cr, 3.5–5.5 W

Compositions of the nickel-molybdenum-base alloys are shown in Table XVII. These alloys may be melted in either induction or electric-arc furnaces and may be cast by either gravity or centrifugal methods. They are particularly suitable for precision casting. The mechanical properties at room and elevated temperatures, shown in Table XVIII, were obtained from precision-cast test specimens 0.250 in. in diam, and the data on stress-to-rupture properties given in Table XIX were obtained from precision-cast specimens, 0.160 in. in diam. It should be noted, from

Table XVIII. Results of Short-Time Tension Tests of Nickel-Molybdenum-Base Alloys

Precision-cast specimens, 0.250 in. in diam, tested in as-cast condition

Temperature of Test, deg Fahr	Tensile Strength, 1000 psi	Yield Strength,(a) 1000 psi	Percentage Elongation in 1 in.	Percentage Reduction of Area
		Hastelloy A		
Room	75.0 to 80.0	43.8 to 48.4	10.0 to 20.0	11.4 to 33.2
1000	63.0 to 72.5	.....	15.0 to 32.0	12.0 to 31.6
1200	57.7 to 66.0	.....	20.0 to 28.0	12.6 to 26.8
1500	41.1 to 52.0	.....	11.0 to 27.0	11.4 to 22.3
		Hastelloy B		
Room	80.0 to 83.5	56.5 to 61.5	9.5 to 15.0	9.8 to 23.2
1100	74.5 to 80.0	.....	13.0 to 17.0	11.3 to 19.6
1200	62.9 to 68.7	.....	10.0 to 25.0	9.5 to 31.2
1500	55.4 to 61.4	.....	11.0 to 32.0	8.9 to 29.5
		Hastelloy C		
Room	76.7 to 88.5	44.5 to 56.4	8.0 to 12.0	8.9 to 14.9
1000	63.0 to 73.1	.....	10.0 to 17.0	7.3 to 23.6
1200	56.2 to 67.2	.....	8.0 to 16.0	9.7 to 23.6
1500	50.4 to 61.4	.....	11.0 to 28.0	8.9 to 21.8
1750	30.0 to 34.0	.....	12.0 to 15.0	41.0 to 56.0
1950	13.0 to 16.0	.....	23.0 to 30.0	53.0 to 66.0

(a) 0.2% offset

the compositions shown in Table XVII, that Hastelloys A and B contain no chromium. This limits the application of these two alloys under oxidizing conditions to a maximum temperature of about 1400 F. These two alloys are particularly satisfactory under reducing conditions. Hastelloy C, having a considerable chromium content, is useful for its resistance to oxidation at temperatures up to 2100 F, and is also satisfactory in atmospheres that are reducing or otherwise corrosive.

These alloys have given outstanding service in a wide variety of applications, such as Hastelloy A for fixtures and parts for continual or repeated submersion in cyaniding baths, including treatments where the heating is followed by quenching in water or in an acid pickling solution; Hastelloy C for tracks and trays for heat treating furnaces operating at temperatures up to 2000 F, as well as for chain conveyers in heat treating furnaces operating up to 1750 F, and for carburizing equipment. These three alloys are also available in the form of wrought material, which may be used with castings in the fabrication of heat treating parts.

Table XIX. Stress-to-Rupture Properties of Nickel-Molybdenum-Base Alloys at 1500 F

Precision-cast specimens, 0.160 in. in diam, tested after the heat treatments indicated

Alloy Designation	Heat Treatment	Stress (psi) for Rupture in			Longest Time to Fracture, hr
		10 Hr	100 Hr	1000 Hr	
Hastelloy A.....	(a)	19,500	11,600	8,800	1953
Hastelloy B.....	(a)	29,000	17,600	10,700	967
Hastelloy C.....	(b)	18,800	14,100	10,700	1222

(a) 2125 F for ½ hr, air cooled, 1700 F for 72 hr, air cooled
(b) 2225 F for ½ hr, air cooled, 2100 F for 8 hr, air cooled

Cobalt-Base Alloys. The cobalt-base high-temperature alloys were first used for highly stressed gas-turbine blading in 1941. The alloy first used was a modification of Vitallium, a dental alloy, employed for a number of years before World War II. The application and modification of the alloy and the production of gas-turbine blading by precision casting on an industrial scale were important wartime developments in the field of metallurgy. The process of precision casting is discussed in the article on page 54 of this Handbook. The wartime application of this alloy was at temperatures no higher than those at which the heat-resistant alloys of the Fe-Cr-Ni and Fe-Ni-Cr types were used, but the alloy served under conditions of high stress, and far surpassed the older alloys in stress-to-rupture strength and creep properties. Stellite 21 alloy, melting at 2547 F, has the highest melting point of this group of alloys. The further improvements on this alloy were obtained in part by an increase in the carbon content, decreasing the melting point by 50 to 100 F.

The cobalt-base high-temperature alloys, except for one, were used in the form of precision castings, although wrought products of sheet and in some grades of bar stock, have recently become available. However, the S-816 alloy was developed as a wrought material and has only recently been tested extensively in the cast form. The original use of Vitallium was based primarily on its high stress-to-rupture properties. Subsequent to the initial application and modification of Vitallium, an extended program of testing was carried out on high-temperature alloys of all types, to establish extensive data on their physical and mechanical properties and to encourage the development of improved alloys. This work was carried out on NDRC contract under the supervision of Battelle Memorial Institute, and on NACA contract under the supervision of the University of Michigan. These programs were of a highly co-operative nature, making use of testing facilities for high-temperature properties wherever such equipment was available throughout the United States. The data presented in this article (Tables XX to XXVII) were taken in large part from these results, although they have been expanded to some extent by test data of the manufacturers and the users, in order to give as complete data as possible concerning the physical and mechanical properties.

Table XX. Chemical Compositions and Densities of Cobalt-Base Heat-Resistant Castings

Original Designation	Composition, percentage									Density, lb per cu cm	Stellite Number
	C	Cr	Ni	Mo	Cb	W	Mn	Si	Fe		
Vitallium	0.25	27	■	6	..	..	0.60	0.60	1	8.30	21
61	0.40	23	2	..	..	5	0.60	0.60	1	8.54	23
6059	0.40	23	32	6	..	..	0.60	0.60	1	8.21	27
422-19	0.40	23	16	6	..	..	0.60	0.60	1	8.31	30
X-40	0.40	23	10	..	..	7	0.60	0.60	1	8.61	31
S-816	0.40	19	20	4	4	4	0.60	0.30	3	8.59	..

The use of cast alloys in preference to forged alloys is indicated by the superior properties in both stress-to-rupture and creep tests of long duration and at higher temperatures, as compared with the similar properties of wrought materials under these conditions. The short-time, high-temperature properties of the cast materials, however, are definitely lower than those of wrought materials.

Table XXI. Thermal Expansion of Cobalt-Base Heat-Resistant Castings

Alloy	Coefficient of Expansion, microinches per inch per °F					
	70 to 600 F	70 to 800 F	70 to 1000 F	70 to 1200 F	70 to 1500 F	70 to 1600 F
Stellite 21	7.83	7.96	8.18	8.38	8.68	...
61	7.64	7.96	8.18	8.48	9.24	...
6059	7.53	7.79	8.04	8.29	8.67	8.84
422-19	7.70	7.86	7.91	8.07	8.42	8.54
X-40	7.97	7.88	7.98	8.18	8.59	8.79

The actual wartime use of Stellite 21 alloy was primarily for the buckets in the General Electric Type "B" turbosupercharger for operation at 1500 F. This alloy, however, was also used in the blading for the turbines of jet engines

for operation at 1200 to 1350 F. At this lower temperature, the mechanical properties of wrought alloys, in general, are somewhat superior to those of cast alloys, but the ease of mass production by the precision casting method and the need for large quantities of blades of this type, resulted in a large percentage of such blading being produced as castings. A considerable proportion of this type of blading is still produced by these methods. Parts for stationary gas turbines, such as the blading for nozzle vanes operating up to 1800 F, were also cast from the Stellite 21 alloy because of its resistance to erosion and corrosion at high temperatures. Many other applications have been made that involve the heat resistance of these alloys, but for the most part these applications are of relatively small volume in comparison with the mass production of blades for gas turbines.

Table XXII. Thermal Conductivity of Cobalt-Base Heat-Resistant Castings

Alloy	Thermal Conductivity, watts per centimeter °C				
	200 C	300 C	400 C	500 C	600 C
Stellite 21	0.145	0.160	0.175	0.190	0.205
61	0.154	0.176	0.180	0.189	0.212
6059	0.141	0.155	0.166	0.181	0.198
422-19	....	....	....	....	....
X-40	0.148	0.175	0.183	0.194	0.219
SAE-4140	0.404	0.390	0.370	0.347	....

These cobalt-base alloys maintain their mechanical properties and resistance to creep at elevated temperatures by progressive aging in a temperature range from 1300 to 2100 F. Tests after aging show higher stress-rupture strengths and lower creep rates, but decreased ductility, in comparison with tests of the material in the as-cast condition. Numerous aged specimens were tested, since it was thought that the aged condition represented most typically the properties of the alloys in service, particularly after moderate service life. However, these alloys were not commonly used in the aged condition in fabrication and assembly, because slight upsetting in mechanical assembly or high stresses in welding require the greatest ductility possible in order to meet the assembly conditions best without trouble from cracking. The welding of Stellite 21 alloy to the high-alloy turbine wheels was carried out satisfactorily in production by manual arc methods and by automatic submerged-melt welding. However, the modifications of these alloys with high carbon contents offer greater difficulty during welding, because of cracks that may develop between buckets, cracks starting in the weld metal, and cracks in the bucket alloy itself, adjacent to the weld metal. The cobalt-base alloys are difficult to machine, because of the rapidity with which they work harden. Although the hardness of these alloys is usually less than Rockwell C 32, it is necessary to use tools tipped with sintered carbide to machine Stellite 21 alloy—the only one on which extensive machining operations have been performed satisfactorily on a production basis. Such operations usually result in increased hardness of the machined surface, as high as Rockwell C 40 to 45, and this hardness increases further as a result of exposure to temperatures from 1300 to 1600 F. Consequently, in blading

Table XXIII. Age Hardening of Cobalt-Base Heat-Resistant Castings (Rockwell A Hardness)

As Cast	Aging Temp, °F	Duration of Aging: 1 hr	2 hr	5 hr	24 hr	50 hr	100 hr
			Stellite 21				
65	1350	65	66	66.5	68.5	69.5	71.5
65	1500	67	67	68	69	69	71
67	1600	69	69	68.5	69	69	70
64.5	1600	67.5	67.5	67.5	68.5	68.5	68.5
65	1700	■	66.5	67.5	67.5	68	69
			61 Alloy				
65	1350	66	68	69.5	71	71.5	71.5
	1500	70	69.5	70	70	69.5	69
	1600	68	68	67.5	68.5	69	69.5
	1700	68	68	■	69	69	71
			6059 Alloy				
61	1350	62	■	66.5	67	67.5	67.5
59	1500	65	64.5	65	65	64.5	65
59.5	1600	62.5	62.5	62.5	62.5	64	64.5
61	1700	62	62.5	63	63.5	64	66
			422-19 Alloy				
65.5	1500	69	69.5	69.5	70.5	71	73
65.5	1600	68	68.5	69	69	70	72
65.5	1700	67.5	68.5	69	70	70	72
			X-40 Alloy				
64	1500	66	69.5	70	69.5	70	70
64	1600	66.5	67.5	67.5	67	68	70
64	1700	67	68	69	68.5	69.5	71

Table XXIV. Results of Short-Time Tension Tests of Cobalt-Base Heat-Resisting Alloys at Elevated Temperature

Test Temp, °F	Tensile Strength, 1000 psi	Yield Strength (0.2%), 1000 psi	Elong, % in 2 in.	Reduc. Area, %	Modulus of Elasticity, 10^6 psi	Condition
			Stellite 21			
Room	101.3	82.3	8.2	9.0	36.0	As cast
1000	69.1	39.1	16.4	25.3	33.3	As cast
1000	86.2	74.4	1.2	4.3	35.0	Aged 50 hr at 1350 F
1200	74.2	38.0	15.7	36.9	33.7	As cast
1200	89.3	71.3	2.0	6.0	23.9	Aged 50 hr at 1350 F
1350	79.3	61.5	3.8	9.0	24.2	Aged 50 hr at 1350 F
1500	59.0	49.0	6.8	19.7	16.8	Aged 50 hr at 1350 F
1600	41.6	32.8	19.3	23.6	15.4	Aged 50 hr at 1350 F
1700	42.5	....	27.	52.4	...	As cast
1700	...	....	...	...	...	Aged 16 hr at 1700 F
1800	33.3	....	35.	52.4	...	As cast
1800	32.9	....	49.	63.1	...	Aged 16 hr at 1700 F
			61			
Room	105.4	58.4	7.0	11.2	29.0	As cast
1000	77.1	41.4	14.8	24.1	27.9	As cast
1000	97.5	72.5	1.7	4.1	27.6	Aged 50 hr at 1350 F
1200	82.9	40.7	15.6	21.5	33.5	As cast
1200	97.5	74.7	1.8	6.6	25.0	Aged 50 hr at 1350 F
1350	79.6	63.1	2.0	6.5	27.0	Aged 50 hr at 1350 F
1500	58.5	40.6	7.8	12.7	23.5	Aged 50 hr at 1350 F
1600	45.8	33.1	9.8	16.8	21.9	Aged 50 hr at 1350 F
1700	37.5	....	7.	35.7	...	As cast
1700	43.6	....	18.	35.7	...	Aged 16 hr at 1700 F
1800	33.1	....	32.	40.6	...	As cast
1800	33.0	....	27.	39.5	...	Aged 16 hr at 1700 F
			6059			
Room	82.5	46.9	7.	10.3	28.0	As cast
1000	50.5	36.6	4.3	10.3	26.2	As cast
1200	48.9	35.0	3.8	8.0	27.0	As cast
1350	66.2	50.8	3.2	4.6	20.2	Aged 50 hr at 1350 F
1500	51.2	38.2	10.1	14.4	18.7	Aged 50 hr at 1350 F
1600	41.4	30.8	11.5	20.1	18.2	Aged 50 hr at 1350 F
1700	43.0	....	23.	26.5	...	As cast
1700	45.4	....	16.	34.0	...	Aged 16 hr at 1700 F
1800	33.4	....	24.	50.3	...	As cast
1800	33.7	....	26.	41.7	...	Aged 16 hr at 1700 F
			422-19			
Room	98.1	55.1	5.0	11.9	33.0	As cast
1000	62.9	42.5	6.2	9.2	25.6	As cast
1200	59.9	37.6	6.3	10.7	27.5	As cast
1350	77.8	61.4	1.8	2.7	24.8	Aged 50 hr at 1350 F
1500	64.0	47.6	3.0	3.4	25.6	Aged 50 hr at 1350 F
1600	48.9	35.9	9.6	17.8	17.3	Aged 50 hr at 1350 F
1700	45.2	....	17.0	26.6	...	As cast
1700	47.1	....	18.0	33.3	...	Aged 16 hr at 1700 F
1800	36.3	....	24.0	33.7	...	As cast
1800	37.8	....	21.0	38.7	...	Aged 16 hr at 1700 F
			X-40			
Room	101.0	74.1	11.0	14.0	28.0	As cast
1000	80.1	40.2	20.0	33.5	33.5	As cast
1200	77.0	37.6	19.0	28.4	22.8	As cast
1350	75.7	53.6	4.6	7.6	23.9	Aged 50 hr at 1350 F
1500	59.6	44.5	10.3	14.1	19.3	Aged 50 hr at 1350 F
1600	48.6	36.2	14.3	18.1	19.0	Aged 50 hr at 1350 F
			S-816			
Room	122.3	....	0.5	1.5	...	Heat treatment
1200	100.5	....	3.5	10.5	...	1 hr at 2300 F, WQ
1500	71.062	....	3.5	14.0	...	6 hr at 1400 F, AC
Room	100.0	44.45	6.0	7.4	...	As cast
Room	104.4	56.2	1.0	1.5	...	Aged 100 hr at 1500 F
1500	61.78	....	17.0	18.0	...	As cast
1500	70.5	....	8.0	15.0	...	Aged 100 hr at 1500 F

Table XXV. Endurance Properties of Cobalt-Base Heat-Resistant Castings

As-cast specimens stressed in alternate bending at a frequency of 120 cycles per second

Alloy	Temperature, deg Fahr	Endurance Strength, psi: 10^8 Cycles	2.5×10^8 Cycles
Stellite 21	Room	35,000 to 40,000	.....
Stellite 21	1200	44,000	.....
Stellite 21	1500	33,000	.....
61	1200	44,000	.....
61	1500	38,000	38,000
6059	Room	36,000	.....
6059	1200	41,000	.....
6059	1500	31,000	30,000
422-19	1200	52,000	.....
X-40	1200	56,000	.....
S-816	1500	33,000	.....

Table XXVI. Results of Creep Tests on Cobalt-Base Heat-Resistant Castings

All creep data given are experimental results, not design values

Alloy	Temp, °F	Stress, psi	Time, hours	Initial Deformation,* %	Rate, % per hour: 500 hours	1000 hours	1500 hours	2000 hours	Total Deformation, %: 500 hours	1000 hours	1500 hours	2000 hours
Stellite 21.....	1350	12,000	1800	0.069	0.00013	0.0001	0.00008	0.00008(a)	0.220	0.275	0.318	0.338(a)
Stellite 21.....	1350	15,000	2106	0.068	0.0003	0.00019	0.00007	0.0001	0.442	0.540	0.596	0.662
61	1350	15,000	1560	0.050	0.00025	0.00016	0.00014	.....	0.234	0.310	0.379	....
61	1350	20,000	1300	0.068	0.00036	0.00042	0.00063(b)	.....	0.292	0.518	0.712(b)	....
6059	1350	12,000	2348	0.042	0.000005	0.000002	0.000002	0.000002	0.135	0.137	0.140	0.140
6059	1350	15,000	1656	0.076	0.00044	0.00008	0.00008	0.00008(c)	0.405	0.479	0.519	0.533(c)
6059	1350	20,000	1536	0.070	0.00045	0.00047	0.00047	.....	0.446	0.690	0.950	....
422-19	1350	15,000	....	0.075	0.00015	0.00007	0.00004	0.00003	0.262	0.320	0.342	0.360
422-19	1350	15,000	2160	0.062	0.000184	0.000119	0.000073	0.000062	0.267	0.363	0.408	0.438
X-40	1350	15,000	1728	0.097	0.000042	0.000069	0.000069	0.000069(d)	0.115	0.160	0.200	0.215(d)
Stellite 21.....	1500	7,000	2002	0.036	0.0001	0.000205	0.00011	0.00009	0.127	0.208	0.296	0.344
Stellite 21.....	1500	7,000	2086	0.046	0.000224	0.0001	0.00006	0.000065	0.285	0.354	0.405	0.439
Stellite 21.....	1500	7,000	2015	0.039	0.00027	0.00014	0.000135	0.0001	0.215	0.348	0.417	0.500
61	1500	12,000	2780	0.080	0.000285	0.00011	0.000085	0.000085(e)	0.506	0.608	0.657	0.682(e)
61	1500	12,000	2136	0.035	0.000022	0.000062	0.000024	0.000024	0.176	0.201	0.205	0.222
6059	1500	12,000	1778	0.078	0.00019	0.00018	0.000080	0.00008(f)	0.305	0.500	0.575	0.600(f)
6059	1500	12,000	2039	0.075	0.00041	0.000198	0.000132	0.00013	0.678	0.815	0.894	0.963
422-19	1500	12,000	1997	0.069	0.00021	0.000068	0.000035	0.000035	0.430	0.487	0.507	0.523
422-19	1500	12,000	2082	0.060	0.000191	0.000079	0.000061	0.000046	0.397	0.453	0.489	0.524
X-40	1500	9,000	2136	0.043	0.000066	0.000035	0.000014	0.000014	0.106	0.120	0.125	0.133
X-40	1500	12,000	1728	0.074	0.000037	0.000021	0.000021	0.000012	0.241	0.250	0.265	0.255
X-40	1500	14,000	1896	0.062	0.00014	0.00004	0.00004	0.00004	0.240	0.364	0.375	0.382
Stellite 21.....	1600	5,500	1488	0.063	0.000036	0.000031	0.000031	.....	0.122	0.130	0.163	
Stellite 21.....	1600	7,000	2184	0.089	0.000125	0.000044	0.000044	0.000044	0.258	0.308	0.330	0.353
Stellite 21.....	1600	10,000	206.5	0.120	0.00033	0.00013	0.00013	0.00013	0.790	0.900	0.980	1.036
61	1600	5,500	2184	0.035	0.000045	0.000025	0.000025	0.000025(h)	0.105	0.127	0.152	....
61	1600	7,000	1536	0.024	0.00005	0.000036	0.000036	.....	0.173	0.193	0.207	....
61	1600	9,000	833	0.058	0.0002	0.0001(g)	.....	.....	0.300	0.332(g)	....	....
6059	1600	7,000	2187	0.045	0.00005	0.00003	0.00002	0.00001	0.141	0.158	0.169	0.171
6059	1600	9,000	2070	0.050	0.00002	0.000013	0.00001	0.00001	0.143	0.153	0.162	0.165
6059	1600	11,000	2059	0.060	0.00036	0.00031	0.00026	0.00025	0.627	0.784	0.922	1.05
422-19	1600	9,000	2207	0.044	0.000065	0.000015	0.000015	0.00001(i)	0.230	0.249	0.258	0.260
422-19	1600	11,000	2250	0.051	0.000085	0.00002	0.00002	0.00002	0.284	0.301	0.313	0.325
422-19	1600	12,000	2035	0.080	0.00027	0.00023	0.00011	0.00028	0.700	0.815	0.880	0.980
X-40	1600	9,000	1872	0.037	0.0001	0.00006	0.00005	0.00005(j)	0.165	0.195	0.218	0.243(j)
X-40	1600	17,500	2599	0.156	0.00065	0.00048	0.00070	0.00178	1.40	1.67	1.95	2.58(k)

* Deformation on application of load
(a) When discontinued at 1800 hr
(b) Data for 1300 hr. Fractured after overheating to 1650 F
(c) When discontinued at 1656 hr
(d) When discontinued at 1728 hr
(e) When discontinued at 2780 hr, rate 0.000023% per hr, total deformation 0.70%
(f) When discontinued at 1778 hr
(g) Specimen broken while being removed from test unit because of burn-out of heating furnace at 833 hr
(h) When discontinued at 2184 hr
(i) Discontinued at 2207 hr. Rate <0.00001%. Elongation 0.26%
(j) When discontinued at 1872 hr
(k) Ruptured at 2599 hr, 7.0% elongation, 7.3% reduction of area

where machining operations are used, it is generally necessary to soften by annealing at 2100 F or higher to put the alloy in the best condition for assembly.

The microstructure of these alloys consists of a cobalt-rich matrix and three types of complex carbides. These carbides may be present separately or in the form of a eutectic, and in certain of the alloys during slow cooling a eutectoid forms, consisting of the cobalt-rich matrix and one form of carbide.

Precision castings of these alloys usually have a coarse grain size in comparison with wrought materials. This is considered desirable for good high-temperature properties, except where single grains may occupy the full cross section of highly stressed parts. It has been shown that very coarse grain size may result in wide variations in the value of the modulus of elasticity. Most of the results reported were from tests on precision-cast specimens ¼ in. in diam, although it has been found that there is no great difference between values of properties obtained from specimens ¼ in. and ½ in. in diam. At 1200 F the endurance properties of these cast alloys are somewhat inferior to those of the best wrought materials, but at 1500 F, the best wrought and cast materials have endurance properties of the same order of magnitude. It is likely that, when endurance

Table XXVII. Results of Stress-Rupture Tests on Cobalt-Base Heat-Resistant Castings

Test Temp, deg Fahr	Stress (psi) for Rupture in: 10 hr	100 hr	500 hr	1000 hr
Stellite 21				
1200	70,000	51,000	.....	44,200
1300	54,000	43,000	.....	27,000
1400	42,000	24,000	.....	15,000
1500	.....	22,000	15,800	14,200
1600	.....	16,700	13,400	13,200
1700	17,000	13,000	10,700	10,000
1800	12,500	9,400	7,700	7,000
2000	4,200	.....	.....	....
61				
1200	.....	58,000	50,000	47,000
1300	50,000	39,000	32,300	30,000
1400	.....	36,000	28,000	25,000
1500	.....	27,200	22,500	21,800
1600	.....	16,000	13,000	12,000
1700	17,000	14,000	12,200	11,500
1800	12,500	8,600	6,200	5,400
6059				
1200	58,000	55,000	49,000	46,000
1300	45,000	37,000	31,500	29,000
1400	35,000	28,000	.....	.....
1500	29,200	23,400	19,700	18,400
1600	.....	16,000	12,900	12,000
1700	16,000	12,000	9,700	8,600
1800	12,500	9,300	7,500	6,800

Test Temp, deg Fahr	Stress (psi) for Rupture in: 10 hr	100 hr	500 hr	1000 hr
422-19				
1350	.....	47,000	.....	.....
1500	33,000	28,600	24,100	21,700
1600	24,200	18,800	15,500	14,800
1700	19,000	16,000	12,300	11,500
1800	14,000	10,000	7,900	7,100
2000	5,500	3,000	.....	.....
X-40				
1200	.....	55,000	49,000	46,000
1300	50,000	46,000	41,000	39,000
1400	44,000	36,000	29,000	26,500
1500	35,000	28,400	24,600	23,400
1600	.....	21,000	19,000	18,000
1700	20,000	17,000	15,300	14,500
1800	13,000	11,300	10,200	9,800
2000	6,300	4,000	.....	.....
S-816				
1200	.....	57,500	.....	47,000
1350	.....	40,000	.....	29,000
1500	33,500	26,000	22,000	21,000
1600	.....	17,500	.....	12,500
1700	19,000	14,500	.....	11,500
1800	14,500	10,500	.....	7,800

Table XXVIII. Physical and Mechanical Properties of 60 Cr – 25 Fe – 15 Mo and 60 Cr – 15 Fe – 25 Mo Alloys

Vickers Pyramid Hardness

Measured at Room Temperature	
60 Cr – 25 Fe – 15 Mo, as cast	455 to 579
60 Cr – 15 Fe – 25 Mo, as cast	498
24 hr at 1600 F (870 C)	480
48 hr at 1600 F (870 C)	488
90 hr at 1600 F (870 C)	478
130 hr at 1600 F (870 C)	563
4 hr at 2400 F (1315 C)	592
20 hr at 2400 F (1315 C)	624
44 hr at 2400 F (1315 C)	626
Measured at 1112 F (600 C)	
60 Cr– 25 Fe – 15 Mo, as cast	430
60 Cr – 15 Fe – 25 Mo, as cast	430
Measured at 1292 F (700 C)	
60 Cr – 25 Fe – 15 Mo, as cast	376
60 Cr – 15 Fe – 25 Mo, as cast	396
Measured at 1600 F (870 C)	
60 Cr – 25 Fe – 15 Mo, as cast	192 to 220
60 Cr – 15 Fe – 25 Mo, as cast	296
Measured at 1700 F (925 C)	
60 Cr – 25 Fe – 15 Mo, as cast	141 to 180
60 Cr – 15 Fe – 25 Mo, as cast	274

Density

60 Cr – 25 Fe – 15 Mo	7.63 g per cu cm
60 Cr – 15 Fe – 25 Mo	7.87 g per cu cm

Tensile Strength at 1350 F (735 C)

60 Cr – 25 Fe – 15 Mo ..... 99,700 and 103,500 psi

Machinability

60 Cr – 25 Fe – 15 Mo can be turned and drilled with high speed steel tools.

60 Cr – 15 Fe – 25 Mo can be machined with carbide-tipped tools and can be ground.

Stress-Rupture Properties

Heat No.	Temperature °F	Temperature °C	Stress, psi	Time for Rupture, hr	% El	% RA	Remarks
			60 Cr – 25 Fe – 15 Mo				
554-2	1350	735	50,000	1414	8	6.2	.....
612-2	1350	735	50,000	484	9	9	.....
634-1	1350	735	50,000	985	5	5	0.70% Si
679-2	1350	735	55,000	611	5	6	.....
679-1	1350	735	63,800	182	5	0	.....
554-1	1600	870	20,000	132	22.0	24.8	.....
621	1600	870	20,000	70.5	14.0	14.5	0.307% C
			60 Cr – 15 Fe – 25 Mo				
469-1	1700	925	20,000	76	5.5	5.0	.....
469-4	1600	870	20,000	1042	9	12	.....
469-2	1600	870	24,000	478	5.0	5.0	.....
469-3	1600	870	30,000	291	5.0	5.0	.....
635-1	1600	870	30,000	290	9.5	7.6	0.13% C
635-2HT	1600	870	26,500	472	9.0	8.6	Test interrupted after 276 hr
636-1	1600	870	30,000	132	4.0	8.5	.....
636-2HT	1600	870	30,000	316.5	3.0	2.4	Test interrupted after 248 hr
667-2	1600	870	30,000	336	4.0	1.2	0.51% Si. Held 90 hr at 1600 F (870 C)
668-2	1600	870	30,000	430.5	6.0	6.3	Held 90 hr at 1600 F (870 C)
668-3	1600	870	30,000	145	8.0	7.4	Held 60 hr at 1800 F (980 C)
613-1	1600	870	37,500	65	1.0	1.2	.....
613-2	1600	870	35,000	371	5.0	3.8	.....

properties are determined at temperatures above 1500 F, the cast alloys will have an advantage at these higher temperatures.

The aging range of the cast cobalt-base alloys is somewhat higher than that of most wrought alloys; this is another reason for their satisfactory operation at the higher temperatures where the mechanical properties of wrought materials decrease more rapidly.

Chromium-Base Alloys. Recent research work[5] has indicated the interesting possibilities of chromium-base alloys for use at high temperature. Preliminary study of 13 binary and 9 ternary systems indicated that the Cr-Fe-W and the Cr-Fe-Mo alloys are the most promising. In later studies of the Cr-Fe-Mo alloys, it was found that the most useful combination of strength and ductility would not be far from the composition line in the Cr-Fe-Mo ternary diagram joining 60 Cr, 25 Fe, 15 Mo with 60 Cr, 15 Fe, 25 Mo. Between these two composition points, the properties appear to vary continuously, increasing in strength at 1600 F as the ratio of molybdenum content to iron content increases, and decreasing in ductility. The properties of these two alloys are summarized in Table XXVIII. These alloys must be both melted and cast in a vacuum.

The ductility of chromium-base alloys at high temperature increases with increasing purity and decreasing grain size. None of the alloys in the as-cast condition exhibited any measurable ductility in tension tests at room temperature. It is believed that further research on the alloys will result in an increase in their plasticity.

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The Forging of Stainless Steel

By Waldemar Naujoks*

STAINLESS steels are considered to include, in a general grouping, the iron-base alloys designed to resist corrosion at normal temperatures and to resist deformation and scaling, as well as corrosion, at more elevated temperatures. All of the stainless steels have in common some basic properties in regard to forging and hot working. Compared with rates for carbon steels and low-alloy steels, the rate of heat transfer into stainless steels is slower, necessitating a longer period of heating for forging; stainless steels offer greater resistance to plastic deformation, which means that more blows or heavier blows are required to perform a given amount of forging. Though stainless steels have less tendency to scale during heating, any scale that is formed is usually of the hard variety, tending to cling tenaciously. These variations in characteristics from carbon and low-alloy forging steels may require a modification of normal forging practice, or may even require a considerable change in technique for the more difficult shapes. Stainless steels are classified in four general groups: (1) the ferritic or nonhardenable chromium steels, (2) the martensitic or hardenable chromium steels, (3) the austenitic or chromium-nickel steels and (4) the special heat-resisting alloys developed for high strength at high temperatures.

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Prepared for the Subcommittee on Forging, with membership as follows: Adam Steever, *Chairman* (Columbia Tool Steel Company), W. W. Criley (The Ajax Manufacturing Co.), A. A. Handler (Deceased), G. R. Houghtaling (Rochester, N.Y.), Waldemar Naujoks (Ohio Injector Co.), William Telfer (University of Michigan) and R. W. Thompson (Transue & Williams Steel Forging Corporation).

General Working Properties. Many of the general considerations discussed in the article on "Heating Steel for Forging", page 348, apply to stainless steels. Stainless

Table I. Forging Temperatures for Ferritic Chromium Steels

AISI Type No.	Composition		Forging Temperatures, deg Fahr		
	Carbon, per cent	Chromium, per cent	Preheat	Initial Forging	Finish Forging
430	0.12 max	14.00 to 16.00	1400	1900 to 2050	1300 to 1450
442	0.35 max	18.00 to 23.00	1400	1900 to 2050	1300 to 1450
446	0.35 max	23.00 to 27.00	1400	1900 to 2050	1300 to 1450

Table II. Forging Temperatures for Martensitic Chromium Steels

AISI Type No.	Composition		Forging Temperatures, deg Fahr		
	Carbon, per cent	Chromium, per cent	Preheat	Initial Forging	Finish Forging
403	0.15 max	11.50 to 13.00	1500	2050 to 2150	1600 to 1700
410	0.15 max	10.00 to 14.00	1500	2050 to 2150	1600 to 1700
416	0.15 max	12.00 to 14.00	1500	2050 to 2150	1600 to 1700
420	Over 0.15	12.00 to 14.00	1500	2000 to 2100	1600 to 1700
440	0.50 to 0.70	14.00 to 18.00	1500	1950 to 2050	1600 to 1700
440	0.75 to 0.95	14.00 to 18.00	1500	1950 to 2050	1600 to 1700
440	0.90 to 1.05	14.00 to 18.00	1500	1950 to 2050	1600 to 1700

steels are sluggish in coming up to temperatures and require a longer soaking period to permit the heat to penetrate through the cross section of the bar or billet. Although preheating is not necessary for all types of stainless steels, it is desirable to preheat thoroughly to a temperature of about 1500 F, allowing sufficient time for uniform temperature to be attained through the piece. This should be followed by fairly rapid heating to the desired forging temperature. Sufficient soaking should be allowed at the preheating temperature, but should be minimized at the forging temperature.

Ferritic or Nonhardenable Chromium Steels. The ferritic chromium steels are forged more easily than the stainless steels in the other three groups but less easily than carbon steels. As indicated in Table I, the steels should be heated slowly to about 1400 F and should then be brought up fairly rapidly to 1900 F for small or medium forgings, and to not more than 2050 F for large pieces. These steels, highly susceptible to grain growth, must not be soaked at high temperatures. The first few blows should be light; then the piece should be worked rapidly at the initial forging temperature but more gradually as the temperature of the steel decreases. If reheating is necessary, the final reheating temperature should not exceed 1900 F. The finishing temperature should be about 1400 F for the best grain refinement. Although these steels do not harden appreciably during rapid cooling, it is desirable to anneal them to remove all forging and hot working strains.

Martensitic or Hardenable Chromium Steels. The martensitic chromium steels require careful heating for good results. As shown in Table II, the low-carbon grades should be heated slowly to about 1500 F, allowing sufficient time for heat to soak through the entire cross-sectional area. Then the steel should be brought up to a temperature of 2050 F for small and medium forgings and to not more than 2150 F for large pieces. The first few blows should be light, followed by more rapid working. In general, the forging practice used on carbon tool steel can be applied. For the higher-carbon grades, preheating is recommended, followed by a more rapid heating up to temperatures of 2000 to 2100 F. Care should be taken to avoid overheating and the finishing temperature should be approximately 1700 F. The work should be reheated if the temperature falls below 1700 F.

Austenitic Chromium-Nickel Steels. The austenitic chromium-nickel steels are forged with greater difficulty than are the straight chromium steels. As indicated in Table III, these steels should be heated slowly and carefully to about 1500 F, allowing sufficient time for the temperature to become uniform through the cross-sectional area; then the metal should be brought up to forging temperature by fairly rapid heating. The first few blows should be light, followed by more rapid working. In general, the forging practice used on carbon tool steel can be applied. Austenitic chromium-nickel steels should not be forged below 1700 F, since there is a tendency toward red shortness; if further forging is required, the metal should be reheated. Because the chromium-nickel austenitic steels have high strength at the higher temperatures, they require more blows or heavier blows than ordinary carbon steels.

Special Heat-Resisting Alloys. A number of highly alloyed heat-resisting alloys have been developed for applications involving high strength at elevated temperatures. These special alloys ordinarily require careful preheating and heating in furnaces designed to provide neutral atmospheres, or atmospheres that can be made slightly reducing or oxidizing for the particular grade of material. These alloys, having high strength at high temperatures, are forged with difficulty and require a special forging technique to prevent fiber rupture during forging.

Table III. Forging Temperatures for Austenitic Chromium-Nickel Steels

AISI Type No.	Composition			Forging Temperatures, deg Fahr		
	Carbon, per cent	Chromium, per cent	Nickel, per cent	Preheat	Initial Forging	Finish Forging
302	0.08 to 0.20	17.00 to 20.00	8.00 to 10.00	1500	2150 to 2200	1600 to 1700
303	0.20 max	17.00 to 20.00	8.00 to 10.00	1500	2150 to 2200	1600 to 1700
304	0.08 max	17.00 to 20.00	8.00 to 10.00	1500	2150 to 2200	1600 to 1700
309	0.20 max	22.00 to 26.00	12.00 to 15.00	1500	2100 to 2150	1700
310	0.25 max	24.00 to 26.00	19.00 to 22.00	1500	2100 to 2150	1700
311	0.25 max	19.00 to 21.00	24.00 to 26.00	1500	2100 to 2150	1700
321	0.10 max	17.00 to 20.00	7.00 to 11.00	1500	2150 to 2200	1600 to 1700
325	0.25 max	7.00 to 10.00	19.00 to 23.00	1500	2000 to 2050	1600 to 1700
347	0.10 max	17.00 to 20.00	8.00 to 12.00	1500	2150 to 2200	1600 to 1700

The Shaping and Joining of Stainless Steel

By V. W. Whitmer*

MANY TYPES of stainless alloys are available, having compositions to meet specific requirements, but nearly all of them can be grouped in two general classes, in regard to fabrication. The first class, containing chromium as an alloying element, with varying amounts of carbon for heat treating purposes, is generally known as the "straight chromium" or "ferritic" type and is magnetic. The second class, containing both chromium and nickel, with low carbon, does not respond to heat treating for hardening. It is known as the "chromium-nickel" or "austenitic" group and is nonmagnetic.

Excluding the higher-carbon alloys in the straight chromium group, the two most commonly used alloys in these groups are probably those containing 18% Cr with low carbon content, and the one containing 18% Cr and 8% Ni. In both groups are numerous other alloys, containing higher percentages of alloying elements chiefly for resistance to heat or corrosion, but these related alloys are worked much the same as the two mentioned above.

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Hence, in this article only these two alloys will be considered, with additional notes when necessary.

Piercing. For piercing, the straight chromium steels should be heated in the same manner as for forging. (*See* "Forging Stainless Steel", page 581.) A higher temperature will generally prove satisfactory. Although the 18% Cr alloy has been the most commonly used in the group, the steels containing 23 and 28% Cr have been pierced successfully.

For piercing, the chromium-nickel steels should be heated in the same manner as for forging the 18-8 alloy, but to a higher temperature. The 18-8 alloy is the most commonly used in the chomium-nickel group. The higher alloys, such as 25-12 and 25-20, have also been pierced successfully—the latter with considerable difficulty.

Welding. *18% Cr Stainless Steel.* This alloy can be welded satisfactorily by any commercial method except forge welding. For gas welding, a wire of the same composition as the steel is used with a slightly reducing flame. For arc welding, a coated electrode is used, protecting the metal going through the arc, from oxidation by the air. The coated electrode will also cover the deposited bead with a slag blanket, which stays molten and prevents loss of any chromium by oxidation. Because of the high temperature employed in welding, large grains will be developed, resulting in a brittle weld. At elevated temperatures, such as 400 F and higher, 18% Cr stainless steel is somewhat tough. However, the 18% Cr steel does not respond satisfactorily to subsequent heat treatment. For optimum results the chromium content should be 15 to 18% since it is possible to anneal after welding, thus producing fair ductility and bending properties.

The higher-chromium alloys behave in a similar manner, but the lower type, around 12% Cr, is suitable for heat treatment and can be annealed to show some ductility after welding. Additions of columbium, titanium or aluminum will reduce air hardening in the 12% Cr alloys. Such additions to the electrodes do not produce soft ductile weld metal; hence, if the welds are to be placed in service as welded, an austenitic electrode such as 18-8, 25-12 or 25-20 should be used, depending on the application. Such welds will be tough and ductile but they will have a higher coefficient of expansion than the straight chromium alloy.

18-8 Cr-Ni Steels. The chromium-nickel stainless steels are well adapted to welding and, like the others, can be welded by any commercial method except fire. Fire welding is not successful, because at the welding temperature a refractory film of oxide forms on the surface of the material; and this film, which will not dissolve or fuse with the commercial fluxes used today, acts as a separator when the pressure is applied on the two sections, thus preventing adhesion.

In gas welding, a rod of the same composition as the material being welded should be used with a slightly reducing flame, having about $\frac{1}{32}$ in. of acetylene feather on the end of the inner blue cone to prevent any possible oxidation of the chromium. If more acetylene is used, the weld may become carburized; if less acetylene is used, the chromium may be burned out. It is also advisable to apply a water paste of a suitable flux to the lower side of the joint, to protect this side from contact with the air.

The 18-8 alloy has a high coefficient of expansion—about 60% more than common steel; therefore it is necessary to hold the work in some manner while welding, in order to prevent the edges from moving away from each other. Because of the greater expansion, the joint should be held so as to produce as little buckling as possible when cooling. Gas welding is used chiefly on sections of 16 gage and lighter, although it can also be used on heavier sheets.

Electric-arc welding is probably the most common method used on stainless steel. A heavy flux-coated electrode of the same composition is necessary. This flux protects the molten metal from oxidation by the air, both while going through the arc and after being deposited. The flux should contain no material that would raise the carbon content of the weld metal, since this would reduce ductility as well as resistance to corrosion. Reverse polarity should be used; that is, the electrode should be positive and the work negative. The 18-8 alloy has a lower melting point than steel, as well as lower heat conductivity; therefore, less heat can be used and good penetration will be obtained in comparison with mild steel. A heavy bead or a series of heavy beads should not be deposited at one time, because the excessive contraction may cause cracks. Light beads should be deposited, about ⅛ in. or less in thickness. All 18-8 welds properly made on ⅛-in. plate will bend back flat on themselves in either direction without cracking.

Occasionally, columbium or titanium is added to 18-8 low-carbon steel, to prevent precipitation of carbide. This is not necessary for the low-carbon alloy in light plates, but is desirable in thicknesses greater than ⅝ in. or in material that will be used in service at temperatures in the carbide precipitation range from 1000 to 1500 F and under corrosive influences. Titanium in the welding electrode is not advantageous, since it is nearly all lost during welding. Columbium is more efficient and will be reduced less.

Atomic hydrogen welding is quite well suited to stainless steels and is frequently used in automatic operations. No flux is required, but the gas should be present on both sides of the weld in order to prevent any oxidation of the metal. If the edges fit closely, good joints can be obtained when little or no filler metal is added.

In the inert-gas shielded-arc process of welding, especially well adapted to stainless alloys, the molten metal is protected from contact with the air by a blanket of helium or argon, and oxidation is eliminated. This process is becoming more and more popular for automatic welding as well as for hand work, particularly on thinner sections.

Spot, seam and flash welding are satisfactory on 18-8 steel, but because of the characteristics of the alloy, a closer adjustment between current, time and upset is important. Automatic control is highly advisable when 18-8 steel is being welded. Less total heat will be required than with common steel sections of the same size.

The same procedure as for 18-8 steel should be employed in welding the higher chromium-nickel alloys. These alloys are usually subjected to high temperatures and the weld metal, as well as the plate or body, must withstand high-temperature service.

Soldering 18% Cr and 18-8 Cr-Ni Steels. Both types of stainless steels are soldered readily; the composition has no effect on the strength of the finished joint. If pickled sheets are employed, the ordinary zinc chloride or cut acid with commercial half-and-half solder will give fair results. However, stronger joints will be produced by use of special soldering fluxes for stainless steel. If the steel is polished, the edges should be roughened with a coarse file or abrasive cloth to obtain adhesion. A large soldering iron should be used with as low a temperature as possible, in order to keep any buckling at a minimum. When the joint has been completed, it should be washed with a solution of about 5% soda. Washing will neutralize any remaining acid, which, if not removed, will corrode the metal. If the joint is of such a nature that washing on both sides is impossible, it should first be tinned with a strong flux and washed; then it should be assembled and finish-soldered with a flux as nearly neutral as possible, so that if it is not removed, the steel will not corrode seriously.

Cold Forming Operations. *Cold Rolling 18% Cr Stainless Steel.* The straight chromium alloys can be cold rolled in sheet or strip, or drawn into wire in the same manner as common steel, except that lighter drafts, less speed and greater pressure are required. High surface finish can be obtained on cold rolled strip and very little polishing is required by an article made from this product. During cold working, the hardness will increase to about 187 to 241 Brinell (95 to 100 Rockwell B) but will seldom exceed this range. Annealing will reduce these values to about 140 to 160 Brinell (60 to 85 Rockwell B).

Cold Rolling 18-8 Cr-Ni Stainless Steel. The chromium-nickel grades can be cold rolled into strip or drawn into wire by methods similar to those employed for the straight chromium steels. Chromium-nickel grades will yield highly finished surfaces, but considerable hardening will result. Cold working will raise the hardness to about 400 Brinell (40 to 44 Rockwell C), with tensile strength as high as 250,000 to 300,000 psi.

Drawing 18% Cr Stainless Steel. This alloy has about two-thirds as much ductility as ordinary deep drawing

steel. Therefore, in stamping, the draw should generally be less for each operation. Under certain conditions it is possible to make two or more reductions without annealing the steel; however, it is usually advisable after each operation to anneal at 1450 F, and then to cool in air. A good drawing lubricant is necessary—one that will adhere to the work under greater pressure than is required for ordinary steel. Good adhesion and lubrication should be stressed rather than a heavy base. In the straight chromium group, the alloys containing more than 23% Cr will be less satisfactory for drawing than alloys in the lower chromium ranges. Reductions of 25 to 30% are common on the first draws, but subsequent reductions should be limited to approximately 15%.

Drawing 18-8 Cr-Ni Stainless Steel. Because of its high ductility, 18-8 stainless steel is used extensively in deep drawing work. This alloy has a much higher elongation, as measured by a tensile test, than extra deep drawing steel, showing about 45 to 50% as compared with 25 to 30% elongation in 8 in. for extra deep drawing steel. Also the Olsen and Erichsen test values are higher. However 18-8 stainless steel is subject to rapid hardening during cold working; hence as much work as possible should be performed in one operation. It is difficult to produce deep draws without annealing between operations, although at times two draws can be made without annealing. This annealing consists of heating at 1950 F, and cooling rapidly either in air or water.

A reduction of 40% or more can be made in the first operation, but subsequent reductions should be about 20%. If too much work is done at one time and the article is permitted to stand too long before annealing, it is likely to crack from excessive cold work. For this reason, if more than 40% reduction is made, the 18-8 stainless steel should be annealed at once. The presence of a flange will reduce this cracking tendency considerably. About twice as much clearance should be allowed as for ordinary steel.

Because of the high mechanical properties and stiffness of the 18-8 alloy, one-third more power will be required to produce a given draw. A lubricant with high adhesive qualities is necessary, capable of withstanding the high pressure without squeezing. All lubricants should be removed completely before annealing, because such materials are likely to injure the metal surface during the annealing operation. The dies for production work should have hard bronze inserts for the rings, and either bronze, steel or cast iron for the punch. The ring should be kept well polished, if possible, in the direction of drawing. Proper choice of lubricant should assist in reducing scoring and thus maintaining this polish.

Spinning 18% Cr Stainless Steel. The straight chromium alloys, especially those that contain 17% Cr or more, have not been particularly successful in spinning operations. Reductions are less, and more annealing is required than with the lower alloys. For best results in spinning, steel should be used that contains about 12 to 16% Cr.

Spinning 18-8 Cr-Ni Stainless Steel. The chromium-nickel type of steel has high ductility, and therefore is well suited to spinning operations, but because of rapid work hardening, this steel may require many annealing treatments. In order to reduce this hardening tendency, somewhat higher nickel content is employed (approximately 12% Ni) permitting about 2 to 3 times as much deformation before annealing. Ordinary tools of the solid round-nose type or roller type are used, though the roller type is preferred. A heavy-body grease or soap must be employed, keeping the surface well covered at all times to prevent scoring or abrading. All lubricants must be removed thoroughly before annealing, and if brass or copper alloy tools have been used, the work material must also be pickled in nitric acid to remove all traces of copper, since even small amounts of this metal will penetrate the sheet during annealing and will cause cracks during further spinning.

Machining. *18% Cr Stainless Steel.* This alloy machines a little differently from ordinary steel and more nearly resembles a 0.40 to 0.50% C steel. For best results, 18% Cr stainless steel should be in the cold worked or cold worked and annealed condition at the time of machining.

The 12% Cr steel, containing higher sulfur along with various other elements, is recommended for machine work. On a basis of 100% for screw stock, the product will rate approximately 90%. The 12% Cr alloy is used on automatic screw machines along with regular screw stock.

18-8 Cr-Ni Stainless Steel. This product is tough and difficult to machine. Best results are obtained with a slow cutting speed and moderately heavy cuts. Tools must be kept sharp, because any dragging may work harden the product and will increase the difficulty. Drills should be ground flatter than usual to produce less wedge effect and the speed should be reduced to about one-half that used for drilling steel. Center punch marks should be as small as possible in order to reduce the effect of cold working.

For drilling or cutting, a good grade of sulfur-base oil should be used. In sawing, a high-speed blade should be used, of the fine-tooth wavy type. A circular saw is preferred whenever possible.

Selenium additions to 18-8 will improve the machining properties sufficiently to compensate for a slight sacrifice of resistance to corrosion.

Grinding, Polishing and Buffing. Both types of stainless steel, if only rough ground with a coarse wheel, will discolor when subjected to a salt spray. However, if a higher finish is applied, no rusting will occur on the 18% or higher Cr steels or on any of the chromium-nickel steels.

Rough grinding should be done with 80-grit, set up with glue and abrasive on a cotton wheel. This should be followed by 100-grit used on a greased wheel surface, then with a succession of fine wheels, such as 120, 150, 180, 200 and 240-grit, depending on the finish desired. Grit as high as 180 should be of the manufactured type, low in iron. Higher than 180, Turkish emery will give best results.

For a higher finish, 240-grit should be used with grease and then buffed with a stainless steel buffing compound on a cotton buff. This operation should be followed with a few passes, using green chromium oxide grease stick for final color. These stainless steels should not be buffed with chromium oxide, because drag pits may develop.

For cutting, a speed of 5000 to 6000 ft per min should be used, and for buffing, 6000 to 8000 ft per min.

Cleaning, Pickling and Electrolytic Polishing of Stainless Steel

By H. A. Grove*

THE REMOVAL of scale from stainless steel is described here under the headings Blast Cleaning and Pickling. The removal of lubricants, grease, drawing compounds and miscellaneous contamination, from finished or semifinished articles, is discussed under Cleaning. Information is included also concerning the electrolytic polishing and passivation of stainless steel.

Cleaning. In many fabricating operations, it is necessary or desirable to employ a lubricant that will prevent excessive scratching, especially where high finishes are concerned. Under such conditions and even when dry forming is involved, the accumulated deposit must be removed from the surface before the equipment is shipped.

If the lubricant or deposit has a grease base, it is best to wash the metal first with a good solvent, such as kerosene, gasoline, naphtha or the like, and wipe dry. Although this method of cleaning removes all the grease, a thin, oily surface film will remain, which can be absorbed by finely bolted whiting. The whiting (precipitated calcium carbonate) should be sifted onto the surface and wiped off

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with a soft cloth, such as flannel. This will bring out the true luster of the metal.

Caustic cleaners are also employed for removing drawing compounds or lubricants. After passing through the caustic cleaning solution, the stainless steel part should be washed in hot water and dried, either by a blast of dry air or by wiping with a soft cloth.

When the stainless steel is to be used for architectural trim—either interior or exterior—it may become spotted, during the building period, by materials such as cement, dust, paint and lacquer. The steel can be covered with a heavy paper applied with paper hanger's paste, which can be washed off later with warm water. If the surface is not protected in this manner, it should first be washed with benzene, benzol, turpentine, paint remover, or a similar solvent, depending on the deposit in question. To remove heavy dirt or other such substances, steel wool should never be used; neither should a metal scraper, or any other mechanical device, because scratching and contamination of the surface are almost certain to result. Steel or iron particles may thus become embedded in the surface and later may rust, discoloring the stainless steel and making it appear as though it were rusting, although it has not been affected.

This preliminary cleaning should be followed by a final washing, using half and half whiting and 00 pumice on a soft rag that is wet with either tap water or water to which a little ammonia has been added. The metal should always be rubbed in the direction of the polishing lines, never with a circular or cross-the-grain motion, since light scratches or light and dark areas may result. The excess of powder should be removed with a clean wet cloth and the remainder should be allowed to dry. Then the steel is wiped with a soft dry cloth, such as canton flannel.

The above procedure will be satisfactory for No. 4 or No. ▮ finishes.* If a No. 7 or No. 8 finish is to be cleaned, pumice should not be used, because it will scratch. Ammonia water and whiting should be used, or better still, dry whiting alone.

The whiting and 00 pumice can be obtained at any hardware or paint supply house. The whiting should be of the best grade, finely bolted and free from all grit and foreign substances.

Blast Cleaning. Blast cleaning of stainless and heat-resisting steels is usually done on semifinished products, though it may be used as a final cleaning operation. In such instances the process should always be followed by a passivation treatment to remove any iron contamination.

Blast cleaning may be done by sandblasting, grit-blasting, or vapor-blasting. The sand for sandblasting should be a good grade of silica sand and as low in iron content as possible. The size of the particles is determined largely by the type of work to be done.

In grit-blasting, the grit is generally made from high-alloy material and is used in the form of sharp particles. Here again the size of the particles and the air pressures used will be governed principally by the work to be done. In the grit-blasting of sheets and plates, care should be taken not to use too heavy a grit or too much air pressure, since the plate may become warped as a result of the grit cold working the surface.

Vapor-blasting or liquid-blasting consists in cleaning the surface with a fine abrasive carried in a liquid blast. The size of the abrasive material, which may vary from 100 to 2500-mesh, is controlled, in this instance too, by the type of surface desired on the work.

Pickling. Pickling is the treating of steel with an acid, salt or base, in such a way as to remove the scale or oxide formed during a heating operation.

The most common method for pickling stainless steel, uses acid solutions and is ordinarily divided into two operations or steps. The first operation consists in immersing the steel in a solution of 8 to 12% (by volume) of sulfuric acid at 150 to 170 F for 10 to 30 min. The time is governed by the type of scale or by the alloy being pickled. A suitable inhibitor is ordinarily used with this solution. Another acid bath that may be used in this primary pickle is ■ solution of 10 to 15% (by volume) of hydrochloric (muriatic) acid at 130 to 140 F. A suitable inhibitor should be used with this solution also. After pickling in either the sulfuric or the hydrochloric acid solution, the stainless steel should be washed thoroughly.

In the second operation or the step after pickling in the above solutions, the steel is immersed in a solution of 10 to 15% (by volume) of nitric acid plus 1 to 2% (by volume) of hydrofluoric acid at 120 to 130 F for 10 to 20 min. The time will be governed by the alloy and the nature of the scale. The stainless steel should then be washed, preferably with hot water, to remove all acid, and should be dried rapidly to give the best surface appearance.

The above solutions are suitable for batch pickling. Wooden tanks are suitable for all the acid solutions mentioned above. Ceramic or lead-lined tanks can be used for sulfuric acid and a rubber lining can be used with hydrochloric acid.

A method widely employed in strip mills that roll stainless steels is a continuous electrolytic pickle, using different acid solutions. The customary pickling line consists of two or more tubs, containing either a solution of 6 to 10% (by volume) of nitric acid or a solution of 4 to 8% (by volume) of sulfuric acid. The current is generally induced into the strip by proper placing of the electrodes. For pickling straight-chromium steels, either of these acid solutions may be used; but for the chromium-nickel grades, it may be necessary to have a final tank, containing a solution of 10 to 15% of nitric acid plus 1 to 2% of hydrofluoric acid at 110 to 120 F. This solution is not used electrolytically. After passing through the pickling tanks, the strip is washed and dried. Methods of descaling are summarized in Table I.

Table I. Methods for Descaling Stainless Steel in Acid Solutions

Acid	Rinse	Acid	Rinse
Sulfuric, 8–12% by vol 150–170 F, 10–20 min Use inhibitor	Water	Nitric, 10–15% by vol Hydrofluoric, 1–2% by vol 120–140 F, 10–15 min	Water
Hydrochloric (Muriatic), 10–15% by vol 130–150 F, 10–20 min Use inhibitor	Water	Nitric, 10–15% by vol Hydrofluoric, 1–2% by vol 120–140 F, 10–15 min	Water
Sulfuric, 8–12% by vol Sodium chloride, 2–4% by wt 150–170 F, 10–20 min Use inhibitor	Water	Nitric, 10–15% by vol Hydrofluoric, 1–2% by vol 120–140 F, 10–15 min	Water
Sulfuric, 8–12% by vol Ferric sulfate, 5% by wt 150–170 F, 15–20 min	Water	Nitric, 10–15% by vol Hydrofluoric, 1–2% by vol 120–140 F, 10–15 min	Water
Sulfuric, 8–12% by vol 150–170 F, 10–20 min Use inhibitor	Water	Ferric sulfate, 6–10% by wt Hydrofluoric, 1–2% by vol 120–140 F, 10–15 min	Water
Sulfuric, 4% by vol Hydrochloric (Muriatic), 4% by vol 150–170 F, 10–20 min Use inhibitor	Water	Nitric, 10–15% by vol Hydrofluoric, 1–2% by vol 120–140 F, 10–15 min	Water
.....	.....	Nitric, 10–15% by vol Hydrofluoric, 2% by vol Hydrochloric, 2% by vol 120–140 F, 10–20 min	Water

Pickling of Stainless Steel in Solutions That Contain Ferric Sulfate. For the austenitic stainless steels, a mixture of approximately 10% (by weight) of ferric sulfate and 1 to 2% (by volume) of hydrofluoric acid may be used at a temperature of 120 to 140 F. For the straight-chromium steels this same solution may be used, but these steels should first be pickled in sulfuric acid, using an 8 to 10% (by volume) solution at 150 to 170 F. Another suggested method is to add ferric sulfate (approximately 5 to 10% by weight) to an 8 to 12% sulfuric acid solution and use at 150 to 170 F. This treatment should be followed by a dip in a solution of nitric acid (10 to 15% by volume) and hydrofluoric acid (1 to 2% by volume) at 120 to 140 F. Inhibitors are not needed with these acid mixtures. Solutions that contain ferric sulfate may also be used as a clean-up pickle, after the steel has been descaled in molten caustic.

* A No. 4 finish is a bright ground or grit-finished surface. No. 6 finish is similar to No. 4 but has been dulled to a "satin" finish. Both No. 7 and No. 8 are buffed finishes; No. 8 has a higher luster than No. 7.

Table II. Methods for Descaling Stainless Steel in Salt Baths

Salt	Rinse	Acid	Rinse	Acid	Rinse
Sodium hydroxide, 60 to 90% by wt Sodium nitrate, 10 to 40% by wt 900 to 1000 F, 5 to 15 min	Water Quench	Sulfuric or Hydrochloric (Muriatic), 8 to 12% by vol Inhibitor 150 to 170 F, 3 to 5 min	Water	Nitric, 5 to 10% by vol Hydrofluoric, 1% by vol 120 to 140 F, 5 to 10 min	.....
Sodium hydroxide, 98% by wt Sodium hydride, 2% by wt 750 to 850 F, 5 to 15 min	Water Quench	Sulfuric, 8 to 12% by vol Inhibitor 150 to 170 F, 1 to 3 min	Water	Nitric, 5 to 10% by vol Hydrofluoric, 1% by vol 120 to 140 F, 5 to 10 min	Water

Sodium Hydroxide–Sodium Hydride Process. This method of descaling employs a bath of molten salt composed of approximately 98% (by weight) sodium hydroxide and 2% (by weight) sodium hydride, at 750 to 800 F. The work material is immersed in this bath for 5 to 15 min, depending on the nature and amount of scale. The steel is then rinsed in water and dipped for 1 to 2 min in a 10% (by volume) sulfuric acid bath at 160 to 180 F. An inhibitor is used with the acid. The steel is again rinsed.

The final operation in this descaling process is a 5 to 10-min pickle in a solution of 7% (by weight) nitric acid and 1% (by weight) hydrofluoric acid at 150 to 170 F. The steel is then rinsed in water.

Other Salt Bath Processes. Another salt bath for descaling stainless steels consists essentially of caustic soda. The bath is operated at 900 to 1000 F; the material to be cleaned is immersed for 2 to 15 min, depending on the quantity of scale on the work, and is then washed in water and dipped in weak hydrochloric or sulfuric acid for 30 to 60 sec. Optionally an additional momentary brightening dip in weak nitric or nitric-hydrofluoric acid is used to obtain higher finish and passivation. Methods of descaling in salt baths are summarized in Table II.

Passivating. Passivating is the treating of the surface of stainless steel with certain acid or acid salt solutions to remove contaminating iron particles and to produce a passive film on the steel surface.

In forming operations, such as machining, bending, drawing and rolling, where the stainless steel is in close contact with steel dies and is probably abraded by them, some iron may become embedded in the stainless steel surface. These particles may rust, causing a discoloration of the stainless material. To remove iron particles and any other foreign substances, the stainless steel parts are dipped into one of the following solutions. For the straight chromium type of stainless steels, a solution of 50 to 70% nitric acid (by volume) is very satisfactory at 130 F for 15 to 30 min. Another good passivating agent for chromium steel is a mixture of about 20% nitric acid (by weight) and 2% sodium dichromate, at 110 to 120 F for 15 to 30 min.

The chromium-nickel stainless steels can be passivated in a 25% nitric acid solution at 120 F for 20 to 30 min, or the nitric acid–dichromate solution mentioned before may be used. After any immersion in the passivating solution, stainless steel parts should be washed in water and dried. If the product is to be polished, the passivation treatment need not be used, since grinding and polishing will remove any particles of iron. However, for exposure outdoors, a final passivation treatment is advisable.

Electrolytic Polishing of Stainless Steel. The polishing of stainless steel by electrolytic methods has become industrially important. This method of polishing has been known for some time, but until recent years was used only as a laboratory method for polishing specimens.

In electrolytic polishing, the work piece is the anode, which is immersed in an electrolytic bath that can form a soluble salt with the metal. The cathode can be made of stainless steel, lead, graphite or other conductive, inactive material. If the part to be polished is of irregular shape, it may be necessary to have a cathode of the same general shape or of a shape that will produce a uniform smoothness on the part.

The current density may vary from a few tenths of an ampere to 30 amp per sq in. Unless sufficient current density is used, an etched or frosted appearance results.

The solutions used for electrolytic polishing are, for the most part, of two classes. The first group of solutions contains phosphoric or sulfuric acid or both, to which may be added such acids or other chemicals as tartaric, citric or chromic acid, alcohol, glycerol, benzoic acid, benzene, commercial inhibitors, and the like. These solutions have low electrical resistance and operate on low voltages, usually not higher than 25 v. The operating temperature of these solutions is about 150 to 300 F, depending on the solution. Higher temperatures require higher current density.

The second type of solution that is employed, is based on perchloric acid, to which may be added acetic acid, acetic anhydride, alcohol and ether. These solutions operate best on voltages of 28 to 45 v. Since the current input will raise the temperature of these solutions, it is necessary to cool them, for they should be operated at temperatures around 85 to 90 F.

The perchloric acid solutions can be operated safely around 85 F. They should not be allowed to become hot and consequently hazardous. Incidental organic compounds should be kept from entering the bath, because they may form explosive mixtures with the perchloric acid. These solutions are a little more expensive, which may account for a wider adoption of the phosphoric and the sulfuric acid solutions.

The article to be polished should be totally immersed, since foaming of the solution may result in poor polishing; also attack may be severe at the interface line between solution and air. The space between the part and the cathode may vary from ½ to 6 in. A good surface is a prerequisite for a good polished finish. Agitation of the solutions is not necessary, but it will reduce any tendency to streak and will increase the efficiency of the anode. If agitation is used, it should be mild, because the greatest solution of metal is where the turbulence is greatest. For flat surfaces, agitation is not recommended. Large surfaces such as sheets are less readily polished than bars, wire and small formed articles and may look hazy or pitted.

Before this method of polishing is adopted, a careful study should be made of the costs as compared with those for other standard mechanical methods of finishing. There are also other factors, such as size and shape of work material, which may encourage the use of one method of polishing in preference to another.

MAGNETIC MATERIALS AND OTHER SPECIAL-PURPOSE ALLOYS

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Magnetically Soft Materials

BY T. D. YENSEN*

SEVERAL conflicting characteristics are often required in magnetically soft materials. For this reason a number of different magnetic alloys have been developed, ranging from pure iron through the silicon irons and high-nickel iron alloys to cobalt-iron alloys.

The following characteristics are important: (1) Hysteresis loss arising from internal magnetic "friction" during a magnetic cycle. This loss should be low. (2) Eddy current loss resulting from electric currents induced in the material by changes in flux. This loss should be low. (3) Magnetic permeability should be high, and sometimes must be high or constant at low field strengths. (4) Saturation value should be as high as other considerations permit. (5) In special applications a definite change in permeability with temperature is required. (6) The cost, availability and ease of processing are important, and frequently determining, factors.

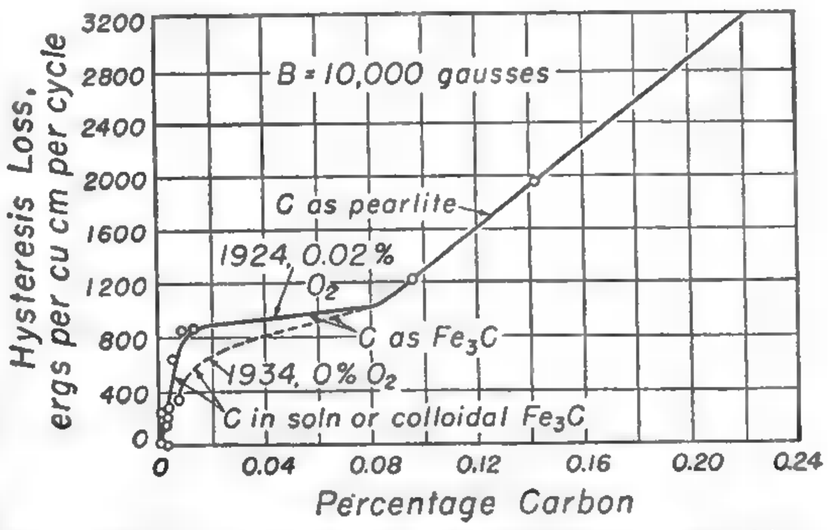

Fig. 1 Effect of carbon content on the hysteresis loss of iron

Effect of Impurities.[1] Since the ferromagnetic properties of metals depend on the regularity of the crystal structure, it follows that anything affecting this regularity will also affect the magnetic properties. Impurities like carbon, sulfur, nitrogen and oxygen are particularly harmful because, in solution, they occupy interstitial spaces in the crystal structure and very small amounts therefore produce large effects.[1] Furthermore, since the solubility is low at room temperature, the excess solute is slowly precipitated in the form of small particles inside the grains, with an even greater disturbing effect usually referred to as "aging". In iron and iron-silicon alloys, the carbon content especially should be kept low in order to obtain low hysteresis loss and high maximum permeability. The carbon content should not be greater than 0.01% and preferably should be less than 0.005%. Figure 1 shows the effect of carbon content on the hysteresis loss of iron. Sulfur and oxygen likewise should be held down to similar values.

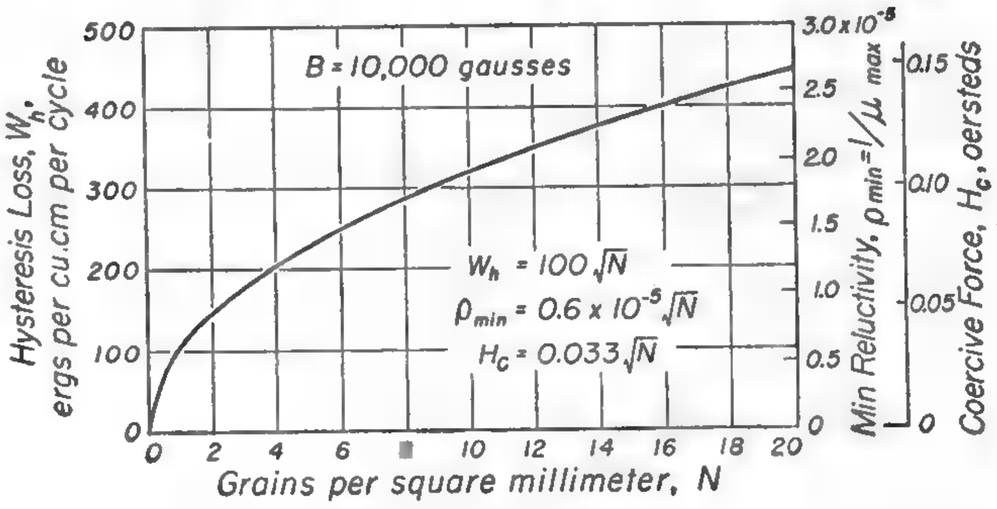

Fig. 2 Net effect of grain size on the hysteresis loss of pure iron

Effect of Grain Size.[1] Because of the disturbances at the grain boundaries, the fewer the grain boundaries the better are the magnetic properties, which is another way of saying that the grain size should be as large as possible with the single crystal as the limit (Fig. 2).

Effect of Grain Orientation. Almost all ferromagnetic materials are magnetically anisotropic; that is, they have different magnetic properties in the different crystallographic directions. This is shown in Fig. 3 for iron[2] in which the direction parallel to a cube edge [100] is the

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one having the highest permeability. Other metals are different in this respect. For example, in nickel the direction of easy magnetization is that of the cube diagonal [111]. In all instances, crystallographic orientation should be taken into account in controlling the magnetic properties of ferromagnetic materials.

Effect of Alloying Elements. Although pure iron is, in many respects, the ideal ferromagnetic material, it has certain drawbacks that make it unsuitable for practical use, especially in a-c circuits. The resistivity is low, which necessitates rolling the iron very thin to reduce eddy

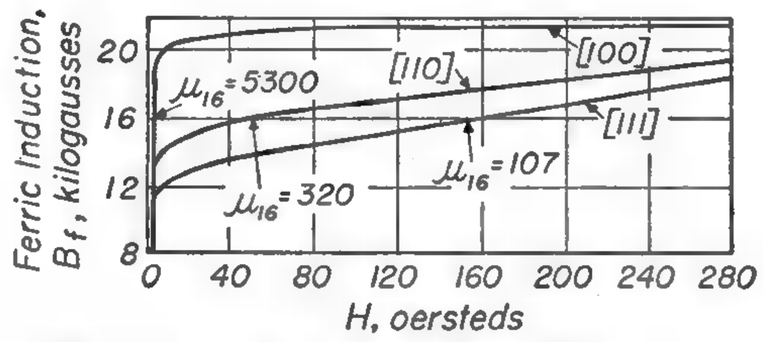


Fig. 3 Effect of grain orientation on the *B-H* properties of iron (Honda and Kaya)

currents, and when this is done, the magnetic properties are poor. Therefore one of the main objects of adding alloying elements is to increase the electrical resistivity of iron so as to make the metal useful in a-c circuits—which means perhaps 75% of all applications of magnetic materials in industry. Figure 4 shows how the various elements affect the resistivity of iron. Except for carbon in solution, silicon and aluminum increase the resistivity more than any other elements.

Silicon and aluminum also have another important effect; they eliminate the allotropic transformations in iron, so that the alloys can be annealed at high temperatures without recrystallization during cooling; thus large grains can be obtained. Both silicon and aluminum are substitution elements and for this reason can be added to iron in

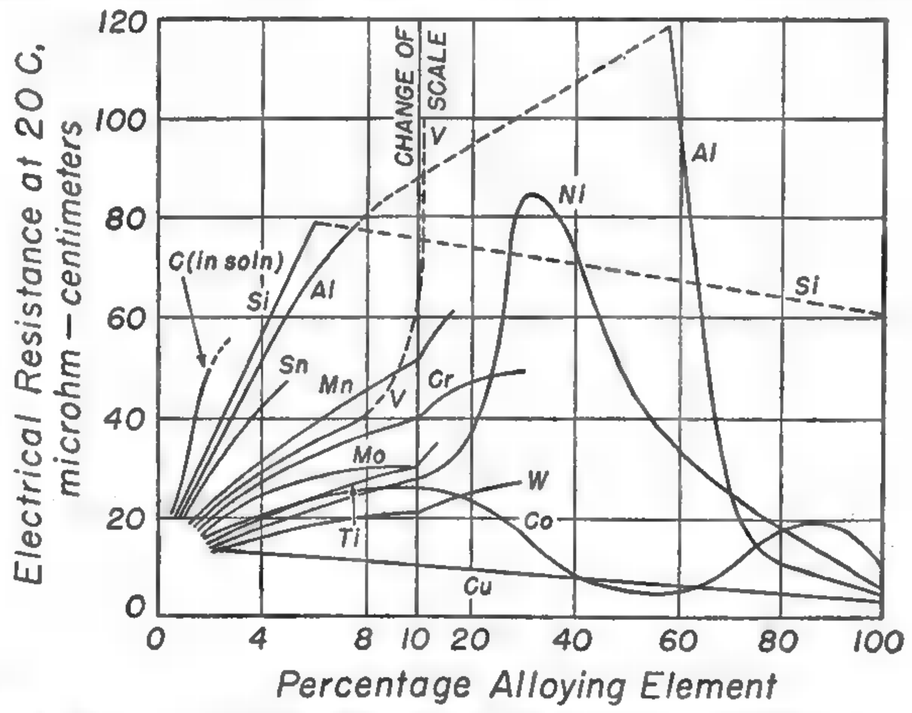


Fig. 4 Effect of alloying elements on the electrical resistance of iron (Stäblein, Yensen)

fairly large quantities without affecting seriously the magnetic properties, although such additions do reduce the saturation value (Fig. 5). More than 4.5% Si or 8% Al makes iron too brittle for most commercial use.

The chief difficulty in connection with silicon and aluminum is that they form stable oxides, so that if the iron is not thoroughly deoxidized before the alloying elements are added, oxide inclusions are formed that cannot again be eliminated, and these have deleterious effects on the magnetic properties. Aluminum is particularly undesirable in this respect.

Valuable magnetic properties are obtained by combining iron with nickel or cobalt, or with both, and by adding to these combinations other elements, such as copper, vanadium, molybdenum or chromium, as will be seen later.

Magnetic Materials. *Iron.* By careful preparation of a single crystal of iron, Cioffi[4] has obtained a maximum permeability of 1,430,000 and Ziegler and Yensen[5] have prepared ring samples of iron, having a hysteresis loss of 70 ergs per cu cm per cycle for $B = 10{,}000$.

For experimental uses, iron can now be obtained with

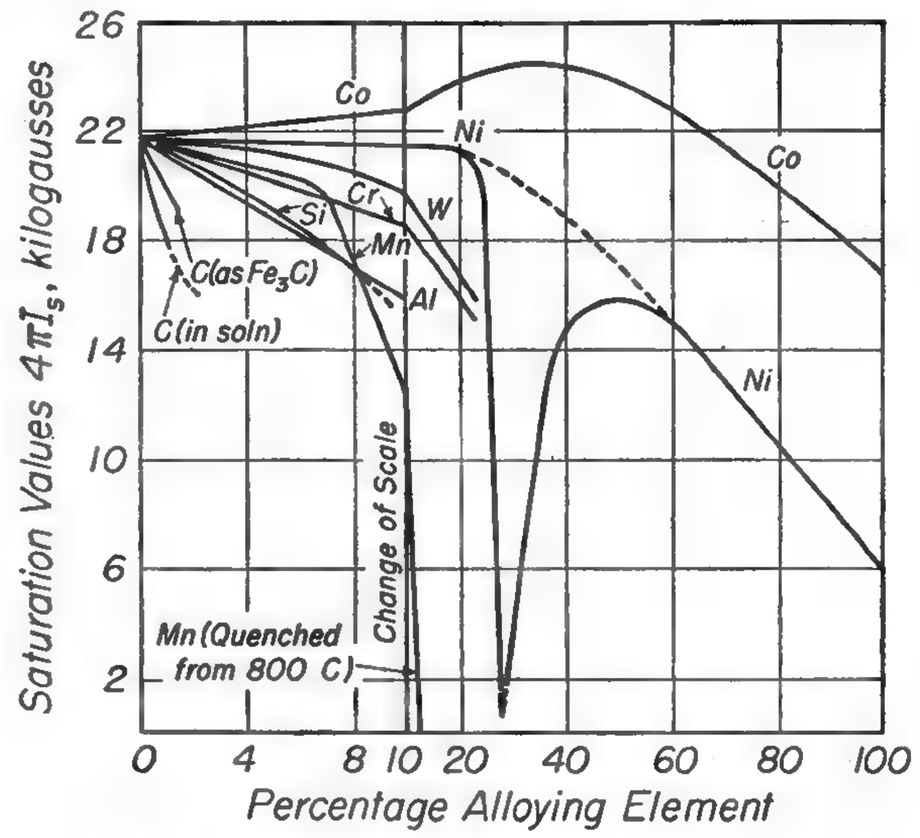


Fig. 5 Effect of alloying elements on the saturation value of iron (Stäblein, Yensen)

a purity of 99.95% or more, having magnetic properties as shown in Fig. 6; maximum permeability of about 100,000 and a hysteresis loss for $B = 10{,}000$ of about 100 ergs per cu cm per cycle (Puron).

The latest saturation value of iron comes from the Physikalisch-Technische Reichsanstalt[6] and is given as:

$4\pi I_s = 21{,}580 \pm 10$ gausses based on a density of 7.878

These values agree well with those given by Cleaves

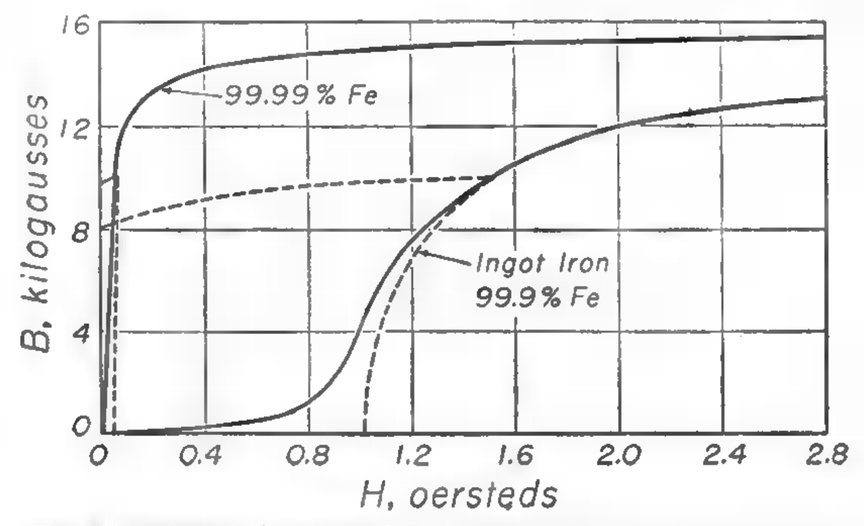


Fig. 6 Hysteresis loops and *B-H* curves for nearly pure iron

and Thompson.[7] The electrical resistivity given by Cleaves and Thompson as the most reliable value is 9.8 microhm-cm at 20 C with temperature coefficient 0.0065 per °C.

Iron-Silicon Alloys. Although pure iron is in many respects an ideal magnetic material, it is easier to obtain good magnetic properties in iron by the use of a small amount of silicon than without it.[8] Brittleness imparted by the silicon limits the amount in practice to about 4.5%, although 6% may be used for special purposes.*

The commercial grades of silicon iron in common use are made in basic open hearth or electric furnaces. These alloys contain from 0.5 to 4.5% Si. Sheets are usually hot rolled from ⅝-in. sheet bars to gages from No. 20 (0.0375 in.) to No. 30 (0.0125 in.). The finished hot rolled sheets may be up to 48 in. wide and of lengths usually in multiples of the widths but not much more than 120 in. long. After being pickled to remove scale, the sheets are cold rolled slightly to ensure satisfactory flatness. They are

* For thermal, electrical and mechanical properties of these alloys, see "Silicon in Steel", page 476.

Table I. Magnetic Properties of Standard Electrical Sheet

Grade	Uses	% Si	Sat. Value, $4\pi I_s$	Min Flux Density for $H = 10$	Max Losses (watts per lb[a]) for 60 cycles, $B = 10{,}000$: 0.014 in. 29 gage	0.019 in. 26 gage	0.025 in. 24 gage	$B = 15{,}000$: 0.014 in. 29 gage	0.019 in. 26 gage	0.025 in. 24 gage	Max Aging Factor, %
Field	Pole pieces, frames	0.5	21,500	14,000	...	...	...	...	...	...	...
Armature	Generators, small motors	1.0	21,000	13,500	1.30	1.55	2.05	3.05	3.65	4.80	...
Electric I	Generators, small motors	1.0	21,000	13,500	1.15	1.35	1.75	2.75	3.15	4.10	5
Electric II	Generators, induction motors	2.5–3.0	20,500	13,400	1.00	1.15	1.30	2.35	2.75	3.05	3
Transformer I	Generators, low-frequency transformers	3.0–3.5	20,200	13,200	0.80	0.95	1.10	1.90	2.25	2.60	2
Transformer II	60-cycle transformers	3.5–4.0	19,800	13,000	0.70	0.85	0.95	1.50	2.00	2.25	nil
Transformer III	High-grade distribution transformers	4.0–4.5	19,500	13,000	0.60	0.75	0.85	1.40	1.76	2.00	nil

(a) To obtain watts per kilogram, multiply by 2.2.

then coated with a refractory and annealed in stacks at a high temperature, in either electrically heated or gas-heated furnaces, and are slowly cooled, after which a certain representative portion (about 0.1%) of the sheets from each anneal are sheared into Epstein strips 3 by 50 cm and are tested for energy losses and permeability. The lots are then graded on the basis of these results. Table I shows the properties of the grades used in this country, tested in accordance with ASTM Specification A 34.

Although most silicon irons are still hot rolled into sheets, there is a tendency, particularly for the alloys of lower silicon content, to change to cold rolling. After being hot rolled to a thickness of about 0.1 in., the strip is pickled and is then cold rolled to the final thickness. For the subsequent anneal, the metal is either passed slowly through a continuous furnace or is cut into sheets for stack annealing, as described for hot rolled sheets.

The properties shown in Table I are for standard Epstein samples cut 50% with and 50% across the rolling direction of annealed sheets, and without being annealed to remove shearing strains. If the sheet is used altogether in the rolling direction, the above losses may be 10%

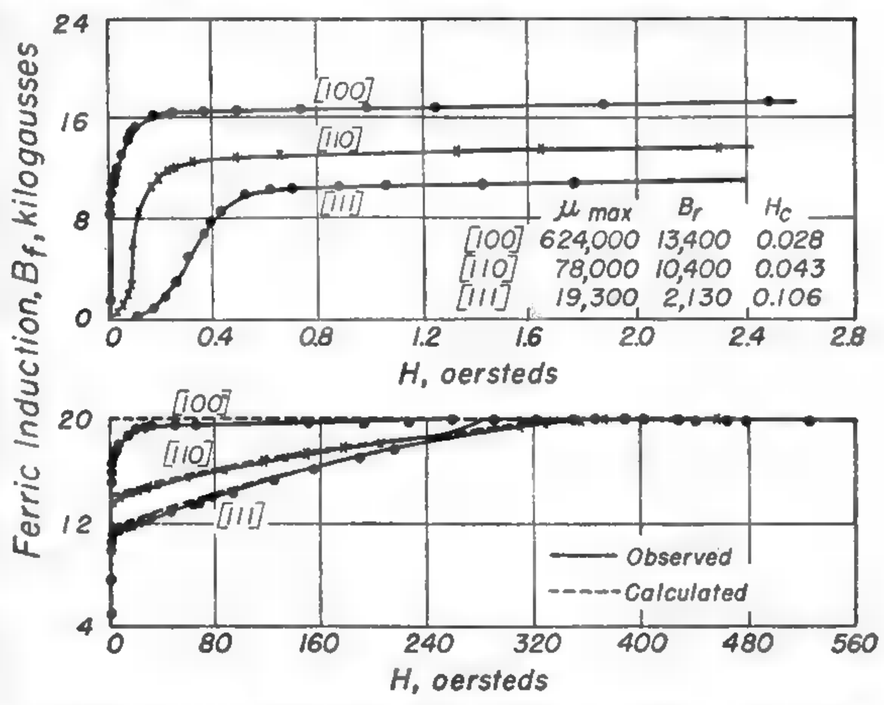


Fig. 7 Observed and calculated *B-H* curves for [100], [110] and [111] directions in single crystals of 3.85% Si iron (Williams)

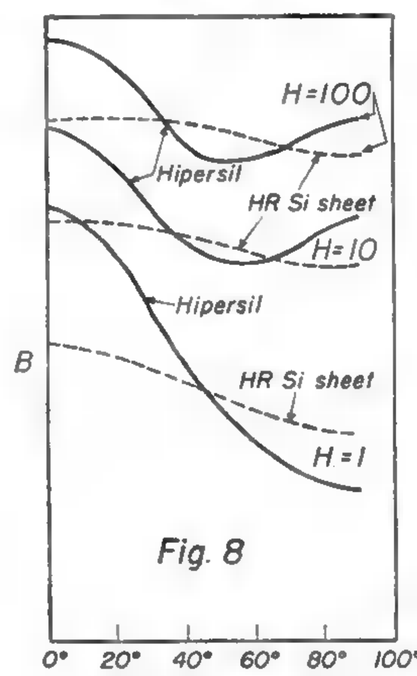
lower, and if the sheared punchings are reannealed, the losses may be lowered by 10%, so that 0.014-in. Transformer III grade, tested in the rolling direction after reannealing, should have a loss for $B = 10{,}000$ of 0.48 watts per lb, or less.

After annealing, the impurities in the above high-grade materials may be as follows: <0.03% C, <0.02% S, <0.02% P, <0.10% Mn. Of these impurities carbon is the most injurious (Fig. 1), and constant efforts have been made to lower the carbon content, as well as the sulfur content.

Grain size in silicon iron is just as important as in iron (Fig. 2) as far as losses and low-density permeability are concerned, but the crystallographic orientation is equally important and is the determining factor with regard to high-density permeability. Like iron, iron-silicon alloys are more easily magnetized in the direction of the cube edge, [100], than in any other direction,[3] as shown in Fig. 7, and methods have been developed during the past ten years for rolling and heat treating iron-silicon alloys so as to obtain most of the grains with a cube edge parallel to the direction of rolling.[9] By this means a flux density is obtainable for $H = 10$, of the order of 30% higher than for hot rolled sheet.

By a combination of the above rolling process with a refining annealing process, it is possible to obtain all-round improved magnetic properties, with the material magnetized in the direction of rolling. The alloy has been designated "Hipersil" and is used exclusively for transformer cores.[10] It contains between 3 and 3.5% Si.

For Hipersil in comparison with the best hot rolled sheet, Fig. 8 shows the variation in flux density with orientation for various values of magnetizing force, and Fig. 9 shows the variation in losses with orientation. These figures indicate clearly the advantage obtainable when such oriented material is used, and also the necessity for using it in the rolling direction. For this reason Hipersil cores are preferably made by coiling the strip on mandrels, welding the ends, annealing the cores, impregnating them, cutting them in two and polishing the



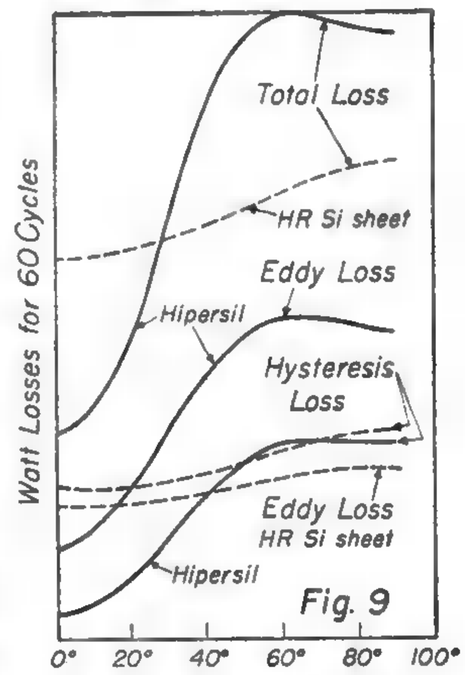


Fig. 8 Comparative flux densities for Hipersil and the best hot rolled sheet as a function of orientation

Fig. 9 Comparative watt losses at 60 cycles for Hipersil and the best hot rolled sheet as a function of orientation

joints to make them as nearly perfect as possible. In this way the transformers are easily assembled and taken apart for repairs, if necessary. Large Hipersil transformers, however, are still made by stacking plates, cut so as to have the flux parallel to the direction of rolling, but in such a way as to have the joints staggered in adjacent layers.

Figures 10, 11 and 12 show curves of B versus H, hysteresis loops and watt-loss curves for Hipersil in comparison with hot rolled 4.25% Si irons, both materials tested in the direction of rolling. It is clear from these curves that by the use of such oriented materials as Hipersil, a flux density can be used 25 to 30% higher than is practical with hot rolled sheet, thus effecting a saving not only in core material but also in copper, oil and tank.

High-grade transformer sheet and strip does not age as received from the makers (*see* Table I); that is, the losses do not increase with time at operating temperatures. But this does not mean that silicon iron is inherently nonaging. Unless the steel manufacturer follows the correct heat treating practice, silicon iron may age considerably under operating conditions.*

Iron-Aluminum and Iron-Aluminum-Silicon Alloys. Although aluminum is known to have an effect on iron

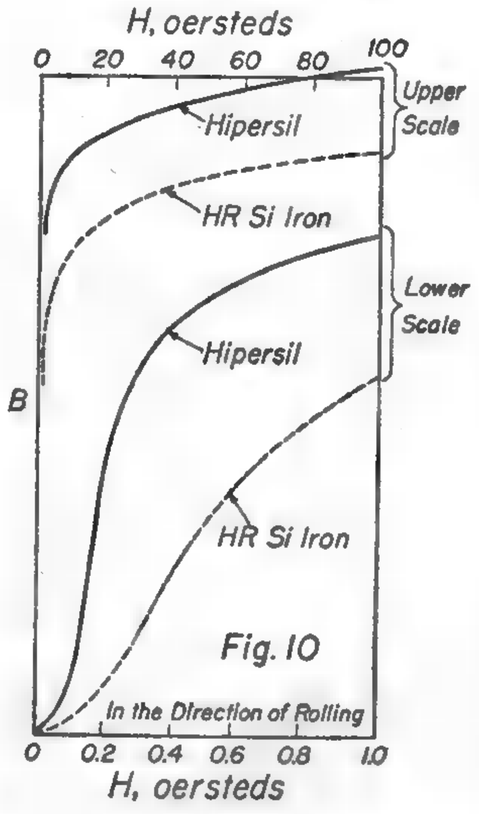


Fig. 10

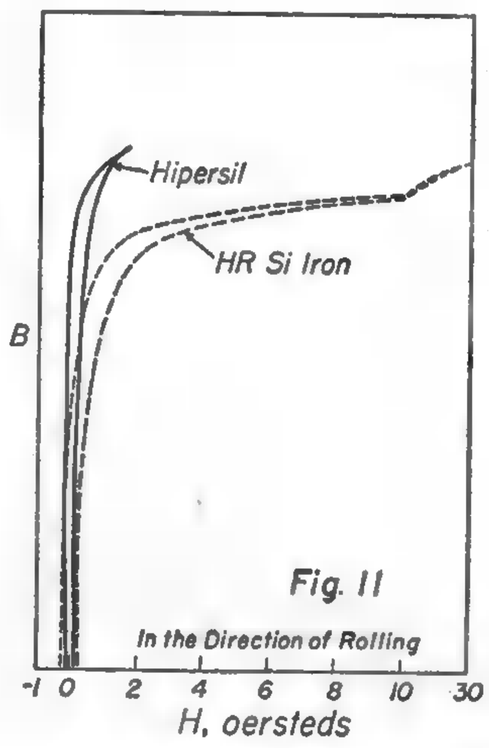


Fig. 11

Fig. 10 Comparative *B-H* curves for Hipersil and the best hot rolled sheet in the direction of rolling

Fig. 11 Comparative hysteresis loops for Hipersil and the best hot rolled sheet in the direction of rolling

somewhat the same as the effect of silicon, both as to electrical resistivity and as to magnetic properties,[11] aluminum has never become a serious competitor on account of the difficulties in the manufacturing processes. Ternary alloys of Fe-Si-Al have been investigated by Masumoto.[12] The alloy containing 8 to 11% Si and 5 to 6.5% Al is reported to have an initial permeability up to 35,000, a maximum permeability up to 162,000 and a hysteresis loss down to 28 ergs for $B = 5000$. With such high silicon and aluminum contents the saturation value is necessarily low ($4\pi I_s = 11{,}000$). The alloys are brittle.

This alloy has been suggested for loading coils, but, in the form of compressed cores, it would have to meet severe requirements for hysteresis and permeability, in

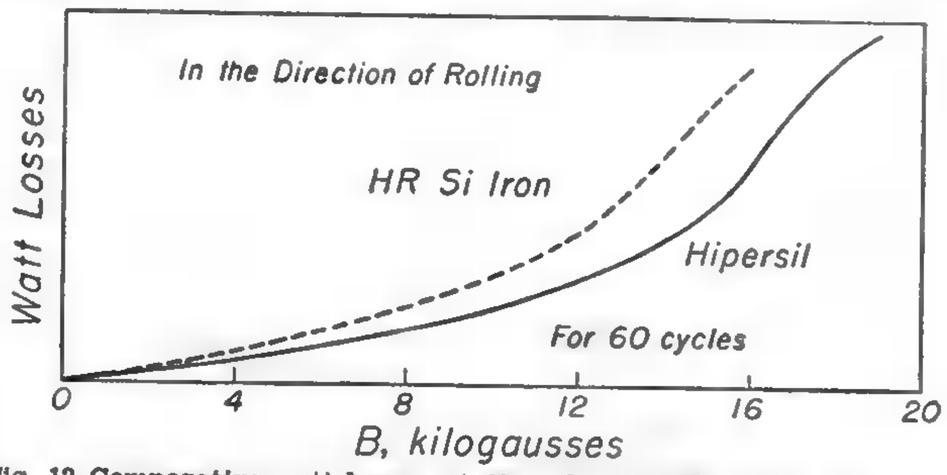


Fig. 12 Comparative watt losses, at 60 cycles, for Hipersil and the best hot rolled sheet in the direction of rolling

order to offer advantages over the powdered iron-nickel alloy now used in the United States.

Iron-Nickel Alloys. In the preparation of this section, liberal use has been made of Data Sheet No. 2, Iron-Nickel Alloys for Magnetic Purposes, prepared by J. W. Sands, of The International Nickel Company, Inc., for their "Iron-Nickel Data Book", 1938.*

* *See* Effect of Impurities, *above.*

* For electrical, thermal and mechanical properties of these alloys see "Iron-Nickel Alloys", page 599.

The average effect of nickel on the permeability of iron after annealing, is shown in Fig. 13.[15] No particular advantage is shown over the best grades of iron and iron-silicon alloys although, in the region of 50% Ni, individual alloys were obtained that had unusually good magnetic properties. At still lower magnetizing forces, the optimum composition is 70 to 80% Ni.

Although these are basically iron-nickel alloys, appreciable percentages of other elements are added, in many instances, to develop or accentuate some particular characteristic that is desirable for the application in view.

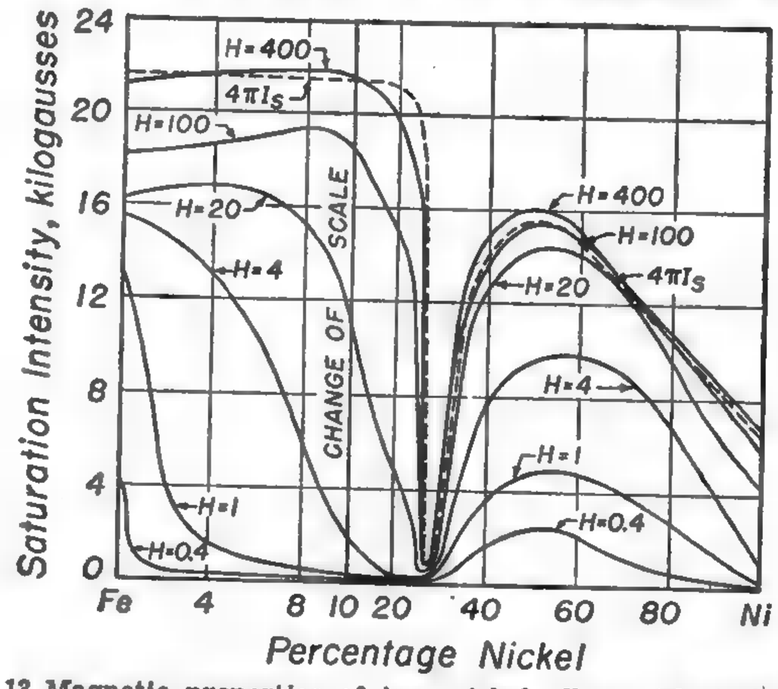


Fig. 13 Magnetic properties of iron-nickel alloys. Electrolytic iron and nickel, melted and annealed in vacuo. From 0.5 to 1.0% Mn added to the alloys containing more than 30% Ni, to facilitate forging.

The trade names, approximate composition and applications of the most important iron-nickel alloys are given in Table II.

Annealed iron-nickel alloys that contain between 30 and 90% Ni, have initial permeabilities higher than that of ingot iron. Alloys that contain more than 50% Ni are sensitive to heat treatment as shown in Fig. 14.[13] The heat treatment that improves initial and maximum permeability, consists in air quenching thin strips on a copper block from the magnetic transformation point. The best results were obtained for alloys containing approximately 80% Ni (the optimum composition is 78½%) and the name "Permalloy" was given to the alloys of this type. Maximum permeabilities of 100,000 are readily obtained with this alloy (Fig. 15) but the saturation value is low (11,000) and the electrical resistivity is only about double that of iron. However, it was found later that the resistivity could be markedly increased by the addition of chromium or

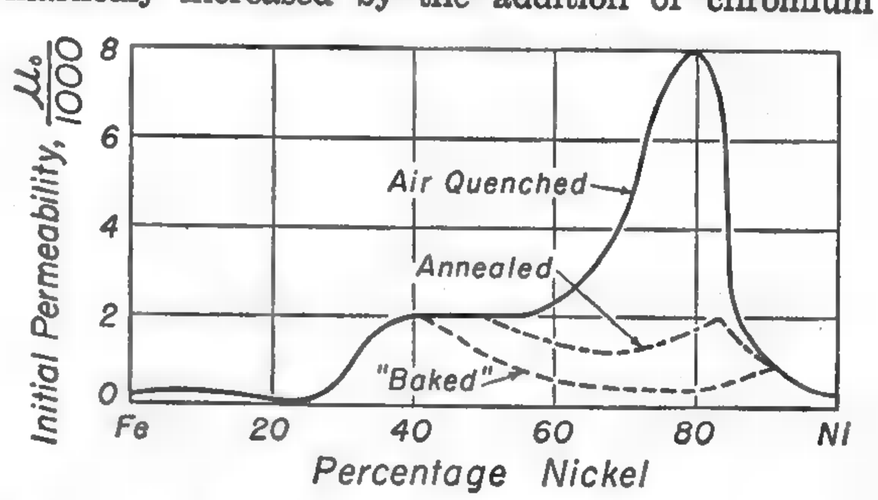


Fig. 14 Initial permeabilities for iron-nickel alloys (Elmen)

molybdenum, while at the same time the necessity for air quenching could be eliminated and the initial permeability could be increased to more than 20,000 (Fig. 15), but at a further sacrifice in saturation value.[14] Table III gives the principal characteristics of the important alloys in this group, and of ingot iron and some other alloys.

50% Ni Iron Alloys. As ordinarily made, the alloys that contain approximately 50% Ni exhibit nothing remarkable (Fig. 13) except that their saturation values are the highest of all iron-nickel alloys above 30% Ni. By ordinary pot annealing, a maximum permeability of 20,000 to

25,000 can be obtained with an initial permeability of 2700, if pure material is used. Such an alloy is 45% Ni listed in Table III. The permeability curve of this alloy is shown in Fig. 15.

The magnetic properties of these alloys can be vastly improved by annealing them in dry hydrogen at 1000 to 1200 C for several hours.[15] This treatment reduces carbon, sulfur and other impurities, but particularly oxygen. In its improved form, the 50% Ni alloy has been given the name "Hipernik" (from high-permeability nickel). Its hysteresis loop is compared with that of silicon iron in Fig. 16. The nickel content, not particularly critical, may be varied from 40 to 60%, but for highest saturation value it should be kept close to 50% (Fig. 13).

Table II. Composition of Commercial Magnetic Iron-Nickel-Base Alloys

Alloy	Percentage nickel
Alloys with Very High Permeability at Low Field Strengths	
Permalloy or Supermalloy	60 to 90 + special heat treatment and sometimes + Cr or Mo
Mumetal	Approx 76 + 6% Cu and 1.5% Cr
Permafy	Approx 80
1040 alloy	72 + 14% Cu and 3% Mo
High-Permeability Alloys for Higher Field Strengths	
Megaperm 6510	65 + 10% Mn
Hipernik	50
Hyperm	50
Nicaloi	49
Audiolloy	48
Permenorm	48
Allegheny Electric Metal	47
Anhyster C and D	45 to 50
Radiometal	45 to 50
2129	45 to 50
Megaperm 4510	45 + 10% Mn
Moderately High-Permeability Alloys of High Electrical Resistance	
Rhometal	40 to 45 + 5% Cr and 3% Si
Gamma	Approx 35
Anhyster A and B	Approx 35
Alloys with Constant Permeability over a Range of Flux Densities	
Perminvar	20 to 75 + 5 to 40% Co + special heat treatment and sometimes + Mo
Conpernik	50 + special heat treatment
Isoperm	40 to 55 + special treatment
Isoperm (precipitation types)	36 to 50 + 9 to 15% Cu 40 to 60 + 3 to 4% Al
Alloys with Permeability Varying with Temperature	
Compensator alloy	29 to 32.5
N30	30
Thermoperm	30
N. M. H. G.	30

The use of this alloy instead of ordinary 4% Si iron for transformer cores, would result in a reduction of energy losses to about one-half. However, because of the high cost, the use of this alloy is limited to special transformers, such as current transformers in which, because of high permeability and low loss, the ratio errors and phase-angle deviations are almost entirely eliminated. Cold rolled in the form of continuous ribbon, this alloy is particularly suitable for the bushing type of current transformers, since in this way there is no waste of material.

Although this 50% Ni alloy cannot compete with the higher-nickel alloys for applications that require the highest initial permeability, it is preferable for most other uses, because of its higher saturation value (Fig. 13).

In Table IV are listed the magnetic properties of this alloy in comparison with values for other alloys.

Miscellaneous. Numerous modifications have been made in these alloys by the addition of other elements and by variation in the heat treatment. The most important of these modifications are listed in Table V.

Some of these alloys have been improved greatly by cooling in a magnetic field through the magnetic transformation point.[16] Particularly good results were obtained with 65% Ni iron and with 45% Ni – 30% Fe – 25% Co. A maximum permeability of more than 600,000 was reported for the 65% Ni alloy. Still higher values have been reported for a 79% Ni – 5% Mo alloy—called "Supermalloy"—annealed in dry hydrogen at 1300 C[16] (*see* Table III).

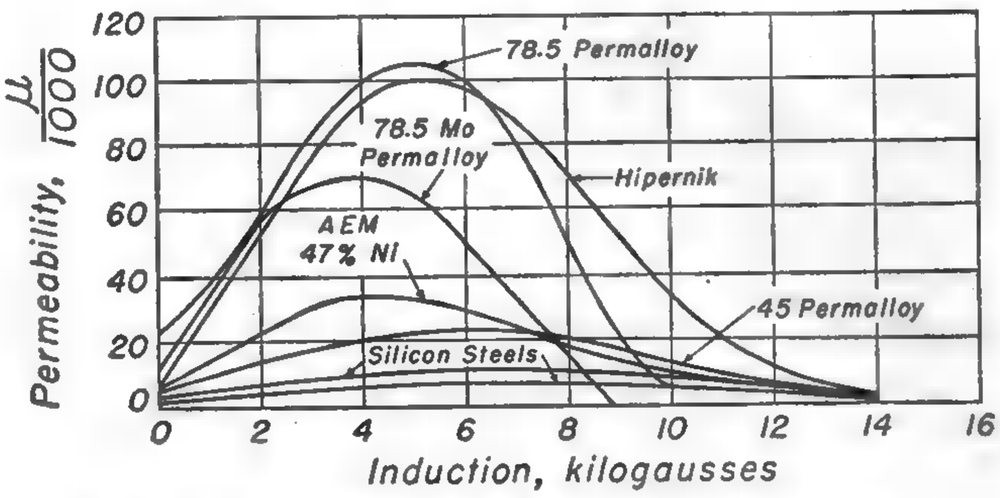


Fig. 15 Permeability curves for various magnetic alloys (Wise)

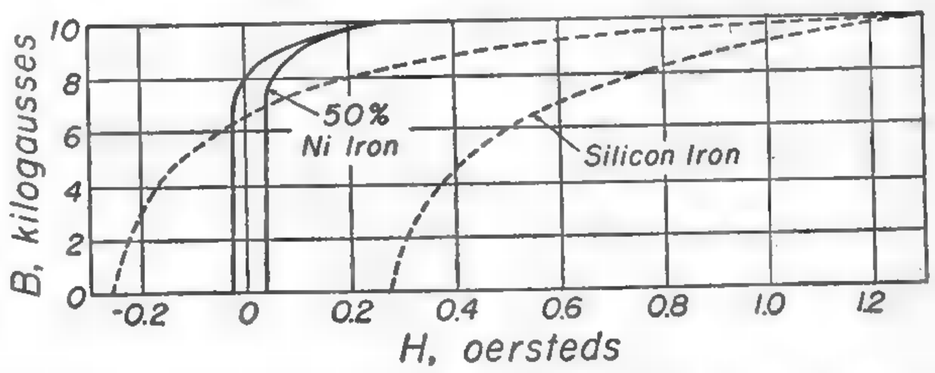


Fig. 16 Comparative hysteresis loops of Hipernik and silicon iron

Materials with High Magnetic Saturation Value. Iron has a saturation value of 21,600 ($4\pi I_s$). To exceed this value, it is necessary to alloy iron with cobalt in amounts between 0 and 65%. The highest value is obtained by using 34.5% Co[17] (Fig. 5); the value for this composition is approximately 24,200.[18] Alloys in the range from 25 to 50% Co would find wide applications in industry were it not for the following disadvantages.

1 The price of cobalt for metallurgical uses is $1.50 per lb, so the raw materials needed to make the 35% alloy, cost about 60 cents per lb; the 50% alloy 80 cents per lb.
2 As ordinarily made, the alloys above 30% Co are very brittle, much like high-silicon iron.
3 Aside from the high saturation value, the magnetic properties after ordinary heat treatment are poor (low permeability and high hysteresis loss).
4 The electrical resistivity is low (Fig. 4).

Table III. Magnetic Properties of Various Alloys

Material[a]	Initial Permeability	Maximum Permeability	Hysteresis Loss, ergs per cu cm per cycle[b]	Residual Induction, gausses	Coercive Force, oersteds	Saturation Value, gausses[c]	Resistivity, microhm-cm
Ingot iron	250	7,000	5000	13,000	1.0	21,600	11
4% Si iron	600	6,000	3500	12,000	0.5	20,000	50
78.5 Permalloy, quenched	10,000	105,000	200	6,000	0.05	10,700	16
45 Permalloy	2,700	23,000	1200	8,000	0.3	16,000	45
3.8–78.5 Cr-Permalloy	12,000	62,000	200	4,500	0.05	8,000	65
3.8–78.5 Mo-Permalloy	20,000	75,000	200	5,000	0.05	8,500	55
5-79 Mo-Supermalloy	100,000	800,000	20[d]	6,000[d]	0.004	8,000	60
45-25 Perminvar, baked	400	2,000	2500	3,000	1.2	15,500	19
7-45-25 Mo-Perminvar, baked	550	3,700	2600	4,300	0.65	10,300	80
70-7.5 Perminvar, annealed	750	3,500	....	....	0.8	12,000	16

(a) Single numbers preceding the word "Permalloy" indicate the nickel content, and double numbers signify first the content of chromium or molybdenum, and second, the nickel content; the remainder is iron in each alloy. The two high numbers before "Perminvar" indicate the nickel and cobalt contents, respectively, and the small initial number indicates the molybdenum content. These alloys have constant permeability up to a certain value of H.
(b) For saturation value of the flux density. (c) Saturation value of the intrinsic induction. (d) Approximate value.

Table IV. Magnetic Properties of 50% Nickel-Iron Alloys in Comparison with Other Alloys
(In accordance with information obtained from the manufacturers)

Material	Initial Permeability	Maximum Permeability	Hysteresis Loss, ergs per cu cm per cycle[a]	Residual Induction, gausses[b]	Coercive Force, oersteds[a]	Saturation Value, gausses	Resistivity, microhm-cm	Form of Sample	Specific Gravity, per cu cm
Puron (99.99% Fe)	....	100,000	150	9000	0.05	21,600	10	solid ring	7.9
4 to 4.5% Si iron	500	12,000	800	6000	0.3	19,500	55	0.014-in. sheet	7.6
Hipernik	4500	100,000	100	8000	0.03	16,000	45	0.014-in. sheet	8.25
45 Permalloy	2700	23,000	1200[b]	8000[b]	0.3[b]	16,000	45	.....	...
Allegheny Electric Metal	5000	32,500	718	5500	0.1	16,000	45	.....	8.25

(a) For $B = 10{,}000$, except as noted (b) For $B = 16{,}000$

Table V. Magnetic Properties of Some Foreign Nickel-Iron Alloys

Material[a]	Initial Permeability	Maximum Permeability	Hysteresis Loss, ergs per cu cm per cycle ($B = 5000$)	Coercive Force, oersteds ($B = 5000$)	Saturation Value, gausses	Resistivity, microhm-cm	Specific Gravity
Mumetal	10,000 to 30,000	60,000 to 100,000	40 to 60	0.03	6,000 to 9,000	42	8.6
Radiometal	2,000	10,000 to 15,000	350	0.4 to 0.5	15,600	55	8.3
Anhyster B	1,300	.....	...	...	9,000	70	...
Anhyster C	1,500	.....	...	...	13,000	59	...
Anhyster D	2,200	25,000	330	...	15,000	46	...
1040 Alloy	Up to 50,000	100,000	50	...	6,000	56	...
Permenorm 4801[b]	2,700	19,000	...	0.20	14,000	58	...
Megaperm 6510	4,800	26,000	...	0.08	8,500	58	...
Rhometal	850	5,000	420	...	4,500	..	...

(a) *See* Table II for chemical compositions. (b) Constant permeability of more than 2000 for $H < 0.06$

However, when small amounts of certain elements are added, such as vanadium and chromium, and special treatments are included among the processing operations, the 35% Co alloy can be cold rolled commercially to any gage, and the cold rolled strip is sufficiently ductile to be punched and sheared for any purpose. Furthermore, annealing processes have been developed for producing magnetic properties suitable both for d-c and a-c applications. Alternating-current applications necessarily require low eddy-current losses and low hysteresis. Eddy-current losses can be kept low by a combination of the alloying elements mentioned above and a judicious selection of gage. The 35% Co alloy has been named "Hiperco".

Figures 17 and 18 show typical *B-H* curves, and loss curves for Hiperco in comparison with other commercial materials; the 1% Si iron is commonly used for applications that require high saturation values. Figure 18 shows that lower losses apparently can be obtained with a high-silicon iron (4 to 5% Si) rolled to 0.010 in. than with 0.010-in. Hiperco; however, it is impossible to use the high-silicon iron at flux densities above 19,000 gausses. The exciting current would be prohibitive.

The only material that can be used for comparison is the 1% Si iron. When this iron has been rolled to 0.010

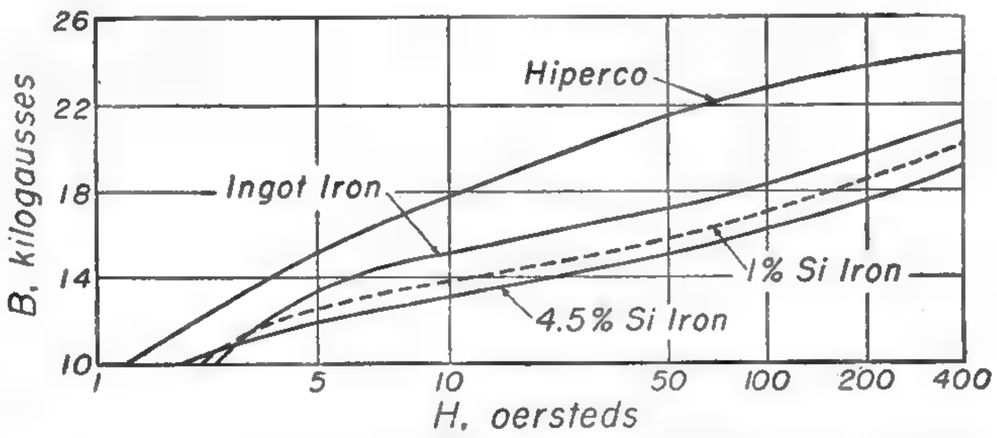


Fig. 17 Comparative *B-H* curves for Hiperco and other materials of high saturation

in. its losses at 20,000 gausses, though comparable with the losses for Hiperco at 60 cycles, are much higher than those for Hiperco at 600 cycles (about double). Even if, from a loss standpoint, 1% Si iron could be used at 20,000 gausses, the magnetizing current would be more than 13 times as high as that for Hiperco. For the same value of H (for example, 30 oersteds) Hiperco can be operated at 20,000 gausses, while 1% Si iron will reach only 15,500, a ratio of 1.3 to 1.0. The chief advantage in using Hiperco is, therefore, that considerably less material is required.

The cost of Hiperco is perhaps ten times that of 1% Si iron rolled to the same gage. For most applications this cost would be prohibitive, but in special uses where saving in weight or space is important, or where it is imperative to obtain the highest possible flux density irrespective of cost per pound, Hiperco or Permendur should be considered. (*See below.*)

According to Elmen,[18] a 50% Co alloy with the addition of 1 to 2% V, can also be forged and cold rolled after

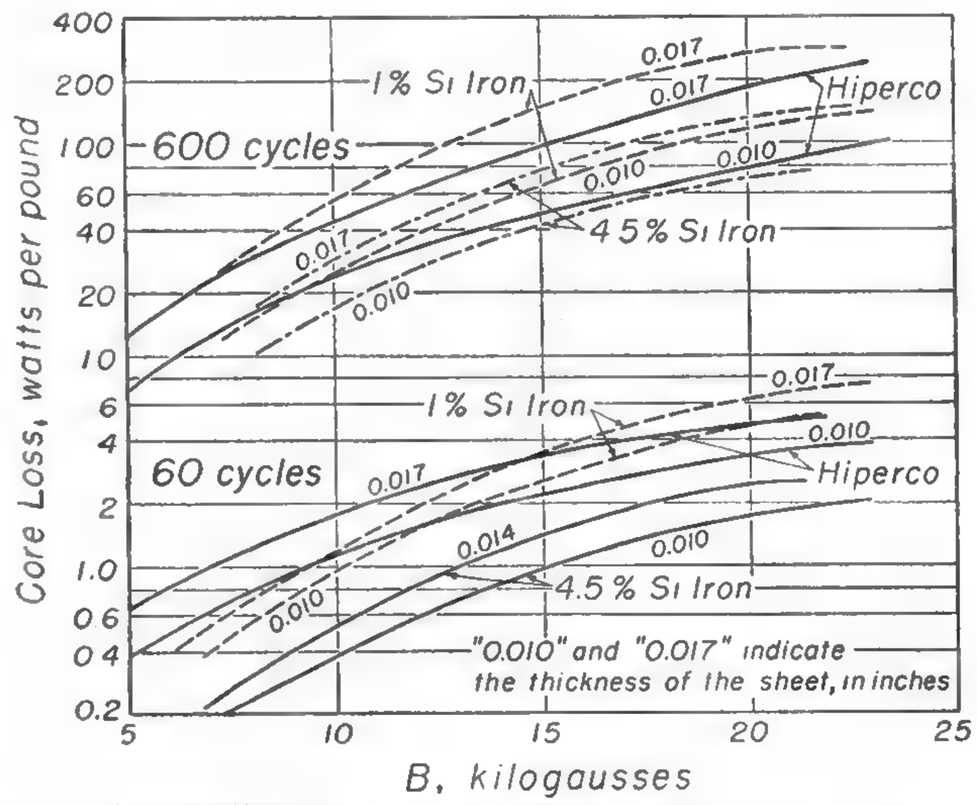


Fig. 18 Comparative curves of watt losses versus induction for Hiperco and other materials of high saturation

special treatments[19] and, because of its slightly better magnetic properties in the range between $H = 10$ and $H = 100$ (*see* Fig. 25), is preferable to the 34.5% alloy for certain applications where cost is of no importance. The name "Permendur" has been applied to this alloy.

Materials with Constant Permeability. *Compressed Metal Powders.* The permeability of ferromagnetic materials is inherently not constant (Fig. 6 and 7). For many purposes, as for filter coils in radio and telephone circuits and for loading-coils for long-distance telephone transmission lines, it is essential that the permeability be constant in order to give fidelity to the reproduction of sound. A concentrated air gap in the core was used at first, but was soon discarded because of the effect of the leakage

flux on the surrounding circuits. Distributed air gaps, such as are obtained by means of compressed insulated iron powder, were resorted to with good results for audio frequencies.[20] Using annealed and uninsulated 80-mesh electrolytic iron powder, compressed into ring cores at 100 tons per sq in., Bell laboratories in 1921 reported cores with a constant permeability of about 75 up to $B = 100$ gausses.

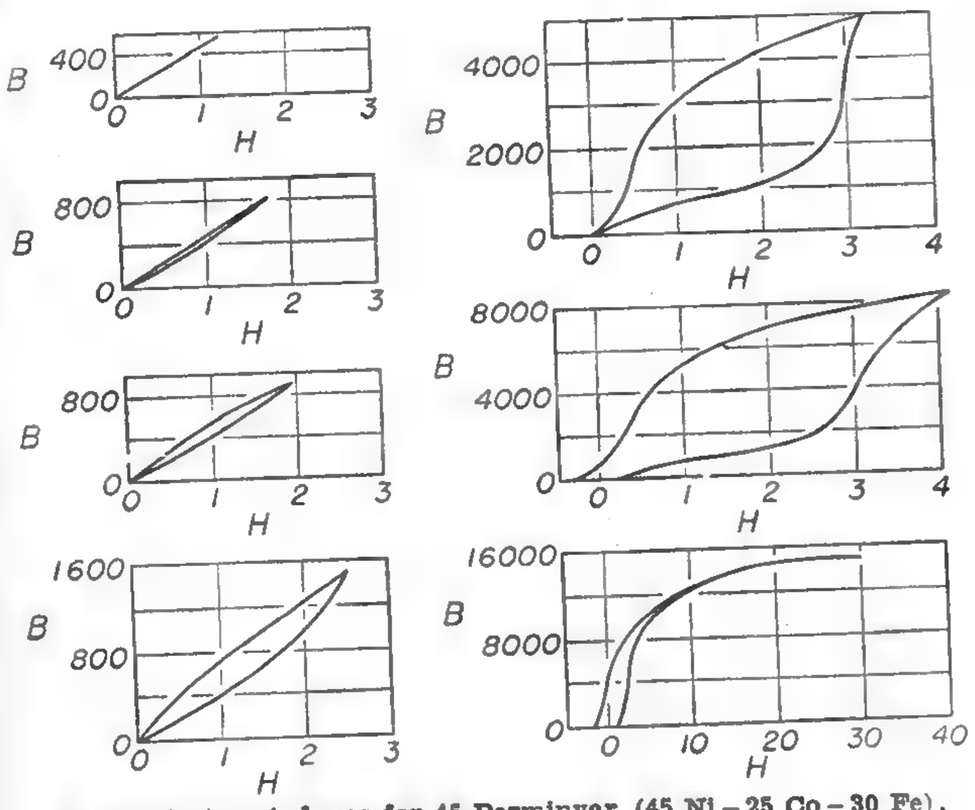


Fig. 19 Hysteresis loops for 45 Perminvar (45 Ni – 25 Co – 30 Fe), annealed

For the same material, when unannealed iron was used, the permeability was about 50.

When the iron powder was insulated with shellac, the permeabilities decreased to 55 and 25 respectively; the permeability was nearly constant up to $B = 100$. Although the permeability is lower than for the uninsulated powder, the eddy-current losses are much lower (about one-tenth), thereby greatly increasing the X_L/R values, a factor of vital importance for loading-coils and filter-coils.

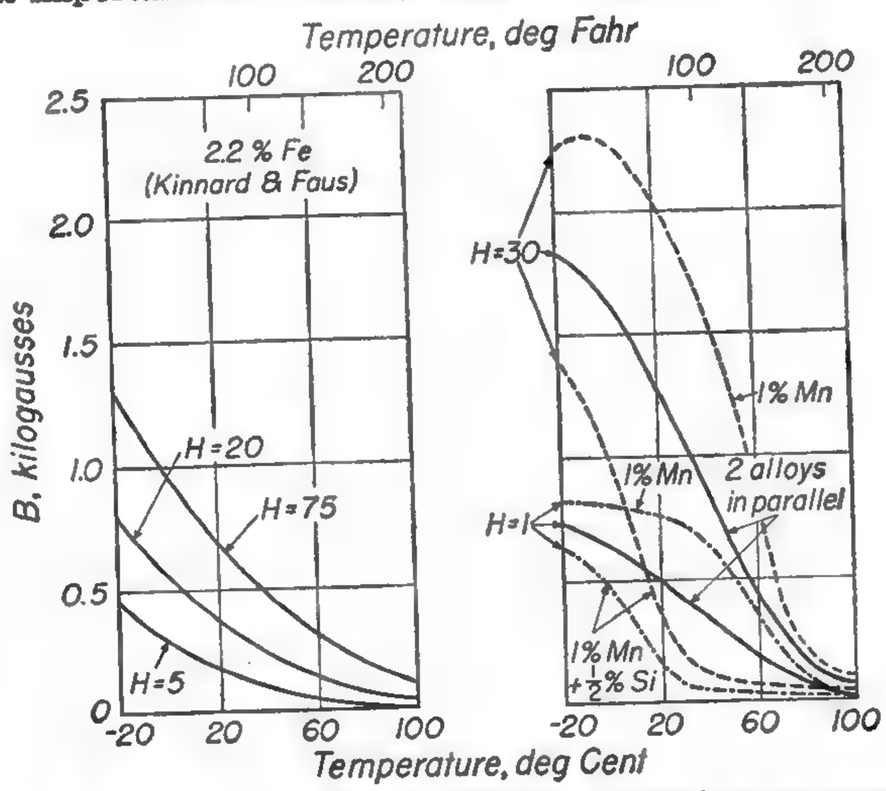


Fig. 20 70 Ni – 30 Cu type of magnetic temperature-compensator with modifications in composition as shown. (*Left*) Calmalloy. (*Right*) Westinghouse alloy

During the late 1920's, hydrogen-reduced iron[21] and carbonyl iron were introduced. Their greater fineness (1 to 40 microns) and uniformity of size and shape, made them particularly suitable for use at radio frequencies.[22]

Rolled Strip. Higher permeabilities than with compressed powders, can be obtained with certain alloys rolled into thin strip and heat treated to give constant permeability over a given range of B.

Certain Fe-Ni-Co alloys[24] called "Perminvars" have been developed, containing about 30% Fe, 45% Ni and 25% Co. Figure 19 shows the hysteresis loops for the optimum composition, having a constant permeability of about 400, up to $B = 1000$, and consequently very nearly zero hysteresis. Similar, but inferior, results can be obtained with 50% Ni iron by means of a special heat treatment, which is an incomplete anneal below 800 C (Conpernik[25]). Permeabilities from 1000 to 2000 are obtainable, constant to $B = 200$ within $\pm 5\%$. (For B-H curve see Fig. 25.)

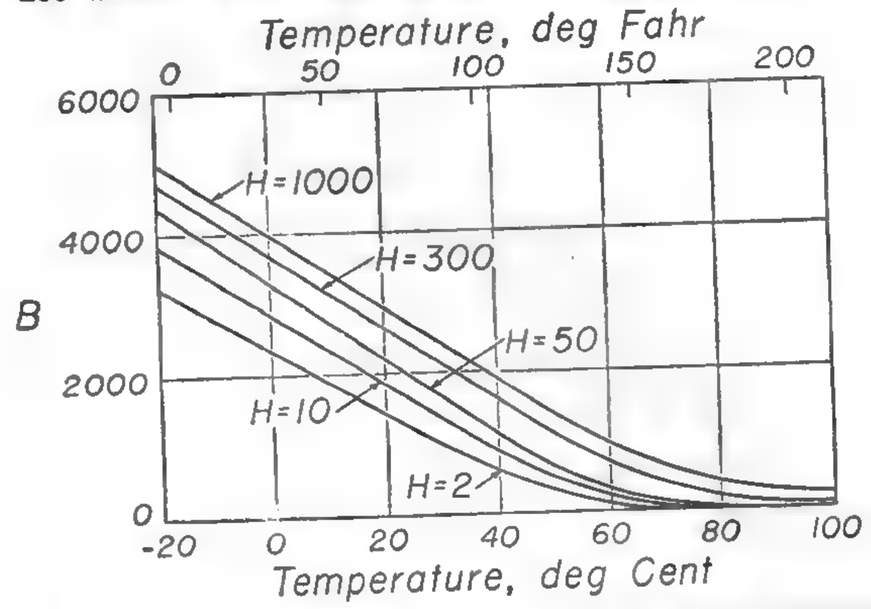


Fig. 21 Data for the 30% Ni type of magnetic temperature compensator, Thermoperm (Stäblein)

A more recent development[26] in Germany has resulted in iron-nickel alloys called "Isoperms", containing 35 to 55% Ni, 45 to 50% Fe and 5 to 15% Cu. The alloy is first drastically cold rolled, then quenched from a high temperature, further cold rolled, and finally annealed—a treatment by which the copper is precipitated in such a way as to produce a preferred crystallographic arrangement that results in low retentivity and constancy of permeability (50 to 60) over a wide range of H (0 to 100 oersteds) (*see* Fig. 25).

Another method[27] for accomplishing similar results consists in welding together thin plates of different compositions, having different coefficients of expansion, and magnetostriction of opposite sign. Thus 90 to 100% Ni iron, which has negative magnetostriction, or stainless

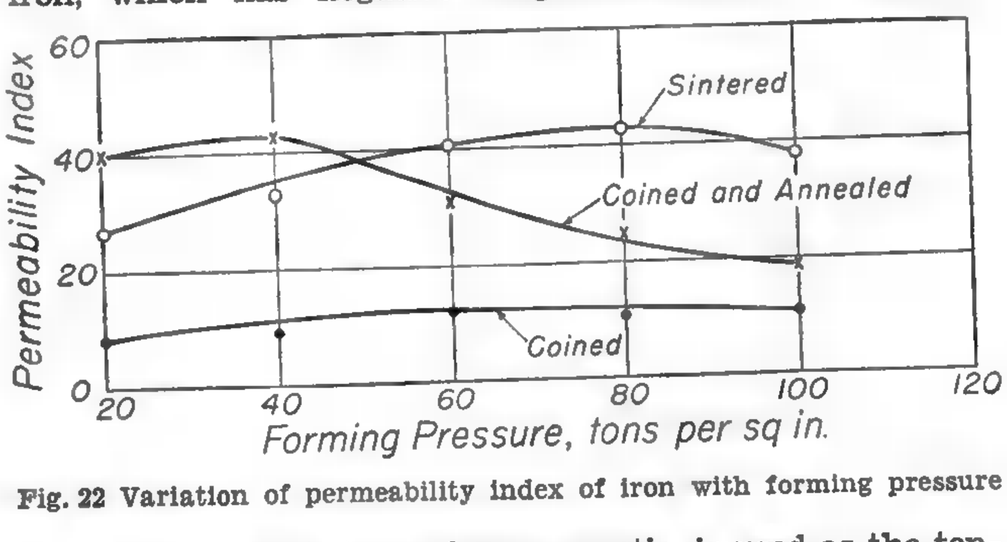


Fig. 22 Variation of permeability index of iron with forming pressure

steel (18-8), which is nonferromagnetic, is used as the tension component, while 36 to 50% Ni iron, which has positive magnetostriction, is used as the compression component. After the proper amount of cold rolling and annealing, a laminated structure is produced which, because of the uniform strains throughout, results in a constant permeability (60 to 120) over a wide range of H (0 to 150 oersteds).

Alloys for Magnetic Temperature Compensation. Because the magnetic permeability of iron and iron alloys decreases with temperature (except for low values of H) the reading of electrical meters that depend on the flux produced by a constant voltage supply or by a certain load current (for example, watt-hour meters) decreases with the ambient temperature. To compensate for such errors it is customary to shunt a certain amount of the magnetic flux around the moving part of the meter by means of an alloy that has an unusually high magnetic temperature coefficient, between 0 and 100 C, so that as the ambient temperature increases, the amount of the shunted flux decreases, forcing more of the flux through the moving member than would be possible otherwise.

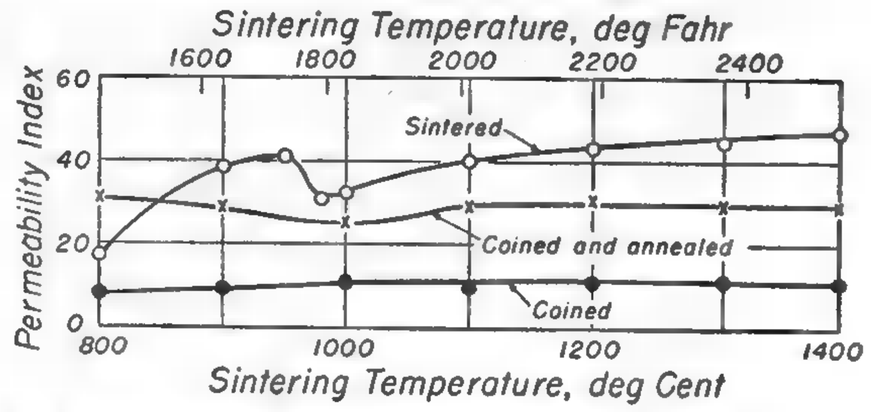


Fig. 23 Variation of permeability index of iron with sintering temperature. The magnetic permeability (for a constant magnetizing force) is shown as a percentage of the permeability of annealed hot rolled low-carbon steel

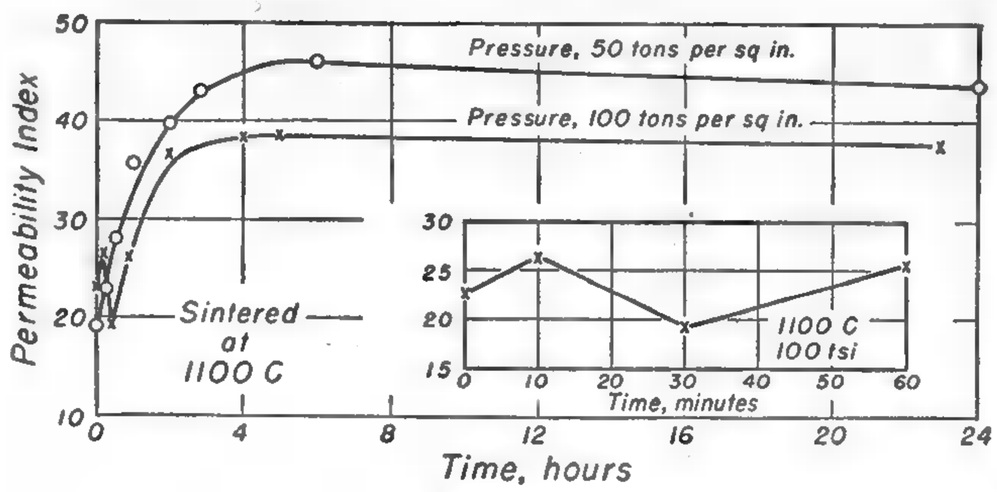


Fig. 24 Variation of permeability index of iron with duration of sintering

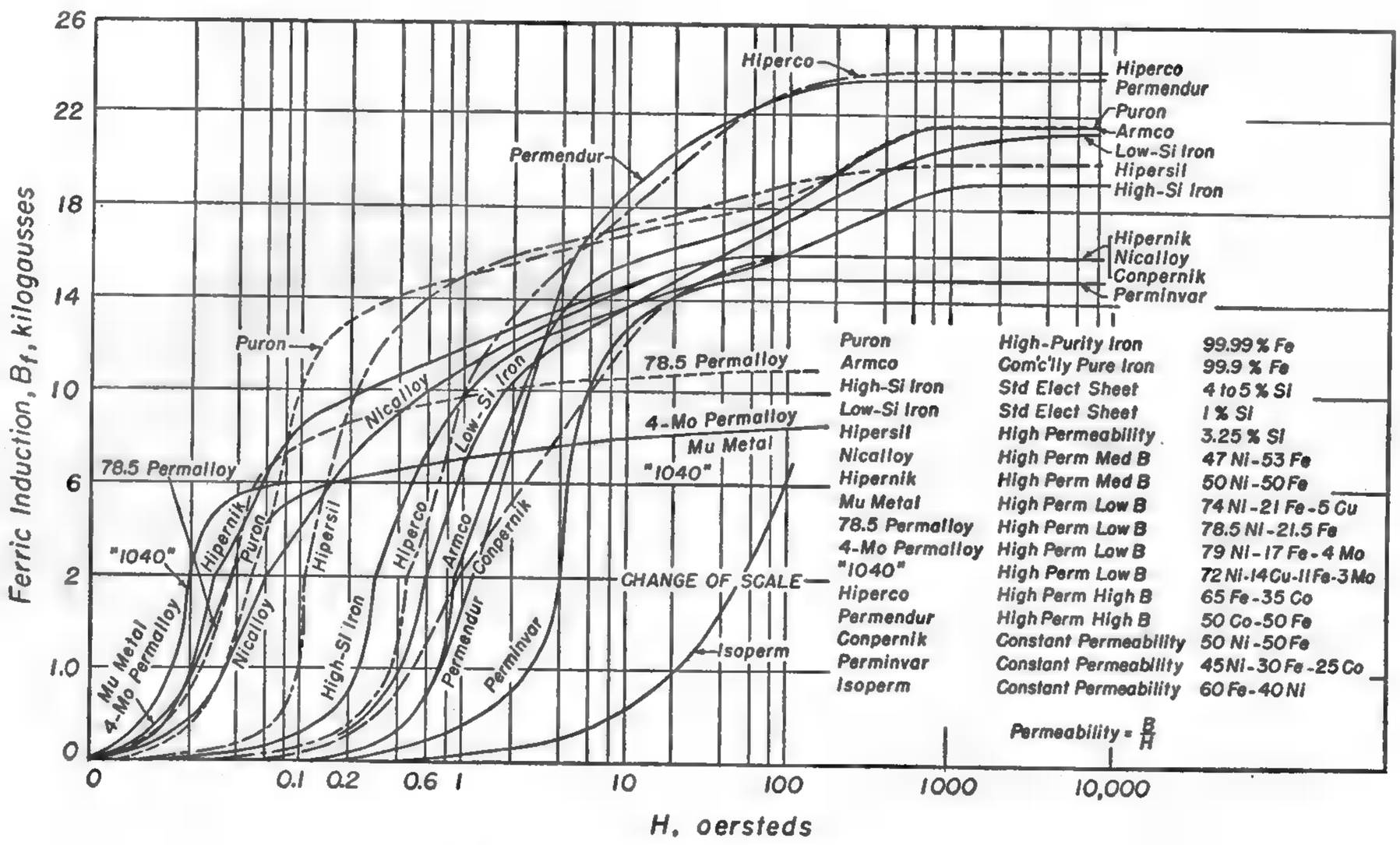


Fig. 25 B-H curves for magnetically soft materials

Table VI. Applications and Magnetic and Electrical Characteristics of Magnetically Soft Materials

Application	Permeability and Flux Density	Saturation Value, $4\pi I_s$	Approximate Hysteresis Loss, ergs per cu cm per cycle for $B = 10{,}000$	Total Watt Loss per Pound[a] W 10/60	Total Watt Loss per Pound[a] W 15/60	Electrical Resistivity, microhm-cm	Material and Gage
Power transformers	>300 for $B = 15{,}000$	19,500	<1000	<0.5	<1.25	65	4½ Si iron, 0.014 in.
Distribution transformers	>5,000 for $B = 15{,}000$	20,000	<300	<0.35	<0.80	45	Hipersil*, 0.013 in.
Instrument transformers	>50,000 for $B = 5{,}000$	16,000	<150	<0.24	<0.60	45	Hipernik*, 0.014 in.
Radio transformers	>50,000 for $B = 5{,}000$	16,000	<150	<0.12	(b)	45	Hipernik*, 0.005 in.
Radar transformers	>20,000 for $B = 5{,}000$	19,500	<300	<0.15	(c)	45	Hipersil*, 0.005 in.
	>50,000 for $B = 5{,}000$	16,000	<150	<0.12	(b)	45	Hipernik*, 0.005 in.
Chokes for radio or radar	>10,000 for $B = 5{,}000$	16,000	<200	<0.12	(b)	45	Hipernik*, 0.002 to 0.005 in.
Filter cores	1000 to 2000 constant over $\Delta B = 200$	16,000	Negligible for $\Delta B = 200$	Neligible for $\Delta B = 200$	...	45	Conpernik*, 0.005 or 0.014 in.
60-cycle generators	>10,000 for $B = 10{,}000$ >650 for $B = 15{,}000$	20,200	<1200	<0.80	<1.90	50	3¼% Si iron, 0.014 in.
High-speed turbogenerators	>7,000 for $B = 10{,}000$ >750 for $B = 15{,}000$	20,500	<1500	<1.00	<2.35	40	2¾% Si iron, 0.014 in.
Induction motors	>5,000 for $B = 10{,}000$ >600 for $B = 15{,}000$	20,700	<2000	<1.20	<2.50	30	2% Si iron, 0.019 in.
Small motors	>5,000 for $B = 10{,}000$ >600 for $B = 15{,}000$	20,900	<2500	<1.35	<3.45	20	1% Si iron, 0.019 in.
Aircraft apparatus[d]	>3,000 for $B = 15{,}000$ >230 for $B = 23{,}000$	24,000	<2000	<1.20	<2.80[d]	>20	Hiperco*, 0.010 in.
Vane-type instruments	>50,000 for $B = 5{,}000$	16,000	<150	....	...	45	Hipernik*

* Or equivalent

(a) "W 10/60" means "watt loss for B = 10,000, frequency = 60 cycles". "W 15/60" means "watt loss for B = 15,000, frequency = 60 cycles".

(b) For W 10/400 the total watt loss is less than 1.9 per lb

(c) For W 10/400 the total watt loss is less than 1.5 per lb

(d) For aircraft apparatus, watt losses per pound are as follows: W 20/60, <4.20; W 10/600, <22; W 15/600, <50; W 20/600, <80.

By correct proportioning of the parts, it is thus possible to compensate almost entirely for the temperature changes. Alloys for such purposes are essentially of two types:

1 The nickel-copper type that contains about 70% Ni, 30% Cu as well as certain admixtures, such as 2% Fe ("Calmalloy"[28]), or about 1% Mn with or without a small amount of silicon (Westinghouse Alloy). Characteristic curves are shown for these alloys in Fig. 20.

2 The nickel-iron type containing 30 to 40% Ni with a small amount of manganese, chromium and silicon. Curves for this type of alloy ("Thermoperm") are shown in Fig. 21.[29] The curves are nearly straight lines all the way from low temperatures up to 60 C, and the temperature coefficients are higher than for the monel type of alloy.

Sintered Compressed Iron Powder.* For many applications in which the magnetic circuit is complicated and would require considerable machining, it is often advantageous to make the parts by pressing iron powder into a mold and sintering the parts thus made, in a reducing atmosphere. In Fig. 22, 23 and 24 are shown the effects of forming pressure, sintering temperature and sintering time, on the magnetic permeability of iron for a constant magnetizing force, as a percentage of the permeability of annealed hot rolled low-carbon steel.

From these curves it appears that a pressure of 80 tons per sq in., combined with a sintering temperature of 1200 C for 3 hr, yields magnetic properties equal to or better than those of annealed hot rolled low-carbon steel or wrought iron.

Summary. As a summary, Fig. 25 shows *B-H* curves for materials considered in this article, and Table VI shows applications in electrical apparatus and instruments, with the required or desired magnetic and electrical properties and the corresponding alloy that will serve best.

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Permanent Magnet Materials

By K. L. Scott*

TWO TYPES of permanent magnet material are in wide use today; namely, the magnet steels, which contain carbon as a hardening constituent, and the more recently developed magnet alloys, which are virtually free from carbon. A third type, composed of metallic oxides, has a limited field of use. Particularly great progress has been made since about 1925 in the development and improvement of the carbon-free type of material. In the present article the first type will be referred to as magnet *steels* and the second type as magnet *alloys;* the oxide magnets will receive little discussion.

Theoretical Discussion. In order to understand the relative importance and usefulness of each type of material, a brief summary of the fundamental theory of permanent magnets will be given. In Fig. 1 are shown a typical hysteresis loop and magnetization curve for a permanent magnet alloy. The variables are magnetizing force H, in oersteds [0.1 (4π) times the ampere turns per centimeter] as abscissas, and magnetic flux density or induction B, in gausses (so-called "lines of force" per square centimeter) as ordinates. Starting with an unmagnetized specimen, if increasing values of H are applied (as by gradually increasing the electric current in a coil or wire wound on the specimen) the corresponding values of magnetic flux produced in the specimen will be as shown by the familiar S-shaped magnetization curve, also called the "normal induction curve". If the values of H are gradually decreased from the highest applied value, H_{max}, to zero, and then increased in the negative direction to a negative H_{max} (accomplished by reversing the current in the magnetizing winding), the value of B will change from a positive B_{max} to a negative B_{max} along the left-hand curve of the hysteresis loop. If this process is repeated, starting with a negative H_{max}, the right-hand side of the hysteresis loop will be traced. If the value of magnetizing force is reduced from H_{max} to zero (as by opening the circuit of the magnetizing winding) the value of B will drop from B_{max} to the intersection of the hysteresis loop with the B axis. The value of B at the point of intersection is called the "residual induction", designated B_r. If sufficient negative magnetizing force is applied now to reduce the value of B from B_r exactly to zero, the value of negative H required will be as shown by the intersection of the hysteresis loop with the H axis. This particular value of H is called the "coercive force", designated H_c. This quantity affords a measure of the resistance of a material to demagnetization.

It is appropriate to distinguish here between the total induction B and the intrinsic induction B_i, which is that part of the total induction B caused by the presence of the magnetic material. B_i is equal to $B - H$, and is numerically equal to B only when $H = 0$, as shown in Fig. 2, in which hysteresis loops based on B and B_i are shown for the same cycle of magnetization. It is to be noted that the values of B_r are the same for both loops, but the value of coercive force for the B_i loop, designated H_{ci}, is greater than the value of H_c. The difference is significant for the magnet alloys that have high values of coercive force, since in some instances H_{ci} affords a more accurate measure of the permanence of a magnet (that is, its resistance to demagnetization) than H_c.

The descending branch of the hysteresis loop between the points B_r and H_c is most important in the theory of permanent magnets. It is known as the "demagnetization curve". If the product of the coordinates B and H of this curve are plotted against corresponding values of B, a new curve is obtained, as shown in Fig. 3. The maximum value of the product $B \times H$—designated $(BH)_{max}$—as obtained

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from this curve, is proportional to the maximum amount of magnetic energy that a magnet of the given material can support in an air gap, per unit volume of material in the magnet. Hence, the most efficient design for a magnet will be one that works the magnet at the flux density corresponding to the $(BH)_{max}$ point of the material.

Since the value of $(BH)_{max}$ is proportional to the maximum obtainable air-gap energy per unit volume of a magnet, $(BH)_{max}$ constitutes the best criterion of the magnetic quality of a permanent magnet material. The co-ordinates of the $(BH)_{max}$ point can be located to a close approximation by the intersection of the diagonal of the rectangle that has sides OB_r and OH_c, with the demagnetization curve, as shown in Fig. 3. The $(BH)_{max}$ point can also be located quite well by the point of tangency on the demagnetization curve, of a straight line parallel to a line through B_r and H_c. However, this method will

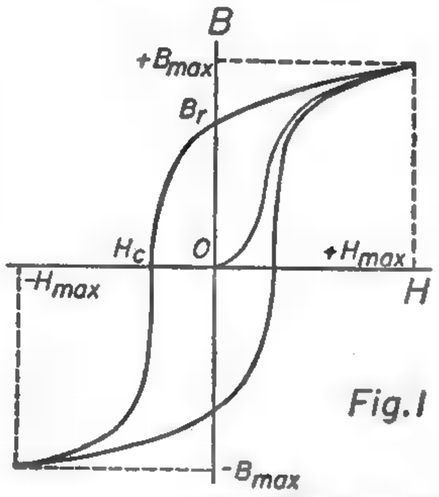

Fig. 1

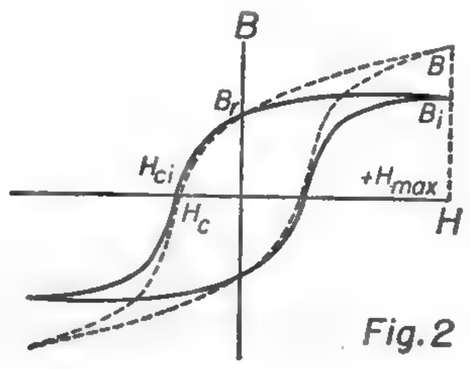

Fig. 2

Fig. 1 Typical hysteresis loop of permanent magnet alloy
Fig. 2 Hysteresis loops showing relation of intrinsic or ferric induction B_i and total induction B

not work for materials with characteristics such as are illustrated in Fig. 8. For the magnet *steels* and some of the magnet *alloys*, the product $B_r \times H_c$ is directly proportional to $(BH)_{max}$ and hence gives an approximate indication of magnet quality. The co-ordinates B and H of the $(BH)_{max}$ point are equal respectively to approximately $0.65B_r$ and $0.65H_c$. Hence the values of B_r and H_c for these materials, are useful as inspection criteria and also indicate approximately the proper working flux density for purposes of design.

It has been shown also that the flux density of a fully magnetized bar magnet, designated B_{rem}, depends on the length L and equivalent diameter D in the manner shown in Fig. 4. This curve holds for most permanent magnet materials, but applies strictly only to straight bars. However, the curve will also apply quite well to magnets of other shapes, unless the ends of the magnets are relatively close together, or are brought effectively close together by iron pole pieces. The preceding simplifications are not permissible for magnet *alloys* such as Alnico 5, for which the demagnetization curve is more concave towards the origin. Thus the product of $B_r \times H_c$ is not a good criterion of quality for Alnico 5. In general, magnet design should be based on actual demagnetization curves and actual values of the energy product.

Testing of Magnet Materials and Magnets. Most manufacturers and large users of permanent magnet steels or alloys, test the materials for magnetic quality by measuring B_r and H_c, and $(BH)_{max}$. After suitable heat treatment, straight bars of cast or rolled material are tested in some form of permeameter. For methods and equipment for making these tests, see ASTM Method A34-46.

Most users of magnets also make a flux test on the finished magnets. This test can be made most accurately with a search coil and a flux meter of the galvanometer type. Greater speed and sufficient accuracy for commercial purposes can be obtained in many instances by using a flux meter of the d-c meter type, in which the test magnet furnishes the field to deflect the moving coil of the meter; or by adapting an a-c meter of the iron vane type. Some have used voltage measurements from air-core coils rotating in the field or air gaps of strong magnets.

Aging of Magnet Materials and Magnets. The magnetic properties of the permanent magnet *steels* are not stable with time; the residual induction and coercive force of most of them begin to change spontaneously as soon as the steels are hardened, and continue to change for an indefinite time. The rate of change is greatest immediately after hardening, and decreases rapidly so that in a few days the rate is low. The rate and amount of change differ for different kinds of steel and are not uniform for any given kind of steel. The direction of the change is always for the residual induction to increase and the coercive force to decrease. Because of this instability it is good practice for a user of magnet *steel,* buying under specifications of magnetic properties, to allow an aging period between the hardening and testing of test bars.

Because of the nature of magnet *alloys* and the kind of heat treatment employed for them, such aging phenomena are much less pronounced in the magnet *alloys* and are negligible for most purposes.

The state of magnetization of magnetized steel magnets is also subject to a peculiar instability. It is observed that magnets magnetized immediately or soon after hardening, but not subjected to adverse fields, will suffer a spontaneous decrease in flux, beginning immediately after magnetizing. The rate of loss of flux is greatest immediately after magnetization, and decreases rapidly with time, so that after several days the flux has reached an approximately stable value. If the magnet is remagnetized, the same phenomenon is repeated, but less flux is lost than the first time. The phenomenon, however, is only temporary, and disappears when sufficient time has elapsed after hardening, so that if a magnet is magnetized after standing at room temperature for about four weeks after hardening, the subsequent spontaneous loss in flux will be negligible. This phenomenon appears to be present in the magnet *alloys* only to a negligible extent, if at all.

The loss of flux that occurs in magnets because of external demagnetizing influences is also commonly but improperly referred to as "aging". External demagnetizing influences include mechanical shock, heat, and adverse magnetic fields, including a-c fields and the fields of other

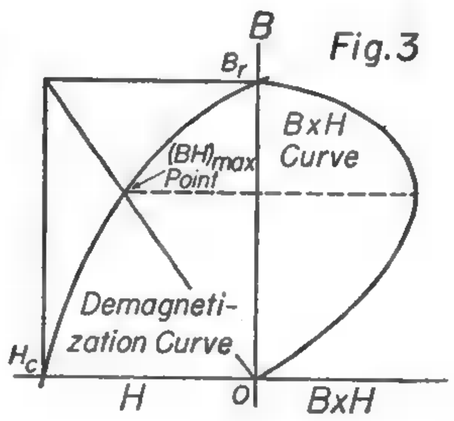

Fig. 3

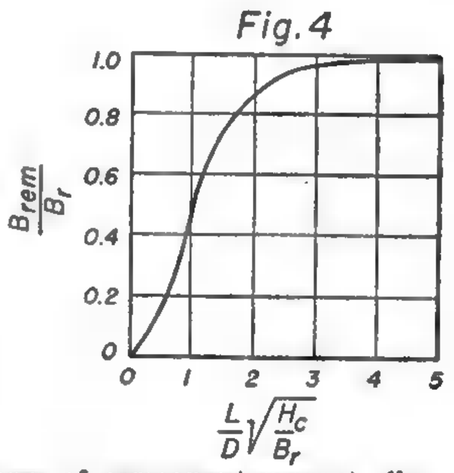

Fig. 4

Fig. 3 Typical demagnetization curve of permanent magnet alloy
Fig. 4 Relation between magnetic properties and dimensions of straight bar magnets

magnets. In general, if a magnet is weakened by any one of the above means and not remagnetized, it will not be further weakened by a repetition of the same treatment, and will suffer only a slight loss in flux from the application of any other treatment that would have weakened it originally by about the same amount. In the process inspection of magnets after hardening, some users follow the magnetizing operation by a partial demagnetization or aging before testing, for the purpose of eliminating magnets that are improperly heat treated or made of defective material. If a stabilizing treatment is required, as for magnets to be used in measuring instruments, the material may be stored for a long time, subjected to heat (as by immersion in boiling water) or partially demagnetized by an a-c or d-c field after final magnetization.

Methods of Magnetizing Magnets. The problem of magnetizing permanent magnets has become increasingly difficult with the advent of materials that have coercive forces in the range of 500 oersteds and higher. The magnetizing field required for magnetizing a magnet fully is from four to five times the coercive force of the material, ranging from 250 amp-turns per cm for the chromium and tungsten steels to 2500 amp-turns per cm for some of

Table I. Commercial Types of Magnet Steels

Type of Steel	Nominal Composition,[a] percentage						Nominal Magnetic Properties[b]		Hardening Temperature, deg Fahr	Quenching Medium
	C	Mn	Cr	W	Co	Mo	B_r, gausses	H_c, oersteds		
C-Mn	0.60	0.80	....	...	...	...	10,000	43	1450	Water
Cr	0.60	0.40	0.90	...	...	...	10,000	50	1450	Oil
Cr	0.90	0.35	2.25	...	...	...	9,000	58	1500	Water, Oil
Cr	0.95	0.20 to 0.60	3.00 to 4.00	...	...	...	9,500	63	1525	Oil
Cr	1.00	0.35	6.00	...	...	...	9,000	72	1550	Oil
Cr-Mo	1.00	0.35	4.00	...	...	0.35	9,000	65	1500	Oil
W	0.70	0.30	0.20	5.50	...	...	10,000	65	1550	Water
W-Cr	0.70	0.50	0.50	6.00	...	...	9,000	70	1525	Oil
Co	0.90	0.35	4.75	1.25	8.50	...	7,500	120	1650	Oil
Co	0.90	0.30 to 0.85	3.50 to 5.75	3.75 to 7.00	35.00 to 41.00	...	9,700	235	1700	Oil
Co-Cr	0.95	0.30	9.00	...	16.00	1.30	8,000	180	(c)	Air
Co-W	0.85	0.50	2.00 to 5.00	8.75	17.00	...	9,000	165	1750	Oil

(a) Limits usually 0.30% Si max, 0.03% P and S max, 0.50% Ni max
(b) Values for previously annealed materials usually 5 to 10% lower in H_c
(c) Heat treatment: 2100 F, cool in air; 1850 F, cool in air.

the magnet *alloys*, such as Alnico 4. Most magnets made of steels and alloys that have low coercive force, can be fully magnetized by means of large electromagnets. Some magnets that have high coercive force and favorable shapes, can also be magnetized by the same means; but magnets of more intricate shapes or greater length may require the use of a magnetizing winding of very heavy wire carrying large currents. Water-cooled copper tubing carrying hundreds or thousands of amperes has been used for some applications. Banks of heavy-duty rectifiers or low-voltage high-current d-c generators, such as plating generators, are suitable sources of current. Short-duration heavy current pulses from half-cycle welders, or large banks of condensers have also been employed successfully. The advantage of these methods over the use of electromagnets is that the required high field strengths can be obtained readily and at the same time the direction of the field can be made to conform to the desired path of flux through the magnet, by suitable shaping of the winding. Where the current flow is of short duration, a lighter and more easily manipulated winding may be used.

Magnet Steels. The types of magnet *steel* produced commercially in the United States are classified by their manufacturers as follows: carbon-manganese, chromium, chromium-molybdenum, tungsten, chromium-tungsten, and various grades of cobalt steel, including cobalt-chromium and cobalt-tungsten. The chromium steels are made in grades ranging from nominal 1 to 6% Cr; the tungsten steels range from 5 to 6% W; and the cobalt steels contain from 3 to 36% Co, with chromium from 2 to 10%, and a fraction of 1% Mo in certain steels. Some tungsten steels contain enough chromium to make them oil-hardening. Otherwise the tungsten steels, the 2% Cr steel and the carbon-manganese steels are water-hardening, and all the rest are oil-hardening. It is noteworthy that the 1% Cr steel has the best magnetic properties when quenched in oil; but water, some water solution, or a light oil is recommended for the 2% Cr steel. Data concerning the various types of magnet *steel* are shown in Table I. Only those types reported by various American manufacturers are included, and the data serve to summarize information furnished by the manufacturers.

Manufacture of Magnet Steel. In general, the methods of melting, rolling and fabricating magnet *steels* are similar to those used for tool steels of similar composition. Exceptions arise from the fact that mechanical properties are of secondary importance and practices that would be harmful to the magnetic properties must be avoided as much as possible. This means that the thermal history of the steel should be as brief as can be. Rolling or forging should be accomplished with a minimum amount of reheating, and overheating should be avoided. The steel should not be annealed unless necessary for machining operations, and the anneal should be as light as is consistent with machinability.

If the magnetic properties are impaired by overannealing or overheating, it is possible to restore a good measure of the loss by a normalizing treatment, quickly heating and cooling the material from a temperature well above the transformation range. Normalizing temperatures in use range from 1700 to 2300 F for 5% W steel, and from 1700 to 2000 F for chromium steel.

Melting and Rolling. Magnet *steels* are almost always melted in electric furnaces, either arc or induction.

Hot Forming. In many instances, the shapes of permanent magnets are such as to require hot forming. This may be done satisfactorily at temperatures between 1400 and 1800 F. Higher temperatures are detrimental to the quality of the steel. A medium temperature is preferable and the heating and forming should be done as quickly as possible. Magnets are usually air-cooled after forming. Sometimes magnets are hardened by quenching immediately after the forming operation; thus one heating operation may be eliminated. This practice requires better than ordinary control of the forming temperature.

Annealing. Great emphasis should be placed on the desirability of designing magnets so that they do not require annealing for machining operations. When the need is unavoidable, or when cold forming or blanking is the chosen fabricating process, as light an anneal as possible should be used, because annealing always impairs the magnetic properties of a magnet *steel.* However, grades of steel that are air-hardening must be annealed by the fabricator after the hot forming operation if the formed magnets are to be machined. If hot forming is not required or if the machining can be done before forming, the material can be annealed at the mill. Magnet *steel* should be heated to the annealing temperature quickly, held at temperature only long enough to be heated through, and cooled just slowly enough to avoid air-hardening. Cooling from 1000 F to room temperature may always be done in the open air.

Hardening. The recommended hardening temperatures are listed in Table I. The optimum hardening temperature is usually the one that gives the highest value of $(BH)_{max}$, or of the product $B_r \times H_c$. However some magnets are not proportioned for maximum efficiency and require higher values of B_r or H_c than are associated with the maximum value of $(BH)_{max}$ or the product $B_r \times H_c$, because high values of B_r are best for long or slender magnets and high values of H_c for short thick magnets. Oil-quenching results in higher values of H_c and lower values of B_r than water-quenching. A much greater amount of warping, cracking and breaking results from water-quenching. For this reason oil-hardening steels are gradually replacing water-hardening steels for most applications. Magnets should not be held at the hardening temperature longer than is necessary for the solution of carbides. A prolonged soak at the quenching temperature is usually detrimental to the magnetic properties of magnet *steels.*

Grinding. Hardened magnets should be ground very carefully in order to avoid grinding cracks, which sometimes develop hours after the grinding operation. Wet grinding, light cuts, and careful selection of the abrasive wheel are the best safeguards against grinding cracks. In general, a grinding practice that is suitable for tool steel will be suitable for magnet steel.

Magnet Steel Castings. Cobalt steel magnets of more or less intricate shapes have frequently been produced by casting. The properties of cast cobalt steel do not differ greatly from those of forged or rolled steel, although the

Table II. Nominal Properties of Carbon-Free Permanent Magnet Alloys

Magnet Material	Chemical Composition	Form	H_{max}, oersteds	B_{max}, gausses	Residual B_r	Coercive Force H_c	External Energy $(B_dH_d)_{max}$	Weight, lb per cu in.	Mechanical Properties	Commercial Methods of Fabrication
Comol Remalloy	12 Co, 17 Mo, rest Fe	Bar Cast	1000	15,200	10,000	225	1,100,000	0.295	Hard, relatively strong, but brittle	Cast, hot forge, machine, punch (thin sections)
Alnico 1	12 Al, 20 Ni 5 Co, rest Fe	Cast	2000	12,350	7,100	400	1,300,000	0.249	Hard, brittle	Cast, grind
Alnico 2 (cast)	10 Al, 17 Ni, 12.5 Co, 6 Cu, rest Fe	Cast	2000	12,600	7,200	540	1,600,000	0.256	Hard, brittle	Cast, grind
Alnico 2 (sintered)	10 Al, 17 Ni, 12.5 Co, 6 Cu, rest Fe	Sintered	2000	12,000	6,900	520	1,430,000	0.245	Hard	Sinter, grind
Alnico 3	12 Al, 25 Ni, rest Fe	Cast	2000	12,000	6,700	450	1,380,000	0.249	Hard, brittle	Cast, grind
Alnico 4	12 Al, 28 Ni, 5 Co, rest Fe	Cast	3000	11,850	5,200	700	1,300,000	0.253	Hard, brittle	Cast, grind
Alnico 5	8 Al, 14 Ni, 24 Co, 3 Cu, rest Fe	Cast	2000	15,700	12,000	575	5,000,000	0.264	Hard, brittle	Cast, grind
Alnico 12	35 Co, 18 Ni, 6 Al, 8 Ti, rest Fe	Cast	3000	12,800	5,800	950	1,750,000	0.260	Hard, brittle	Cast, grind
Cunife	60 Cu, 20 Ni, 20 Fe	Wire	2400	8,400	5,400	550	1,550,000	0.311	Ductile, malleable	Cold roll, machine, punch
Cunico	50 Cu, 21 Ni, 29 Co	Strip Rod Wire Cast	3200	8,000	3,400	710	850,000	0.300	Ductile, malleable	Cast, cold roll, machine, punch
Vectolite	30 Fe_2O_3, 44 Fe_3O_4, 26 Co_2O_3	Pressed pieces	3000	4,800	1,600	900	500,000	0.100	Low strength, brittle	Sinter, grind
Silmanal	86.75 Ag, 8.8 Mn, 4.45 Al	Rod Strip Sheet	20,000	20,830 (a) $B_i = 830$	550	H_{ci} (a) 6000	85,000	0.325	Workable	Machine, punch, cold roll

(a) B_i and H_{ci} values are on the basis of intrinsic induction.
Data from the General Electric Company, including demagnetization curves

coercive force is usually higher and the residual induction lower. The same annealing and hardening practices are recommended. The cast material is ordinarily more brittle than the forged. Casting the other magnet *steels* affords no appreciable advantage.

Miscellaneous. The magnetic properties of magnet *steels* have not been correlated reliably with the microstructure. In general, a fine, silky fracture is associated with good material. Of course decarburization should be avoided. After hardening, heating above 212 F is detrimental to the magnetic properties. Serious impairment begins to take place between 300 and 400 F. Defective magnets may frequently be reclaimed by rehardening. For immersing magnets during water-quenching, there is no standard method that will minimize warpage or breakage. In handling magnets that must be formed to size just before the

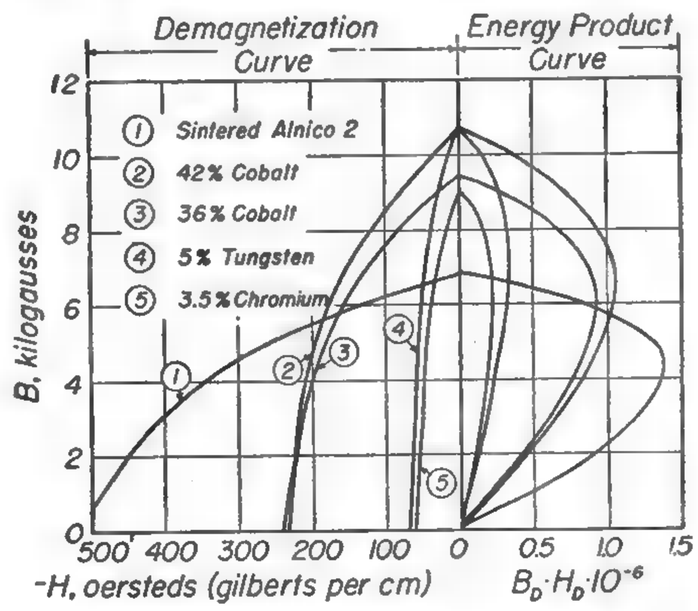

Fig. 5 Demagnetization curves and energy product curves of various magnet materials

quench, the tongs should make as little contact as possible with the magnets to avoid cooling them too much by contact with cold metal before the quench.

Magnet Alloys. The range of possibilities for the design of permanent magnets has been extended greatly by the introduction of alloys that are substantially free from carbon. The magnetic properties of any of the permanent magnet *steels* can be substantially duplicated by some of these alloys. Furthermore, materials are commercially available that have far greater coercive force and residual induction values than any of the magnet *steels*, and other such alloys are being developed. The following materials of this class are known or are in use at the present time

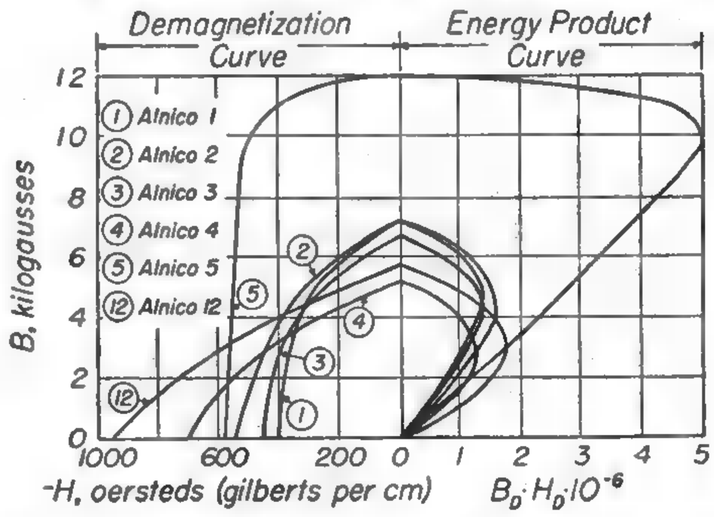

Fig. 6 Demagnetization curves and energy product curves of various magnet alloys

(but not all are commercially available): an alloy of iron, cobalt and molybdenum, known as Remalloy or Comol; various alloys of iron, nickel, aluminum and one or more other elements—cobalt, copper and titanium—with the common name of Alnico, plus an Arabic or Roman numeral to designate the grade; a series of alloys of copper and nickel with iron or cobalt or both, bearing the derived names of Cunife or Cunico; an alloy of silver, manganese and aluminum known as Silmanal; an alloy of platinum and cobalt that has extremely high coercive force; an alloy of cobalt, iron and vanadium called Vicalloy; and a mixture of iron and cobalt oxides called Vectolite (Table II).

Remalloy or Comol has magnetic properties slightly better than 36% Co steel. Magnets are produced from hot rolled or hot forged bars, or may be cast. The metal may be hot formed at or near 2000 F. The range of hot forming temperatures is rather narrow. After a solution heat treatment between 2200 and 2400 F, followed by an oil quench, the alloy is readily machinable but rather brittle. Magnetic properties are developed by reheating for approximately 90 min at about 1250 F after the solution heat treatment.

The Alnico alloys cannot be worked hot or cold. Magnets are produced by casting and grinding. Drilling, tapping and such processes can be performed only with the aid of soft inserts in the castings. Heat treatment consists of a solution treatment between 1900 and 2100 F, air-cooling, and then aging for approximately an hour at about 1100 to 1300 F. Small magnets may require a slower rate of air cooling and heavy ones may require accelerated cooling in an air blast to develop the desired properties. Rapid cooling favors high values of B_r and slow cooling, high values of H_c. The heat treatment for Alnico 5 is an exception in that the solution temperature is about 2400 F and the aging treatment consists of holding for 4 to 10 hr at 1000 to 1150 F. Alnico 5, which is highly directional

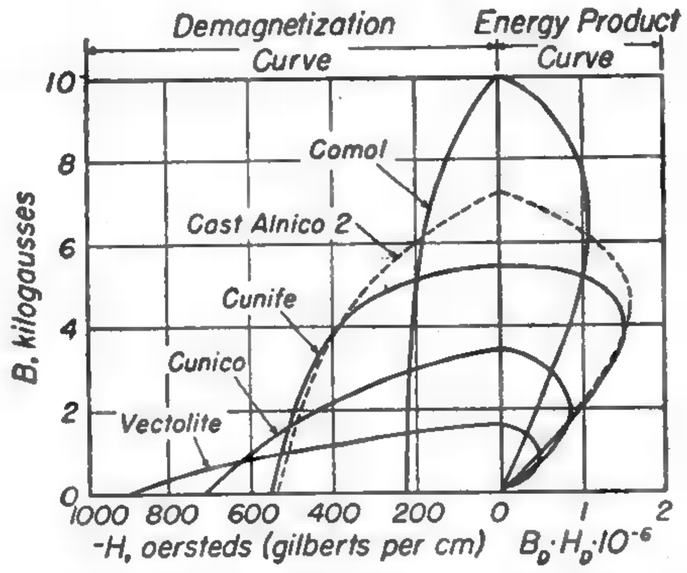

Fig. 7 Demagnetization curves and energy product curves of various magnet alloys

magnetically, requires cooling from the solution temperature in a magnetic field oriented to conform to the pattern of magnetization desired in the finished magnet. Suppliers of Alnico magnets customarily furnish them ground to size, heat treated and magnetized.

Cunife, Cunico and Silmanal are ductile alloys that can be produced in a wide variety of designs by forming, drawing, punching or machining. Cunife is directional and should be magnetized in the direction of cold working. In sheet form this alloy has properties considerably below those of other wrought forms.

Vectolite and sintered Alnico magnets are made from powdered oxides or metals pressed in a die to approximately the final shape and size, and sintered. Both can be ground to final size if very close tolerances are desired, but Vectolite is mechanically weak and is preferably sintered to final size. Vectolite is an electrical nonconductor. Sintered Alnico is fine-grained and stronger mechanically than cast Alnico. The chief advantage of sintered Alnico lies in the production of small sizes and intricate shapes.

Vicalloy is a ductile material with magnetic properties somewhat better than Comol or 36% Co steel. The chief use of Vicalloy has been in magnetic recorder tape.

Comol or Remalloy, Vicalloy, and the platinum-cobalt alloy are not commercially available at present (1947).

Curves of demagnetization and energy product for the magnet alloys are shown in Fig. 5, 6, 7 and 8.

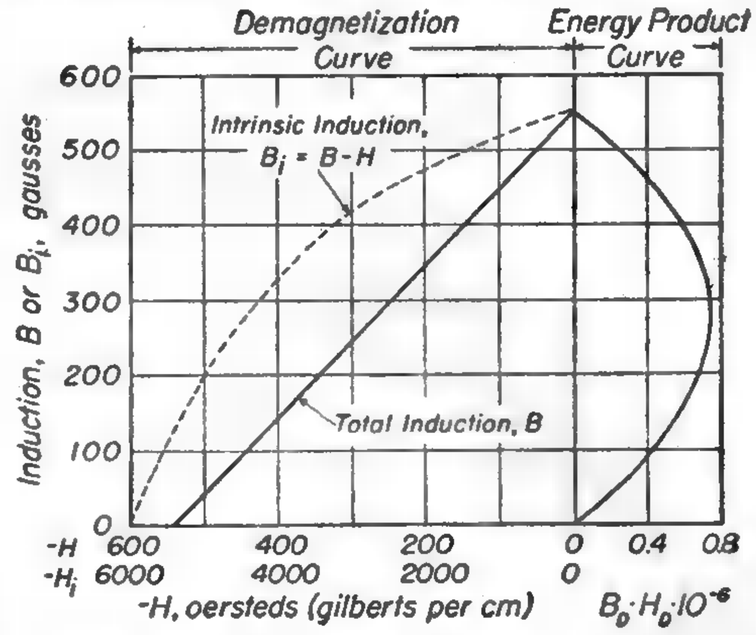

Fig. 8 Demagnetization curves of intrinsic induction and total induction and energy product curve for Silmanal

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Iron-Nickel Alloys

By J. W. Sands*

IRON and nickel are soluble in all proportions in the molten state and form solid solutions during solidification. At room temperature the alloys may be either ferritic or austenitic in structure, depending on the nickel content and, in some instances, on the thermal history of the sample. Additions of carbon also affect the phase relationships. Nickel lowers progressively the temperature of the gamma-to-alpha transformation in iron, imparts a considerable hysteresis in the temperature of the occurrence of this transformation during heating and cooling, and introduces a considerable spread between the temperatures of the beginning and end of transformation. The lowering of the transformation range is so pronounced that when the nickel content is about 34%, the transformation cannot be reached, even at the temperature of liquid hydrogen (20 C above absolute zero). Hence, all the alloys containing more than this amount of nickel are austenitic (face-centered cubic) under all conditions.

Alloys of lower nickel content may be either ferritic or austenitic or a mixture of both, depending on the thermal

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history of the sample. Alloys that are not wholly austenitic at room temperature are considered to be steels, and are therefore outside the scope of this article. They are discussed in the article "Nickel in Steel", page 473.

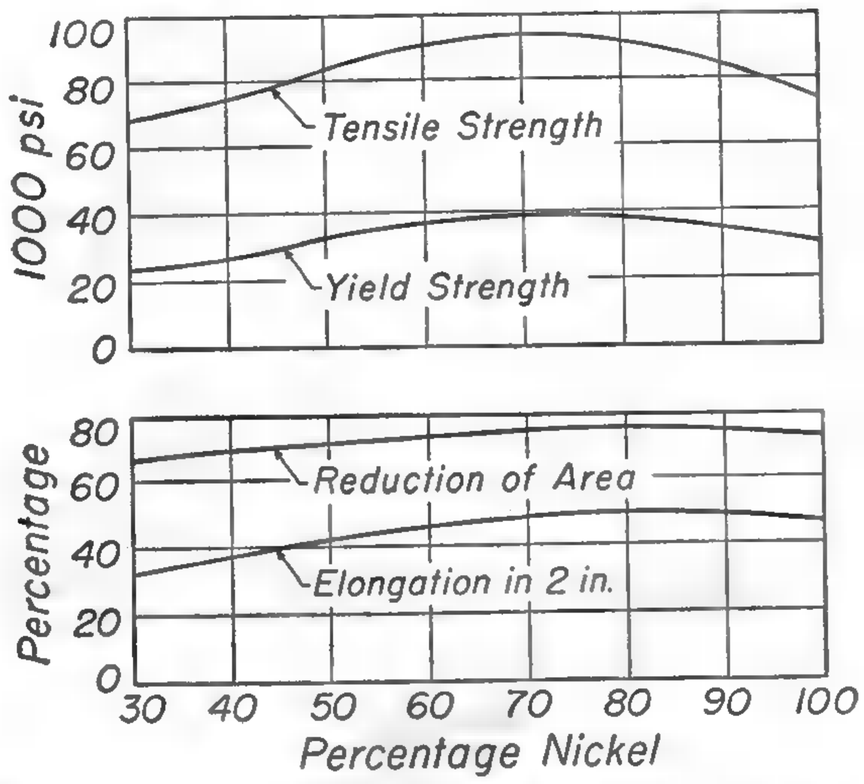

Fig. 1 Approximate mechanical properties of annealed commercial austenitic iron-nickel alloys

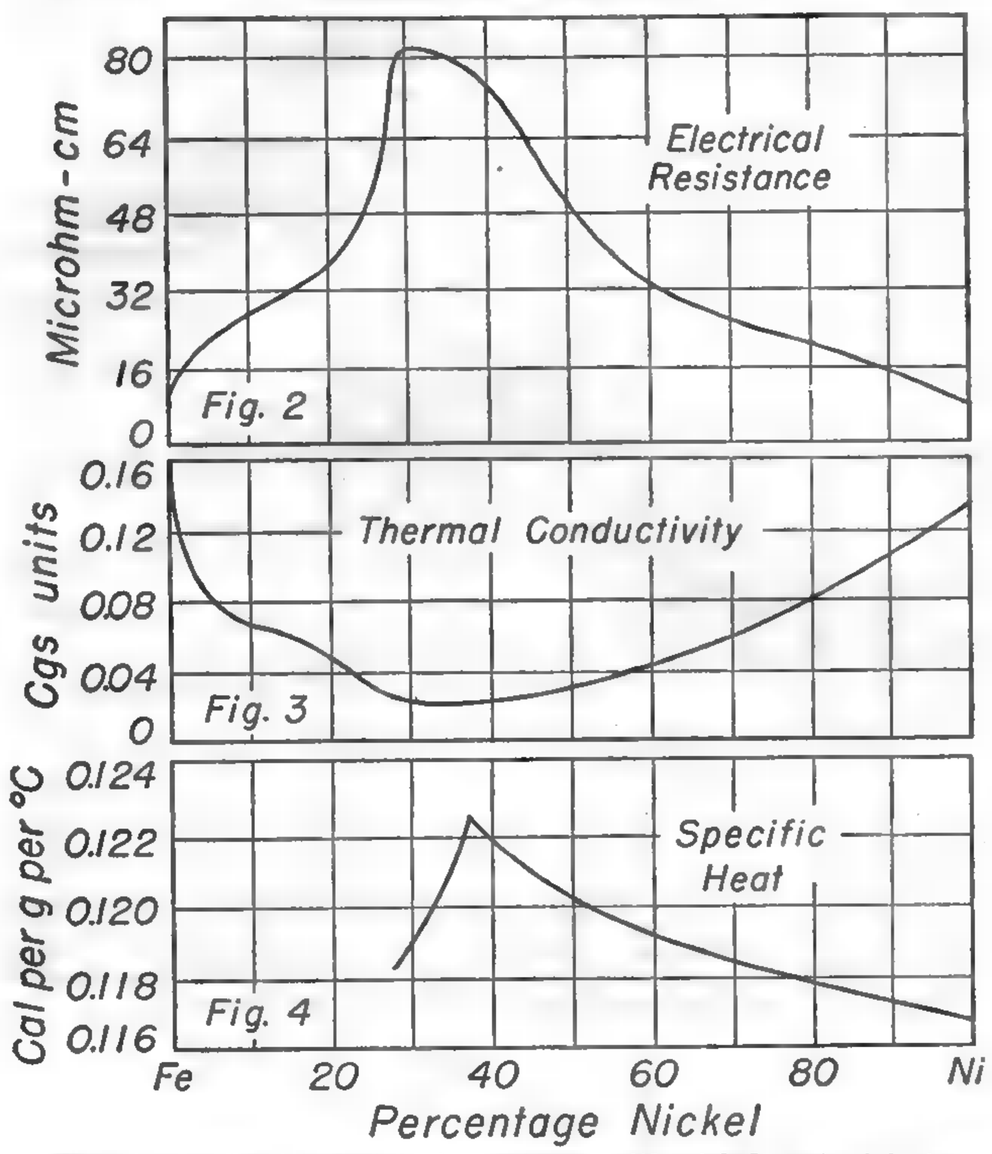

Fig. 2 Variation of electrical resistance with nickel content in iron-nickel alloys. Multiply by 6 to convert to ohms per mil ft.

Fig. 3 Variation of thermal conductivity (cgs units) with nickel content in iron-nickel alloys. Multiply by 2900 to convert to English units. (Ingersoll)

Fig. 4 Variation of specific heat in cal per ■ per °C with nickel content in iron-nickel alloys (Ingersoll)

The iron-nickel system includes alloys that have unusual thermal expansion, magnetic and thermoelastic characteristics; these properties are used to advantage in a number of alloys for special purposes. Thermal expansion over an appreciable range of temperature becomes virtually negligible in the vicinity of 36% Ni, but increases in compositions that contain more nickel and less nickel. Thus in the range of composition between 30 and 60% Ni, it is possible to select alloys of appropriate expansivity to fit particular applications. These alloys are used for a wide variety of applications including precision variable condensers for radio apparatus, alloys for sealing glass (often with the addition of cobalt or chromium), and material for the low-expansion side of thermostatic bimetal. The high-expansion side also is frequently an alloy with an iron-nickel base and an addition of chromium. A favored composition is 22% Ni and 3% Cr. The low-expansion alloys are discussed in detail in the article beginning on page 601.

Most metals possess a negative thermal coefficient of the elastic modulus; that is, they lose stiffness with increasing temperature. Iron-nickel alloys with nickel between about 27 and 44% exhibit positive coefficients, reaching a rather high maximum at about 36%, which is also the point of minimum thermal expansion. The coefficient of elastic modulus is of value for certain applications involving temperature compensation. Composite springs of steel and 36% Ni-Fe can be made to maintain a constant stiffness regardless of fluctuations in temperature, because of the opposing effects of temperature on the moduli of the two materials.

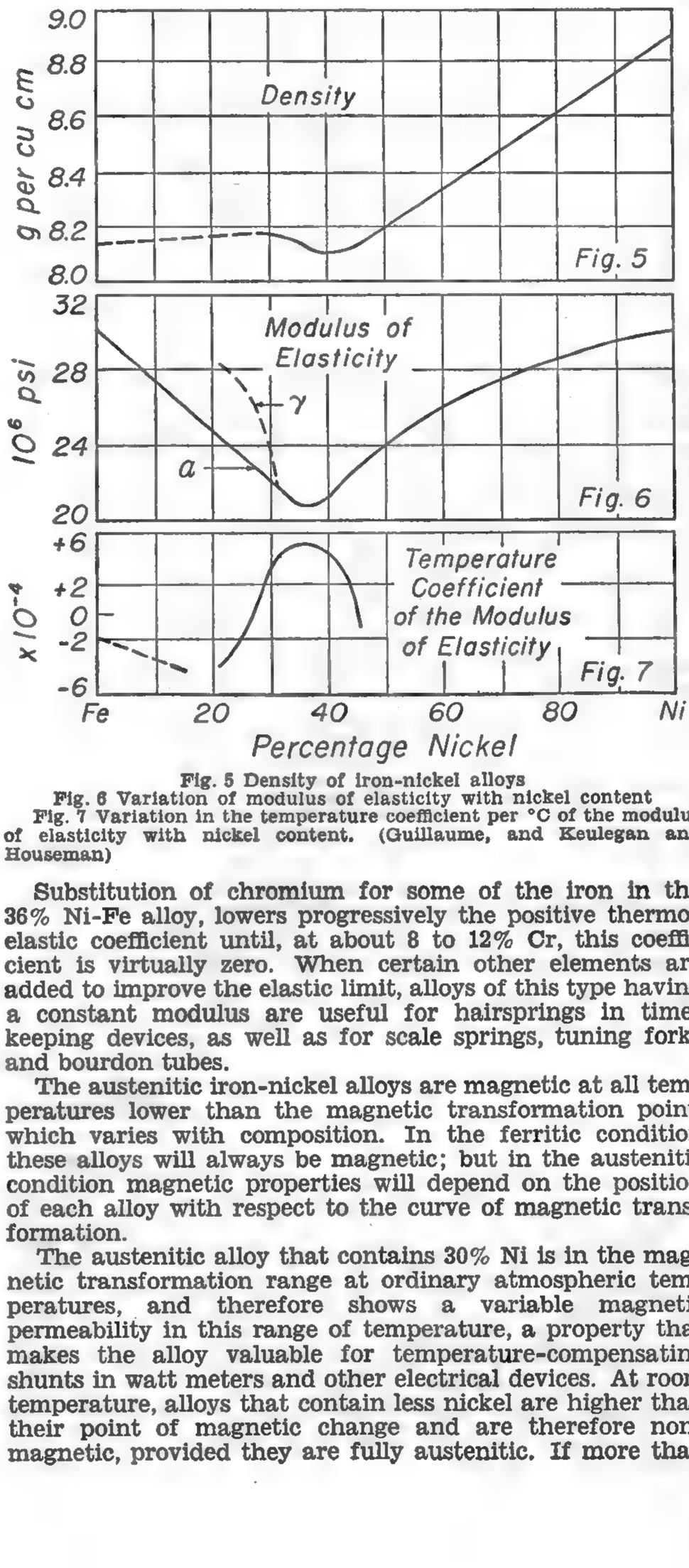

Fig. 5 Density of iron-nickel alloys

Fig. 6 Variation of modulus of elasticity with nickel content

Fig. 7 Variation in the temperature coefficient per °C of the modulus of elasticity with nickel content. (Guillaume, and Keulegan and Houseman)

Substitution of chromium for some of the iron in the 36% Ni-Fe alloy, lowers progressively the positive thermoelastic coefficient until, at about 8 to 12% Cr, this coefficient is virtually zero. When certain other elements are added to improve the elastic limit, alloys of this type having a constant modulus are useful for hairsprings in timekeeping devices, as well as for scale springs, tuning forks and bourdon tubes.

The austenitic iron-nickel alloys are magnetic at all temperatures lower than the magnetic transformation point, which varies with composition. In the ferritic condition these alloys will always be magnetic; but in the austenitic condition magnetic properties will depend on the position of each alloy with respect to the curve of magnetic transformation.

The austenitic alloy that contains 30% Ni is in the magnetic transformation range at ordinary atmospheric temperatures, and therefore shows a variable magnetic permeability in this range of temperature, a property that makes the alloy valuable for temperature-compensating shunts in watt meters and other electrical devices. At room temperature, alloys that contain less nickel are higher than their point of magnetic change and are therefore nonmagnetic, provided they are fully austenitic. If more than

20% Ni is present, air cooling is sufficiently rapid to suppress the change from gamma to alpha phase; therefore these alloys are useful for applications requiring nonmagnetic metals of good strength, high toughness and favorable resistance to corrosion. For reasons of economy, however, the usual practice is to reduce the nickel content and restore the stability of austenite by additions of manganese and chromium.

Table I

Electrical and Thermal Properties of Iron-Nickel Alloys[a]

Nickel, %	Temperature Coefficient of Resistance,[b] 32 to 212 F	Thermoelectric Power (against Copper) 32 to 205 F, microvolts per °F	Thermal Conductivity, 68 to 212 F, Btu/hr/sq/ft/in. °F	Specific Heat, 77 to 212 F, Btu/lb/°F
21.0	0.0010	13.1	....	.....
22.1	0.0010	11.7	142.0	0.1163
25.2	.....	...	92.8	0.1181
26.4	0.0009	9.3	....	.....
28.4	.....	...	80.6	0.1191
35.1	0.0006	5.4	76.0	0.1228
40.0	0.0012	12.4	....	.....
45.0	.....	16.1	....	.....
47.1	0.0020	17.7	106.4	0.1196
75.1	.....	...	200.2	0.1181

Nickel, %	Temperature Coefficient of Resistance,[b] 0 to 100 C	Thermoelectric Power (against Copper) 0 to 96 C, microvolts per °C	Thermal Conductivity, 20 to 100 C, cal/sec/sq cm/cm/°C	Specific Heat, 25 to 100 C, cal/g/°C
21.0	0.0018	23.5	.....	.....
22.1	0.0018	21.0	0.0490	0.1163
25.2	.....	...	0.0320	0.1181
26.4	0.0016	16.7	.....	.....
28.4	.....	...	0.0278	0.1191
35.1	0.0011	9.8	0.0262	0.1228
40.0	0.0022	22.4	.....	.....
45.0	.....	29.0	.....	.....
47.1	0.0036	31.9	0.0367	0.1196
75.1	.....	...	0.0691	0.1181

(a) Data from Ingersoll, Phys Rev, 16, 126 (1920)
(b) For specific resistance, see Fig. 2.

In the range of stable austenitic iron-nickel alloys that contain from 35 to 90% Ni, a number of alloys have been developed that possess extremely useful magnetic characteristics. One of the important properties of these materials is high permeability under the influence of weak magnetic fields, making them valuable as loading materials in electrical communication circuits. As a class, these alloys show high permeability and low hysteresis loss. By variation in the percentage of nickel and judicious additions of other elements, such as cobalt, copper, molybdenum, and chromium, various characteristics can be emphasized and different combinations of magnetic properties can be secured. Molybdenum and chromium are particularly useful in increasing the electrical resistivity, thus reducing eddy-current losses. Further details are given in the article "Magnetically Soft Materials", page 587.

Thus alloys in the iron-nickel series vary all the way from the completely nonmagnetic to those offering maximum softness. It is interesting to note that additions of aluminum to appropriate iron-nickel alloys promote the opposite extreme, high magnetic hardness. Such alloys are now used extensively for permanent magnets, since they provide more magnetic energy per unit of volume than any other permanent magnet material commercially available. They are made in several grades; some contain various combinations of cobalt, titanium and copper, in addition to the nickel and aluminum.

Variations, with nickel content, of some of the important physical and mechanical properties of the iron-nickel series are shown in Table I and Fig. 1 to 7.

Since the iron-nickel alloys are austenitic, they can be hardened only by cold work. This is sometimes a disadvantage when high elastic properties are desired in spring materials that have a constant modulus and in thermostatic bimetal. Recently it has been found that additions of titanium and aluminum make these alloys precipitation-hardenable.* Heat treatment plus cold work is even more effective.

Data concerning the properties of these hardenable alloys are included in the next article in this Handbook.

* N. B. Pilling and A. M. Talbot, Dispersion Hardening Alloys of Nickel and Iron-Nickel-Titanium, "Symposium on Age Hardening of Metals", American Society for Metals, 1940, p 231

Low-Expansion Alloys

By M. A. Hunter*

ALLOYS of iron and nickel have many anomalous properties, depending on the relative proportions of the two elements in the alloy. Guillaume discovered the alloys of low coefficient of linear thermal expansion. In an intensive investigation of a series of various compositions, he found coefficients of linear expansion ranging from a small negative value (-0.5×10^{-6} per °C) to a large positive value (20×10^{-6} per °C). The alloy containing 36% Ni with minor amounts of manganese, silicon and carbon, amounting to less than 1% in all, had a coefficient of expansion so low that its length was almost invariable for ordinary changes in temperature. For this reason Guillaume gave the alloy the name "Invar".

Subsequently in the work of Guillaume and Chevenard an intensive study was made of the thermal and elastic properties of this class of alloys. Alloys with higher contents of nickel were found to possess higher coefficients of expansion. The alloy containing 39% Ni had a coefficient of expansion corresponding to that of the low-expansion glasses. The 46% alloy had a coefficient equivalent to that of platinum (9.0×10^{-6} per °C) and received the name "Platinite". A 42% Ni alloy, when covered with copper to prevent gassing at the seal, is known as "Dumet wire" and is used to replace platinum as the "seal-in" wire in incandescent lamps and vacuum tubes. The 56% alloy has a coefficient approaching that of ordinary steel (11×10^{-6} per °C). Nilvar is identical with Invar (36% Ni).

While studying the elastic properties, Guillaume disclosed the alloy Elinvar, containing 36% Ni and 12% Cr and having an invariable modulus of elasticity over a considerable range of temperature, as well as low thermal expansivity.

Alloys that contain less than 36% Ni have much higher coefficients of expansion. The 18% Ni alloy has an expansion coefficient of 20×10^{-6} per °C. These alloys are of the so-called "irreversible" type and, by reason of their high coefficients, are excluded from the present discussion.

It has been found that certain percentages of cobalt can be used with advantage to replace nickel in the 36% alloy. Substitution of 5% Co for 5% Ni gives an alloy with a coefficient even lower than that of Invar, and less susceptible to variations in heat treatment.

Effect of Composition on Expansivity. The effect of variations in nickel content on the linear expansivity is shown in Fig. 1.

The minimum expansivity occurs at about 36% Ni. Minor additions of other metals have a considerable influence on the position of this minimum expansivity. The effect of additions of manganese, chromium, copper or carbon is shown in Fig. 2.

Minimum expansivity is shifted toward higher contents of nickel when manganese or chromium is added and toward lower contents of nickel when copper or carbon is

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added. The minimum expansivity for any of these ternary alloys is, in general, greater than that of a typical Invar (Fig. 2).

Additions of silicon, tungsten or molybdenum produce effects similar to that of manganese or chromium; the

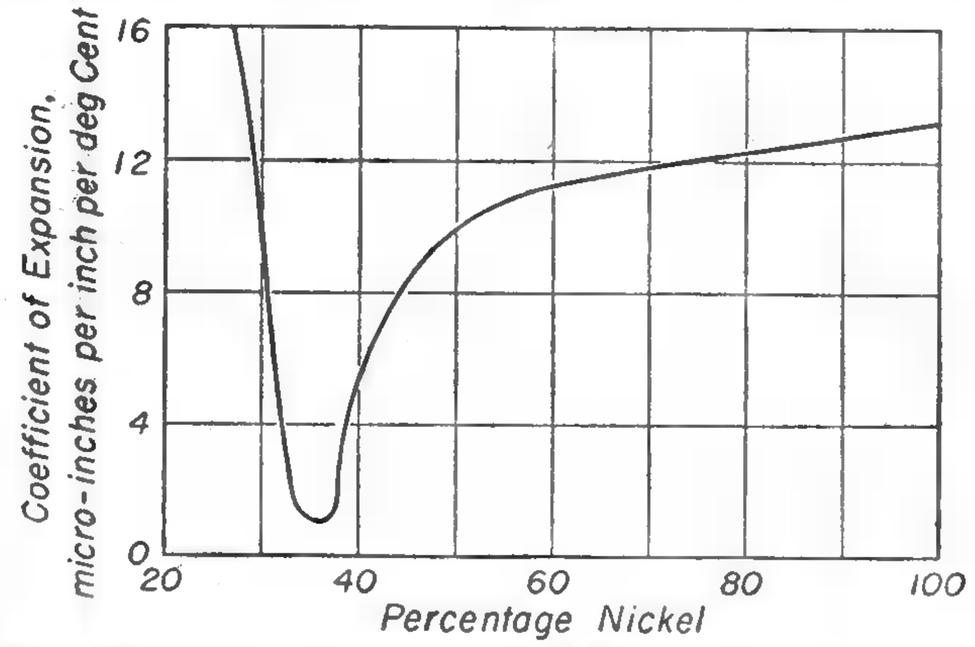

Fig. 1 Effect of nickel on the coefficient of linear thermal expansion of iron-nickel alloys at 20 C (0.4% Mn, 0.1% C) (Guillaume)

composition of minimum expansivity is shifted toward higher contents of nickel.

Carbon is said to produce instability in Invar. Guillaume attributes this to the changing solubility in the austenitic matrix during heat treatment.

Expansivity. It is not generally recognized that the low

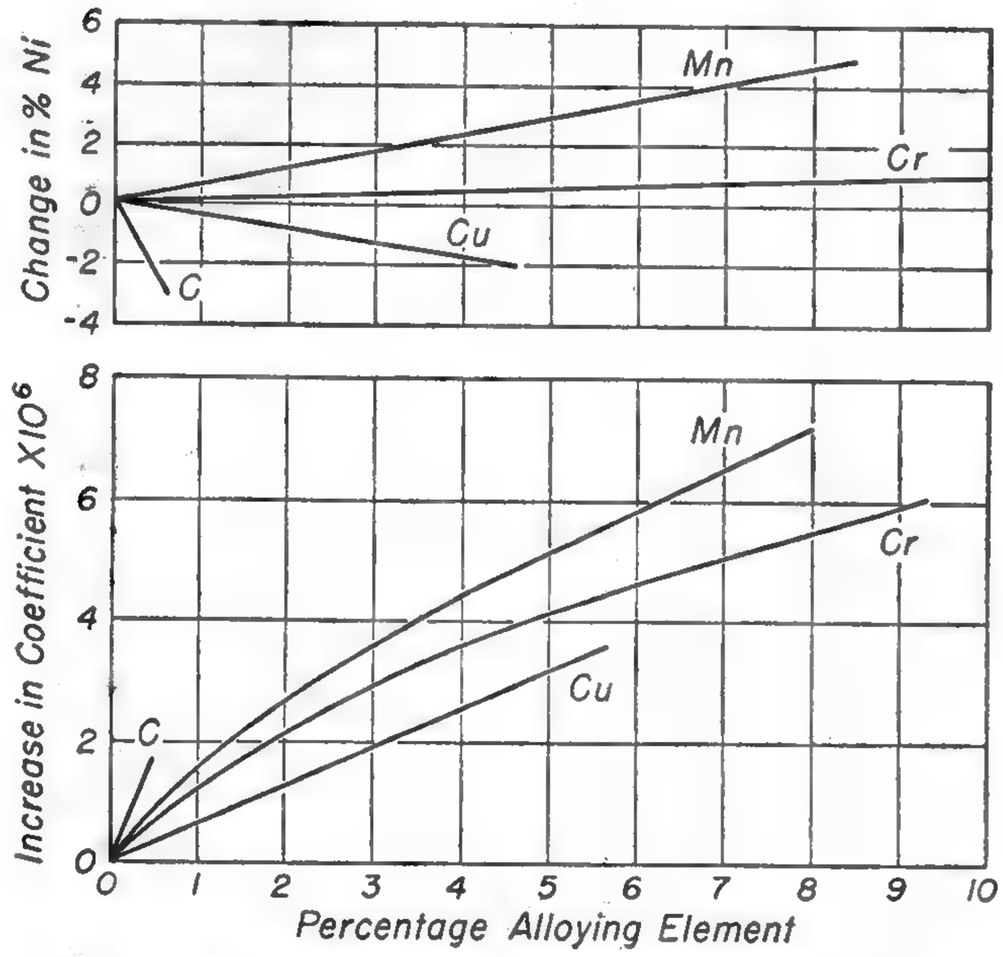

Fig. 2 Effect of alloying elements on the expansion characteristics of iron-nickel alloys. (*Upper*) Displacement of the nickel content of alloy of minimum expansivity caused by additions of manganese, chromium, copper, and carbon. (*Lower*) Change caused in the value of minimum coefficient of expansion by additions of manganese, chromium, copper, and carbon (Guillaume)

expansivity of Invar and related alloys is applicable over a rather narrow range of temperature. At low temperatures, in the region from *A* to *B* (Fig. 3) the coefficient of expansion is high. In the interval between *B* and *C* the coefficient decreases, reaching a minimum in the region from *C* to *D*. With increasing temperature, the coefficient begins again to increase in the range from *D* to *E*, and thereafter (from *E* to *F*) the expansion curve follows a trend somewhat similar to that of the nickel or iron of which the alloy is composed. It is clear that the minimum expansivity prevails only in the range from *C* to *D*.

Between *D* and *E* the coefficient is changing rapidly to a higher value. The temperature limits for a *well-annealed* 36% Ni iron alloy are 162 and 271 C. These temperatures correspond to the initial and final loss of magnetism in the material. The slope of the curve between *C* and *D* is then

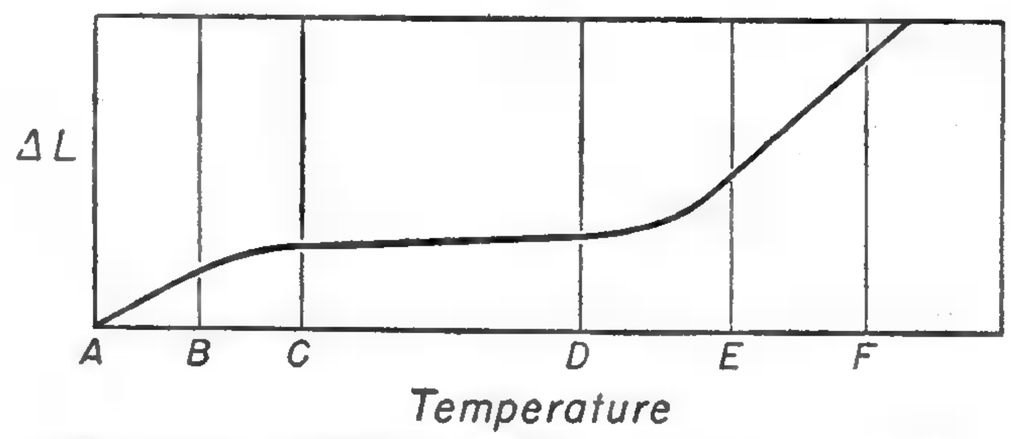

Fig. 3 Change in length (ΔL) with temperature (T) of a typical Invar (Guillaume)

a measure of the coefficient of expansion over a limited range of temperature. The data in Table I are given by Guillaume for the coefficient of linear expansion between 0 and 38 C.

Over wider ranges of temperature, the behavior of the alloys is represented by the curves of Fig. 4. For comparison, the curve of length versus temperature for an ordinary steel is included.

Heat treatment or cold work changes the expansivity of Invar (or Nilvar) considerably. The effect of heat treatment is shown in Table II by Russell. The expansivity is

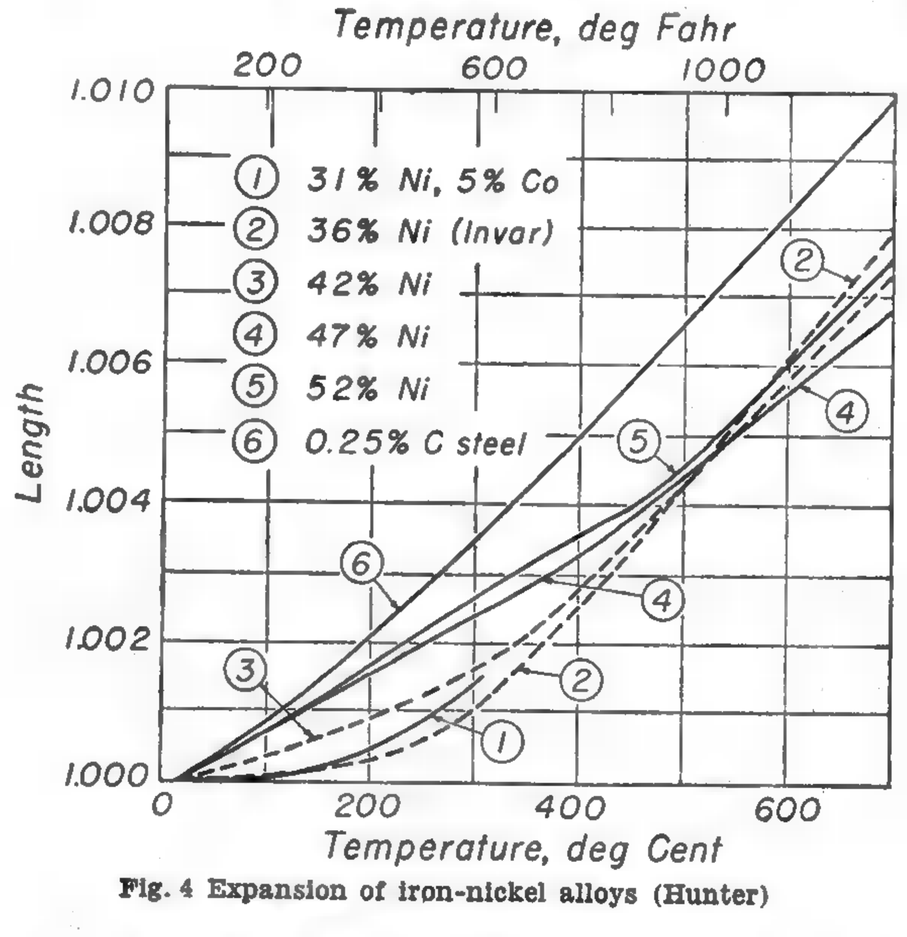

Fig. 4 Expansion of iron-nickel alloys (Hunter)

greatest in well-annealed material and least in the quenched samples.

Cold drawing also decreases the expansivity. The values for the coefficient in Table III are from experiments by the author on two heats of Nilvar (Invar).

By cold work after a quenching operation it is possible to produce material with a zero coefficient of expansion or even a negative one. A negative coefficient may be increased to zero by careful annealing at a low temperature. All these artificial methods of securing a low coefficient produce instability in the material. With lapse of time and variation in temperature, the low coefficients will usually recede to the normal values for the material. This aging is responsible for the secular and transitory changes that take place in the material. Although these variations are important in special applications, such as geodetic tapes, they are of little significance in ordinary operations. For such special applications it is essential to stabilize the material by cooling it slowly from 100 to 20 C over a period of many months, followed by prolonged aging at room

temperature; but unless the material is to be used subsequently within the limits of the atmospheric variation in temperature, such stabilization is of no value.

Magnetic Properties. All iron-nickel alloys of the Invar class are magnetic at room temperature. They lose their magnetism at higher temperatures and become paramagnetic. The points of inflection in the curves of Fig. 4 indicate the loss of magnetism. For a true Invar (36% Ni) Russell found that, in a well-annealed sample, the loss of

Table I. Thermal Expansion of Iron-Nickel Alloys

% Ni	Mean Coefficient × 10^6 per °C	% Ni	Mean Coefficient × 10^6 per °C
31.4	$3.395 + 0.00885\,t$	43.6	$7.992 - 0.00273\,t$
34.6	$1.373 + 0.00237\,t$	44.4	$8.508 - 0.00251\,t$
35.6	$0.877 + 0.00127\,t$	48.7	$9.901 - 0.00067\,t$
37.3	$3.457 - 0.00647\,t$	50.7	$9.984 + 0.00243\,t$
39.4	$5.357 - 0.00448\,t$	53.2	$10.045 + 0.00031\,t$

magnetism began at 162 C and was complete at 271 C. In a quenched sample, the loss began at 205 C and was complete at 271 C.

Slow cooling through this range of temperature eliminates, to a large extent, the transitory and secular changes that are always troublesome in materials of this class.

Electrical Properties. The electrical resistivity of Invar is in the range from 75 to 85 microhm-cm at ordinary

Table II. Effect of Heat Treatment on the Coefficient of Expansion of Invar

Treatment	Mean Coefficient, × 10^{-6} per deg Cent	
After forging	17 to 100 C	1.66
	17 to 250 C	3.11
Quenched from 830 C	18 to 100 C	0.64
	18 to 250 C	2.53
Quenched from 830 C, tempered	15 to 100 C	1.02
	15 to 250 C	2.43
Cooled from 830 to room temperature in 19 hr	15 to 100 C	2.01
	15 to 250 C	2.89

temperatures. The temperature coefficient of electrical resistivity is of the order of 0.0012 per °C over the range of low expansivity. The thermoelectric power (against copper) is about 10 microvolts per °C.

Other Physical and Mechanical Properties. From various sources Sands has collected information on the miscellaneous properties of Invar, from which the data of Table

Table III. Effect of Quenching and Cold Drawing on the Expansivity of Invar per degree Centigrade

Direct from Hot Mill	Annealed and Quenched	Quenched and Cold Drawn 0.125 to 0.250 In.
1.4×10^{-6}	0.5×10^{-6}	0.14×10^{-6}
1.4×10^{-6}	0.8×10^{-6}	0.3×10^{-6}

IV are taken. The alloy was in the hot rolled or forged condition.

The effect of temperature on the mechanical properties is shown in Fig. 5.

Processing. Considerable care must be used in the hot working of these iron-nickel alloys, since they have a tendency to check and break up unless carefully handled. Invar and related alloys should be annealed in a reducing atmosphere. These alloys are susceptible to intercrystalline attack during annealing; therefore, the best results are usually obtained by annealing in an atmosphere that contains a large percentage of a neutral gas, such as nitrogen, and a small percentage of a reducing gas.

The cold rolling and drawing of these iron-nickel alloys is quite similar to that of nickel.

Heat Treatment of Invar. Annealing between 750 and 850 C (1380 and 1560 F) gives good results. When the alloy is quenched in water from these temperatures, the expansivity of the material is decreased, but instability is induced both in actual length and in coefficient of expansion. To overcome these defects and to stabilize the wire, an anneal is necessary at a low temperature (200 to 300 F) followed by slow cooling to room temperature over a period of months. Slow cooling through the magnetic transformation has also been found satisfactory.

Table IV. Some Physical and Mechanical Properties of Invar

Solidus temperature	1425 C (2600 F)
Density	8.0 ■ per cu cm (500 lb per cu ft)
Tensile strength	65,000 to 85,000 psi
Yield point	40,000 to 60,000 psi
Elastic limit	20,000 to 30,000 psi
Elongation	30 to 45%
Reduction in area	55 to 70%
Scleroscope hardness	19
Brinell hardness	160
Modulus of elasticity in tension	21,400,000 psi
Thermoelastic coefficient	500 × 10^{-6} per °C
Specific heat (25 to 100 C)	0.123 cal per ■ per °C
Thermal conductivity (20 to 100 C)	0.0262 cgs units
Thermoelectric power (against copper) (minus 96 C)	9.8 microvolts per °C

Applications. Invar is used for absolute standards of length; rods and tapes for geodetic work; compensating pendulums and balance wheels in clocks and watches; elements in moving parts where control of expansion is necessary as in automobile pistons; and thermostatic strip.

Other Iron-Nickel Alloys. Alloys of iron and nickel that contain more nickel than Invar, retain to some extent the expansion characteristics of Invar.

Since further additions of nickel raise the temperature at which the inherent magnetism of the alloy disappears, the inflection temperature in the expansion curve rises with the increasing nickel content. Although this increase in range is an advantage in some circumstances, it is obtained at a sacrifice of the low coefficient of expansion.

Scott[3] has published information on the coefficient of expansion of iron-nickel alloys up to the inflection tem-

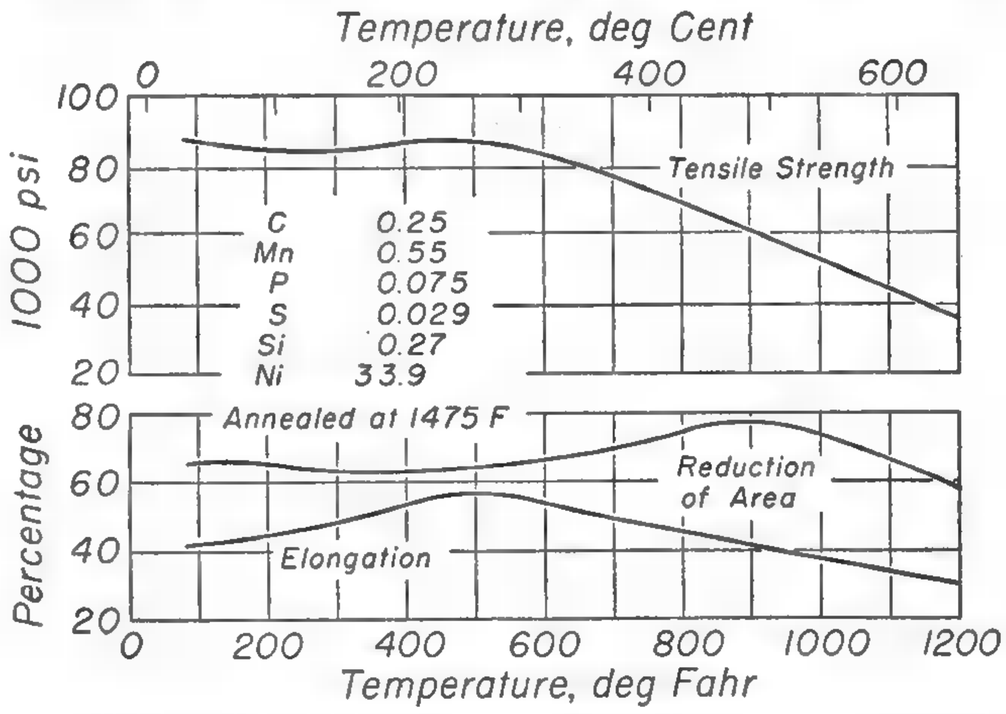

Fig. 5 Effect of temperature on the mechanical properties of forged 34% Ni iron-nickel alloys (MacPherran)

perature. Lohr and Hopkins[5] give data on a more extended range of nickel contents up to 68%, as presented in Table V and Fig. 6.

Special Alloys. Certain ternary alloys that contain nickel and iron are interesting by reason of their special properties.

Super Nilvar. The replacement of some of the nickel by cobalt in an alloy of the Invar composition results in a lowering of the linear coefficient of expansion of the alloy. An alloy containing 31% Ni and 4 to 6% Co, has a zero coefficient of expansion in the hot rolled condition. Annealing and quenching appear to raise the coefficient somewhat, but in general the coefficient obtained from these alloys is lower than that obtained from Invar unless it is subjected to cold work. An extensive investigation of this class of alloys has been made by Masumoto.[1]

Fe-Ni-Co Alloys. Scott[3] has investigated the expansion properties of a series of low-expansion Fe-Ni-Co alloys

over a range of cobalt additions as high as 40%. Such additions increase the coefficient of expansion at room temperature, but since they also raise the inflection temperature, they produce an alloy with a moderately low coefficient of expansion over a wider range of temperature.

Table V. Expansion Characteristics of Iron-Nickel Alloys

Composition, % Mn	Si	Ni	Inflection Temperature,(a) deg Cent	Average Coefficient of Expansion to Inflection Temp, × 10⁻⁶ per deg Cent
0.11	0.02	30.14.....	155	9.2
0.15	0.33	35.65.....	215	1.54
0.12	0.07	38.70.....	340	2.50
0.24	0.03	41.88.....	375	4.85
...	...	42.31.....	380	5.07
...	...	43.01.....	410	5.71
...	...	45.16.....	425	7.25
0 35	...	45.22.....	425	6 75
0.24	0.11	46.00.....	465	7.61
...	...	47.37.....	465	8.04
0.09	0.03	48.10.....	497	8.79
0.75	0.00	49.90.....	500	8.84
...	...	50.00.....	515	9.18
0.25	0.20	50.05.....	527	9.46
0.01	0.18	51.70.....	545	9.61
0.03	0.16	52.10.....	550	10.28
0.35	0.04	52.25.....	550	10.09
0.05	0.03	53.40.....	580	10.63
0.12	0.07	55.20.....	590	11.36
0.25	0.05	57.81.....	...	12.24
0.22	0.07	60.60.....	...	12.78
0.18	0.04	64.87.....	...	13.62
0.00	0.05	67.98.....	...	14.37

(a) Note that in alloys containing more than 55% Ni, the inflection temperature is not in evidence.

Scott expresses his observations in the form of equations. If θ is inflection temperature in degrees Centigrade, X the nickel content, Y the cobalt content, Z the manganese content and W the carbon content, the inflection temperature of any alloy in the group studied is given by:

$$\theta = 19.5\,(X + Y) - 22Z - 0W - 465$$

Introducing the restriction that the nickel and iron contents shall be so related as to depress the Ar_3 point to about minus 100 C, then:

$$Y = 0.0795\theta + 4.8Z + 19W - 18.1$$
$$X = 41.9 - 0.0282\theta - 3.7Z - 19W$$

for inflection temperatures between 200 and 600 C.

Table VI. Minimum Coefficient of Expansion in Relation to Nickel and Titanium Contents

Percentage Ti	Optimum Ni	Coefficient of Expansion, × 10⁻⁶ per °C
0	36.5	1.4
2	40.0	2.9
3	42.5	3.6

The expansivities obtainable with these compositions are given by:

$$a_1 \times 10^6 = 0.024\theta + 0.38Z - 1.2W - 6.65$$
$$a_2 \times 10^6 = 0.024\theta + 0.38Z - 1.2W - 5.6$$

The former represents minimum expansivity and the latter mean expansivity when θ is between 350 and 600 C.

Applications of these alloys for sealing wires in glass are given by Scott[4] and by Hull and Burger.[5] Scott's alloy "Kovar" and Hull's alloy "Fernico" contain approximately 54% Fe, 28% Ni, and 18% Co.

Fe-Co-Cr Alloys. Masumoto[2] has studied an alloy containing 36.5 to 37% Fe, 53 to 54.5% Co, and 9 to 10% Cr, which has an exceedingly low coefficient of expansion, at times negative over the range from 0 to 100 C. An alloy in this class is suggested by Hull as a seal-in wire in special glasses, "Fernichrome", containing 37% Fe, 30% Ni, 25% Co and 8% Cr.

Elinvar. In determining the thermoelastic coefficients of iron-nickel alloys, Guillaume found that Invar has the highest elastic coefficient of all the alloys in the related group. However, two alloys at 29 and 45% Ni have zero thermoelastic coefficient; that is, the modulus of elasticity does not change with variations in temperature. But since, in these alloys, small variations in the nickel content produce large variations in the thermoelastic coefficient, the

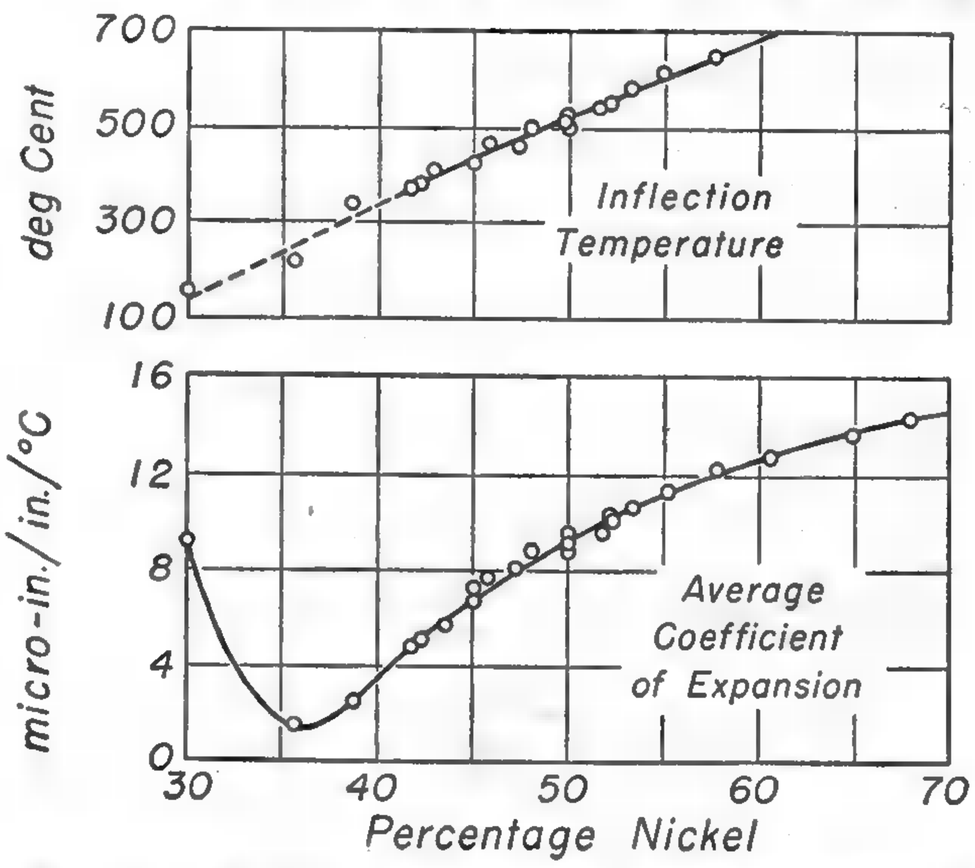

Fig. 6 Effect of nickel content on the expansion characteristics of iron-nickel alloys. (*Upper*) **Effect on the inflection temperature.** (*Lower*) **Effect on the average coefficient of expansion between room temperature and the inflection temperature**

commercial application of the discovery has been a difficult one. Guillaume found that the addition of 12% Cr to an alloy containing 36% Ni produces an alloy that has zero thermoelastic coefficient without susceptibility to small variations in nickel content, which are to be expected in commercial melting. This alloy was named "Elinvar".

Elinvar has a particular application in the construction of such articles as hairsprings and balance wheels in clocks and watches, and in tuning forks used in radio synchronization where an invariable modulus of elasticity is required. This alloy has the further advantage of being comparatively rustproof.

The composition of this material has been somewhat modified from the original specifications. Shubrooks gives the following limits for the material as now used:

Nickel	33 to 35%	Manganese	0.5 to 2%
Iron	61 to 53%	Silicon	0.5 to 2%
Chromium	4 to 5%	Carbon	0.5 to 2%
Tungsten	1 to 3%		

Hardenable Alloys. Alloys of the type having a low coefficient of expansion and those having a constant modulus of elasticity can be made age hardenable by additions of titanium.[12,13,14]

In alloys of the low-expansion type, the nickel content

Table VII. Mechanical Properties of Iron-Nickel Alloys with 2.4% Ti, 0.06% C

Condition	Yield Strength (0.2% offset), psi	Tensile Strength, psi	Elong, % in 2 in.	Bhn
42% Ni, Inflection Temperature 220 C, Min Coefficient Expansion 3.2 × 10⁻⁶ per °C				
Solution treated.....	40,000	90,000	32	140
Solution treated and age hardened..	120,000	165,000	14	330
Solution treated, cold rolled 50% and age hardened..	165,000	195,000	5	385
52% Ni, Inflection Temperature 440 C, Min Coefficient Expansion 9.5 × 10⁻⁶ per °C				
Solution treated.....	35,000	85,000	27	125
Solution treated and age hardened..	95,000	120,000	17	305

must be increased, as shown in Table VI, when titanium is added, since any titanium that has not combined with the carbon content of the alloy, will neutralize more than twice its own weight of nickel by forming an intermetallic compound during the hardening operation.

Table VIII. Thermoelastic Coefficients of Fe-Ni-Cr-Ti Alloys

Composition, % Ni	Cr	C	Ti	Thermoelastic Coefficient × 10^6, per °C	Possible Variation by Heat Treatment
42	5.4	0.06	2.4	0	+ 18 to − 23
42	6.0	0.06	2.4	+ 36	+ 54 to + 13
42	6.3	0.06	2.4	− 36	− 18 to − 60

The addition of titanium (1) raises the lowest attainable rate of expansion, (2) raises the nickel content at which the minimum occurs, and (3) lowers the inflection temperature.

Mechanical properties of alloys containing 2.4% Ti and 0.06% C are given in Table VII.

In alloys of the constant-modulus type, the titanium additions can be used to control the thermoelastic coefficient by variation in heat treatment. The three compositions listed in Table VIII cover the usual range.

Recommended solution treatment for the alloys that contain 2.4% Ti is 950 to 1000 C for 20 to 90 min, depending on size. Recommended duration of aging varies from 48 hr at 600 C to 3 hr at 730 C for solution-treated material and from 4 hr at 600 C to 1 hr at 730 C for material that has been solution-treated and subsequently cold worked 50%.

Table IX. Mechanical Properties of a Constant-Modulus Alloy Containing 42% Ni, 2.4% Ti, 5.4% Cr

Condition	Yield Strength, psi	Tensile Strength, psi	Elong, % in 2 in.	Bhn	Modulus of Elasticity, million psi
Solution treated.....	35,000	90,000	40	145	24
Solution treated and aged 3 hr at 730 C	115,000	180,000	18	345	26.5
Solution treated and cold worked 50%.	130,000	135,000	6	275	25.5
Solution treated, cold worked 50% and aged 1 hr at 730 C....	180,000	200,000	7	395	27

Table IX lists the mechanical properties of a constant-modulus alloy containing 42% Ni, 2.4% Ti and 5.4% Cr.

Engineering Applications. The use of alloys that have low coefficients of expansion has been confined mainly to such applications as geodetic tape, bimetal strip, and glass-to-metal seals. Newer applications appear in the electronic and radio fields.[15] Variable condensers are built almost entirely of Invar. Struts used on jet engines are made of Invar to ensure rigidity with temperature changes. Contact tabs of 47% Ni alloy, used in electrical resistors, match the expansion characteristics of the enamel.

Where exacting specifications call for definite and invariable properties, these alloys with low coefficients of expansion are being made by powder metallurgy.

Machining Properties. Where free-machining is desirable, the addition of 0.25% Se to the alloy produces satisfactory results.

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Ferrous Alloys Containing from 3 to 20% Aluminum

By Kent R. Van Horn*

ALUMINUM is added to certain ferrous alloys in appreciable quantities to improve the electrical and magnetic properties or the resistance to oxidation. The aluminum additions ranging from 3 to 20% exceed the quantities used for the nitriding steels or irons and for the deoxidation of steel. The alloys may be classed according to two general types of application—electrical and heat resistance.

Permanent Magnet Alloys Containing Aluminum. The improvement of the magnetic properties of iron or steel by aluminum is generally recognized. The beneficial influence of aluminum, like that of silicon, on magnetic permeability is indirect; that is, aluminum influences permeability beneficially through its effect on carbon, oxygen and perhaps other elements, although directly aluminum would probably affect pure iron adversely. Except for carbon in solution, aluminum and silicon, more than any other elements, increase the resistivity of iron, a property very important in a-c circuits.[1] The specific electrical resistance of iron is increased by 12 microhm-centimeters for each per cent of aluminum up to 3%. The electrical resistance of the 3½% Al composition is slightly less than that of the 3 to 4½% Si type. However, with the same method of preparation (vacuum melting), the silicon alloys are characterized by brittleness, while the 3½% aluminum iron has considerable ductility. There are some electrical installations where the aluminum-iron alloy has replaced the less expensive silicon types because the comparative brittleness of the iron-silicon alloys was undesirable. In general, aluminum has never become a serious competitor of silicon, because of difficulties encountered in manufacturing processes.

In 1934, patents were granted describing alloys containing aluminum and intended for permanent magnets. An iron alloy (Alnico) containing 10 to 20% Al, 20% Ni, 5% Co, and no carbon, has qualities surpassing those of the 30% cobalt-tungsten permanent magnet type.[2] The exceptional properties of this material have been utilized in an expanding field of magnetic applications.

Electrical Resistor Alloys. A series of electrical resistors containing iron, chromium and aluminum, is marketed as Alcres, Ohmax,[3] and Megapyr.[4] An alloy containing about 20% Cr, 5% Al, and the remainder iron, has a specific resistivity of 800 ohms per circular mil ft. If the aluminum content is increased to 10%, the material has a specific resistivity of 1000 ohms per circular mil ft. The value for a common nickel-chromium resistor is 650 ohms. The alloys containing aluminum also have excellent resistance to oxidation at elevated temperatures. These two qualities, and a lower density than the nickel-chromium type, are utilized for applications where large total resistances are required for a minimum space, as in radio resistors. The alloys are

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more difficult to fabricate but can be produced in diameters as small as 1 mil for radio wires.

There is another group of resistors similar in composition and properties, except that cobalt is added. This Kanthal series[5] has about 25% Cr, 5% Al, 3% Co, and the remainder almost pure iron. The electrical resistance ranges from 810 to 875 ohms per circular mil ft. The density is lower than that of the nickel-chromium resistors, being 7.15 as compared with 8.35 g per cu cm. When fabricated from these metals, ribbons or wires of the standard sizes are recommended for use at temperatures from 2000 to 2450 F, because of the superior resistance to oxidation. However, the tensile strength is low at elevated temperatures, so it is necessary to provide suitable supports for the elements in the installation.

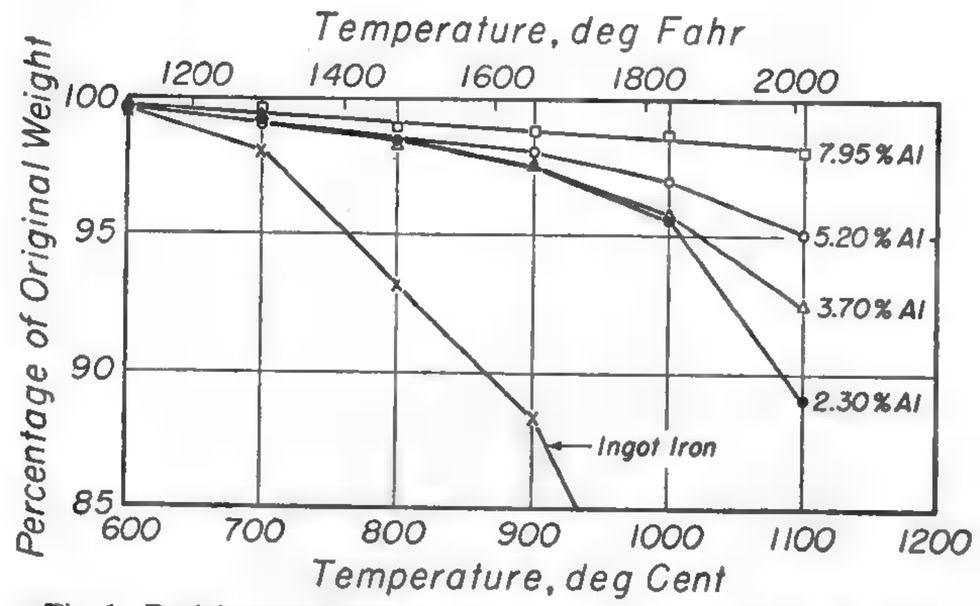

Fig. 1 Resistance of iron-aluminum alloys to oxidation at elevated temperature. Samples were held for two hours in air at the various constant temperatures, then ground to remove the oxidized surface, and the unoxidized portion was weighed. The alloys contained less than 0.01% C. Data for ingot iron are plotted for comparison. (N. A. Ziegler[8])

A third iron-base alloy[6] of this type is Smith Alloy No. 10. The chromium and aluminum contents, appreciably higher than in the first two groups, are 37.5% Cr, 7.5% Al, the remainder iron. The electrical resistance is 1000 ohms per circular mil ft and the density of the material is 6.9, so the volume is 22% greater than the volume of the same weight of the nickel-chromium type. The alloy can be hot formed into the required bends and helices. It is necessary to provide the correct type of nonsilica refractories and supports that allow for thermal expansion, growth and sagging of the elements. The three Fe-Cr-Al types are effective for high-temperature applications, such as furnaces for the heat treatment of high speed steel, heating steel for forging, and burning ceramic materials. These resistors also compete with the silicon carbide type in the higher part of their recommended temperature range.

Table I gives a comparison of some properties of iron-chromium-aluminum alloys and other materials used for electrical resistors.[13]

Iron-Aluminum Heat-Resisting Alloys. The outstanding resistance of iron-aluminum alloys to oxidation at elevated temperatures was reported in 1931 by Hauttmann.[7] The resistance to oxidation of the binary iron-aluminum alloys increases with the aluminum content from 4 to 9% Al (*see* Fig. 1[8]). In 1932 Ziegler[8] found that 4% Al when added to iron (vacuum melting) produced a forgeable alloy with good resistance to oxidation. Compared with the 80% Ni, 20% Cr type, alloys containing 6% Al have slightly inferior resistance to the softening effect of heat, but alloys containing 8% Al have superior resistance. These iron-aluminum alloys are forgeable to some extent and the presence of carbon has little effect on the resistance to scaling. The recognition of these characteristics has resulted in the development of a number of steels and irons containing aluminum.

The American Iron and Steel Institute has formulated specifications for a standard heat-resisting alloy, 406D, containing 12 to 14% Cr, 4.5% Al, 0.12% C, with the remainder iron. A well-known steel of this type is No. 1 JR. Castings and forgings are produced to a limited extent.

Alloys containing 7 to 15% Cr, 2 to 6% Al, and 1% C, are forgeable if the total aluminum and silicon content does not exceed about 5.5% with the silicon[9] about 1%. The steels may exhibit good resistance to oxidation at 1550 to 1850 F, depending on the total quantity of aluminum, chromium and silicon. These alloys have no wide application, because the beneficial properties can be procured more economically with silicon.

Aluminum has been added to the 18% Cr, 8% Ni stainless steel in quantities as large as 3%, to prevent scaling at high temperature and to increase machinability without impairing the other properties.[10,11] Modified casting alloys of this type containing aluminum have trade names of "Fahralloy" and "Hybnickel", with certain designating numbers.

High-silicon, high-aluminum cast irons constitute one of the four types of "refractory" cast irons widely used in Europe.[12] These alloys, containing 6 to 9% Si, 3 to 7% Al, have excellent resistance to oxidation but are not employed where high tensile strength is required. The silicon-aluminum cast irons are considerably cheaper than the other three common types of "refractory" irons.

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Table I. Data Concerning Electrical Resistors[13]

Typical Composition, percentage	Resistance, ohms per circ mil-ft	Temperature Coefficient per °F to 212 F	Resists Oxidation Below (°F)	Begins to Melt at (°F)	Strength at High Temperature	Growth at Working Temperature	Relative Prices
Ni-Cr, Ni-Cr-Fe, Fe-Cr Alloys							
80 Ni, 20 Cr	650	0.00006	2100	2540	Excellent	Slight	Medium
60 Ni, 15 Cr, 25 Fe	675	0.00007	1830	2460	Excellent	Slight	Medium
30 Ni, 20 Cr, 50 Fe	600	0.00017	1560	2550	Good	Slight	Low
28 Cr, 72 Fe	400	0.0006	1750	2375	Poor	Considerable	Low
Fe-Cr-Al Alloys							
80 Fe, 15 Cr, 5 Al	750	0.00005	2100	2910	Poor	Excessive	Low
68 Fe, 27 Cr, 5 Al	850	0.00002	2275	2780	Poor	Excessive	High
55 Fe, 37.5 Cr, 7.5 Al	1000	0.00012	2600	2830	Fair	¼ in. per ft	High
67 Fe, 25 Cr, 5 Al, 3 Co	900	0.00003	2375	3000	Poor	Excessive	High
Molybdenum and Platinum							
Molybdenum	33	0.0022	1300	6510	Good	Slight	Very high
Platinum	72	0.0021	3190	3190	Good	Slight	Very high

HEAT TREATMENT OF STEEL

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Isothermal Transformation Diagrams of Steel

By E. S. Davenport*

WHEN a steel in the austenitic condition is held at any constant temperature below the range in which its austenite is stable, it will in time transform to the ferritic condition, with accompanying precipitation of carbide, if the holding temperature is within the range in which carbide exists as a separate phase. The progress of the transformation can be followed experimentally by methods that will not be discussed in detail here, since they have been described in the literature.[1,2,3] A graphic representation of the course of transformation is best obtained by plotting the percentage of austenite that has transformed, against the corresponding time that has elapsed at temperature, as illustrated in the upper portion of Fig. 1. The general form of this graph is typical of the course of transformation of a particular steel at constant temperature; the position of the curve on the time scale, and the slope depend both on the temperature level and on the actual composition and grain size of the austenite undergoing transformation.

For any one steel, most of the useful information given by a series of such graphs, each representing a different temperature level, can be summarized in a single diagram, as illustrated in the lower portion of Fig. 1, in which the symbol *A* represents untransformed austenite, *F* represents ferrite, and *C*, carbide. This type of chart, variously known as the isothermal transformation diagram,[3,4] S-curve,[1] or transformation-temperature-time (TTT) curve,[5,6] is a convenient means of showing the time required for austenite to begin and to finish transforming at any temperature level below its range of stability. Thus the diagram may be regarded as a kind of map or working drawing that enables one to visualize or anticipate approximately how the steel will behave and what structural changes will take place when it undergoes transformation from the austenitic state. The form and position of each of the curves constituting the diagram depend on the composition and grain size of the austenite that is undergoing transformation. Certain alloying elements or combinations of elements change the form of the curve in a characteristic way; a few typical examples, illustrating these alloying effects in terms of the isothermal transformation diagram, are presented in this article. With few exceptions, an increase in alloy content or in grain size of the austenite always *retards* transformation (moves the curves toward the right), at least at temperature levels higher than about 900 F—that is, at and above what is known as the "nose" or "knee" of the curve. This retardation is reflected in the greater hardenability of steels of higher alloy content or of coarser grain.

The significance and usefulness of the diagram in modern heat treating practice have been discussed at length

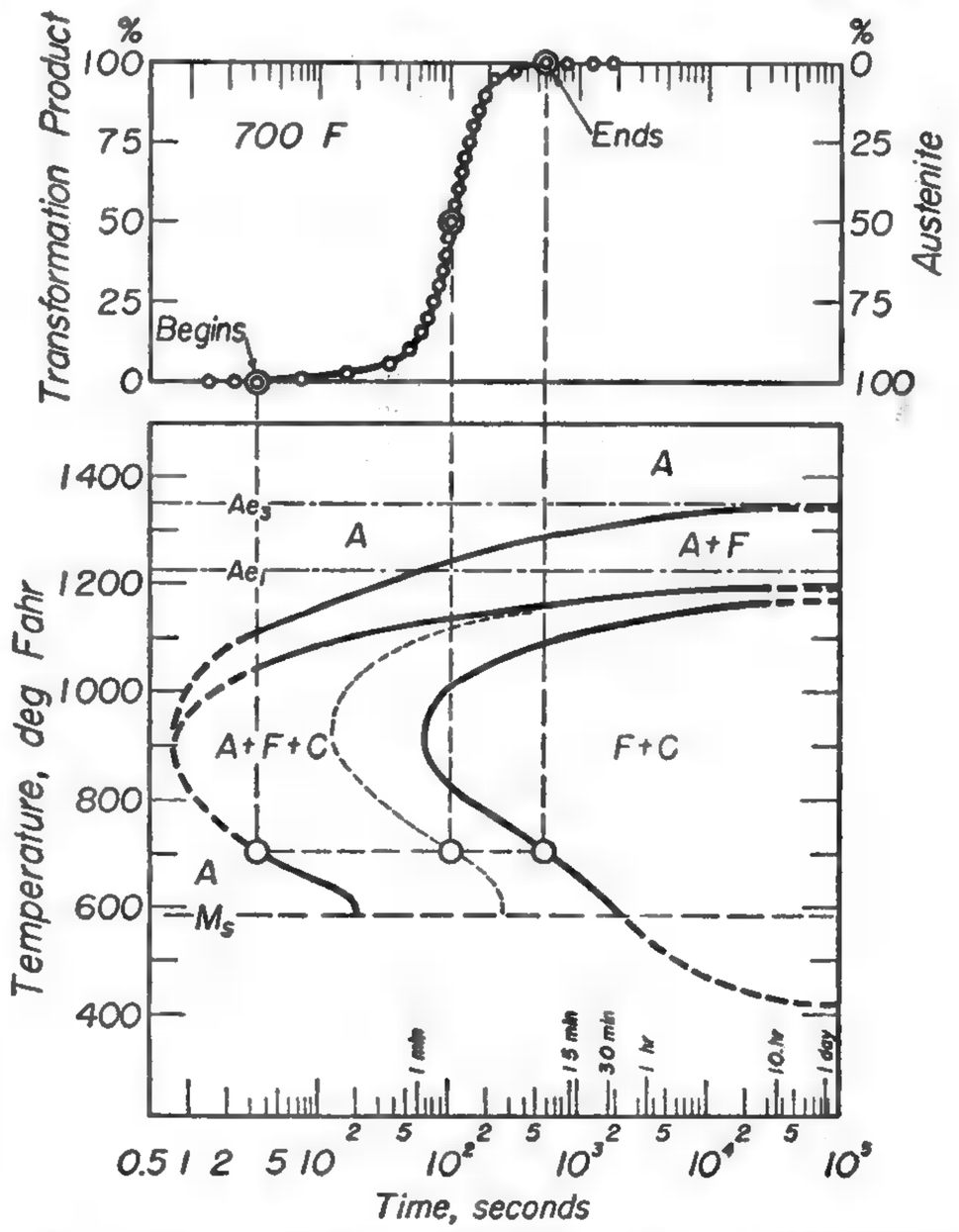

Fig. 1 Typical isothermal transformation curve at a single temperature, and its relation to the complete isothermal transformation diagram

elsewhere[1,3,4,6,7,8] and cannot be covered fully in this article. It must suffice to say that the isothermal transformation diagram is being used, on an ever widening scale, as the scientific basis of heat treatment; for it is

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Prepared for the Subcommittee on Alloying Elements in Steel.

now generally recognized that the response of a steel to any specified heat treatment which involves the transformation of austenite is governed largely, if not entirely, by those factors which influence the time required for such transformation and the temperature at which it occurs; hence by the shape and position of the curves comprising the isothermal diagram. Perhaps the greatest usefulness of the diagram lies in the over-all picture that it presents of the transformation behavior of austenite. With this general concept in mind, it is possible to interpret and correlate many observed phenomena on a rational basis. Thus the metallurgist or heat treater can plan more intelligently the steps he must take to solve many of his problems.

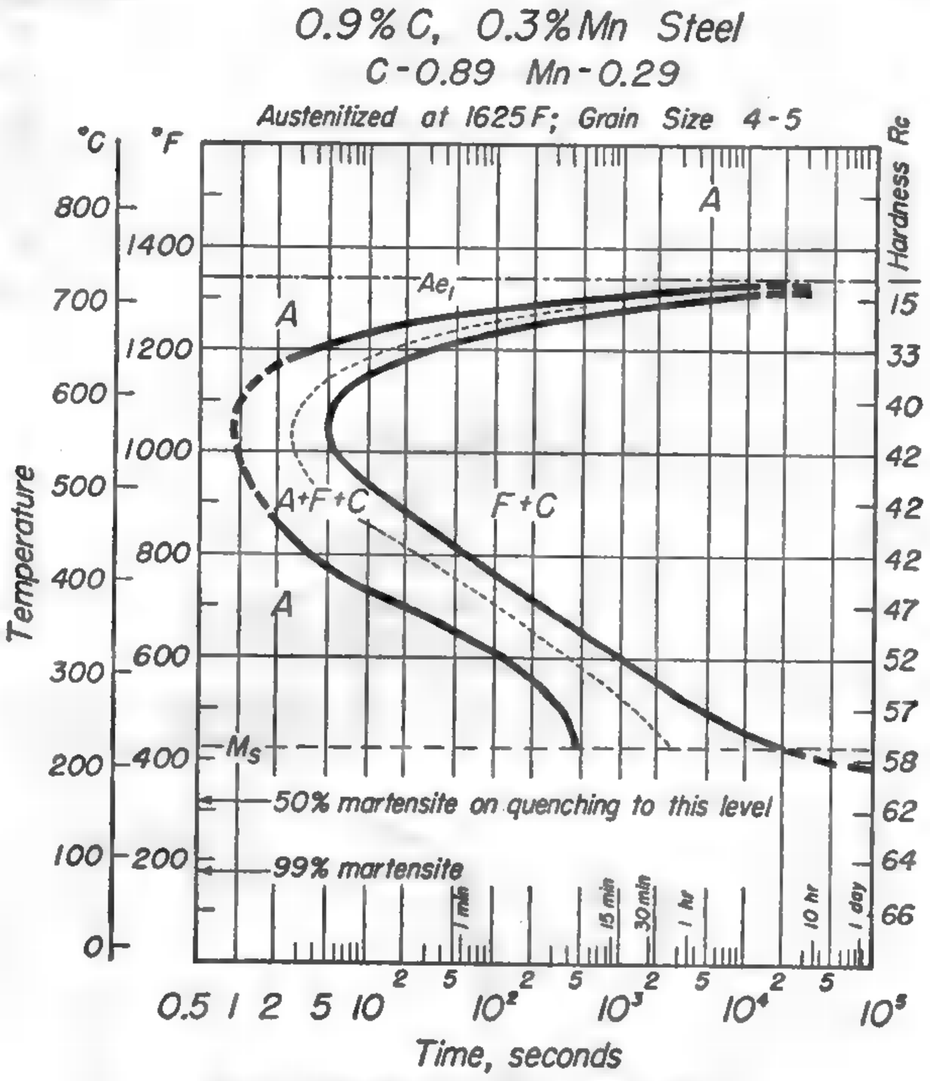

Fig. 2 SAE 1095, eutectoid carbon steel

Features Common to All the Diagrams. Before passing to a discussion of typical diagrams illustrating the effects of specific alloying elements in steel, it may be helpful to point out certain features more or less common to all the charts, and to discuss briefly the significance of the various lines and fields of the diagram. Figure 3 will serve to illustrate this discussion.

At the top of each chart there is sufficient information to identify the steel with respect to significant chemical composition, the austenitizing temperature employed and the grain size of the austenite developed at that temperature. In the left-hand margin appear the temperature scales; the basic scale is in degrees Fahrenheit. Time is plotted on a logarithmic scale along the horizontal axis; the basic scale at the bottom of the chart is in seconds, with a few representative time intervals shown in terms of minutes, hours or days, for convenience in locating quickly some familiar reference points on the time scale. In the right-hand margin is the Rockwell C hardness of the structure at room temperature, after substantially complete transformation at each different temperature level. At the bottom of this column is the full martensitic hardness achieved by quenching a small sample in brine, directly from the austenitizing temperature employed.

The Ae_1 and Ae_3 temperatures, shown as horizontal dot-dash lines at the appropriate temperature levels, are based on actual determinations under equilibrium conditions. When the lines of the diagram are considered in order, from left to right, the first heavy, curved line represents the time for beginning of transformation at any temperature level. In hypoeutectoid steels, this initial transformation consists of the separation of proeutectoid ferrite at temperatures between Ae_3 and the "knee" of the curve, which is in the range from 900 to 1100 F for most hypoeutectoid steels. The field above and to the left of this beginning line is marked *A* to indicate that in this time-temperature region the steel consists entirely of austenite *A*, which may be either stable or unstable, depending on whether it is above or below the Ae_3 temperature. At temperatures between the "knee" of the curve and the Ae_1 temperature, the initial separation of proeutectoid ferrite in hypoeutectoid steels is followed, without interruption, by simultaneous separation of both ferrite and carbide in the form of pearlite. The beginning of this pearlite reaction is represented by the second heavy curved line, and the field between these two uppermost curved lines is marked $A + F$ to indicate that austenite *A* and ferrite *F* exist simultaneously in this time-temperature region; the amount of ferrite increases with time at the expense of the austenite. Below the "knee", only a single beginning line is needed, since no proeutectoid constituent separates before bainite, which is the product of transformation at temperatures below the knee and down to "M_S", the highest temperature at which any martensite forms.

The right-hand curved line represents the time for completion of transformation at each temperature level, and the field between the left-hand and right-hand curves is labeled $A + F + C$ to indicate that austenite *A*, ferrite *F*, and carbide *C* all coexist in this time-temperature region; the ferrite and carbide increase in amount at the expense of the austenite as transformation proceeds to completion. The thin dotted line within the $A + F + C$ field represents the time required for half of the total transformation to take place at each temperature level. The field to the right of the right-hand curve is labeled $F + C$ to indicate that all the austenite has disappeared when this field is reached and that the final structure at completion of transformation consists only of ferrite and carbide.

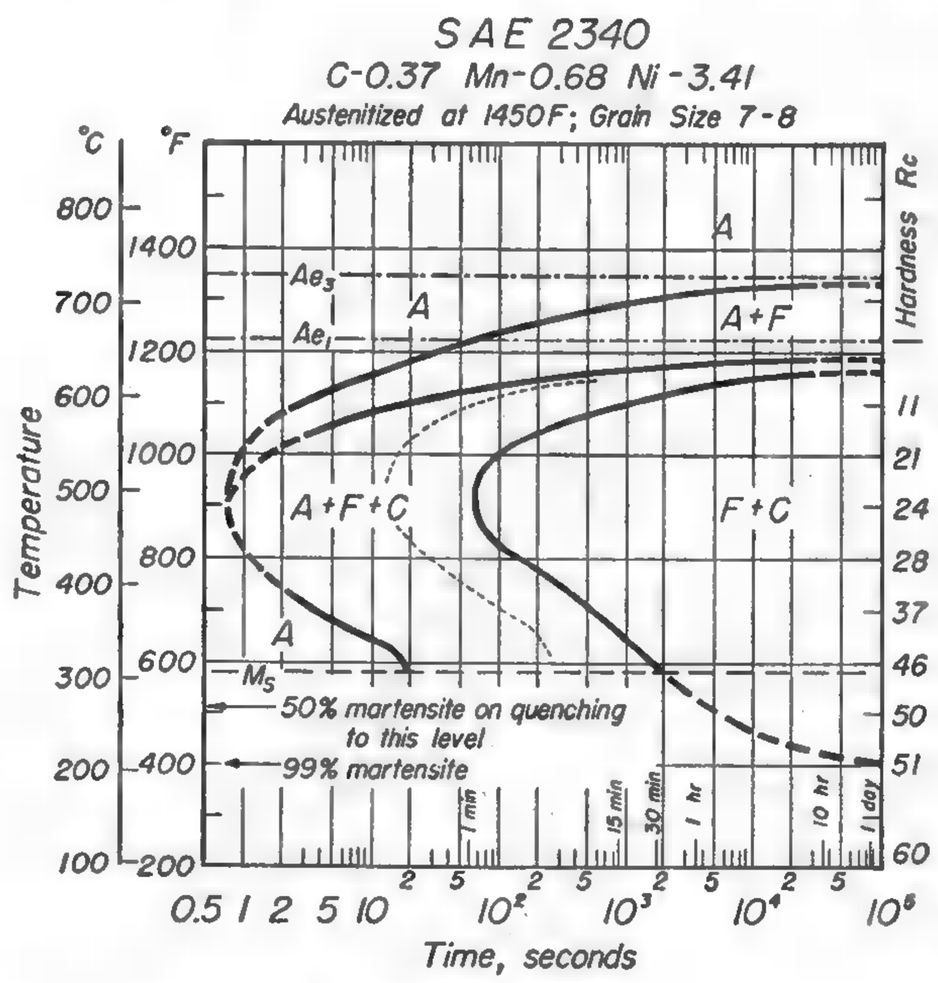

Fig. 3 SAE 2340, nickel steel

The lower portion of the diagram is arranged to indicate, by a horizontal dashed line, the location of the M_S temperature, which is the highest temperature at which any detectable amount of martensite forms on continuous cooling of austenite at rates faster than the critical cooling rate. Strictly speaking, such a datum has no place on a diagram that otherwise depicts only isothermal transformation, as contrasted with transformation during continuous cooling. It is included, nevertheless, because knowledge of the M_S temperature is useful in practical heat treating operations, and in the future most isothermal transformation diagrams will undoubtedly

include this information in some form. (*See* the articles on pages 263 and 611 in this Handbook.) In addition to the M_s temperature, the lower portion of the diagram shows the temperatures at which approximately 50% and 99% martensite are achieved on continuous cooling at rates faster than the critical cooling rate. The prolongation of the isothermal ending line, shown at the lower right of the charts as a heavy dashed curve, represents the probable time for completion of isothermal transformation of any austenite remaining after initial formation of martensite during cooling.

A typical diagram has been described above. Now a few actual examples will be discussed to show the influence of alloying elements on the isothermal transformation diagram. The diagrams selected, taken from a single publication,[4] have been modified to the extent of adding the M_s temperature and related data pertaining to the formation of martensite.

SAE 1095, Plain Carbon Steel of Eutectoid Composition. Figure 2 shows the isothermal transformation diagram for eutectoid carbon steel, which, because of the eutectoid composition of the steel and its consequent freedom from proeutectoid constituents, is the simplest of all the diagrams to be discussed in this article. It consists merely of the two principal curves, one for the beginning and the other for completion of transformation. Since the steel is of eutectoid composition, no proeutectoid ferrite is formed; hence there is no $A + F$ field in the diagram.

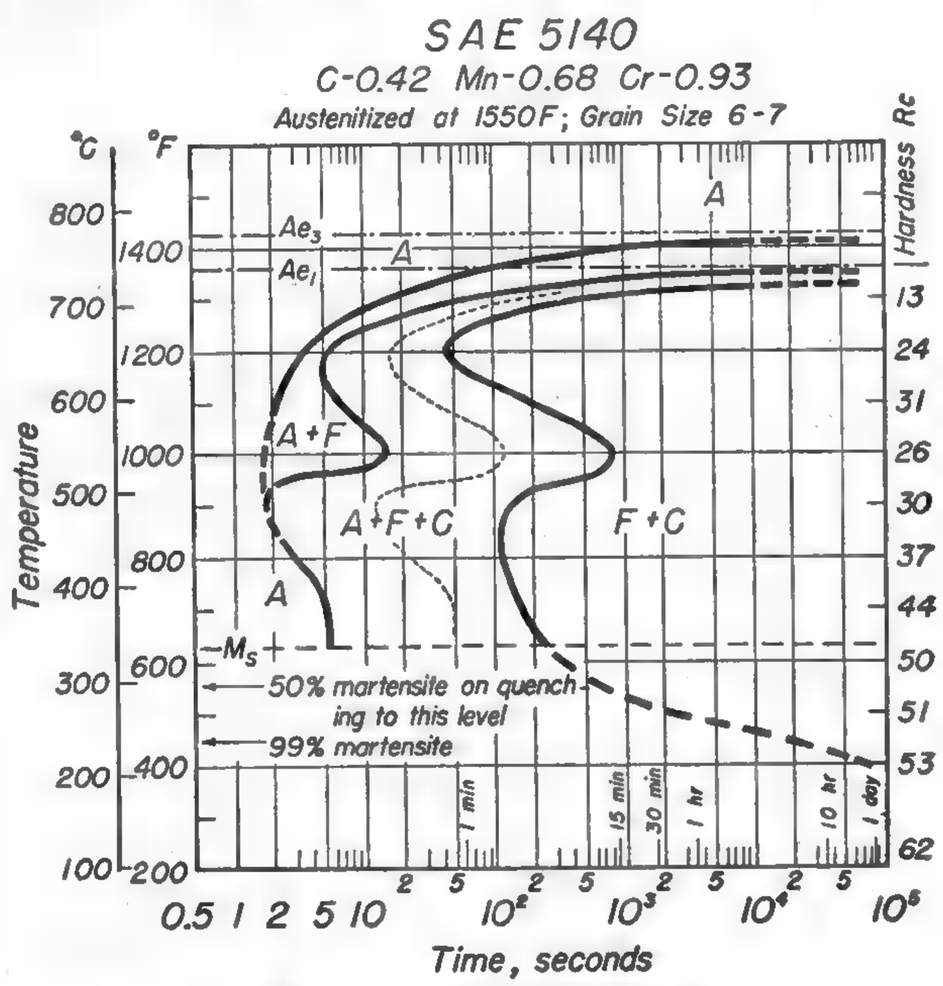

Fig. 4 SAE 5140, chromium steel

In diagrams for hypoeutectoid steels, an $A + F$ field appears above and to the left of the curve representing the beginning of pearlite formation, as shown in Fig. 3, 4, 5, 6 and 7a. On the other hand, in diagrams for hypereutectoid steel there is an $A + C$ field in ■ corresponding location, because proeutectoid carbide is the excess constituent rather than the ferrite which appears in hypoeutectoid steels; Fig. 7b is an example of such hypereutectoid behavior. Both hypoeutectoid and hypereutectoid carbon steels transform more rapidly than eutectoid steel in the vicinity of the knee of the curve (900 to 1100 F). This is particularly true for hypoeutectoid steels, and the lower the carbon content the more the beginning curve is moved toward the left of the diagram. The low hardenability of low-carbon steels is, of course, a direct reflection of this rapid transformation behavior. Increasing the carbon content depresses the M_s point and retards transformation appreciably at the lower temperature levels, as illustrated in Fig. 7a and 7b, to be discussed later; this effect of carbon content on M_s and on transformation rates at low temperature level shows no reversal when the carbon content exceeds that of the eutectoid.

SAE 2340, 3.5% Ni Steel. Figure 3 shows the isothermal transformation diagram for a typical hypoeutectoid alloy steel containing about 3.5% Ni and 0.4% C.

The hypoeutectoid nature of this steel is clearly indicated by the well-defined $A + F$ field. Note the rather low Ae_1 and Ae_3 temperatures resulting from the nickel content. Comparison of this diagram with Fig. 2 serves to emphasize the considerable increase in sluggishness of transformation contributed by the addition of nickel and manganese, as shown by the greater spread between beginning and end of transformation, particularly in the temperature range from 1100 to 600 F. It should be noted also that the higher M_s temperature of the SAE 2340 steel is caused by its lower carbon content and not by the alloying elements present in the steel.

In general, this diagram for SAE 2340 is simple in form and may be considered the hypoeutectoid counterpart of the eutectoid steel shown in Fig. 2, allowing for the special features contributed by nickel and manganese, as discussed above.

SAE 5140, 0.9% Cr Steel. Figure 4 is the isothermal transformation diagram for another typical hypoeutectoid alloy steel, in which chromium is the principal alloying element.

The relatively small size of the $A + F$ field should be noted; also the small gap between Ae_1 and Ae_3, as compared with SAE 2340 (Fig. 3). These features indicate that SAE 5140 is much closer to eutectoid composition than SAE 2340. Note also the peculiar form of the lines that represent the beginning and ending of transformation to the $F + C$ aggregate structures in the vicinity of 1000 F. These features are characteristic of diagrams for chromium steel and are accentuated in alloys that have a higher percentage of chromium. In fact, most of the alloying elements that are classed as strong "carbide formers" tend to introduce similar retarding effects in the beginning and ending of transformation at temperatures in the range from 1200 to 900 F. Attention is again directed to the relative sluggishness of transformation, once it is started, in this alloy steel as compared with eutectoid carbon steel (Fig. 2).

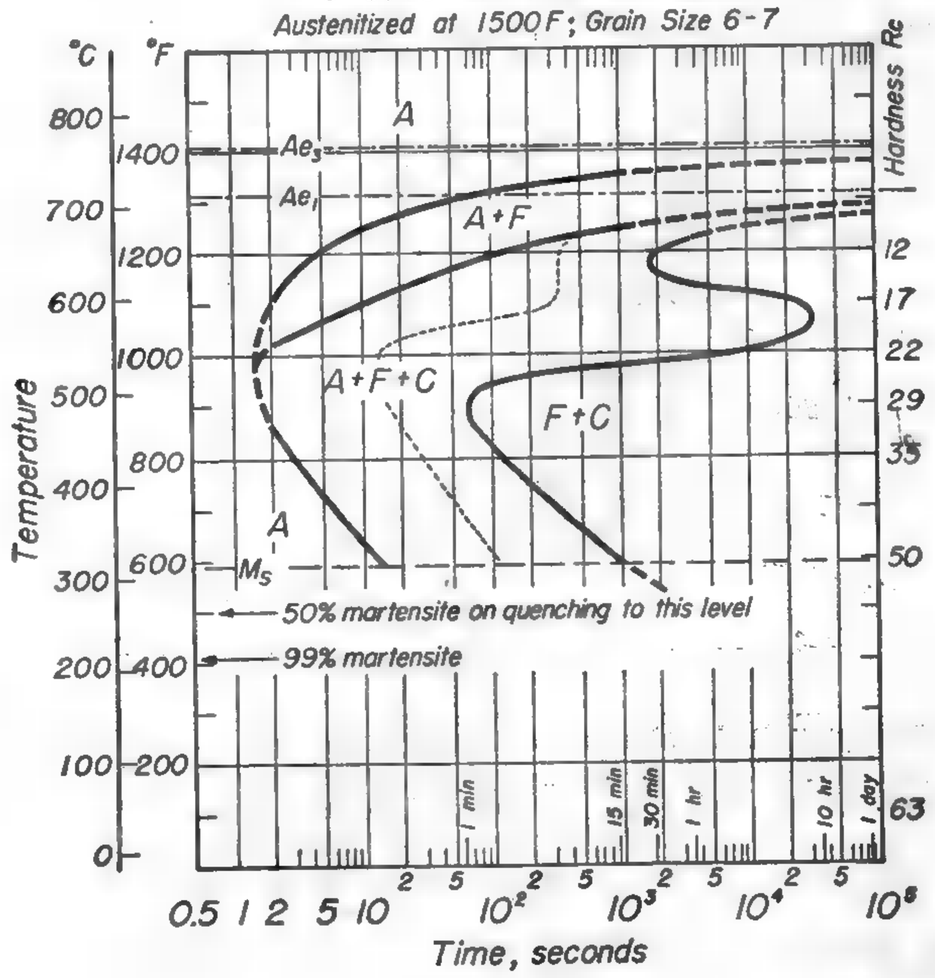

Fig. 5 SAE 4047, molybdenum steel

The effect of chromium, as discussed above, is to slow down transformation and hence contribute to increased hardenability.

SAE 4047, 0.5% C–0.25% Mo Steel. The isothermal transformation diagram for this steel (Fig. 5) serves to illustrate the powerful influence of a small amount of molybdenum in retarding transformation, particularly at temperatures above approximately 900 F.

This steel is distinctly hypoeutectoid, as indicated by the well-defined $A + F$ field. The marked protuberance in the ending line, at about 1050 F, is rather characteristic of diagrams for molybdenum steel and is accentuated by higher percentages of molybdenum; however, this retarding effect does not seem to increase proportionally when the molybdenum content is more than about 0.5%.

SAE 4340, Nickel-Chromium-Molybdenum Steel. Figure 6 illustrates the isothermal transformation diagram of this deep-hardening, triple-alloy steel and constitutes a striking example of the influence of this particular combination of alloying elements in changing the shape and location of the curve.

In spite of the relatively high alloy content, this steel exhibits hypoeutectoid characteristics as evidenced by the $A + F$ field, which in this diagram extends to about 1100 F, beneath the pearlite knee, in contrast with the $A + F$ field in diagrams discussed previously. It should be noted that this diagram has two knees in the beginning line, as does SAE 5140 (Fig. 4)—an upper one at approximately 1150 to 1200 F, and a lower one at approximately 850 F. The upper or "pearlite knee" is pushed quite far to the right on the time axis by the high alloy content, while the lower or "bainite knee" juts out to the left below the 950 F "shelf". It is characteristic of such steels that, at temperatures just below the shelf, the isothermal transformation more nearly approaches completion the lower the temperature.

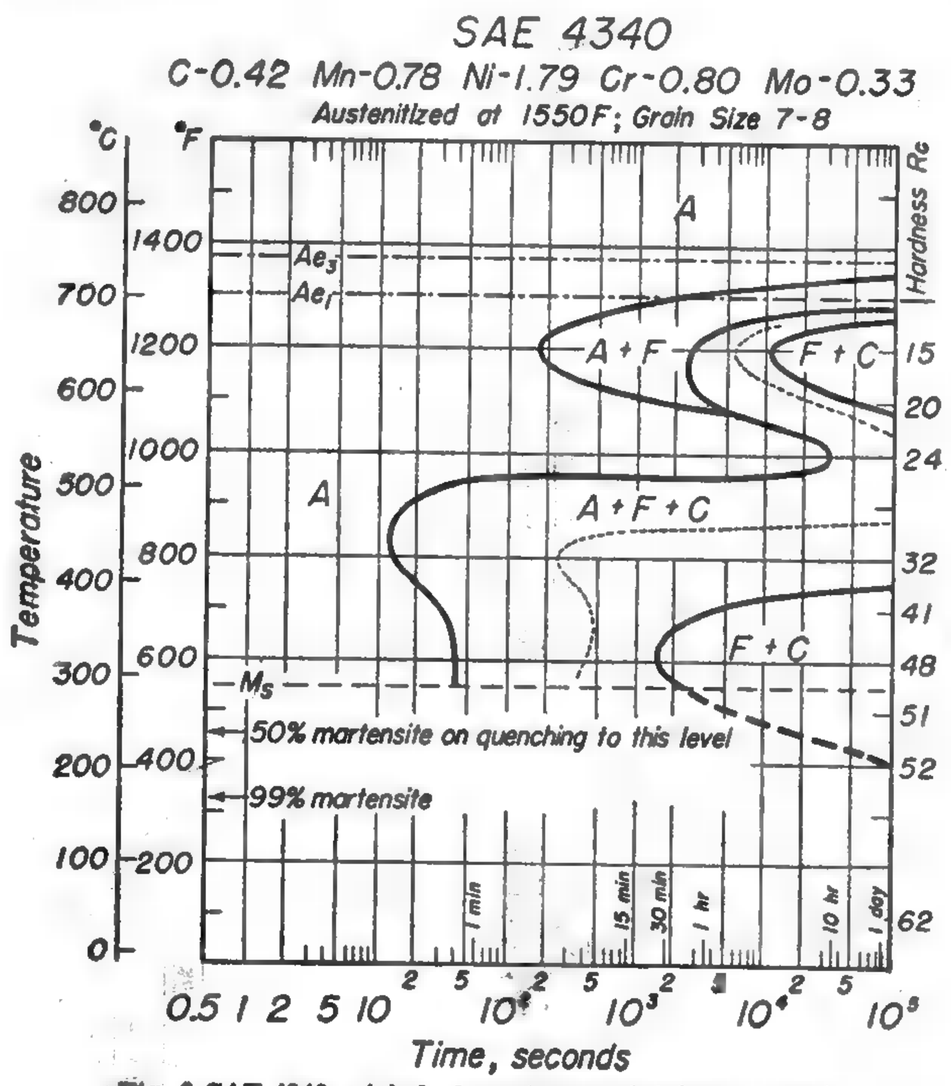

Fig. 6 SAE 4340, nickel-chromium-molybdenum steel

In quench hardening a steel that has an isothermal transformation diagram of this general type, it is the lower knee that is of primary interest, rather than the upper one, since the cooling curve must fall essentially to the left of this lower knee if full hardening to martensite is to be achieved. A substantial number of steels have an isothermal transformation diagram of this general type.[7] In such steels the vicinity of the lower knee, in the range from 800 to 950 F, is where transformation starts rather promptly but is extremely sluggish in going to completion. The reaction in this range exhibits certain complexities in the form of multiple-stage transformation of the austenite; these complex reactions have been discussed in some detail elsewhere.[3] The structures which form in this temperature range in some steels may have mechanical properties less desirable for certain applications than a fully hardened and tempered martensitic structure.

SAE 4815, Nickel-Molybdenum Steel, Uncarburized and Carburized. Figures 7a and 7b show the isothermal transformation diagrams of a typical alloy carburizing steel in the uncarburized and carburized condition, respectively. The diagrams illustrate the effect of low and high carbon content on the shape and characteristics of the curves, when all other variables are essentially constant.

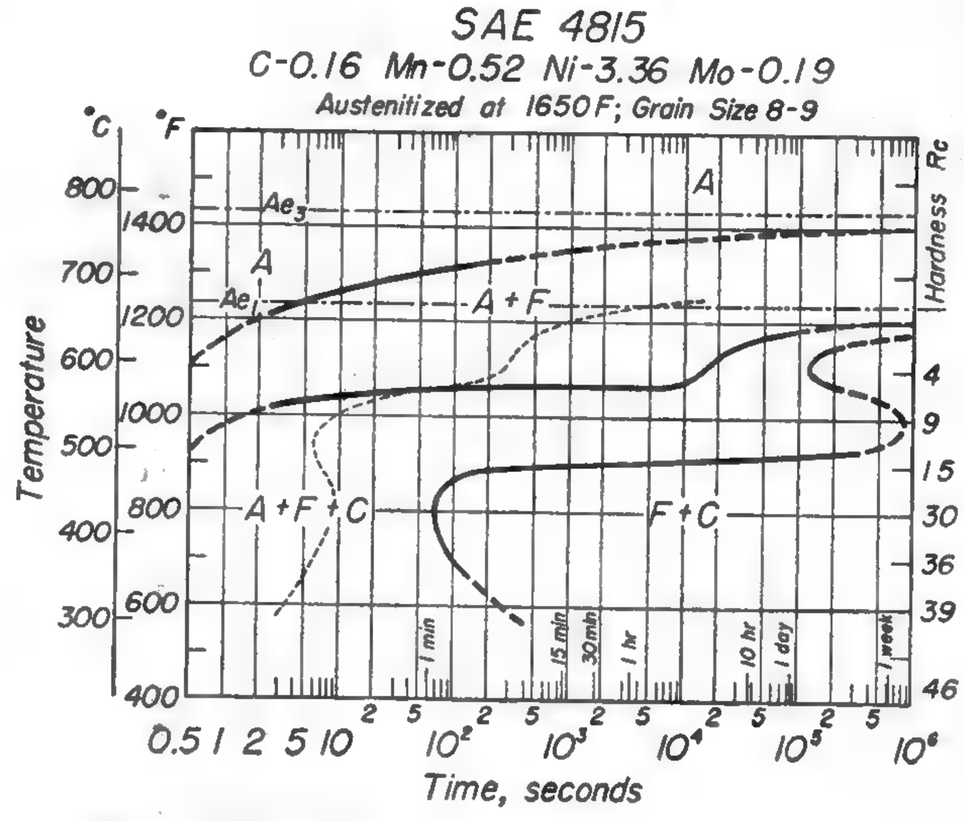

Fig. 7a SAE 4815, nickel-molybdenum steel, uncarburized

The diagram for the uncarburized material (Fig. 7a) exhibits the characteristic features of a distinctly hypoeutectoid steel; namely, a pronounced $A + F$ field and very rapid onset of transformation at temperatures in the vicinity of the knee and below. Note the lowering of the Ae_1, resulting from the relatively high nickel content; note also the marked protuberance in the ending line, characteristic of steels containing molybdenum.

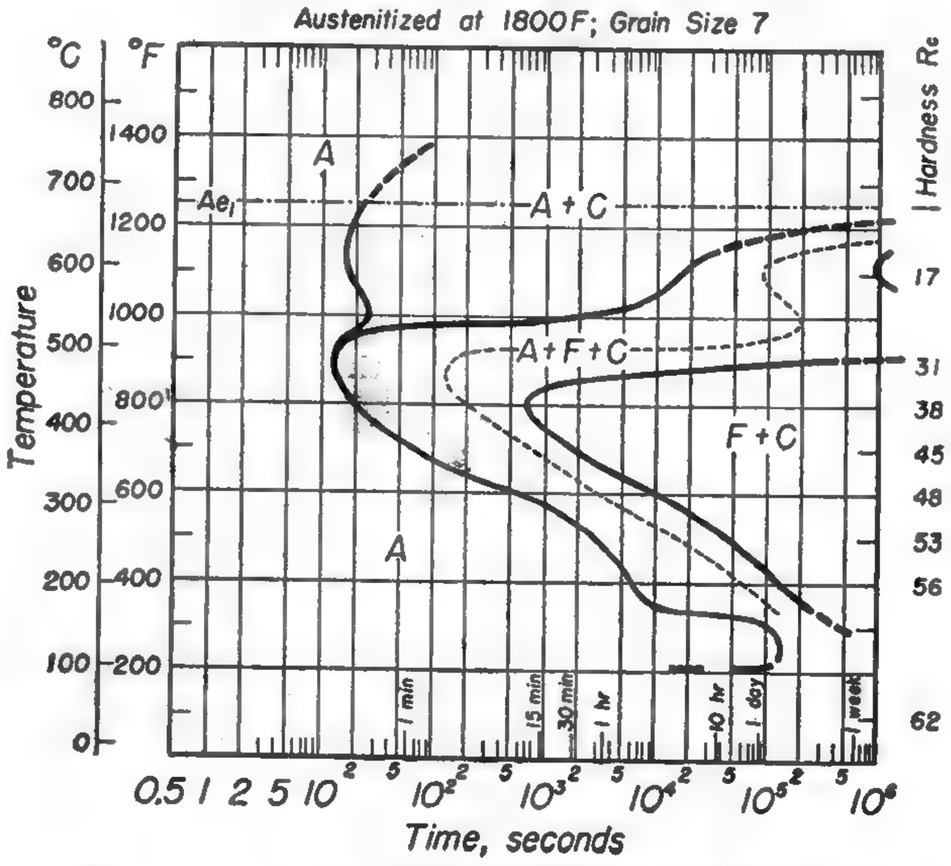

Fig. 7b SAE "48100", nickel-molybdenum steel, carburized

In contrast, the diagram for the carburized material (Fig. 7b) is distinctly different in almost every feature. In the first place, the steel necessarily exhibits hypereu-

tectoid behavior, as evidenced by an $A + C$ instead of an $A + F$ field. The increase in carbon content has retarded both the beginning and ending of transformation at all temperature levels; this is particularly evident at 1000 F and below. Note also the marked lowering of the M_s temperature as a result of the high carbon content. As a matter of fact, the M_s temperature could not be measured reliably for the uncarburized material, because of its low carbon content and consequent rapid transformation, but a calculated value based on chemical composition indicates that it would be about 730 F, in comparison with an M_s temperature of about 205 F for carburized material.

Summary. The typical diagrams discussed above should give a fairly comprehensive picture of the effects of alloying elements as revealed by studies of isothermal transformation. Some variation in details of diagrams may be expected, depending on the particular combinations and amounts of alloying elements present in the steel,[7] but most of the diagrams that have been determined to date will correspond approximately to one or another of the types illustrated and discussed in this article. It should also be borne in mind that significant variation may occur in some details of the diagram for a nominal grade of steel, depending on whether the composition is on the high or low side of the specification range.

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The Temperature Range of Martensite Formation in Steel

By P. Payson* and R. A. Grange*

THE FIRST to study the temperature range of the austenite-to-martensite transformation in carbon steels were apparently Portevin and Garvin[1] in 1919. A short time later, Matsushita[2] observed that continuous formation of martensite requires continuous cooling, and that if cooling is interrupted, the formation of martensite stops; if cooling is resumed, more martensite is formed. Based on an investigation by Hanemann and Wiester,[3] a movie film was prepared that showed martensite needles forming from austenite in a 1.65% C steel; the time required for each needle to form was less than 0.05 sec. These classic investigations, together with many of more recent date, show that martensite forms when austenite in any given steel is cooled below a certain temperature, now generally designated "M_s". Each martensite needle forms almost instantaneously. The proportion of martensite depends on the temperature finally reached during cooling. The temperature at which virtually all the austenite has transformed to martensite is called "M_f".† Between M_s and M_f, the proportion of martensite is greater the lower the temperature reached during cooling; thus, martensite forms only during cooling and not during a time period that is measurable by any ordinary method, at constant temperature. For further discussion concerning the characteristics of the martensite transformation, the reader may refer to the article on page 263 in this Handbook.

Table I. Influence of Alloying Elements on the M_s Temperature of Steel

Alloying Element	References	Qualitative Effect
Carbon	4, 5, 6, 7, 8, 9, 10, 11, 12, 13	Lowers M_s strongly
Manganese	13, 14, 15, 16, 17, 18, 19, 20	Lowers M_s
Silicon	16, 19, 21	Almost no effect
Nickel	13, 16, 19, 20, 21	Lowers M_s
Chromium	13, 16, 19, 20, 22, 23, 24, 33	Lowers M_s
Molybdenum	16, 19, 20, 21, 25	(?) (a)
Vanadium	16, 26	Lowers M_s
Tungsten	16, 19	Lowers M_s
Copper	16, 19	Lowers M_s
Aluminum	16, 19	Raises M_s
Cobalt	16, 19, 21	Raises M_s

(a) Some investigators[21, 25] report that molybdenum has no effect on M_s; others [16, 19, 20] report a lowering.

The M_s and M_f temperatures depend on the chemical composition of austenite, but not on over-all steel composition in instances where an appreciable percentage of any element remains undissolved in austenite. The grain size of austenite does not appear to be a significant factor, but segregation (banding) may have some influence since, locally at least, it affects the composition of austenite.

Effect of Composition. In recent years a number of technical publications have dealt specifically with the effect of composition on the temperature range of martensite formation. Such experimental measurements have been greatly facilitated by a metallographic technique first described by Greninger and Troiano.[4] Table I lists the qualitative effects of the various elements as determined by the investigators named in the references.

The several investigations have rarely been in good agreement as to the quantitative effect of a particular element on M_s, and a survey of the literature indicates the need for more experimental measurements; for this reason, a rather complete list of references has been given. Despite such limitations in the data available at present, empirical formulas given below have been proposed for calculating M_s on the basis of chemical composition; these have been found useful for estimating M_s in carbon and low-alloy steels. The M_s thus calculated and the measured M_s agree well enough for many practical purposes.

(1*) M_s (°F) $= 930 - 570 \times \%C - 60 \times \%Mn - 50 \times \%Cr - 30 \times \%Ni - 20 \times \%Si - 20 \times \%Mo - 20 \times \%W$ (reference 19)

(2*) M_s (°F) $= 1000 - 650 \times \%C - 70 \times \%Mn - 35 \times \%Ni - 70 \times \%Cr - 50 \times \%Mo$ (reference 20)

(3) M_s (°F) $= 925 \times (1 - 0.620 \times \%C) \times (1 - 0.092 \times \%Mn) \times (1 - 0.033 \times \%Si) \times (1 - 0.045 \times \%Ni) \times (1 - 0.070 \times \%Cr) \times (1 - 0.029 \times \%Mo) \times (1 - 0.018 \times \%W) \times (1 + 0.120 \times \%Co)$ (reference 27)

(4†) M_s (°F) $= 930 - 540 \times \%C - 60 \times \%Mn - 40 \times \%Cr - 30 \times \%Ni - 20 \times \%Si - 20 \times \%Mo$ (reference 34)

Any one of these formulas may be used to calculate the approximate M_s temperature of any *carbon* or *low-alloy* steel subject to the following limitations:

1 Essentially all carbides (therefore carbon and alloying elements) must be dissolved in austenite.
2 The carbon content must not be greater than about 0.85%; it is not known at present whether the formulas are applicable to steels of very low carbon content. In the development of the formulas only steels containing more than about 0.2% C were considered.

* Crucible Steel Company of America, Harrison, N. J.
* United States Steel Corp., Research Laboratory, Kearny, N. J.
Prepared for the Subcommittee on Alloying Elements in Steel
† There is some evidence that small amounts of austenite may be retained in almost any steel, even if quenched considerably below M_f, as ordinarily determined experimentally.

* Rowland and Lyle[32] suggest $-600 \times \%C$ instead of $-570 \times \%C$ for the carbon factor in this formula.
* Limited to steel containing less than 1.5% Cr and 1% Mo.
† Formula 4 is more accurate than Formula 1.

Very little work has been done concerning the effect of composition on the M_f temperature; what data are available[19,20] indicate that elements which lower M_s probably have an even greater lowering effect on M_f, thus widening the temperature range of martensite formation.

Significance and Usefulness of Data Concerning Martensite Reactions. A knowledge of the M_s temperature and of the progress of the martensite reaction with decreasing temperature, is important in the heat treatment and welding of steels, and may also be used for measuring depth of carburization, or of decarburization, in steels. In the ordinary hardening operation—that is, in the quenching and tempering procedure—it is desirable to know not only the M_s temperature but also the temperature at which the austenite-to-martensite reaction is virtually complete, so that the steel may be cooled sufficiently in the quench, or subsequent to the quench, before it is tempered. The M_s temperature establishes the temperature of the hot quench in the martempering treatment. For alloy steels of high hardenability, the M_s temperature determines the correct preheating temperature to be used when the steels are to be welded.[35] Finally, it is possible, by means of correlation between carbon content and the M_s temperature, to measure not only the extent of carburization or decarburization, but also the depth at which a particular carbon content exists.

As stated above, when steel is quenched from the austenitizing temperature at a sufficiently rapid rate to avoid transformation at higher temperatures, the austenite will begin to transform to martensite when it has cooled below the M_s temperature, and will continue to transform to martensite until it has cooled to the M_f temperature, at which virtually all the austenite will be transformed. If the cooling is stopped at any temperature above the M_f temperature, some austenite will remain that will not transform completely to martensite until the steel has eventually cooled to the M_f temperature or below. If, before being cooled to the M_f temperature, the steel is heated to the tempering temperature, and the tempering is done at a temperature at which the residual austenite does not transform isothermally during the time used, as would be true of many alloy tool steels,[28] the resulting structure will be a mixture of tempered martensite and austenite, and this austenite may finally transform to martensite when the steel is cooled to room temperature after the tempering operation. This final formation of martensite after tempering, may set up sufficient stress to crack the steel. At best, it will leave the steel with a mixture of tempered and untempered martensite, and retempering will usually be required in order to relieve the residual stresses.[28] In the higher-carbon alloy steels, such as high speed steel and the high-chromium die steels, the cessation of cooling in the original quench before the M_f temperature has been reached, causes the remaining austenite to become "stabilized" so that it will not transform in the usual manner when the steel is eventually cooled to room temperature or below. This "stabilized" austenite may require special treatments, such as conditioning tempering, or refrigeration at very low temperature, to cause it to transform to martensite.[29]

Inadequate cooling, which fails to permit nearly complete formation of martensite before the steel is tempered, is likely to cause distortion or cracking, particularly in large quenched sections. In these sections, the outside may be cooled to the M_f temperature at a time when the inside is at a temperature where the transformation to martensite may be, for example, only 50% complete. If the piece is tempered before further cooling takes place, the outside will be tempered martensite, but the inside, when the steel has cooled to room temperature after the tempering treatment, will be a mixture of 50% tempered and 50% untempered martensite or, if austenite transformed during the tempering, of up to 50% isothermal product.

The martempering procedure consists in quenching the steel into a bath at just above the M_s temperature, to avoid transformation at higher temperatures, and then allowing the steel to cool to room temperature in air. This permits the steel to transform gradually to martensite, and possibly to bainite, during the slow cooling in air, and allows the steel to accommodate itself, without cracking,[30] to the volume change that accompanies the transformation.

When medium-carbon and high-carbon steels are welded, the zone adjacent to the weld reaches a high temperature and then, if no precautions are taken, cools rapidly and transforms to martensite. This frequently causes cracks next to the weld bead. To prevent such cracking, the stock is usually heated just before the welding operation, and then is reheated immediately afterward. (These operations are referred to as "preheating" and "postheating".) The purpose of preheating is to prevent the formation of much martensite in the stock that is being welded. The purpose of postheating is to temper any martensite that may have formed and to permit the residual austenite to transform to the relatively soft products that are formed at the higher temperatures.

In the past, the selection of the preheating temperature has been more or less by rule of thumb. However, if the steel is preheated at, or close to, the M_s temperature and then is postheated at a high temperature at which the austenite will transform in a relatively short time, there can be no formation of martensite subsequent to the welding operation, and consequently there is complete assurance of freedom from cracking because of martensite formation, even in high-carbon steels of high hardenability.[35]

Since the M_s temperature is affected appreciably by the carbon content of the steel, it is possible, by following the quench-temper procedure of Greninger and Troiano,[4] to establish the carbon content at a given position in decarburized or carburized zones of a piece of steel. After the steel has been completely austenitized, if it is quenched into a bath known to be at the M_s temperature corresponding to a given carbon content, and is then tempered immediately, the portion that is lower in carbon content than the given value, will contain tempered martensite needles, and the portion that is higher in carbon content will be free from tempered martensite. The difference between the tempered and untempered martensite can be recognized readily in the etched microsections, and therefore demarcation between zones of different carbon content can be recognized quite easily by use of the data concerning martensite reactions.[19,31,32]

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Principles of Heat Treatment of Iron and Steel

By E. S. Davenport*

THE purpose of this article is to outline the principles underlying the heat treatment of ferrous materials. These fundamental principles are used when the mechanical properties of steel are intentionally altered by heat treatment in order to make the steel more serviceable for some particular purpose.

An article on the subject of heat treatment of metals in general appears on page 255. The present article is confined to the heat treatment of steel and, moreover, is limited to a discussion of principles. The closely related subject of isothermal transformation of steel (S-curves) is discussed in an article on page 607.

In general, all heat treating processes involve two fundamental operations: heating and cooling. A third factor — the element of time at one or more temperatures, either in the heating or the cooling step — must be taken into consideration in making a schedule for heat treatment of any particular steel. Some of the questions that must be answered in developing such a schedule are: How hot and at what rate should the steel be heated? How long should it be held at temperature? At what rate should it be cooled? Is the heat treatment to be considered finished at the end of the cooling step or is a tempering treatment required? If tempering is necessary, what heating, cooling and time-temperature procedures are to be followed? In the following paragraphs these questions are considered in some detail, and an attempt is made to base answers on general principles.

Heating. The first step in the heat treatment of steel is the heating of the material to some temperature either in or above the transformation range, to put the iron in the gamma condition; carbon and other elements are thus dissolved in the gamma iron, forming the solid solution, austenite. The solution of these elements may be either partial or complete, depending on the time-temperature cycle. This austenite solid solution is the raw material from which is built the final structure of ferrite and carbide in the subsequent cooling and tempering.

Rate of Heating. For many purposes the rate of heating is less important than certain other essential factors of the heat treating cycle; for example, maximum temperature, time at temperature, and rate of cooling. The initial condition of the material, with respect to residual stress produced by cold work or otherwise, may have an important bearing both on the optimum rate of heating, because of the influence of this rate on distortion and cracking, and on the initial size and growth characteristics of the austenite grains; moreover, in the selection of a heating rate, it is necessary to consider the volume change accompanying the alpha-to-gamma transformation as the metal passes through the transformation range. Hard, brittle, highly stressed materials, such as steels in the martensitic or fully hardened condition, should be heated more slowly and carefully than stress-free materials; otherwise cracking may occur. However, materials that have been subjected to a certain amount of cold working may exhibit a tendency toward germinative or excessive grain growth when heated slowly through the transformation or recrystallization range; such materials require rather rapid heating through the germinative temperature range to avoid excessive grain growth.

The thermal conductivity of the material, the nature of the furnace atmosphere (scaling or nonscaling) and the thickness of section, all influence the behavior of the steel in relation to the rate of heating. The difference in temperature rise within thick and thin sections of articles of variable cross section is a problem always present in practical heat treating operations; whenever possible, provision should be made for retarding the heating of the thinner sections in order to minimize thermal stress and distortion. Uniformity of proper temperature throughout the material is the ultimate objective of the heating cycle; usually this uniformity will be attained more safely by slow heating than by rapid heating, and with less over-all damage to the steel.

Maximum Temperature. The selection of the maximum temperature will be determined partly by the chemical composition of the steel, the proportion of carbide or ferrite desired in solution in the austenite, and the maximum permissible size of austenite grains if the grain size has been defined or specified. In general, the higher the temperature, within limits, the greater the solubility of the phases (carbide or ferrite) and the greater the rate at which they are dissolved in the austenite; likewise, the higher the temperature, the larger the austenitic grain size, if other factors are equal.

For plain carbon hypoeutectoid steels (carbon content less than about 0.8%) a temperature just *above* the upper transformation or critical temperature (A_3) is usually recommended. At this temperature (A_3), which varies with the carbon content of the steel, the transformation from alpha to gamma during heating is just completed; that is, all the carbide and proeutectoid ferrite is in solid solution; thus maximum solubility of the constituents is achieved with minimum growth of the austenite grains. As the temperature is raised above the A_3 for any given steel, the austenite grains begin to grow. Such grain coarsening is sometimes desirable for improving machinability; less frequently grain coarsening is employed to increase hardenability (depth of hardening) although deeper hardening can usually be achieved better by other means.

For plain carbon hypereutectoid steels (carbon content more than about 0.8%) a recommended temperature is usually *between* the lower transformation or critical temperature (A_1) and the upper transformation (A_{cm}). The upper transformation line (A_{cm}) in the iron-carbon diagram rises so steeply when the carbon content is increased to more than 0.85% that an excessively high temperature may be required for dissolving all the proeutectoid carbide in the austenite; this tends to develop undesirably coarse austenitic grain size with consequent deep hardening and cracking. If it is desirable to take full advantage of the hardening effect of the carbon and of the alloy content, it may be necessary to have most of the carbide in solution, a condition that requires a temperature just at, or slightly above, the A_{cm} temperature; otherwise, it may be preferable to leave some of the carbides undissolved, in order to restrain austenitic grain growth and to act as transformation nuclei during cooling. When this is done, part of the potential hardenability of the steel is sacrificed in order to limit or control grain growth and depth of hardening. Undissolved carbides are almost always present in the austenite of alloy steels that contain the reluctantly soluble carbides of elements such as chromium, vanadium, molybdenum and tungsten; excessively high temperature or an absurdly long heating period would be required to put all these carbides into solution.

To summarize, the maximum temperature in the austenitic range should be just high enough to achieve the necessary extent of solution of the ferrite or carbide.

Time at Maximum Temperature. In general, time at temperature has an influence similar to maximum temperature, as discussed in the preceding section. In any heat treating process, *temperature* and *time* must be considered simultaneously since virtually all changes in metals take place more rapidly at higher temperatures, as a result of increased atomic mobility. Thus the longer the time at any given temperature in the austenitic range, the greater will be the amount of carbide and alloying elements (if present) taken into solution; the more homogeneous the austenite because of diffusion of these dissolving elements; and the larger the austenitic grain size—all within limits fixed by the equilibrium conditions of these reactions at the specific temperature under consideration. Carbide par-

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ticles, in particular, require a surprisingly long interval of time for complete solution, even when the temperature is such as to cause their ultimate solution, that is, above A_{cm}.

Since the constitutional changes that may be brought about at the maximum temperature are comparatively rapid, the element of time is less important than the actual temperature. In general, a relatively small increase in temperature will have a far greater effect in accomplishing the desired change than a longer time at a lower temperature; this is true in the diffusion and grain-growth changes mentioned above. However, the factor of time appears more significant when the question of time at temperature is considered from the standpoint of thickness of section, thermal conductivity of the metal, scaling, decarburization and other surface reactions that depend on furnace atmosphere. The heavier the section or the lower the thermal conductivity, the longer the time necessary to attain uniform temperature throughout the piece; and in the heat treatment of most parts, uniformity of temperature throughout the part is highly essential. Scaling, decarburization and similar surface phenomena all proceed continuously with time at temperature; if these effects prove detrimental, the heat treater had best keep the time as short as possible. Many of these surface reactions can be limited or even advantageously utilized by proper adjustment of the furnace atmosphere as, for example, when elements are introduced intentionally into steel by carburizing, nitriding or a similar treatment.

Ordinarily the time at maximum temperature should be long enough to attain uniformity of temperature and to bring about the desired constitutional changes. Frequently these two aims require approximately the same time.

Cooling. When the steel has attained the predetermined temperature throughout, the next step is to cool it at the proper rate to develop the desired structure. When, during the cooling of a given steel, the austenite transforms to an aggregate of ferrite and carbide or to martensite, the resultant structure—hence the mechanical properties—is determined largely by the temperature at which this transformation actually takes place. With a slow rate of cooling only moderate undercooling occurs; the transformation takes place at a temperature slightly lower than the lower transformation temperature (A_1), and the resulting structure is characterized by coarse lamellar pearlite of relatively low strength and hardness and high ductility. In addition to the pearlite reaction, when cooling is slow, there is a precipitation of proeutectoid ferrite in hypoeutectoid, or carbide in hypereutectoid steels; these proeutectoid constituents usually precipitate in the austenite grain boundaries and thus outline the austenite grains that existed at the maximum temperature; advantage is taken of this behavior when the grain size of austenite is measured in hypoeutectoid and hypereutectoid steels.

With progressively higher rates of cooling, the actual temperature of transformation is progressively lowered by undercooling, until eventually it is depressed to temperatures in the vicinity of 950 to 1000 F; the lamellar pearlite becomes progressively finer, stronger, harder and less ductile, and the precipitation of the proeutectoid phases—ferrite or carbide—gradually diminishes in volume until finally, at the faster cooling rates, this precipitation may be suppressed altogether. However, in the very low carbon steels (0.20% and lower) so much excess ferrite is available that precipitation cannot be suppressed ordinarily, even with the most drastic cooling.

If the speed of cooling is increased still further, as in quenching, the transformation is depressed by undercooling to temperatures approaching room temperature; the product of the austenite transformation at these low temperatures is not pearlite, but martensite, the characteristic constituent of fully hardened steel. The cooling rate that just causes the steel to harden fully to the martensitic condition is known as the "critical cooling speed"; it depends on the composition and the austenitic grain size of the steel. Martensite is now generally considered to be an unstable, supersaturated solid solution of carbon in alpha iron; it is glass-hard, brittle and, in steels carrying more than about 0.5% C, always in a condition of high stress, caused in part by the volume changes accompanying the gamma-to-alpha transformation, by the solid-solution effect, and by the drastic cooling which the material underwent in the hardening operation. In this condition, steel is ready to precipitate the carbon that it contains and to be relieved of stresses at the first opportunity; for example, on reheating for tempering. Under some circumstances, fully hardened steel may be relieved of stresses by spontaneous cracking, a fact well known to practical heat treaters.

At cooling rates intermediate between those that give rise to the pearlitic structures and those that yield martensite, mixtures of the two structures may be formed, since part of the transformation occurs at the higher temperatures and part at the lower; this mixed structure is always encountered in the transition zone between the hardened exterior and unhardened core of quenched heavy sections in which the surface may have cooled fast enough to form martensite, while the interior cooled more slowly and transformed to the softer pearlitic products at higher temperature. Thus it is evident that thickness of section has a great influence on the depth to which a given steel may harden under any specific cooling conditions.

Effect of Alloying Elements. The mechanism is now fairly well understood by which, at any particular cooling rate, dissolved alloy content depresses the transformation to lower temperatures, as compared with carbon steel. The alloying elements generally retard the transformation rate of the austenite, causing the finer, harder pearlitic structures to be formed at any given slow rate of cooling, or causing deeper hardening characteristics during rapid cooling—all as compared with plain carbon steels. The net effect corresponds to a faster cooling rate before the beginning of transformation, as compared with carbon steel. A so-called "air-hardening" steel, therefore, is one in which the transformation rate has been so retarded by the addition of alloying elements as to form fully hard martensite, even on moderately slow cooling from the austenitic condition. In high-alloy steels that contain substantial amounts of the elements that stabilize austenite, the austenite solid solution may be retained all the way to room temperature by the use of very moderate cooling rates, such as air cooling. These steels constitute extreme examples of the retarding of the transformation rate by the addition of alloying elements.

Effect of Austenitic Grain Size. Increasing the grain size of the austenite by employing higher maximum temperatures before cooling, has an effect on hardenability similar to that of adding alloying elements; coarsening the austenitic grain retards the transformation rate and results in harder, finer pearlitic structures or in deeper hardening characteristics for any given rate of cooling, as compared with the same steel in the fine-grained condition.

Effect of Thickness of Section. The influence of size of section must be taken into account in any consideration of heat treatment from the standpoint of cooling rate. A heavy section cannot be cooled as rapidly as a thin section; the interior of a heavy section, cooling more slowly than the surface, transforms not only at a later time but also at a higher temperature, and hence to a softer product than the exterior, which cools more rapidly. This gives rise to differences in properties between the interior and exterior, as well as to possible distortion, nonuniform stress and other difficulties well known to those familiar with heat treating practice; the subject is discussed more fully on pages 629 and 636 in this Handbook.

Effect of Surface Condition. Another factor involved in cooling practices is the surface condition of the metal about to be cooled. Steel that carries a heavy insulating coating of scale from the heating operation cannot be cooled as rapidly, under a given set of cooling conditions, as steel free from scale. This may result in erratic and nonuniform properties in the final product, particularly in connection with treatments designed to achieve full hardening. Soft spots or, in extreme instances, complete lack of hardening may result from attempts to quench badly scaled steel. The remedy is either to descale in some manner before cooling, or more practicably, to carry out the heating operation in a less severely scaling atmosphere. Decarburization may cause nonuniform hardening and other undesirable effects, particularly as reflected in the behavior of the material under repeated or alternating stress (fatigue).

In summary, slower cooling rates yield softer pearlitic structures while rapid rates yield harder, martensitic structures. The pearlitic structures are relatively stable and stress-free; the martensitic structures are quite unstable and are likely to have such high residual stresses as to be unserviceable for most purposes. The question at this point is whether the heat treatment is to be considered completed at the end of the cooling operation or whether a further treatment is necessary. Ordinarily, the softer, pearlitic products resulting from the slow cooling operations require no further treatment, since they are relatively stable from a structural standpoint (although not entirely so). Occasionally the fine pearlitic structures are given a low-temperature subcritical anneal for relieving stress. Such treatment tends to spheroidize the fine lamellar carbides; the extent of spheroidization depends on the temperature and time of the annealing operation. On the other hand, the harder, martensitic products, resulting from rapid cooling or quenching, are usually so unstable and brittle as to be of little practical value in the "as-quenched" condition; hence a further treatment known as *tempering* is almost invariably applied.

Tempering. Fully hardened steel is tempered for relief of quenching stresses and for recovery of a limited degree of toughness and ductility. The operation consists of heating at temperatures lower than the lower transformation temperature (A_1); that is, at temperatures at which the steel is in the ferritic condition. The stress relief and recovery of ductility are brought about through precipitation of carbide from the supersaturated, unstable solid solution (martensite) and through diffusion and coalescence of the carbide while the tempering operation proceeds.

It should be clearly understood that the carbide precipitation which occurs during the tempering of martensite does not take the form of plates, or lamellae characteristic of the pearlitic structures formed directly from austenite during slow cooling; on the contrary, the carbide precipitated during tempering takes the form of a fine dispersion of more or less spheroidal particles, the size of which depends on the time-temperature conditions of the tempering operation. This cannot be emphasized too strongly, since there appears to be considerable confusion on this particular point. No one has ever succeeded in making lamellar pearlite from martensite by a tempering treatment at subcritical temperature.

The higher the tempering temperature or the longer the time at temperature, the coarser the spheroidal carbide particles, and the softer and more ductile the steel. Alloy steels containing the elements that form carbide tend to show greater resistance to softening during tempering than do plain carbon steels; hence, higher temperatures or longer times may be employed in tempering such steels. More thorough relief of quenching stresses is obtained in this way without proportionate sacrifice in hardness.

Some steels are susceptible to embrittlement, or at least to a reduction in ductility, when tempered in the so-called "blue heat" range, or when cooled slowly through this range after tempering. This embrittlement, caused presumably by some precipitation in the steel, can be minimized either by tempering at temperatures lower than the range in which the steel is sensitive, or by cooling rapidly through the range if the tempering temperature is higher.

In general, the tempering operation may be conducted so as to give almost any desired combination of properties by suitable selection of the time-temperature conditions. The correct time-temperature cycle for any given set of properties depends largely on the composition of the steel, and particularly on the composition of the austenite with respect to the amount of dissolved carbon and alloying element that it contains before conversion to martensite by rapid cooling.

Quenching Mediums

BY THE SUBCOMMITTEE ON QUENCHING MEDIUMS*

THE PURPOSE of quenching steel generally is to produce a completely martensitic structure on the surface of the piece to be hardened (a minimum requirement) or in the center of the piece (a maximum requirement). Hardening implies the formation of martensite, which, before tempering, provides the highest hardness obtainable in a steel of low alloy content. This hardness is directly related to carbon content. If the hardening is incomplete, that is, if some pearlite or ferrite is present, usually the mechanical properties will be inferior to those of a completely martensitic steel, even though both are tempered to the same hardness. Accordingly, when highest mechanical properties are required, quenching must be controlled with precision.

Requirements of Liquids for Quenching Determined by the Piece to be Hardened. Whether or not satisfactory hardening is achieved, depends on the composition and structure of the steel, the shape of the piece, and relation between size and section, as well as on the composition of the quenching medium. Because of the complex relations among all these variables, few of which can be expressed quantitatively, hardening remains largely an art. However, failures during hardening can be minimized by recognition of a few well-established relations among hardening variables.

In considering the effects of steel composition and structure, it is necessary to distinguish between shallow-hardening and deep-hardening steels. The shallow-hardening steels are those of low alloy content that remain fine-grained at the austenitizing temperature. Deep-hardening steels contain substantial amounts of alloying elements that promote penetration of hardening. In fact, hardenability is now recognized as a factor so important in heat treatment that special tests for its evaluation have been developed (*see* page 489 in this Handbook).

The fundamental property distinguishing shallow-hardening from deep-hardening steels is the critical cooling rate, which is the slowest cooling rate—measured at about 1020 F—at which a completely martensitic structure can be obtained. The temperature specified is that of maximum rate of reaction in eutectoid carbon steel, established by the "S-curve".[1] For pure iron-carbon alloys of fine grain size the critical cooling rate is extremely high—so high that effective hardening is impracticable. Even in plain carbon steels this rate is high, ranging from 126 to 360 °F per sec. Evidently, then, an extremely fast quench is required for the hardening of shallow-hardening steels. A rapid rate of cooling must be attained at a considerable depth, ⅛ to ¼ in., to assure uniform surface hardening. The cooling rate increases exponentially as the surface is approached, so a very high rate is required at the surface for hardening shallow-hardening steels effectively.

Under favorable conditions, water provides the surface cooling rate necessary for the hardening of carbon steels—approximately 1800 °F per sec. Surface cooling at this rate produces rates within the steel that approach the maximum values theoretically possible to attain.[2] Therefore, water or an aqueous solution is generally used for hardening these steels, which are often identified as "water-hardening" steels. The cooling characteristics of water, however, are markedly affected by a number of variables, which are discussed below.

A necessary consequence of fast surface cooling is a high temperature gradient from surface to center. This gradient, which may exceed 70% of the temperature range (Fig. 1), produces severe distortion in all but simple symmetrical shapes that have a low ratio of length to diameter or thickness. Shallow-hardening steels, therefore, cannot be used in complicated shapes where distortion is objec-

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tionable. Furthermore, there is no possibility of changing this situation by the selection of quenching medium, if full surface hardening is required.

Despite the admirable properties of carbon steels, including low price, these steels cannot be used for complicated shapes where distortion must be avoided. For complicated shapes, water quenching should be abandoned

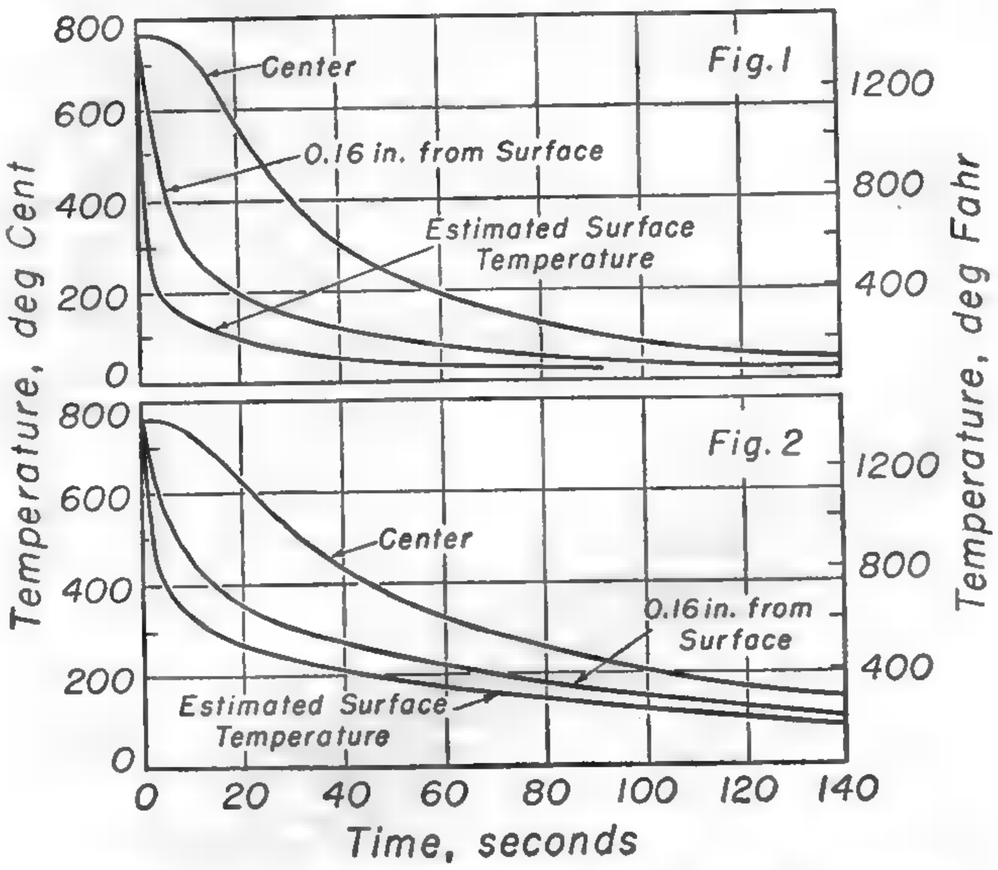

Fig. 1 Observed cooling curve of center and of a point 0.16 in. from the surface of a long austenitic steel cylinder 2.00 in. in diam, during quenching in agitated water

Fig. 2 Observed cooling curve of center and of a point 0.16 in. from the surface of a long austenitic steel cylinder 2.00 in. in diam, during quenching in agitated oil

and a less active quench should be used, which reduces the temperature gradient considerably during quenching (Fig. 2). Certain oils perform this function well, but are incapable of hardening shallow-hardening steels of substantial size. Therefore a drastic change in steel composition is required with a change from a water to an oil quench. Accordingly, steels adapted for deep hardening are often identified as "oil-hardening" grades.

Oil quenching introduces entirely different problems from those of water quenching. Gradients of cooling rate are no longer high, so a completely martensitic surface shell can seldom be obtained over a fully pearlitic core. Usually there is considerable martensite at the center when the surface is fully hardened. If hardening is incomplete at the surface, soft spots are present, which may not be detected easily by a hardness test, but which lower the toughness otherwise obtainable at the same hardness.

Table I. Relative Cooling Rates in Several Mediums[a]

Quenching Medium	Relative Cooling Rate for Diameter of: 1 in.	2 in.	3 in.
Fastest theoretically attainable	1.23	0.30	0.14
Agitated water	1.00	0.27	0.13
Agitated oil	0.48	0.18	0.093
Air stream	0.032	0.0157	0.0102
Still air	0.0152	0.0075	0.0048

(a) These cooling rates apply to the center of a long cylinder made of an austenitic iron-nickel alloy having heat conductivity approximately equal to that of a carbon or low-alloy steel in the austenitic condition.

Since the cooling rate is slower, the larger the section, the alloy content must be increased with increase in thickness of the section. In Table I are listed the cooling rates at the center of long cylinders during quenching in several mediums when the center temperature is 1020 F, compared with the cooling rate of a cylinder 1 in. in diam, quenched in agitated water at a rate of 100 °F per sec. This table shows the major effect of both size and quenching medium on cooling rate and emphasizes the need for adjustment of composition to variations in either.

Residual stresses as well as distortion determine the choice of steel and quenching medium. Water-hardened steels as quenched, are under high compressive stress at the surface and tension in the core,[3] chiefly because the density of martensite is less than that of pearlite. Such stresses, however, are not dangerous, and may even be beneficial, if the core is sound and if no holes bring a surface into the tension zone. Cracks occur under tensional stress only, and hardened steel can support tensional stress that is only a small fraction of the tolerable compressive stress. For these reasons, cracks in water-hardened steels originate in the core or at positions of sharp change in section, except when thin sections harden to the center, behaving then as oil-hardening steels.

Like the temperature gradients from which they originate during quenching, the residual stresses that develop in oil-hardened steels as quenched and fully hardened are lower than the residual stresses that result from water quenching, but more dangerous. This condition arises from the fact that residual stresses in oil-hardened steels are usually tensional at the surface and compressive at the center of the work. This reversal of the expected relations of residual stress arises from the fact that the residual stresses are determined by the temperature gradients during the large increase in volume that accompanies the martensite transformation.[4] Though "set" during this transformation, the residual stress does not reach maximum magnitude until the work is cold, which accounts for cracks occurring at atmospheric temperature.

Cracks developed by oil quenching are widest at the surface and penetrate deeply, a characteristic distinguishing them from the relatively shallow cracks caused by decarburization or grinding. Oil-quenching cracks are common only in moderate size. Residual stresses in small sections are low because temperature gradients during hardening are also low. As thickness of section increases, the surface stress tends to revert to compression, thus reducing the danger of cracking in heavy sections also.

Since the martensite transformation occurs at relatively low temperatures—starting usually in the range from 900 to 400 F and depending chiefly on carbon content—cooling rates are then low, and the temperature gradients that determine the residual stress are accordingly subject to some control. An ideal quenching medium would cool very slowly in this range, but would cool as fast as desired at the temperature of maximum rate of reaction, 1020 F. Oil is a great improvement over water in this respect, but is still far from ideal. Several expedients by means of which both distortion and residual stresses can be reduced to a minimum are discussed on pages 619 and 620.

Liquids for Quenching Shallow-Hardening Steels. Pure water, adequately agitated, meets effectively the requirements for extremely fast surface cooling demanded by shallow-hardening steels. A submerged water-spray quench, for example, appears to offer the fastest practicable surface cooling and to be highly reproducible as well. In application, however, this quench is definitely limited to simple short objects not likely to warp. Because of the difficulty in obtaining symmetrical flow of the water in relation to the work material, the spray quench is highly conducive to warping. The ideal fast quench is therefore one that will cool the surface as required, without any agitation of the bath.

It has been shown that concentrated sulfuric acid approaches this ideal.[5] However, sulfuric acid is too dangerous a liquid for practical use. Ordinary tap water, without agitation, is a poor substitute that will not harden the material consistently, with freedom from soft spots. The addition of common salt (sodium chloride) greatly improves the performance of unagitated water, as will be shown presently. The manner in which it improves performance can be seen clearly from a consideration of the variation in the mechanism of heat extraction with change in surface temperature.

By plotting cooling curves for a small specimen during quenching, Pilling and Lynch[6] determined how the power of the liquid to cool the surface changed with the surface temperature of the piece. Their observations are highly significant in that they show three distinct mechanisms of heat dissipation, which have been verified by Speith and

Lange.[13] Figure 3 is a typical curve illustrating the three stages of cooling, which have been described by Scott[5] as follows:

Stage A. Vapor Blanket Cooling. In this, the first stage, a thin stable vapor film surrounds the hot metal. Cooling is by conduction and radiation through the gaseous film and is therefore relatively slow.

Stage B. Vapor Transport Cooling. Termination of the *A* stage is marked by the wetting of the metal surface. Vapor forms copiously in bubbles and is carried away by gravity and convection currents to condense in cooler surrounding liquid. This is the fastest stage of cooling.

Stage C. Liquid Cooling. The *B* stage ends when the surface temperature of the metal approaches the boiling

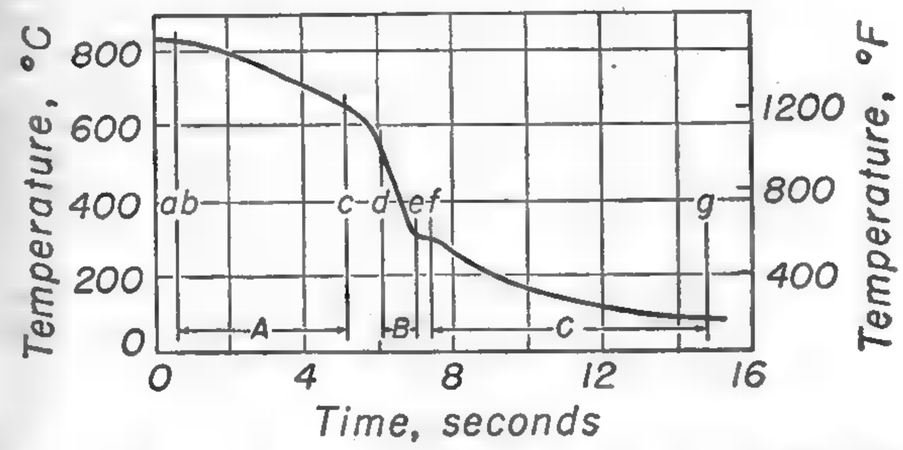

Fig. 3 Typical cooling curve for the center of a small cylinder during quenching in still water at 137 F, illustrating the three stages of surface cooling (Scott[5])

point of the quenching liquid. Vapor no longer forms, so cooling is by conduction and convection and the difference in temperature is greatly decreased. This mode of cooling is slower than that of the *B* stage.

Cooling in the *B* and *C* stages is in fair accord with Newton's law of cooling; that is, the cooling rate is proportional to the surface temperature, which holds closely for short temperature ranges.[2] In the *A* stage, however, cooling is at a nearly constant rate, decreasing somewhat with increase in the bath temperature.

Zavarine has noted from photographs made at high speed that bubbles collapse at a relatively slow rate in the *A* stage and extremely fast in the *B* stage, vanishing in the *C* stage; and that crystals of salt are precipitated momentarily during quenching in brine.

There has been much debate concerning which of the fundamental properties of liquids determine the quenching power. Properties mentioned include thermal conductivity, viscosity, specific heat, and heat of vaporization. Evidently, which property is dominant depends on the stage concerned. Certainly boiling point is a major factor in the *A* stage, heat of vaporization in the *B* stage, and thermal conductivity in the *C* stage. Viscosity also contributes to cooling power in both the *B* and *C* stages. Each stage has an important part in determining the success of a quench. No distinction has been made between the *A* and *B* stages in the data of Table II; the column at the left represents a combination of both stages, the column at the right represents *C* stage cooling only. As a consequence of this overlap, water at 120 F, for example, is placed below certain oils, though its cooling rate in the *B* stage is just as fast as that of the LiCl solution. The three stages have been distinguished sharply in Table IV.

The vapor stage, *A*, is of most concern in water solutions. Cooling is slow in this stage, and if it persists for more than a few seconds, transformation will occur at Ar_1, producing soft spots. To avoid such transformation, the vapor stage must be suppressed or nearly so. The duration of the vapor stage may be measured in time units on the quenching curves plotted by Pilling and Lynch, giving a quantitative measure of the extent to which the vapor stage is suppressed (Fig. 4). This figure shows that the duration of the vapor stage in water and water solutions increases rapidly with temperature of the bath; hence the first rule of quenching is: Keep water-base quenching liquids cold, preferably below 70 F.

Figure 4 also shows clearly why salt is an advantageous addition to water; it greatly reduces the duration of the vapor stage, particularly at elevated temperatures. The liquid adjacent to the work material is, of course, much above the average temperature of the bath. The best concentration might then appear to be a saturated solution, about 26%, but the disadvantages of so high a concentration have been demonstrated by tests on solutions in which the content of solute was varied systematically.

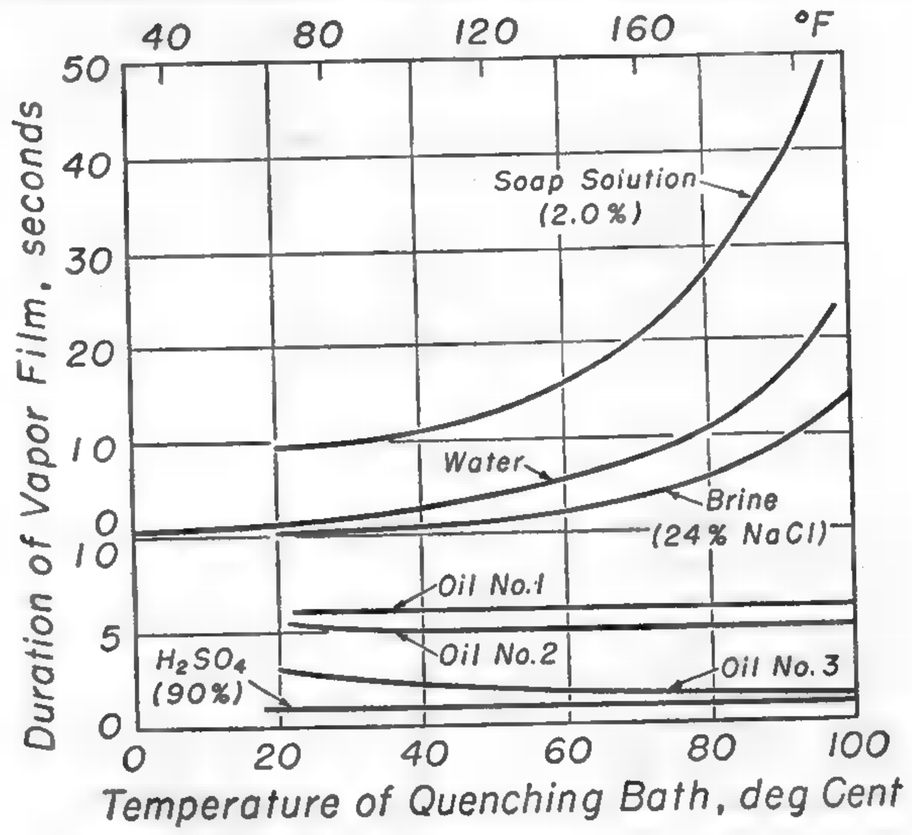

Fig. 4 Duration of the vapor-film stage of surface cooling during quenching in several liquids (Pilling and Lynch[6])

Brine (sodium chloride) and caustic soda (sodium hydroxide) solutions are used extensively for their beneficial effect in reducing the duration of the vapor, *A*, stage.

Table II. Cooling Rate at the Center of a 4-mm Diam Nichrome Ball Through the Temperature Range 1328 to 1022 F During Quenching in Various Mediums from 1580 F[10]

Quenching Medium	Cooling Rate Relative to that for Water at 65 F[(a)] 1328 to 1022 F	At 392 F
Aqueous solution 10% LiCl	2.07	1.04
Aqueous solution 10% NaOH	2.06	1.36
Aqueous solution 10% NaCl	1.96	0.98
Aqueous solution 10% Na_2CO_3	1.38	1.09
Aqueous solution 10% H_2SO_4	1.22	1.49
Water at 32 F	1.06	1.02
Water at 65 F	1.00	1.00
Aqueous solution 10% H_3PO_4	0.99	1.07
Mercury	0.78	0.62
70 Cd–30 Sn alloy at 356 F	0.77	0.009
Water at 77 F	0.72	1.11
Rapeseed oil	0.30	0.055
Trial oil No. 6	0.27	0.045
Oil P20	0.23	0.055
Oil 12455	0.22	0.022
Glycerin	0.20	0.89
Oil 20204	0.20	0.13
Oil, Lupex light	0.18	0.20
Water at 122 F	0.17	0.95
Oil 25441	0.16	0.18
Oil 14530	0.14	0.022
Emulsion of 10% oil in water	0.11	1.33
Copper plates	0.10	0.067
Soap water	0.077	1.16
Iron plates	0.061	0.011
Carbon tetrachloride	0.055	0.34
Hydrogen	0.050	0.011
Water at 166 F	0.047	1.31
Water at 212 F	0.044	0.71
Liquid air	0.039	0.033
Air	0.028	0.007
Vacuum	0.011	0.004

(a) Cooling rate for water at 65 F is 3260 °F per sec through the range from 1328 to 1022 F, and 810 °F per sec at 392 F.

Optimum concentrations of these two compounds have been found by tests to be effective in avoiding the formation of soft spots in steels that have a strong tendency to harden irregularly.[14] Regardless of the temperature of the quenching solution, from 75 to 140 F, 9% NaCl or 3%

NaOH gave minimum soft spots; effectiveness decreased as the temperature increased. With a temperature in the upper part of this range, 9% NaCl was somewhat more effective than 3% NaOH; when the temperature was kept below 120 F, either gave better results than plain water at 75 F. The lower the temperature of the solution, the less critical was the concentration, although the certainty of local heating of the bath during quenching makes it desirable to control the composition of the bath carefully. Concentration may be checked readily with an ordinary hydrometer of suitable range. Table III gives relationships between concentrations of these two compounds and the hydrometer readings for solutions tested at 68 F.

Table III. Specific Gravity of NaCl and NaOH Solutions

NaCl or NaOH, %	Specific Gravity	Deg Baumé	Lb NaCl or NaOH per gal
Sodium Chloride Solutions			
4	1.0268	3.■	0.343
6	1.0413	■.8	0.521
8	1.0559	7.7	0.705
9	1.0633	8.7	0.800
10	1.0707	9.6	0.894
12	1.0857	11.5	1.087
Sodium Hydroxide Solutions			
1	1.0095	1.4	0.0842
2	1.0207	2.9	0.1704
3	1.0318	4.5	0.2583
4	1.0428	6.0	0.3481
5	1.0538	7.4	0.4397

Brine is used more widely than caustic soda, although brine creates problems by promoting rapid rusting of handling equipment and of the steel being quenched. Sodium hydroxide solutions have a protective influence against rusting, but such solutions offer more hazard to the operator, because contact with the skin is painful unless the solution is promptly washed off. Since the eyes are especially sensitive, goggles should be worn.

Although certain concentrations of some other inorganic compounds have a beneficial effect on quenching, there appears to be no merit in using them. Many materials soluble in water have a detrimental effect; soap is especially undesirable, because it extends the duration of the *A* stage and therefore acts in the same manner as an increase in the temperature of water (Fig. 4). Therefore, hands must not be washed in quench tanks, and no other contamination should enter the water or solution.

Mixtures of water and "soluble" oils, such as are used for coolants in machining, are occasionally used for quenching, but rarely give satisfactory uniformity of hardening. The mean cooling rate of such mixtures for *A* and *B* stages is lower than for most plain oils (Table II). However, a 10% mixture is sometimes used for cooling the work material quickly after tempering, because of the rust-delaying film thus produced. When steel hotter than about 900 F is cooled in such a liquid, the surface is darkened and a thin film of oil is retained, so this treatment is occasionally given to bolts and such after tempering or annealing below the transformation range.

Liquids for Quenching Deep-Hardening Steels. Deep-hardening steels are used in order that a fully martensitic structure may be obtained with an oil quench and therefore without excessive distortion.

The vapor-film stage of cooling, *A*, is less important in oil than in water quenching. Actually, the vapor stage may persist longer (see Table IV) but is not harmful unless exceptionally long, because the rate of cooling is faster in this stage with oil than with water, and the critical cooling rate of an oil-hardening steel is slower than that of a water-hardening steel. The duration of the vapor stage is longer, the lower the boiling point of the oil, so some lower limit should be placed on the boiling point of the oil used. Of course, the boiling point of oil is rather indefinite and must be defined arbitrarily.

The boiling points of the oils listed in Table IV are so high that moderate increases in temperature of the oil have little effect on the duration of vapor-film cooling. Consequently, oils, unlike water solutions, can be used while warm, without danger of incomplete hardening and with advantages in some respects. The cooling power of warm oil in the *B* stage is actually higher than that of cold oil. This is undoubtedly a result of lowered viscosity, which permits more rapid movement of vapor in carrying heat away from the metal surface. However, a real advantage in using warm quenching oil arises from consideration of residual stresses.

There is danger of cracking deep-hardening steels by cooling rapidly into the martensite transformation, as already shown. This transformation occurs during cooling, usually in the *C* stage. If cooling in this stage can be slowed down considerably, the steel will be less likely to crack. In this respect, cold oil has an advantage over water (*see* Table IV). The cooling rate in the *C* stage of oil is about 1/10 that in the *B* stage, while with water the ratio is about 1 to 6.5. However, the major advantage of oil is that the temperature can be raised considerably without bad effects, thereby lowering decidedly the cooling rate just above the martensite transformation range.

Caution is needed when warm quenching oil is used, except under careful control of temperature. The oil should not be so hot that it flashes or burns after the work material is immersed, thus becoming dangerous to the workmen. However, oil should not be used when below 90 F, because of the hazard of cracking certain steels. The usual types of quenching oil operate best when the temperature of the oil near the work being quenched is maintained between 90 and 140 F. Good circulation of oil is imperative (1) to eliminate stagnant pockets where stage *A* may persist long enough to produce incomplete hardening, (2) to maintain temperature uniformity, and (3) to dissipate heat from the work.

Table IV. Cooling Rates at Center of ¼-in. Diam Cylinder of Nickel-Base Alloy During Quenching in Still Liquids at 104 F, Showing Variation in Cooling Action with Surface Temperature of Pieces.[6]

Quenching Liquid	Boiling Point, deg Fahr	Duration of Vapor Film, sec	Relative Cooling Rate[a] in Stage: A	B	C
Tap water, up to 104 F	212	3	0.10	1.00	0.16
Brine (24% NaCl)	221	1	...	1.00	0.15
Sulfuric acid (90%)	504	1	...	0.96	0.09
Soap solution (2%) up to 104 F	...	11	0.08	...	0.15
Oil No. 1	712	6	0.16	0.36	0.035
Oil No. 2	756	5	0.17	0.48	0.042
Oil No. 3	860	2	...	0.27	0.027

Physical Properties of Oils	No. 1	No. 2	No. 3
Flash point, deg Fahr	370	399	581
Fire point, deg Fahr	419	466	646
Boiling point, deg Fahr	712	756	860
Density, g per cu cm	0.882	0.912	0.916

(a) Cooling rates in *A* stage taken at 1472 to 1292 F; in *B* stage at 1022 F; and in *C* stage at 392 F

So far only general qualities of oils have been considered. Among the numerous compositions available, it is difficult to be specific about the selection of an oil. The only suitable way of identifying quenching oils is by the physical properties of them and only a few investigators have recorded identifying properties, notably those whose data are given in Tables IV and V.

It has been shown[15] that oils over ■ wide range of viscosity at room temperature, when heated to an optimum temperature for each oil, give almost identical cooling curves. By varying the temperature of the oil, it is possible to change the cooling rate from a low value to one approximating that of the best oil under best conditions. The use of hot oil introduces not only the obvious problems and hazards but also the danger that the martensite transformation will be incomplete and that austenite will be retained, unless the work is further cooled after quenching and before tempering; therefore it is good practice to use an oil that gives the maximum quenching rate when maintained at 90 to 140 F. A low-priced straight mineral oil with Saybolt viscosity of about 100 at 100 F, is generally used.

Compound oils, having additions of special fatty or petroleum derivatives, have been developed to give faster

cooling than the plain mineral oils, and are particularly useful where the quenching system or the hardenability of the steel is inadequate. The use of such oils, however, is not a satisfactory substitute for proper control of temperature and circulation of quenching oil. Compound oils should be considered as possible improvements when cooling practice is already good.

Water gives quenching oil a murky or red appearance and causes irregular quenching rates. Consequently, contaminated oil should be replaced, and the cause, such as leakage from cooling coils or splash from adjacent water tanks, should be eliminated.

Standard tests, such as those of which the results are shown in Tables IV and V, are probably inadequate to determine the necessary qualities in quenching oils. The list of standardized tests of oils given in Table VI is probably sufficiently inclusive to assure duplication of good quenching properties found in a particular oil.

The standard tests are also important in regard to secondary requirements of quenching oils. Low viscosity assures free draining of oil from the work material and consequent low loss of oil. A high flash and fire point assure a high boiling point and reduce the fire hazard, which is increased by keeping the oil warm. A low pour test assures ample viscosity when cold. A minimum carbon residue suggests stability of properties and little sludging with continued use. The steam-emulsion number should be low to assure minimum water content; water is objectionable because of its great cooling power and its tendency to form a vapor film. A low saponification number assures that the oil has a mineral base and is not subject to organic deterioration, which causes offensive odors. The viscosity index is a valuable property for maintenance of composition.

Tests for these properties are suggested, however, only as a means for maintaining the composition of an oil found to be satisfactory by experience. Stability and reproducibility of properties are perhaps the most important requirements for quenching oils. It is important also to permit no deposit of sludge on cooling coils. Films of salt on tne work—for instance, when it is being quenched from a fused cyanide bath—are detrimental to oil.

Table V. Cooling Power and Other Properties of Various Oils[a]

Quenching Medium	Cooling Rate Relative to Water	Sp gr at 60 F	Flash Point, deg Fahr	Fire Point, deg Fahr	Absolute Viscosity at 68 F, poises	Approx Saybolt Viscosity at 100 F
Prepared[b] oil No. 1	0.44	0.862	365	405	0.421	110
Prepared[b] oil No. 2	0.35	0.874	375	415	0.417	110
Transformer oil	0.17	0.869	311	360	0.218	75
Machine oil	0.22	0.909	405	464	1.29	250
Paraffin oil	0.29	0.879	325	370	....	...
Fuel oil	0.36	0.856	205	219	....	...
Palm oil	0.15	....	435	486	0.449[c]	220
Rapeseed oil	0.22	0.874	379	444	....	250
Castor oil	0.29	0.963	565	640	10.43	1500
Cottonseed oil	0.36	0.925	610	680	0.795	175
Olive oil	0.37	0.917	590	680	0.800	200
Lard oil	0.19	0.917	565	685	0.836	180 to 200
Fish oil	0.31	0.933	401	446	0.698	130
Sperm oil	0.33	0.885	500	581	0.374	110
Neatsfoot oil	0.33	0.922	500	621	1.25	230 to 270
100% A[d]	0.26	0.864	360	410	100	65
95% A + 5% B[e]	0.39	....	...	...	....	...
90% A + 10% B	0.41	....	...	...	....	...
85% A + 15% B	0.42	....	...	...	....	...
60% A + 40% B	0.35	....	...	...	....	...
30% A + 70% B	0.32	....	...	...	....	...
100% B	0.29	0.897	534	610	3600	1200

(a) Cooling power is measured by the cooling rate of a ½-in. diam cylinder of 1% C steel when it has cooled to 1328 F from 1607 F while in still oil. Values of cooling rate are relative to that for quenching in still water, which is 356 °F per sec = 1.00[13]
(b) These are probably oils with a mineral base and contain 3.3% fatty acid
(c) Taken at 95 F
(d) Pennsylvania pale neutral oil; Saybolt viscosity, 65 at 100 F; flash point, 360 F
(e) Pennsylvania heavy-residuum crude oil, steam refined; Saybolt viscosity, 1200 at 100 F; flash point, 534 F

Table VI. Significant Standard Tests for Oil, Indicating Quenching Behavior

Test	ASTM Standard Method Number
Specific gravity	D 158-28
Viscosity	D 88-36
Flash point	D 92-33
Fire point	D 92-33
Pour test	D 97-34
Carbon residue	D 189-36
Steam emulsion	D 157-36
Saponification number	D 94-36
Viscosity index (See reference 9)	

Efforts have been made to secure in water-base liquids quenching characteristics equivalent to those of oil. This is an admirable objective but so far the attempt has been entirely unsuccessful. Rates similar to those obtained during cooling in oil, can be secured in particular temperature ranges, but not through the whole temperature range of quenching; that is the reason for the difficulty. Scott,[8] for example, shows that a mixture of glycerin and water will give a cooling rate in the *B* stage which is the same as that of a popular proprietary quenching oil. The cooling power of this liquid in the *C* stage, however, is much faster than that of oil; this condition is highly objectionable because of residual stresses. The same objection applies to solutions of ethylene glycol and sodium silicate in water. Also, the duration of the *A* stage in all these liquids is increased by the presence of water, which endangers completeness of hardening.

Emulsions of oils in water also have been used as quenching mediums, although the characteristics are even worse than those of the solutions just mentioned. In the *A* stage, cooling is greatly extended, and in the *C* stage, cooling is virtually as fast as in water. This reversal of the ideal relations between the stages is shown clearly in Table II. It is unlikely that a water-containing substitute for quenching oil will be developed soon.

Quenching Mediums for Minimum Distortion and Residual Stress. Quenching in oil is much more satisfactory than quenching in water as far as distortion is concerned, but even in oil, distortion may be quite severe in thin or complicated sections of pieces like many that are used by the aircraft industry. Also, cracking is a hazard in critical sections. These problems associated with quenching in oil, have been solved to some extent by the practice of supporting work material on trays during quenching. The trays are automatically oscillated vertically in the oil bath, which in turn is agitated chiefly by the movement of the work material. This symmetrical cooling, in combination with judicious placement of the work material, achieves consistency in dimensional changes, as well as a reduction in the magnitude of these changes. Commercial furnaces are available for quenching steel under a protec-

tive atmosphere so that the work material is removed from the quench free from scale and decarburization.

To harden steel without measurable distortion or residual stress, it is necessary to use a much slower cooling medium than oil—for example, a gas. This expedient requires a steel of exceptionally high alloy content and consequently high cost, both of metal and of machining time. The additional cost is well justified, however, in producing expensive and intricate tools or dies.

Many steels designed for hardening in gas are now on the market. They are identified as air-hardening steels but can be hardened as well or better in protective atmospheres. For example, in one commercial furnace the work material is surrounded by dissociated ammonia during the cooling as well as the heating period. Though this gas has a thermal conductivity considerably higher than air, actual cooling rates are no faster at high temperatures, because of lower emissivity of heat, resulting from the bright surface maintained through the cycle. This atmosphere, if maintained at the high state of purity at which it is generated, prevents decarburization as well as oxidation, and even permits bright hardening of stainless steel.

Results approximating those obtainable with gas-hardening steels can now be attained consistently with the less expensive oil-hardening grades by the use of "martempering".[11] The work material is quenched in a liquid at or close to 400 F. The liquid is preferably a molten salt that has cooling properties similar to those of quenching oils. Oil having a high flash point may be used also, if covered by a suitable protective atmosphere. Work material is removed when it approaches the temperature of the bath, and is then cooled in still air to atmospheric temperature, with precautions to minimize temperature gradients.

Martempering is very effective in controlling residual stress by reduction of temperature gradients during the martensite transformation. Particularly important is the elimination of temperature differences between heavy and light sections while in the quench bath, before transformation starts or is well advanced. The martensite transformation starts at approximately 400 F in high-carbon steels, but at progressively higher temperatures as the percentage of carbon in solid solution at the austenitizing temperature is reduced. For this reason martempering is less effective when applied to low-carbon steels than to high-carbon steels, though this process is considerably more satisfactory than a conventional quench, because of reduction in cooling rate in the range from 900 to 500 F as a result of the high terminal temperature, 400 F. This treatment should not be confused with austempering, which permits the transformation of austenite to go to completion at the holding temperature. In martempering, the aim is to complete the transformation of austenite to martensite during air cooling to room temperature.

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The Quenching Process and Industrial Quenching Equipment

BY THE SUBCOMMITTEE ON QUENCHING*

MANY treatments for steel involve cooling the metal from an elevated temperature. This article discusses only the processes of cooling steel during the hardening operation. Such quenching processes include accelerated cooling by either liquid immersion, gas or liquid agitation, or contact with a cold metal.

Great progress has been made in the development of modern equipments to heat steel properly. The equipment to remove the heat properly has received far less attention. Recently there has been closer study of the hardenability of steel and, consistent with this trend, has been a greater interest in the cooling rates that may be obtained in quenching processes.

The purpose of this article is to outline the underlying metallurgical and thermal aspects of quenching and to describe the factors entering into the design and use of modern industrial quenching equipment.

Metallurgical Aspects of Quenching. The general principles of the heat treatment of steel are discussed in the article on page 613 of this Handbook.

In a metallurgical sense, the effective quenching of steel consists of cooling austenite through the transformation range in such a manner as to allow the formation of martensite, which is hard, and to prevent the formation of ferrite or pearlite, which are soft. The "critical cooling rate" is the slowest that will accomplish this result.

The maximum hardness obtainable in steels cooled at a rate equal to or greater than the critical rate, depends on the carbon content, in the manner shown in Fig. 1.

When the cooling rate is less than the critical rate, transformation to ferrite, pearlite, or bainite takes place with a corresponding decrease in the amount of martensite formation and a lower resultant hardness. When the cooling rate is such that only 50% martensite is formed, the resultant hardness versus carbon content for medium alloy and plain carbon steels is that shown in Fig. 2.

When plain carbon steel is quenched from the correct austenitizing temperature, the critical cooling rate is 100 to 360 °F per sec, measured at 1300 F. Therefore, the steel must cool at least as fast as this throughout the entire cross section of the piece if full hardening is to be obtained. Water, under favorable conditions, provides cooling rates of approximately 1800 °F per sec at the surface. Cooling the surface at this rate produces cooling rates throughout the cross section at about the maximum theoretically attainable. Hence, for relatively light sections, where the ratio of surface to volume is large, extremely rapid cooling throughout can be obtained by a quenching method that cools the surface rapidly, as in water quenching. In such instances plain carbon steels with more than about 0.35% C, although possessing relatively high critical cooling rates, may be fully hardened.

A necessary consequence of fast surface cooling as obtained in water quenching, is a high temperature gradient

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from surface to center. This produces severe distortion and the hazard of cracking in all but simple, symmetrical shapes that have a low ratio of length to diameter or thickness. Under favorable conditions, oil quenching provides a cooling rate at the surface of approximately 135 °F per sec as compared with 1800 °F per sec with water; hence a much lower temperature gradient from surface to center. Steels with high critical cooling rates requiring a water quench, should therefore not be used in complicated shapes or nonuniform sections where distortion is objectionable. Such parts require alloy steel with a low critical

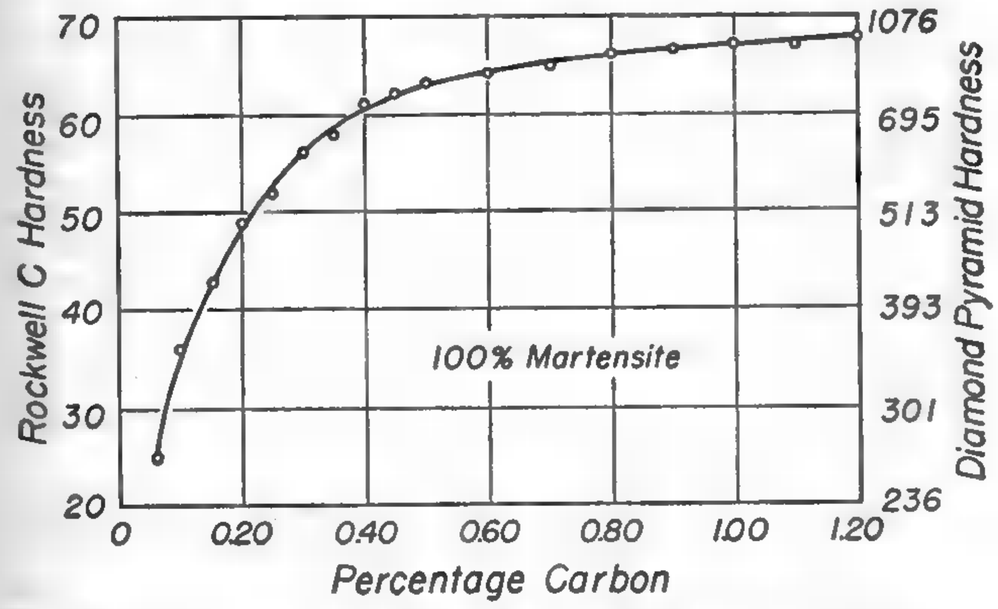


Fig. 1 Influence of carbon content on the hardness of fully martensitic steel, as quenched

cooling rate, which may be attained throughout the section in an oil quench, thus reducing substantially the temperature gradient during quenching.

With heavy sections, the cooling rate is limited by the rate of conduction of heat from the interior to the surface. Hence it becomes impossible to cool the center of a large section rapidly by any quenching method, because of "mass effect". For full hardening of heavy sections, it is necessary to use steel that contains a sufficient amount of alloying elements to lower the critical cooling rate to equal that attainable at the center by oil quenching.

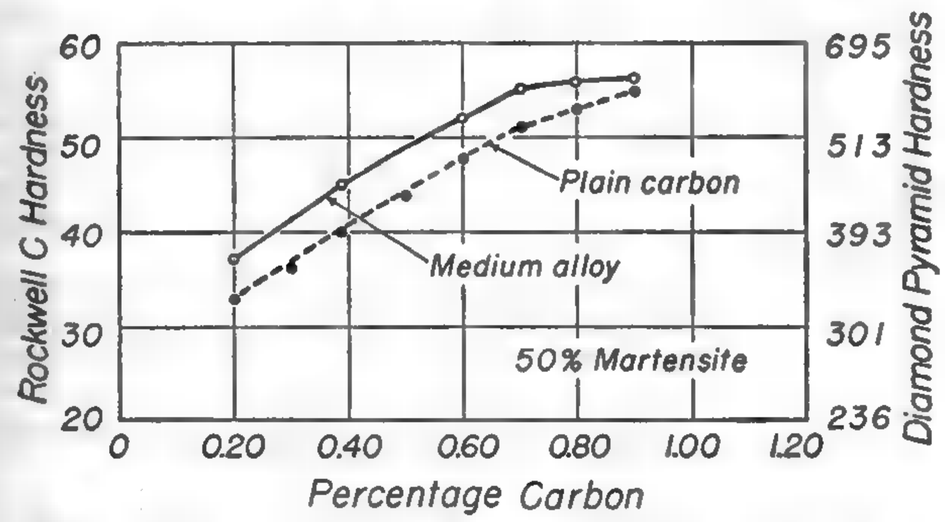


Fig. 2 Influence of carbon content on the hardness of steel that contains 50% martensite, as quenched

The term "hardenability" is used for describing the relations between cooling rate and depth of hardening. For information on hardenability testing, see page 489.

Physical and Thermal Aspects of Quenching. In addition to metallurgical transformations, certain thermal considerations are important in the quenching process.

Since heat can be removed from a solid object only by dissipation from the surface, the rate of cooling depends on the temperature of the surface of the object during the quenching process. The shortest possible time of cooling is obtained when the surface is at the temperature of the cooling medium. The decreased surface temperature necessary to promote rapid cooling may be obtained by bringing the cooling medium into contact with the surface of the object. The rate of cooling produced depends on the temperature, mass, and shape of the object, the inherent characteristics and speed of circulation of the quenching medium, or the speed of movement of the object being quenched. Whether or not hardening occurs during a particular cooling operation depends, of course, on the composition of the steel, as well as on the quenching medium.

Elements of the Quenching System. The following functional equipments are usually required and installed for a suitable quenching system: (1) work tank or machines, (2) facilities for handling the parts quenched, (3) quenching medium, (4) agitation, (5) coolers, (6) heaters, (7) pumps and strainers, (8) supply tank and (9) equipment for ventilation and for protection against hazards.

Just how elaborate a quenching system should be depends on many factors—primarily on the hourly production, the accepted quenching technique, and the justification of the initial cost. For example, a small plant making machine parts might require the hardening of a few small pieces per day in the as-forged condition, parts that weigh 3 lb each and are made from 1045 steel. A satisfactory

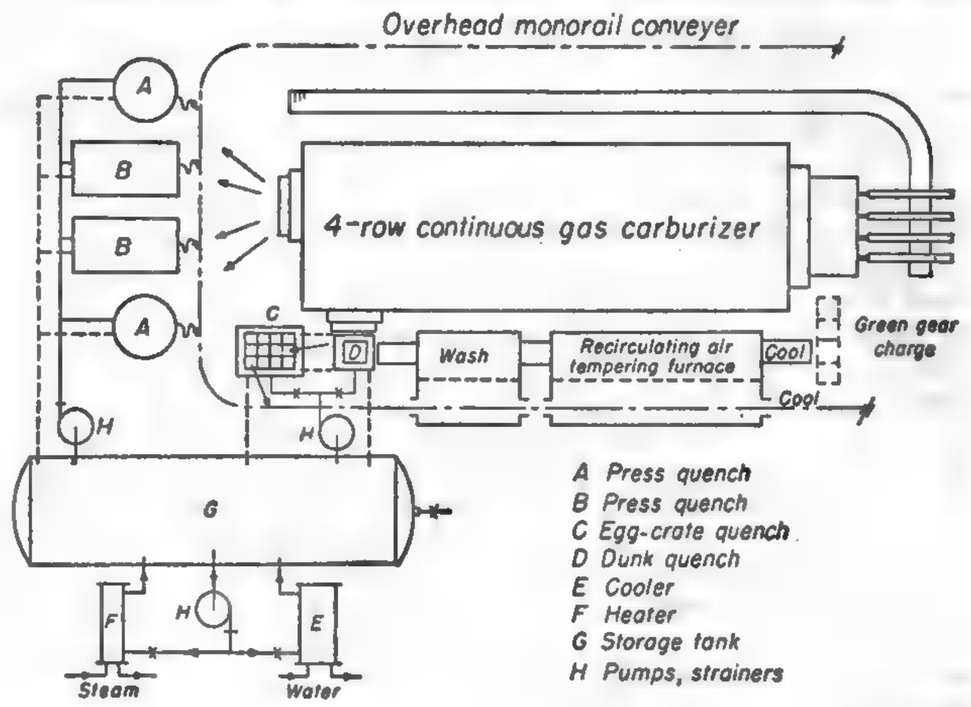


Fig. 3 Layout showing the elements of a quenching system

quenching system for this requirement would involve a barrel of water with piping for the supply, and a gravity drain to a sewer. The work would simply be removed from a furnace with tongs and immersed in the water.

In contrast with this simple setup is an automotive plant manufacturing rear-end assemblies. The problem is to quench carburized gears in large-scale production. There are several models of assembly and each requires a ring gear, stem pinion, differential side gears and differential pinions. Gears weigh from less than 1 lb to 10 lb each. All must be processed efficiently in order to match the final requirements of the assembly line. The as-quenched gears must meet close inspection for metallurgical and mechanical properties. Since a low cost per unit must be maintained for the whole heat treating operation, the quenching process is integrated with the heat treating equipment, and handling facilities are laid out accordingly.

Green gears, fully machined except for finish grinding, are charged into a continuous pusher-tray type of gas carburizer. Work pieces are loaded on alloy trays with suitable fixtures that permit direct quenching.

The following elements, as shown in Fig. 3, might comprise the quenching system for such an operation:

1 Work tanks and machines
   - *a* Quenching press for one model of ring gear
   - *b* Quenching press for another model of ring gear
   - *c* Special "egg-crate" quenching tank for stem pinions
   - *d* Special "dunk tank" for quenching side gears and differential pinions without removing from trays or fixtures

2 Handling facilities
   - Special "peel" to remove hot ring gears from a tray in the furnace to the gear presses
   - *b* Overhead conveyer for washing, tempering, cooling and inspection
   - *c* Hooks to remove hot stem pinions from tray to "egg-crate" quench (Pinions would then be placed on an overhead conveyer for subsequent processing.)
   - *d* Alloy trays and fixtures to immerse trays of differential side gears and pinions directly into the "dunk tank". (From here the trays and work pieces go directly to the washing, tempering, cooling and inspection operations.)

3 Quenching medium, a properly selected oil that will provide consistently the desired rate of cooling.

4 Agitation
   a Special provision for agitation is taken care of in the quenching presses themselves
   b Pump to supply proper circulation of oil to the "dunk tank" as well as the special "egg-crate" work tanks
5 Coolers and heaters to maintain a definite temperature of the quenching oil, whether starting from shut-down or working under continuous production conditions
6 Pumps and supply tanks as noted in Fig. 3

Factors Determining the Design of Work Tanks. *Study of Parts.* The laying out of work tank equipment for the quenching operation should start with a study of the parts to be manufactured. All steps of manufacturing are normally established from the print for the parts, and equipments, including work tanks, are selected to handle the required production schedule.

The following information is immediately available from the print for the parts: (1) size, (2) shape, (3) weight, (4) section, (5) steel used, (6) hardness specified and (7) tolerance allowed.

Technique of Quenching. The technique of quenching may be defined as the method employed in applying the work piece to the quenching medium, or the quenching medium to the work piece, to produce desirable metallurgical and mechanical properties in the steel in the as-quenched condition. This, of course, must be accomplished without excessive cost and with suitable handling facilities.

With the above-mentioned information on the parts, the next step is to determine what quenching technique is to be used for treating the parts. Past experience is helpful and there are many "rules of thumb" that may indicate what methods are practicable. Conversely, other methods may be ruled out on the basis of experience. If the part is new and of such size and shape that it does not conform to past experience and practice, then tests should be made to determine what quenching technique is required.

In addition to the necessity for the quenching process to remove heat from the work piece rapidly enough to impart the desired metallurgical and mechanical properties to the parts, consideration must be given also to thermal factors such as the following:

1 Mass determines the amount of heat removal.
2 Exposed surface area influences the rate of cooling.
3 Thermal differential between work surface and quenching medium influences the rate of cooling.
4 Depth of metal section determines the duration of quench.

Items 1, 2 and 4 are fixed by the design of the work piece. Item 3 introduces the subject of agitation.

Agitation. Agitation may be defined as the mechanical means employed to accelerate relative motion between the work piece and the quenching medium, thereby ensuring a high thermal differential between the surface of the work piece and the quenching medium. Practical experience has shown that accelerated rates of heat abstraction from quenched steel are possible by means of forced circulation or agitation. Thus over-all quenching efficiency is improved and full benefit is derived from the use of the steel so quenched and of the medium employed.

After entering the liquid quenching medium, the hot steel is cooled in three stages, known as "vapor blanket cooling", "vapor transport cooling" and "liquid cooling".*

Agitation of the liquid quenching medium against the hot steel accelerates quenching, especially during the "vapor transport" stage of cooling. Liberal circulation keeps the temperature of the quenching liquid more uniform and thus increases the efficiency of quenching. Agitation also keeps the surface temperature of the work piece uniform during the final stage of quenching, which tends to equalize quenching strains that would otherwise cause distortion of the steel.

It might be asked: if a little agitation is good, is a lot of agitation better? And if so, what determines the volume of circulation to be employed for the average work tank? In the entire subject of quenching, these are probably the simplest and most direct questions to ask, and the hardest to answer satisfactorily.

It can be stated that the volume of circulation or agitation to be provided in the work tank depends on (1) size, shape and surface area of work piece, (2) type of medium used, whether it is rapid or slow in its quenching speed, (3) steel used, whether shallow hardening or deep hardening, (4) hardness and other properties required, (5) allowable distortion, (6) temperature uniformity of quenching medium in the work tank, (7) surface condition of work as it enters the tank and (8) rate of production.

Some of the above points are self-explanatory. A heavy section of deep-hardening alloy steel is often quenched in water with generous agitation when treated in the "rough". The part is then tempered and full-finish machined as a means of eliminating distortion. This is common practice, for example, in the treatment of axles and splined shafts.

On the other hand, if the part to be quenched is a fairly large axle or splined shaft that is carburized, it must be full-finish machined except for dimensional finish grinding. Such a part should be immersed vertically in a still medium, with no agitation for the first few seconds of immersion, so that a hardened "crust" will hold the shaft in alignment. Then a heavy volume of agitation is applied to remove the heat from the center of the piece in order to develop the properties desired in the core.

Agitation can be produced in several ways. In conventional work tanks, circulation is usually provided by pumps, by agitators or by the gravity fall of the piece through the quenching medium.

Pumps are perhaps most commonly used, since they provide a flexible means for directing the quenching medium where it is most effective. Also, the flow can be split to provide circulation to one or more locations in the tank with easy adjustment. When the medium is oil and a cooler is used, the same pump that forces liquid through the cooler can often act at the same time as an agitator pump. In special work tanks that involve a "floating fountain" quench, or in a design that requires the rapid removal of heat from a cavity of the work piece, the recirculating pumps may be the preferred equipments for producing agitation.

Agitators with mechanical propellers are popular and effective in producing general agitation in a conventional work tank. The self-contained mechanical agitator is compact, requires no piping, and is easily removed for maintenance. Other forms of driven propellers are excellent, although they must be properly located in the work tank in order to function effectively.

The third method of agitation depends on the gravity fall of the hot piece through the liquid. This method is usually employed in quenching light parts that have high surface area per unit weight. If pumps or mechanical agitators were used, the work piece would probably drift undesirably in the tank and it would be difficult to handle the load with a conventional elevator-conveyer discharging work tank.

There are other instances where the work piece is driven mechanically with respect to the quenching medium. Shafts, for example, are sometimes rotated in the quenching medium, in order to produce the effect of agitation.

Several of the methods of agitation just described may be combined in the design of a single work tank.

Practical Suggestions for the Design of Work Tanks

1 The time necessary to "quench out" the part treated, should be measured, and allowance should be made for this cycle when the hourly rating or capacity of the work tank is determined. When this factor is considered and the mechanism determined that provides for the desired quenching technique, the size of the enclosure of the work tank follows. This volume of medium is then used in other calculations concerning equipment and in the selection of size; for example, the volume of medium influences the selection of the size of cooler and whether a supply tank is necessary, as will be explained later.
2 Adequate space should be provided around the work piece in order to get the full benefit of circulation and maximum heat absorption from the quenched parts.
3 At best, it is difficult to control distortion caused by thermal strains when quenching. Therefore, the hot and plastic work piece should not be mutilated and deformed by allowing it to fall on the chute or quench conveyer until sufficient quenching has taken place to form a hard crust that will protect the part. On the other hand, if the part is large enough not to be deformed by such handling, premature destruction of the chute and conveyer mechanism is likely to result.
4 The work tank should be accessible to facilities for maintenance and cleaning.
5 If removal of scale from the tank is a serious problem, the use of a furnace that has a controlled atmosphere should be considered.

* These three stages of quenching are discussed in the article on page 615.

6 If caustic or brine is used in the work tank, ventilation should be provided in order to protect workmen from fumes and to improve working conditions.
7 If the quenching medium is oil, protection against fire hazard should be provided.
8 The use of clean-out plates on the work tank should be avoided unless otherwise necessary. The gaskets are difficult to maintain and will leak unless many studs are used on closely spaced centers.
9 It is possible to use almost any mechanism in the work tank when oil is the quenching medium.
10 Special selection of materials for mechanisms is usually necessary if brine or caustic is used. A high cost of maintenance will usually result.
11 Alloy trays and fixtures of the 25 Cr – 12 Ni or 35 Ni – 15 Cr type can be quenched in oil quite satisfactorily, but not in water, caustic or brine.
12 If water, caustic, or brine must be used, the use of special materials for pumps, coolers, and other equipment, should be considered.
13 Wherever possible, the design of the work tank should provide for flexibility and control of such conditions as: (*a*) time cycle of quench, (*b*) volume of circulation and (*c*) uniformity of bath conditions.
14 It should not be expected that agitation will solve all problems. Excessive agitation that will blow light parts off the conveyer and thereby lose them, should not be employed. A medium that has a higher speed of quenching should be used instead.
15 A quenching bath should not be agitated so violently that foaming occurs on the bath surface. This means that air pockets are forming and that the maximum benefit of circulation is not being obtained.

The above are some of the more important considerations that apply in the design of work tanks. Many others could be mentioned.

Typical Work Tanks. Typical sketch layouts are given in Fig. 4 to 9. These are intended to show various types of work tanks, the quenching technique employed, the method of handling the parts treated and the application of agitation. Obviously, there can be many other combinations and variations not shown here.

Quenching Presses. One type of commercial quenching press is designed for holding and quenching gears and other parts so that they may be brought to the required hardness with minimum distortion. These presses and dies are designed and built to remove distortion that results from the heating cycle* and to apply the quenching medium in a controlled manner so that uniform quenching at the desired rate is obtained. This action is illustrated schematically in Fig. 10. The die contacts the heated part and the pressure of the press aligns the part mechanically as illustrated in Fig. 10*b*. This occurs before quenching starts and while the part is hot and plastic. The machine and dies then force the coolant into contact with the part in a controlled manner as illustrated in Fig. 10*c*. The quantity and rate of flow are controlled by the press. The distribution of the flow is controlled by the dies. The speed of the quench depends on the quenching medium and the amount of agitation. Exact control of the rate of cooling can be obtained by adjusting the rate of flow through the die.

The design of quenching dies is based on definite rules, and the basic equipments have been standardized to a considerable degree. Although basic types of dies are used on typical shapes, certain special parts must be made for each die in order to adapt it to the particular piece to be quenched. The manufacturers of the presses should be

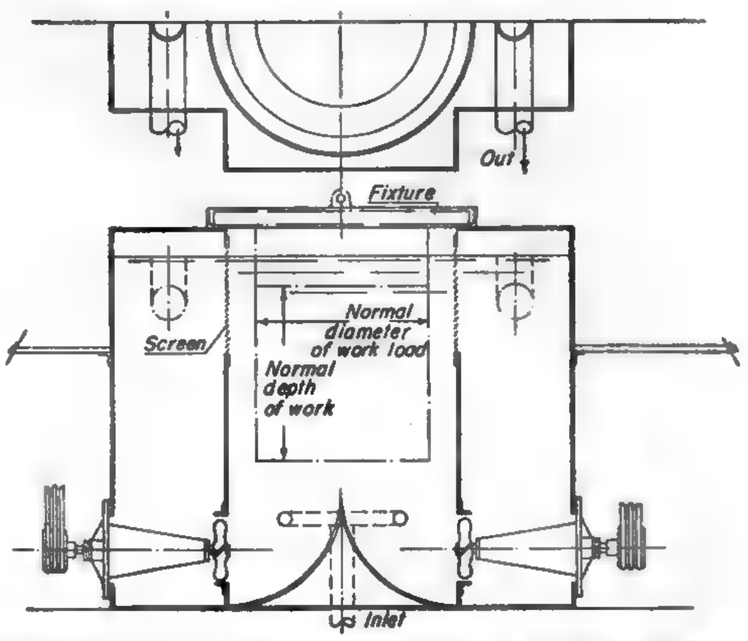


Fig. 8 Work tank for mass quenching of shafts, axles, gears and other parts at the rate of 500 to 1500 lb per charge. Crane charge, crane discharge, agitation by double motor-driven impeller

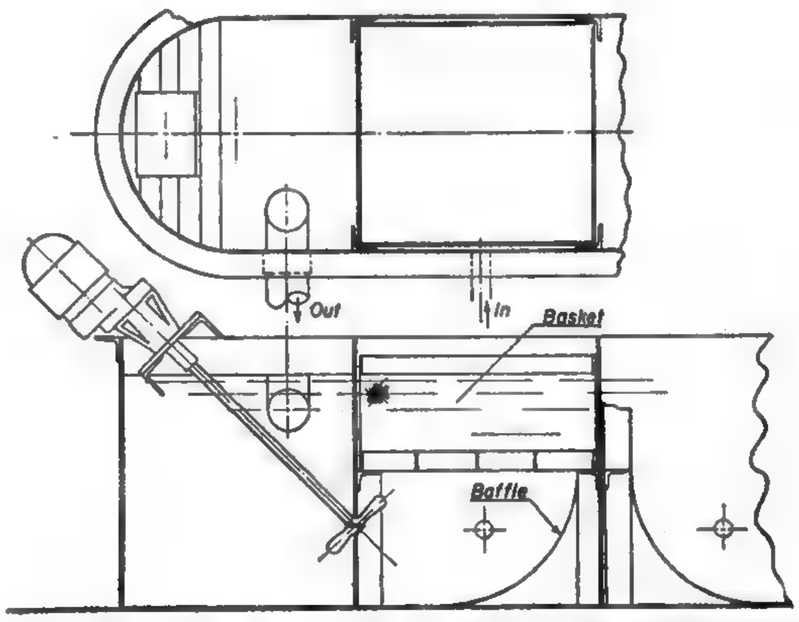


Fig. 9 Double batch work tank for quenching miscellaneous work pieces at the rate of 500 to 1000 lb per hr. Manual charge, basket discharge, unit mechanical agitation

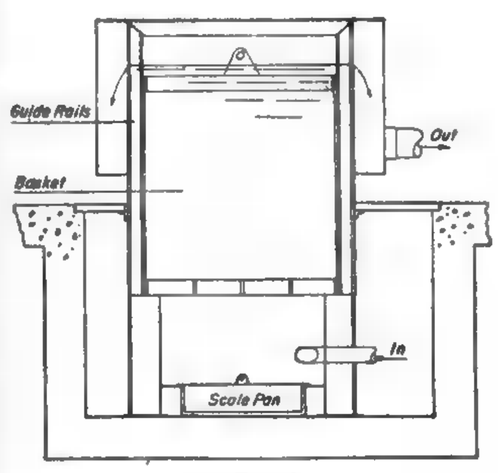


Fig. 4

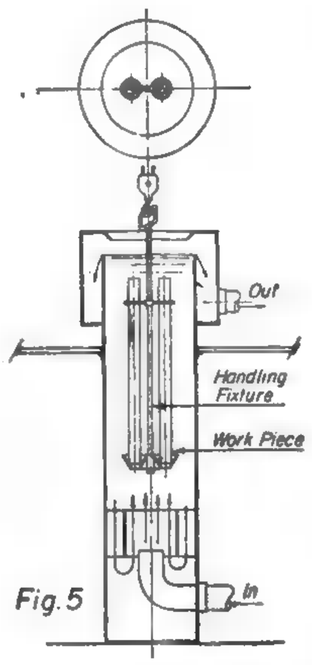


Fig. 5

Fig. 4 Cylindrical work tank for quenching batches of small to medium-size work pieces at the rate of 150 to 500 lb per hr. Manual charge, basket discharge, tangent agitation from ■ pump

Fig. 5 Batch work tank for quenching axles and shafts with pump agitation, and hoist and fixture for handling as much as 2000 lb per hr

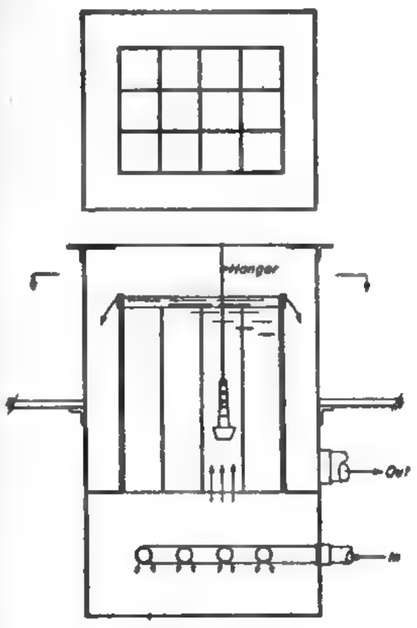


Fig 6

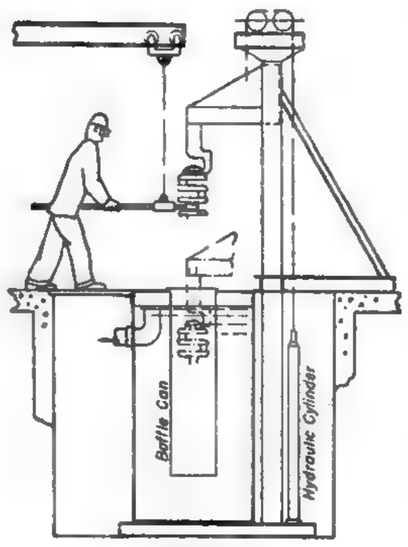


Fig. 7

Fig. 6 Egg-crate work tank for quenching parts such as stem pinions

Fig. 7 Unit-immersion quenching station. Adjustable sequence for timed quenching and timed agitation by pumps

* As an example of distortion during heating, consider the situation where one section of a part that is above or below the transformation temperature range is expanding with each increment of temperature rise at the same time that another section at the transformation temperature is contracting; in this manner serious upsetting can take place. Relief of residual stresses during heating can also cause distortion.

consulted in regard to die problems. One of the most important factors in all die design is that the piece to be quenched must have precise tolerances on those dimensions necessary for die contacts if optimum results are to be attained. The correlation of the areas of the part where the die is to make contact is equally important. For example, when quenching a gear, it is always desirable to "round up" the piece by die contact in the same bore that was used for chucking the part when the teeth were being cut. In a similar manner, die contacts on other types of parts are selected for their relation to the part as a whole and for their ability to bring the part to its original shape when suitable pressure is applied. All quenching dies are designed and built with provisions for adjusting the proportion of quenching flow through a given passage. Quenching to tolerances of 0.001 to 0.003 in. for round and flat is common practice when correctly designed dies are used on properly machined parts.

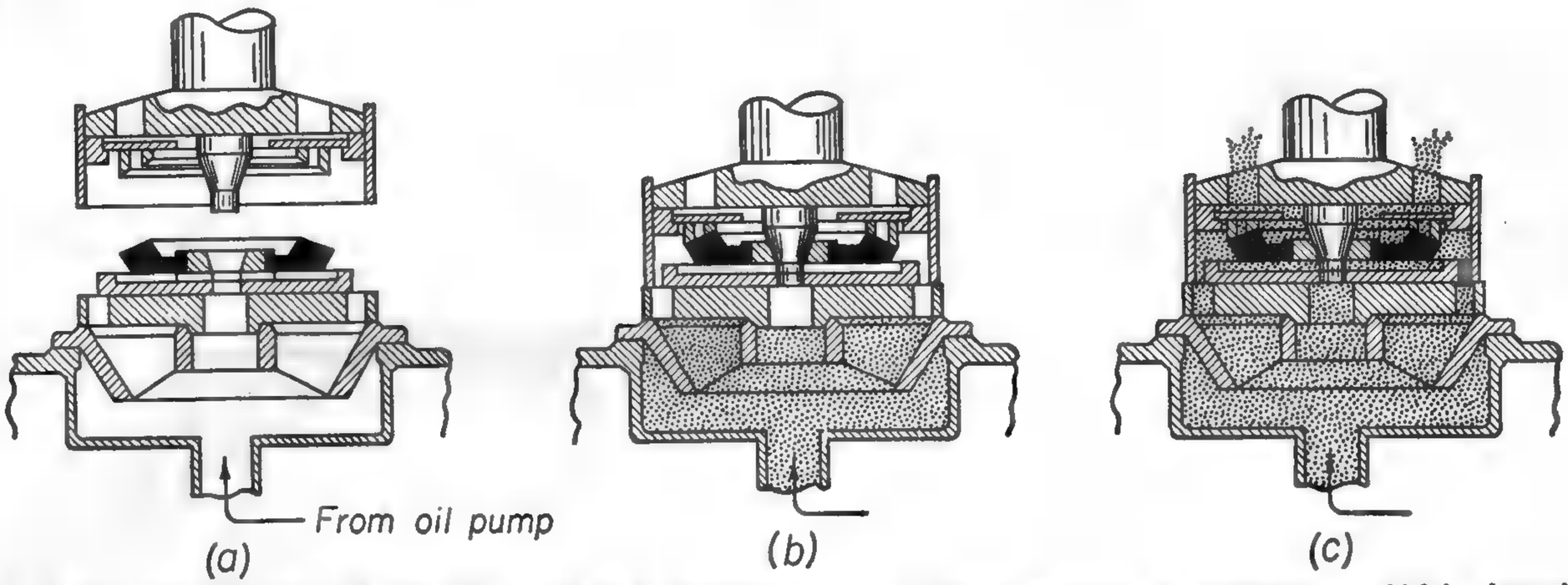


Fig. 10 (*a*) Quenching press with hot gear on the lower die in quenching position. (*b*) Upper die in contact with work piece, which has been aligned while still in the plastic condition. (*c*) Beginning of timing cycle; quenching oil forced into quenching chamber and around gear

The machines have a reservoir and recirculating pump system with valve and time controls so that at all stages of the quenching cycle, the volumes and rates of flow through the die are automatically changed to values preset to suit the requirements of the part. The built-in pumping system and reservoir reduce the external supply of quenching medium required, to approximately 35 gal per min while providing controlled flow through the die of as much as 225 or more gal per min, depending on the size of the machine. The external supply of quenching medium needed is determined by the heat absorption required and by the desired temperature rise of the medium. Because the die passages direct all the quenching fluid into close proximity to the piece, the supply from external sources need not be increased to allow for wastage and unutilized overflow.

In another commercial quenching press, the quench enclosure, the quenching dies and the work piece are rotated during quenching. This press is used to quench gears and other similar machined parts to meet required mechanical properties with a minimum of change in dimensions. With a given set of dies or tooling, this machine will mechanically re-align the hot and plastic work piece, in order to correct distortion caused previous to the actual quench, and will then automatically proceed with the quenching under controlled conditions. Quenching is facilitated by means of favorable die designs and the centrifugal action of the quenching fluid in the press.

This press will quench almost any machined part symmetrical to a common axis that fits the standard quench enclosure. Parts can be either quenched all over or, as with certain full-web, forged gears, a soft hub can be retained without masking off any portion of the work piece. The method of performing these operations, as illustrated in Fig. 11, is as follows:

1 Hot gear charged on lower die (Fig. 11*a*).
2 Pilot ram leads main ram to clamp hub to lower die. (Can also be used to center and expand arbor for ring gear tooling.)
3 Main ram closes to flatten rim of gear shown.
4 Quench enclosure, dies and gear rotate.
5 Quenching medium fills enclosure and approaches the hot gear that is clamped and corrected to dimensional change before quenching (Fig. 11*b*).
6 Quenching proceeds by pumping liquid into the chamber entering at the outside internal diameter. The liquid forms a dense cylinder with the inside "bore" decreasing rapidly until it reaches exhaust ports. In this instance the overflow pipes are set at a prescribed diameter to retain a soft hub. This feature is often desirable in full finishing the hub when the otherwise hardened gear is chucked from the "pitch line". Cool liquid at a definite temperature rapidly displaces hot liquid contacting the gear, so that controlled agitation removes heat from work surfaces for optimum quenching results (Fig. 11*c*). For work requiring "all-over" quench, the dies and exhaust ports are set up accordingly.
7 At the end of time cycle the upper die rises as rotation stops, and liquid flows out of the chamber.

These quenching presses incorporate design features to provide control over the following factors required in press quench operations:

a Adjustable pressures in both main and pilot rams.
b Variable and controlled volume of the flow of quenching fluid by use of built-in pumps that have a capacity of 250 gal per min.
c Full "all-over" quench or adjustable segmental quench to retain soft hubs.
d Adjustable controlled time of quench.
e Auxiliary reservoir built into machine to reduce demand on supply of quenching fluid.
f Controlled agitation that results in rapid quenching cycles.

Cold Die Quenching.[1] Heat treaters who have tried to avoid stresses caused in steel by nonuniform quenching, will naturally view rather skeptically any suggestion that these stresses may be employed to help straighten parts during heat treatment. However, this is essentially what happens when "cold die" quenching is used to harden certain steel parts. Use of the dies for quenching was originally developed for a particular job in which blades of an air-hardening steel were quenched and flattened between cold steel blocks. Cold dies that eliminated contact of liquid with the part, gave excellent results for flattening and hardening.

The process has been applied to other parts and it has developed into a useful tool for heat treaters. A hardening operation on a thin washer or disk, or on ■ long slender rod, has always been looked upon as the chief source of distortion; therefore, costly hand straightening and high losses in the form of scrap have been common on this class of material.

For example, large, thin thrust-washers, blanked out of cold rolled steel, which have oil grooves machined halfway through the thickness, always come from the blanking and machining operations considerably out of flat. A bow of 0.050 in. is quite common and even more may be found occasionally, but the washers after hardening are held flat within 0.005 in. The method used is an extremely simple one—the parts are squeezed between a pair of water-cooled die blocks, which replace the conventional quench.

The use of a die surface for a cooling medium is obviously limited to parts of large surface and small mass.

This might seem to be a severe limitation; however, it should be remembered that these parts give the worst trouble with warpage in hardening.

Coolers. *Thermal Cycle of Medium.* While quenching proceeds in a given system, heat is removed from the work piece and the temperature of the quenching medium obviously rises, unless otherwise cooled. Since uniform metallurgical results in the hardening operation depend on controlled conditions in the quenching process, coolers (and sometimes heaters) are necessary to maintain selected temperatures in quenching mediums.

Many types of heat exchangers are used in the cooling of quenching liquids and each offers certain advantages.

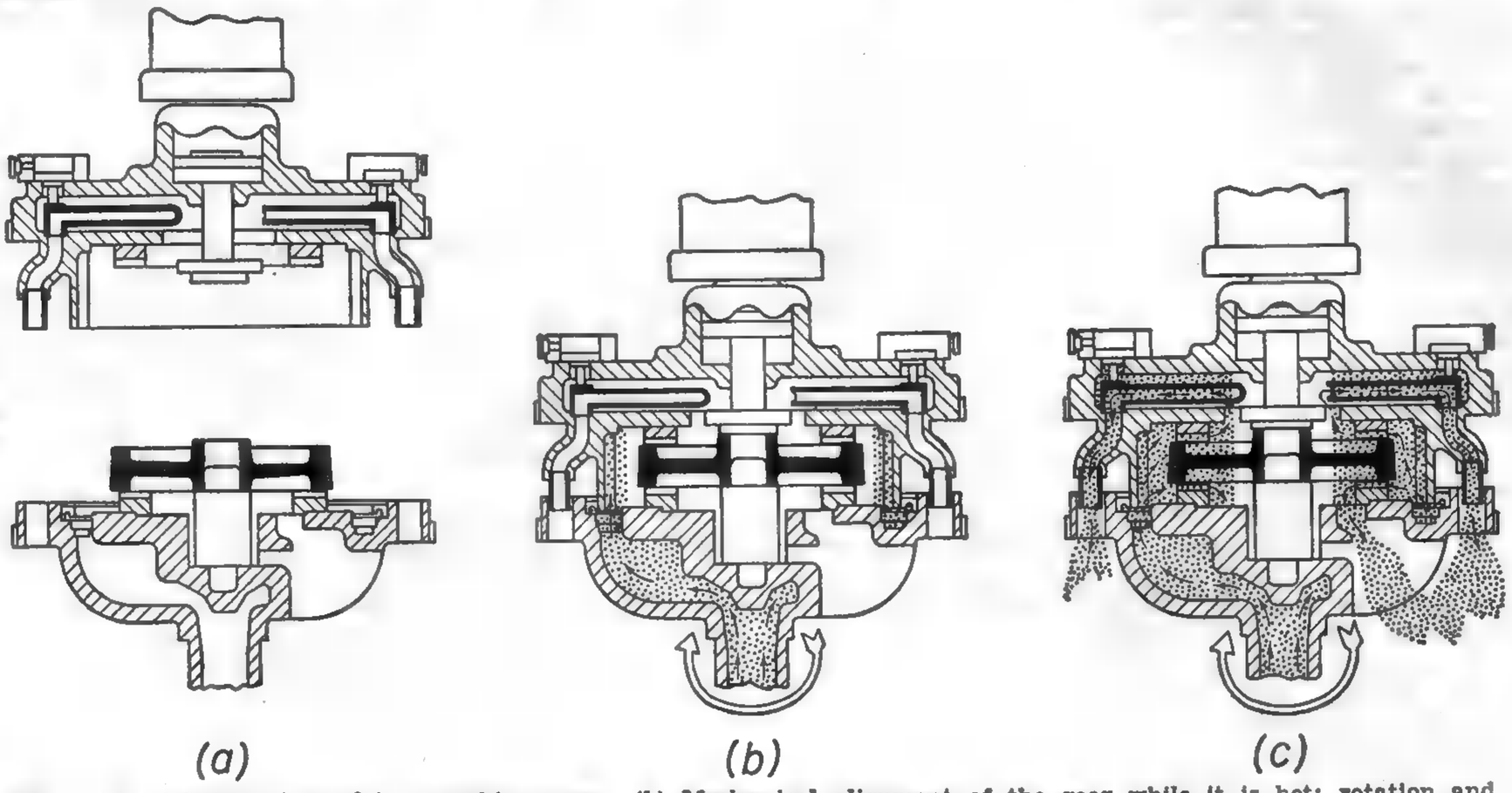


Fig. 11 (*a*) Hot gear charged in quenching press. (*b*) Mechanical alignment of the gear while it is hot; rotation and start of quench. (*c*) Continuation of centrifugal quench.

The rate of heat transfer through the unit always depends on the velocity of the liquids passing through the cooler; as the velocity increases, the rate of heat transfer increases. Therefore, if a unit is designed for high efficiency and suitable velocity of flow, the pumps that move the liquid are related to the cooler application.

Again, maintenance of cooling equipment is related to design. If a uniform temperature is held in the quenching oil, the problem of fouling is held to a minimum. Cooling equipment should always be designed for easy cleaning.

Shell-and-Tube Heat Exchangers. This type of oil cooler consists of a series of copper or steel tubes built into a steel shell. The quenching liquid is circulated through either the tube or the shell section, and the cooling liquid through the opposite section. City water is often used as the coolant, although with larger heat loads an evaporative water-cooling unit may provide the cooling water used in the heat exchanger. Well water is also used frequently. In general, city water is used when the total quenching load is less than 2000 lb per hr. However, the selection of the cooling medium depends on the cost of city water as compared with the operating and initial cost of the evaporative unit. In most instances the evaporative unit does not provide water at as low a temperature as can be expected from a well or the normal city source. Therefore, the heat exchanger is usually larger when the source of cooling water is an evaporative unit.

Maintenance of the shell-and-tube heat exchanger is negligible. A well-designed heat exchanger will provide for removal of the tubes for cleaning.

The shell-and-tube heat exchanger is flexible in its application and can easily be designed to meet all conditions, such as velocity requirements and the specifications regarding heat transfer.

Evaporative Coolers. This unit employs the evaporative principle of cooling. The unit consists of a pump or pumps used in recirculating water from a pan at the bottom of the unit through a series of nozzles near the top. A high-velocity fan circulates air over the spray water, thus lowering the temperature of the water. The cooled water is passed over the series of copper or steel tubes inside of which is circulated the quenching liquid that is being cooled.

If the cost of city water is high, this unit offers a definite operating economy. Maintenance of the fan and water-circulating pumps, and periodic cleaning of tubes are necessary.

Spray Towers. Spray towers, in general, are of three types: atmospheric, induced draft, and forced draft. The unit is usually installed outside the building and often on the roof. The water to be cooled is circulated from a pan or tank at the base, through the spray nozzle at the top of the tower. As the water is sprayed from the nozzle, it is cooled by evaporation caused either by normal movement of air or by mechanical circulation of air.

Such units are usually provided when the requirements for cooling water are great. Limitations, as in the evaporative cooler, are related generally to the local wet-bulb temperature. The unit may be installed to provide cooled water directly to the quenching tank or to furnish a cooling medium for the shell-and-tube heat exchanger.

Maintenance costs are, of course, related to the number of mechanical units involved. Pumps are necessary in all types for water circulation and, in some types, motor-driven fans, used for air circulation, are another maintenance factor.

General. In addition to the three popular types of cooling equipment listed, direct refrigeration has been used, as well as combinations of the three types described above. Local conditions of cost, temperature, pressure and availability have a direct bearing on the selection of equipment for cooling the quenching medium.

The quenching mediums used and the allowable range of metallurgical results in the as-quenched steel have a direct influence on types of coolers to use. For example, if water quenching is used on rough carbon steel forgings, more often than not, no coolers are used. The inlet of cold water under thermostatic control will maintain satisfactory temperatures in the work tank as the excess fluid overflows to a sewer or to a well for reclaiming.

In caustic or brine quenching, often a closed recirculation system is used in conjunction with a storage tank only. The volume in the circuit, balanced against the increase in temperature of the quenching medium, is such that acceptable temperatures are maintained in the medium without coolers, for a given hardening operation.

However, for the oil quenching of full-finished gears or axles, elaborate heat-exchanger and cooler equipment is installed under accurate thermostatic control. Such sys-

tems usually employ heaters in order to control further the complete temperature cycle of the oil.

Selection. To select a cooler properly in the quenching circuit, the maximum demand or heat load must be determined from the following known data:

1 Weight of steel quenched during a specified period
2 Specific heat of steel
3 Temperature of steel entering the quench
4 Temperature of steel leaving the quench
5 Temperature of quenching liquid entering the work tank
6 Temperature of quenching liquid leaving the work tank
7 Characteristics of the quenching medium, such as: (*a*) specific heat, (*b*) specific gravity, (*c*) viscosity, flash point, boiling point and (*d*) point of vaporization, for some toxic solutions.

From the above data and with full knowledge of costs and acceptable metallurgical results, proper cooling equipment can be selected for the quenching system.

Oil Heaters. Often it is necessary to increase the temperature of the quenching liquid after a week-end or overnight period of shutdown. The actual increase in temperature may not be great but in some instances the large volume involved results in a considerable heating load. By the use of automatic time-control equipment, it is possible to allow four or five hours for complete heating of the liquid in the system, and thus the heat exchanger is not necessarily large.

If a shell-and-tube heat exchanger is used in the system for cooling, it can also be employed for heating. It is necessary, however, that steam or hot water be available as a heating medium. The heating cycle can be made fully automatic by the installation of temperature-control valves.

Electric heating elements are often used to increase the temperature of quenching liquid, but the cost of power is often prohibitive if the heating load is of any consequence.

Supply Tanks. In general, storage tanks are necessary for two reasons: (1) If large batches are quenched, it is necessary to provide sufficient quenching liquid in storage to satisfy the cooling demand set up during the quench. If this storage is not available, it is necessary, of course, that the cooling equipment be large enough to handle the heat transfer based on the load per minute during the batch quench. (2) Space is also provided for storing the quenching liquid, in order to allow for draining the other units in the system for cleaning and maintenance.

Whenever possible, the storage tanks should be installed so that all other equipment will drain to them. This will simplify the operation of the system and will eliminate the need for additional return pumps, which are difficult to balance. Since the storage tank will become a point of settlement for all sediment in the system, a manhole should be included in the tank to allow for entrance in cleaning. If a foot valve is to be installed in the tank, a removable suction tube is advantageous. This tube is constructed in such a way that both the tube and the foot valve can be removed from outside the tank.

Pumps. Pumps are installed primarily for one or both of two purposes: (1) It is necessary to maintain a specified flow of the quenching liquid through the heat exchanger. This is usually a continuous flow and need be only enough to compensate for the heat transfer. (2) Agitation is necessary in the quenching tank and quite often a second pump is installed for this purpose.

Centrifugal pumps are used wherever possible, since wearing is minimized and usually the initial cost is lower. However, where a storage tank is employed, it is usually necessary to raise the oil from the storage tank to the quenching tank.

Since a centrifugal pump is not self-priming, it is customary to install a small positive-displacement pump for priming the centrifugal pump when necessary. Since a continuous-duty pump is usually small, this is often a positive-displacement pump and is used both for continuous circulation when necessary and also for priming the centrifugal pump used in agitation.

By the installation of valves, it is usually feasible to connect the pump in such a way that it can be used for emptying or filling the quenching tank or tanks. Valves should also be installed to simplify the repair of pumps. Valves should always be installed on both sides of the pump so that it is not necessary to empty any of the tanks or piping when repairs are made.

Centrifugal pumps are not designed for great suction-lift operation and therefore should be installed as near the oil supply as possible. Consideration should also be given to the resistance to flow set up by the piping system so that the pump itself may be properly sized. If resistance of the piping is considerably less than anticipated, the motor of the pump is likely to overload.

Mechanical Conditioning. In addition to the coolers that control the temperature of the quenching medium, other equipments are necessary in the installation to condition the medium mechanically.

Strainers are necessary in order to protect the pumps from dirt and scale picked up in the quenching medium. They are very important in oil systems and should be of large size and designed so as to provide free flow and accumulation of scale without clogging. Strainers should be installed in pairs, suitably valved off so that one can be cleaned while the other is operating.

Sometimes for precise oil-quenching operations, a filtering system is installed to remove trapped air from the oil, as well as free carbon and water.

Hazard Protection. Special consideration should be given to quenching systems that use brine or caustic solution. During quenching, fumes are released that should be drawn off into hoods by a proper ventilating system.

When oil is used, the question of fire hazard is important and particularly when large unit loads are handled in the work tank. There are several fire-extinguishing systems, but the most effective types use carbon dioxide (CO_2) as the agent.

Carbon dioxide extinguishes fire rapidly because it reduces the concentration of oxygen to a point at which burning cannot occur. It does not contaminate the quenching oil or cause damage to steel in process, and it leaves no residue to be cleaned up.

Two types of carbon dioxide fire-extinguishing systems are in general use—high pressure and low pressure. In high-pressure systems the liquid CO_2 is stored in steel cylinders that may be manifolded together. In low-pressure systems liquid CO_2 is stored in a single refrigerated, insulated pressure vessel at approximately 0 F, and at corresponding relatively low pressure of 300 psi. In either type of system, actual protection of quenching operations may be provided as part of a larger system covering additional hazards, or the quenching tank system may be complete in itself.

In low-pressure systems, increased cooling capacity is added to the other fire-extinguishing properties of carbon dioxide, since liquid CO_2 stored at 0 F yields 47% of CO_2 "snow" (finely divided particles of "dry ice") when released, as contrasted with a yield of 24% at 80 F. The cooling capacity of CO_2 is in large measure related to the amount of CO_2 snow in the discharge. Control of temperature of the stored liquid also provides uniform characteristics in regard to discharge and extinguishing. Low-pressure CO_2 systems have capacities from 500 lb to scores of tons of CO_2.

A typical low-pressure CO_2 fire-extinguishing system for the protection of an average continuous quenching tank and its associated oil pit would utilize a one-ton storage unit. Two thermostats over the quenching tank and three in the pit would provide complete automatic operation. In addition, a pushbutton timer station enables the system to be put into its automatic sequence of operation if fire is observed before the thermostats have been actuated. The electrically operated valves are supplemented with pilot valves for manual operation of the system in the event of failure of electrical power.

Linear nozzles running the full length of the tank on two sides, discharge across the surface of the oil. Three orifice-type nozzles release CO_2 into the pit in order to extinguish immediately any fire that may have spread from the quenching tank. Further protection is given the machinery controlling the conveyer and oil circulation by means of a special type of nozzle. For this given typical system the entire discharge period for all nozzles is 40 sec, during which approximately 600 lb of CO_2 is released.

Thermal Formulas and Basic Calculations. In designing any quenching system for the heat treatment of steel, certain basic formulas are used in calculations that determine

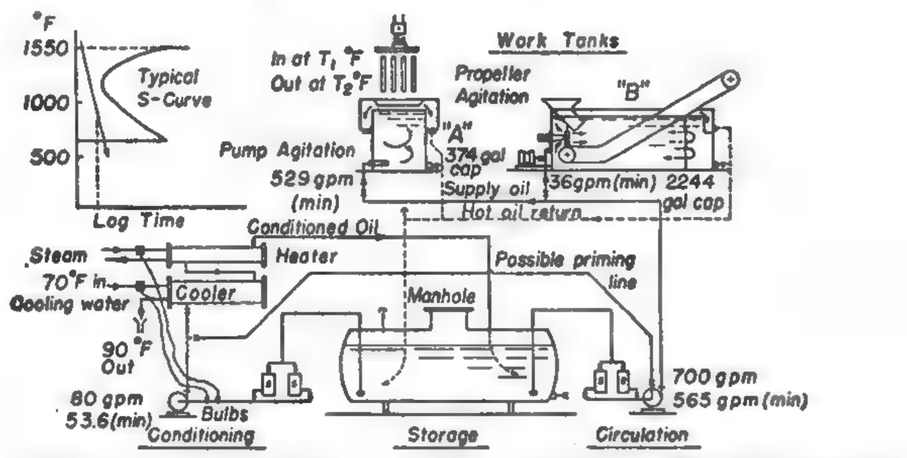
the minimum theoretical requirements. The following symbols are used in the sample calculations given below:

W = Weight of steel, pounds quenched per hour
S_s = Mean specific heat of steel
T^1 = Temperature of steel entering bath, deg Fahr
T_2 = Temperature of steel leaving bath, deg Fahr
H = Btu removed per hour (maximum heat load)
W_m = Weight of quenching medium, pounds
S_m = Specific heat of quenching medium
T_3 = Initial temperature of quenching medium before quench, deg Fahr
T_4 = Final temperature of quenching medium after quench, deg Fahr
R = Temperature increase in medium during quench, deg Fahr
V_m = Volume of medium, gallons, in the system

The following sample calculations are based on a given system, shown in Fig. 12. The known factors are:

S_s = Mean specific heat of steel = 0.17
W_a = 500-lb batch quench, once each hour in Tank *A*
W_b = 1000-lb continuous quench in Tank *B*, evenly distributed through the hour
T_1 = 1550 F steel entering both tanks
T_2 = 150 F steel leaving both tanks
Medium = Oil, 7.5 lb per gal, 0.5 specific heat or S_m
T_3 = 120 F, design temperature of oil entering work tanks
T_4 = 150 F, temperature of oil leaving work tanks
Well water at 70 F available for cooling
374 gal = Volume of Tank *A*
2244 gal = Volume of Tank *B*

NOTE: Based on S-curves, hardenability characteristics and section of parts quenched, it can be estimated that heat will be removed from steel quenched in Tank *A* in 2 min. Generally it may be assumed that the average work piece will lose heat to oil at a rate of 1 min per in. of thickness at the smallest cross section.



Known Factors
W = 500 lb for "A" Mass Load
W = 1000 lb for "B" Continuous Load
S_s = 0.17
T_1 = 1550 F
T_2 = 150 F
Oil Medium, 7.5 lb per gal; sp ht, 0.5
T_3 = 120 F
T_4 = 150 F

Determined Factors
Circulation pump 700 gal per min
Vm = 1058 gal, "A"; 2116 gal, "B"; Total, 3174 gal (min)
Storage = 374 + 2244 = 2618 (min) + 50% = 4000 gal
H = 119,000 Btu per hr avg, "A"
238,000 Btu per hr avg, "B"
357,000 Btu per hr avg, Total
Cooling water rate = 36.7 gal per min
Conditioning pump rate = 80 gal per min

Fig. 12 Quenching system for which the various factors are calculated in the text

Tank A

The heat load for Tank A:

$H = W_a S_s (T_1 - T_2) = 500 \times 0.17 \quad (1550 - 150) = \quad 119{,}000$ Btu per hr

Since this load must be absorbed by the quenching oil in approximately 2 min, enough oil must be provided to allow no more than $T_3 - T_4$ or 30° rise. Therefore, the volume of quenching oil required in the system is:

$$V_m = \frac{H}{W_m S_m (T_4 - T_3)} = \frac{119{,}000}{7.5 \times 0.5 \quad (150 - 120)} = 1058 \text{ gal}$$

To determine the rate of flow through the cooling equipment for Tank *A*:

$$\frac{1058}{60 \text{ min}} = 17.6 \text{ gal per min}$$

To determine rate of flow to Tank *A* to absorb heat as specified:

$$\frac{1058 \text{ gal to absorb heat}}{2 \text{ min (period of heat transfer)}} = 529 \text{ gal per min}$$

Tank B

The heat load for Tank *B*:

$H = WS_s (T_1 - T_2) = 1000 \times 0.17 \quad (1550 - 150) = 238{,}000$ Btu per hr

This heat load is evenly distributed through the cooling system during the hour, and therefore the cooling requirements are as follows:

$$V_m = \frac{H}{W_m S_m (T_4 - T_3)} = \frac{238{,}000}{7.5 \times 0.5 \quad (150 - 120)} = 2116 \text{ gal or } 36 \text{ gpm}$$

Theoretically, the volume of oil in the system need not be held at a minimum in continuous quenching, since the cooling equipment is designed to remove the heat from the quenching oil at the rate at which it absorbs heat from the steel being quenched. However, for purposes of design, a certain volume is desirable as noted.

Referring to Fig. 12, a circulation pump of 529 gpm is required for agitation in Tank *A* and 36 gpm to displace oil in Tank *B* so that 2116 gph can return to storage. This total of 529 plus 36 or 565 gpm, plus a safety factor of 25%, calls for an installed capacity of 700 gpm.

In Tank *B*, quenching is continuous and a motor-driven agitator is indicated. Here the problem is to maintain the velocity of quenching oil that passes over the continuously falling steel as it is discharged from the chute to the quench conveyer. For the small pieces considered, a 5-hp motor is provided for the agitator and it can be assumed that the velocity of oil will be satisfactory to assure required cooling rates to the steel quenched.

Referring to the storage tanks in Fig. 12, to clean either or both work tanks, 374 + 2244 = 2618 gal must be provided.

Practical design would call for 50% increase for a total storage capacity of 4000 gal. If oil is purchased in tank car lots, obviously the storage must be increased accordingly.

With 70 F cooling water, 90 F outlet, the cooling water rate for coolers is:

H = 119,000 Btu per hr for Tank *A*
H = 238,000 Btu per hr for Tank *B*
357,000 Btu per hr total

$$\text{Flow through cooler} = \frac{357{,}000}{8.33 \times 20° \text{ rise} \times 60 \text{ min}} = 36.7 \text{ gpm}$$

Circulation of medium from storage through the cooler for conditioning must be at the rate noted above; 17.6 gpm for Tank *A* plus 36 gpm for Tank *B*, or 53.6 gpm. For practical design, an 80-gpm pump would be installed to circulate oil through the cooler.

This pump will usually be a positive-displacement pump, operating continuously. In any heat-exchanger equipment, increasing the velocity increases the rate of heat transfer; therefore, this pump capacity may increase or decrease according to recommendations of the manufacturer of the cooler. The pressure drop through cooler and heater should be such as not to overload the motor of the heat-exchanger pump.

Because this is a positive-displacement or gear-type pump, the sketch shows it hooked up to prime the centrifugal large-volume pump supplying oil to the tanks.

In almost every instance, experience indicates that a quenching system designed to handle a heavier load than intended will be more satisfactory than a system designed to the minimum requirements. For instance, an oil system overdesigned will lower ventilating requirements, will tend to eliminate fire hazard, and will maintain quenching oil in improved condition for longer usage, since sludging will be reduced and the only loss will be drag-out.

Gas Quenching.[2] "Gas quenching" is the term applied to the rapid cooling of heated metals in a high-velocity stream of a gaseous medium. If the gas is of suitable composition, the original surface of the work remains bright and free from any surface decarburization during this heat treatment.

The cooling rates secured by bright gas quenching are intermediate between those obtained by liquid quenching and by normalizing (Fig. 13). Normalizing is the slowest form of gas quenching since the cooling is carried out in still air at ordinary temperature.

An example of gas quenching may be drawn from the heat treatment of X4130 steel aircraft tubing. In large production furnaces, the cooling rates for normalizing are too slow for obtaining desired properties in this material. The necessary rates of cooling must be considerably faster

and can be secured only by forced cooling in a continuous stream of cold gases so arranged that the gases being heated by contact with the hot steel are constantly replaced by a fresh supply of cold gases that strike the work at high velocity for maximum rates of heat transfer.

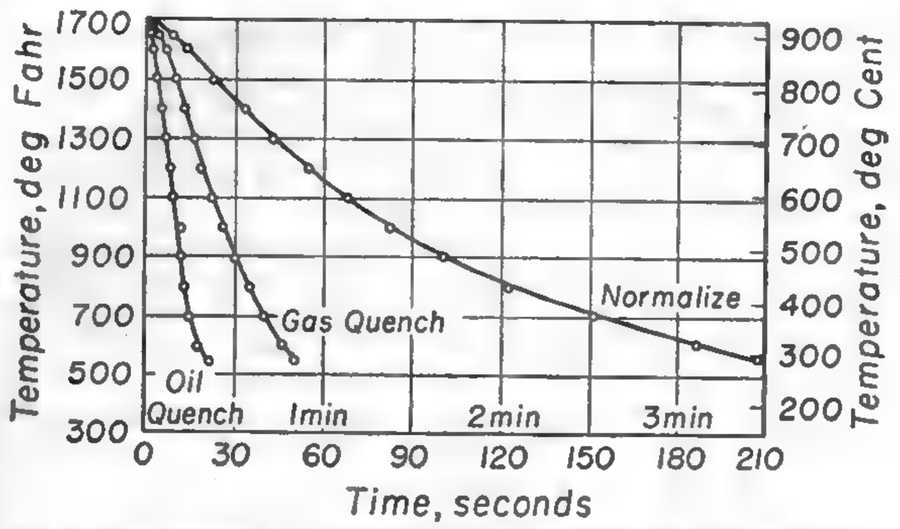


Fig. 13 Comparison of cooling rates obtained by gas quenching, oil quenching and normalizing (cooling in still air)

Gas Quenching Apparatus. This result is readily accomplished by use of a gas quenching zone (*see* reference 2). It is located immediately adjacent to the discharge end of the heating zone. As the tubes leave the heating chamber, they are blasted from both top and bottom by large volumes of cold gases issuing from a series of nozzles. Having absorbed heat from the hot steel, the gases are withdrawn from the cooling chamber through a number of outlet openings provided on both sides of the chamber. The gases are then flowed over four water-cooled coils by means of two large recirculating fans that deliver the cooled gases back to the gas nozzles for discharge at high velocity. The gas recirculating system is gastight and consists of two separate units, one of which is placed above the work material and the other one below the work material. Suitable dampers are provided for control of the volume of recirculated gas.

Rate of Gas Quenching. The gas quenching zone of a 4-ft effective width is capable of bright gas quenching at a continuous rate 4500 to 5000 lb per hr of X4130 welded aircraft tubing, from 1650 F to black heat in less than 1 min. The actual quenching time depends on the rate of recirculation of gas and on the speed of the conveyer, which in turn is governed by the size and wall thickness of the tube. In a continuous furnace of the above hourly capacity, tubes having a wall thickness of 0.049 in. were gas quenched from 1650 F to black heat in 30 sec.

tion of austenite will then occur at constant subcritical temperature or during later cooling, depending on the time-temperature combination employed in the heat treatment. Martempering, austempering and modifications of these processes involve interrupted quenching.

The cooling rates of the outside and center of pieces that have similar size and shape, quenched in water, oil, air and salt, and the process of transformation by these various quenching methods are illustrated in Fig. 14. In each process that is depicted, the quenching speed exceeds the critical cooling rate.

The greater the quenching speed, the greater the temperature difference between the surface and center of the work piece. With a very rapid quench, such as shown by the curve representing water quenching in Fig. 14, there

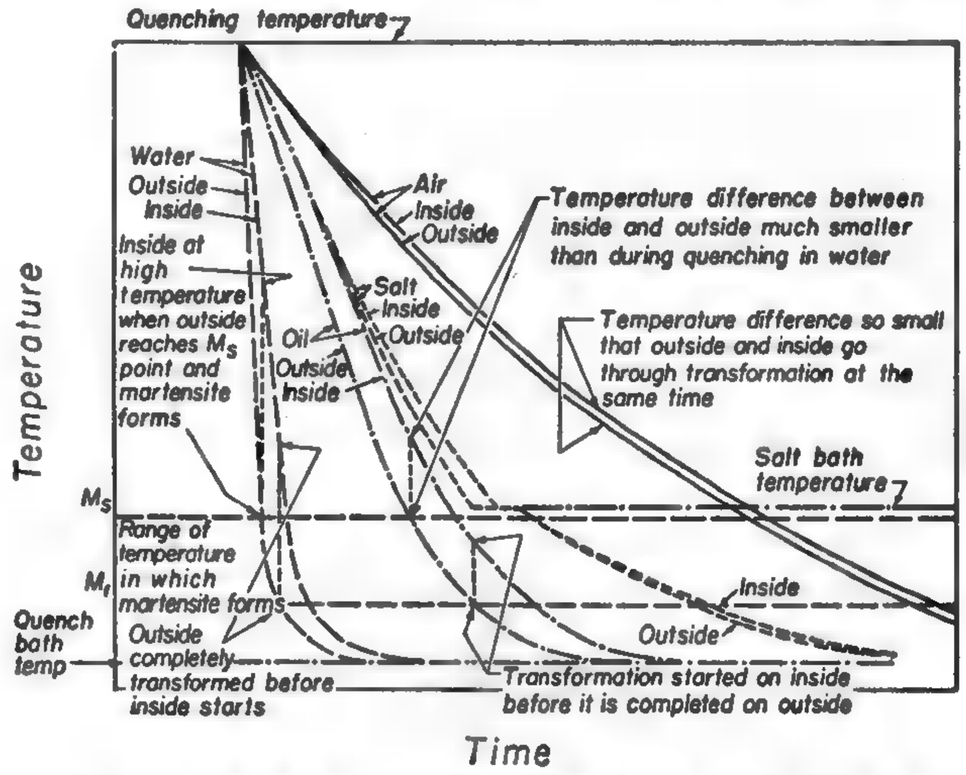


Fig. 14 Cooling curves for the surface and center of a steel cylinder quenched in water, oil, hot salt and air

is a rather large temperature difference between the outside and center of the part. Transformation of austenite to martensite progresses during cooling through the martensite transformation range and, for the conditions of Fig. 14, the outside is completely transformed before the austenite in the center of the piece has cooled to the M_s temperature. Thus a large volume of unstable austenite is entrapped in a case of hard, brittle martensite. Later, as the center cools through the transformation range, the entrapped austenite transforms to martensite, with an increase in volume. This nonuniform expansion causes excessive residual stresses that result in distortion and sometimes in cracking.

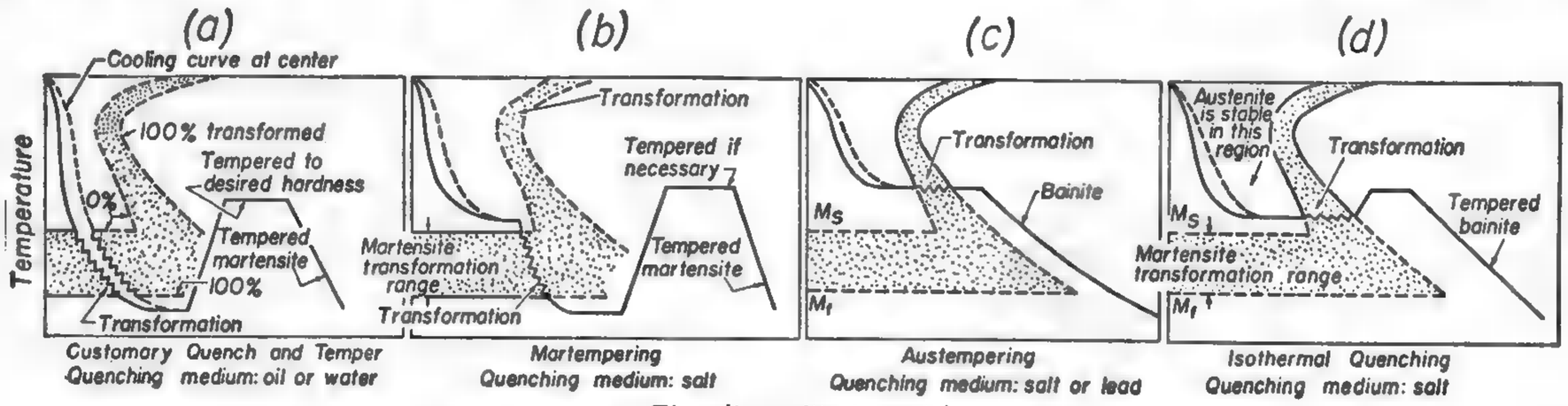


Fig. 15 Diagram of four important quenching methods

Cooling Medium. The gaseous quenching medium normally employed is the bright-annealing gas that is produced by the partial combustion of a fuel gas. It consists of approximately 5% CO_2, 10% CO, 12% H_2, 1% H_2O, and 72% N_2. This gas provides a faster rate of cooling than air, because of its higher heat capacity and because of the avoidance of scale on the surface of the work. Since the gas quenching zone is of gastight construction, any of the other commercial gas atmospheres may readily be applied.

The Interrupted Quench.[3, 4, 5] The interrupted quench is a controlled method of heat removal in which cooling is stopped at some temperature above or just within the martensite transformation range of the steel. Transforma-

The curves that indicate oil quenching show a slower rate of cooling and a smaller temperature difference between the outside and the center of the piece. This results in a greater amount of martensite formation in the center before the surface reaches the M_f point.

Steels that harden during air cooling are used for complicated dies and sections because the center and surface transform to martensite at virtually the same time, thus minimizing the possibility of quenching cracks.

Martempering. This process (Fig. 15*b*) involves quenching from the austenitizing temperature into a molten bath at a temperature near the M_s point of the steel, and holding in the bath long enough for the center and outside to equalize in temperature; then cooling further at a moderate rate, usually in air, so as not to allow any great difference in temperature between the outside and center (Fig. 15*b*). Formation of martensite then occurs fairly uniformly throughout the piece during cooling to room temperature, avoiding excessive residual stress.

The temperature of the quenching bath should be near the M_s point; if the temperature is much below M_s, an appreciable quantity of martensite will form and may defeat the purpose of the treatment. A temperature of 400 F is satisfactory for the martempering of many steels containing about 0.40% C. As discussed elsewhere in this Handbook (page 611) the M_s temperature varies with carbon and alloy content and this influences the choice of temperatures for the quenching bath.

Austempering. This process (Fig. 15*c*) consists of transferring the austenitized steel rapidly to a hot liquid quenching bath held at constant temperature below the transformation range, usually at from 450 to 800 F, for a sufficient time to allow transformation to a nonmartensitic structure. The steel is then cooled to room temperature by any convenient means, usually water quenching.

Another form of the interrupted quench is a modification of the austempering method (Fig. 15*d*). This method is a three-step process: heating to austenitize; quenching in an agitated heated salt at 400 F or higher and holding at this temperature to permit isothermal transformation; then immersing in a third bath at a higher temperature in order to temper the isothermal product. In this way advantage may be taken of the greater cooling rate of the liquid salt at a lower temperature and larger pieces may be successfully quenched and austempered.

The cooling rates, measured at 1000 F, obtained during quenching a ½-in. steel sphere from 1475 F in oil at room temperature and in salt at 400 and at 500 F are:

Mineral oil at 70 F	100 to 145 °F per sec
Molten salt at 400 F	115 °F per sec
Molten salt at 500 F	95 °F per sec

Agitating the molten salt at 400 F will bring the cooling power of the bath up to the equal of that of still mineral oil at room temperature. Stated in another way, the quenching speed of agitated salt at 400 F has an H-value (*see* page 495) of 0.25 to 0.30 on parts that have a machined surface. The quenching value is somewhat lower for materials having a light scale.

Salt mixtures that melt at about 300 F and may be used as high as 1100 F are most often employed in interrupted quenching. A compounded oil that has a high flash point has been used satisfactorily in martempering.

Quenching from Surface Heating. Surface heating by flame or induction produces in a relatively short time a more or less steep thermal gradient that results in loss of heat to the cold core. This loss of heat varies from a mild effect to a drastic heat transfer, which, in some induction or oxyacetylene-heated jobs, obviates an external quench.

Surface hardening nearly always produces high stresses because of the rapid heating and cooling, and local heating and transformation. The danger of cracking, particularly of surface checking, is usually present and must be guarded against with careful quenching practice. In general, drastic quenches are required, particularly since carbon steels are usually employed.

Quenching from surface heating is carried out in a number of ways, made possible by the flexibility of the heating processes. However, they may all be grouped under two general types: immersion quenching, and pressure-spray quenching.

The simpler of these is immersion quenching. This consists of placing the part in a tank of quenching medium, either automatically or manually with tongs. A modification of immersion quenching is the use of a submerged inductor, where the part is heated while immersed in the quenching medium. This requires considerable power per unit area, and is generally done with radio frequency; the advantages are instantaneous quenching and a profound effect on heating pattern where odd shapes are involved.

The great majority of parts to be surface hardened are pressure-spray quenched. Spray quenching methods may be classified as area or continuous. The area method consists in heating an area and then applying a spray quench, usually with a "quench ring", a shaped fixture containing a channel for quenching medium and small holes through which the liquid is applied to the heated area. Continuous spray quenching involves passing the work pieces through the heating zone into a quenching spray at such a rate that the proper cooling rate is obtained. Either work piece or treating equipment may be moved.

Pressure water-spray quenching may result in cracking. Cooling rates are extremely high and care must be taken not to use a more drastic quench than is necessary. For uniformity it is advisable that the pressure and temperature of the quenching water be controlled. For this purpose a circulating system is often used, which frequently supplies both quenching water and any necessary cooling of the equipment, such as for an induction generator or flame head. When the system is used for cooling equipment, hardness of the water must be investigated and treating equipment provided if necessary, since hard water would clog the cooling passages. Water used for both cooling and quenching is generally held at 90 to 105 F. An important precaution in surface hardening is to provide adequate quenching area. A quench that does not reach all the heated portion may cause serious cracking.

Occasionally oil is used in a pressure-spray quench, particularly with induction heating. Oil temperature is generally in the neighborhood of 80 to 100 F, and here again temperature and pressure must be controlled. Oil pressures as high as 100 psi or more are used, and with these higher pressures, cooling rates at the surface approach those of a conventional water quench. In one application seven-pitch plain carbon steel gears (C1045) are being pressure-oil quenched to the maximum hardness available for steel of that carbon content.

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The Influence of Mass in the Heat Treatment of Steel

By E. J. Janitzky*

It is well known that the properties of quenched steel depend on the mass of the piece that is being quenched as well as on the chemical composition of the steel. For example, if a series of cylinders of SAE 1045 steel with different diameters are quenched from the same temperature by the same procedure in the same quenching medium, the mechanical properties of the quenched cylinders will vary in a regular manner depending on the diameters of the cylinders. The difference will also be evident, although different in magnitude, after the usual tempering operation. The difference in mechanical properties results from the rate of decomposition of austenite. Alloying elements such as nickel, chromium and manganese increase the hardenability in the same size and shape of piece; that is, they make the steel deep hardening by decreasing the rate of decomposition of austenite.

The hardness depends not only on the diameter of the section that is heat treated but also on the depth at which the hardness is measured within the piece; that

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is, if the section is large enough so that it has not hardened completely to the center. This would also be true of properties such as tensile strength, yield point, elongation and reduction of area, if they were to be determined at different depths within the piece. Characteristic hardenability curves are shown in Fig. 1, in which the Rockwell C hardness of water-quenched cylinders of various diameters is plotted against diameter of the section. Fig. 1 shows a plain carbon steel, SAE 1045, at the left, and a deeply hardening alloy steel, SAE 6140, at the right. In cylinders ½ in. in diam the SAE 6140 hardens completely and in those 1 in. in diam almost completely.

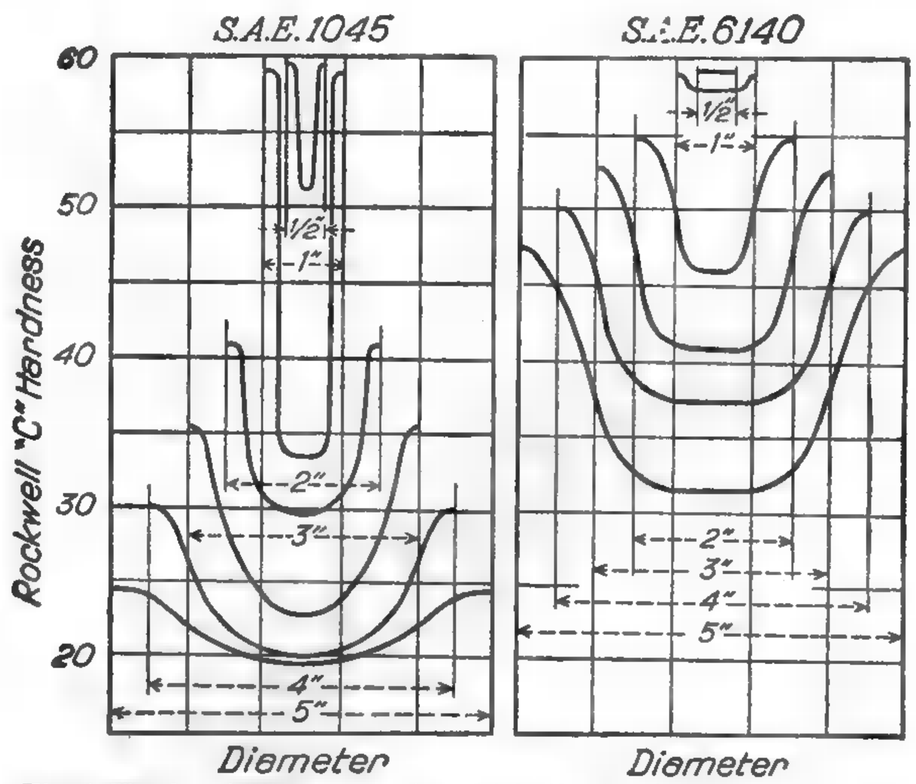

Fig. 1 Hardenability curves in which the Rockwell hardness is plotted against the diameter of the sections (Grossmann).

In cylinders ½ and 1 in. in diam of SAE 1045, about the same surface hardness is obtained as in the SAE 6140, but the hardness decreases much more rapidly toward the center of the piece. Even in cylinders ½ in. in diam, the SAE 1045 is not hardened completely. In sections 2 in. in diam, and larger, the surface hardness as well as the hardness in the interior of the piece is less in SAE 1045 steel than in SAE 6140. In sizes that harden completely there is little change in hardness with size. As soon as a size is reached that fails to harden completely, the difference between the surface and center hardness first increases as the size of the section is increased and, after reaching a maximum, decreases again as the mass becomes so great that the steel is virtually inert to heat treatment.

Tensile strength and elastic limit will decrease with increase in the diameter of the section; elongation and reduction of area will increase. In bars smaller in diameter than one that will just harden completely, there is relatively little change in mechanical properties with size in commercial quenching operations. In the sizes that fall somewhat short of complete hardening, the change in mechanical properties with size is relatively rapid, but the change becomes less marked as the size is increased, until the mass becomes so great that the steel is virtually inert to heat treatment. Alloying with chromium, nickel, or manganese counteracts this inertness, while combinations of chromium, nickel, or manganese with vanadium, molybdenum, or tungsten may or may not have deep hardening potentialities, depending on the composition, grain size and heating temperature.

If a series of cylinders of SAE 1045 and a similar series of cylinders of an alloy steel, such as SAE 2340, are quenched under identical conditions, a series of mechanical properties changing with increasing size will be obtained for each steel. However, the mechanical properties of the SAE 2340 series will be different for identical diameter from the SAE 1045 series because of the presence of nickel in the SAE 2340 steel. A similar effect will be obtained by the use of any of the alloying elements mentioned above, although the amount of the change in hardenability will depend on the particular element and its percentage in the steel, together with the carbon content of the steel. These alloying elements not only affect the hardenability in quenching but also cause the steel to resist tempering more than do plain carbon steels.

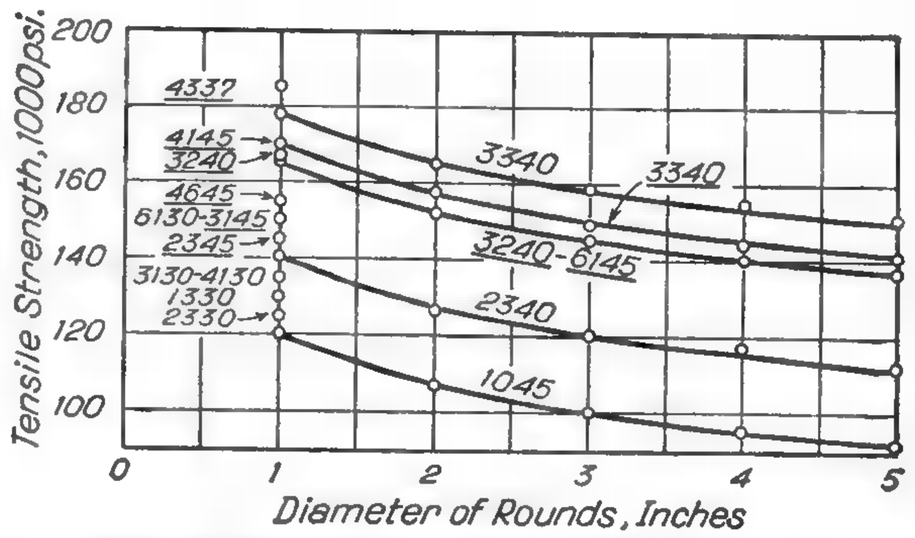

Fig. 2 Relationship between tensile strength and diameter of section for several steels. Normalized, quenched, tempered at 1000 F.

The relationship between tensile strength and diameter of section for SAE 1045 and several common alloy steels, is shown in Fig. 2. These steels were normalized, then quenched from appropriate temperatures in oil or water, as indicated, and tempered at 1000 F. The oil-quenched specimens are underscored in Fig. 2. The specimens for the tension tests were taken from midway between center and surface of the quenched and tempered cylinders, except for those 1 in. in diam, in which the specimens were taken from the center. It is evident that the loss in tensile strength in each steel bears a regular relationship to the increase in diameter of the section. The following relationship was observed: As the diameter of the section increases in arithmetic progression, the tensile strength decreases in hyperbolic order according to the following equation:

$$P_2 = P_1\left(\frac{d_1}{d_2}\right)^n$$

in which P_1 = the tensile strength corresponding to the diameter d_1
P_2 = the tensile strength corresponding to the diameter d_2 and
n = an exponent (different for each curve).

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The Heat Treatment of Carbon Steels

By M. L. Frey* and R. W. Roush*

THIS article covers the heat treatment for wrought carbon steels of all the types generally used except those classified as tool steels. The more common applications are discussed, with the exception of case hardening, spring making and the hardening of metal-cutting tools and dies. Treatments and applications that are not included here may be found in other sections.

Chemical Composition. The chemical compositions of the steels given here are according to the SAE and AISI specifications for carbon steels on page 307.

Temperature and Quenching Medium. Table I gives the commonly used temperatures and quenching mediums for heat treating these steels. The only steels listed in the table are those necessary to illustrate the carbon range to which a particular treatment applies. Similar steels of approximately the same carbon content will require the same treatment. For a discussion of the principles involved, the reader is referred to the articles "Heat Treatment of Metals" and "Principles of the Heat Treatment of Iron and Steel" in this Handbook.

To simplify consideration of the treatments for various applications, the steels will be classified as follows: Group I, 1010 to 1025; Group II, 1030 to 1050; Group III, 1055 to 1095.

Group I, Steels 1010 to 1025. The three principal types of heat treatment used on these low-carbon steels are: (1) process treating of material to prepare it for subsequent operations; (2) treating of finished parts to improve mechanical properties; and (3) case hardening, which is covered elsewhere in this Handbook.

Table I. Heat Treatments for Carbon Steels

Steel No.	Normalize, deg Fahr	Anneal, deg Fahr	Quench	
			Temp, deg Fahr	Medium
1010	1650 to 1750	1000 to 1350[a]	1650 to 1700	Water[c]
1015	1650 to 1750	1000 to 1350[a]	1650 to 1700	
1020	1650 to 1750	1000 to 1350[a]	1600 to 1675	Oil[d, e]
1025	1600 to 1700	.....	1600 to 1675	
1030	1600 to 1675	1250 to 1375[b]	1575 to 1650	Water[c]
1035	1575 to 1650	1575 to 1650[b]	1525 to 1600	Water[c]-Oil
1040	1575 to 1650	1550 to 1625[b]	1500 to 1575	Water[c]-Oil
1045	1550 to 1650	1525 to 1600	1475 to 1550	Water[c]-Oil
1050	1550 to 1650	1525 to 1600	1475 to 1550	Water[c]-Oil
1055	1525 to 1625	1500 to 1575	1450 to 1550	Water[c]-Oil
1060	1525 to 1625	1500 to 1575	1450 to 1550	Water[c]-Oil
1064	1525 to 1625	1500 to 1575	1450 to 1550	Water[c]-Oil
1070	1525 to 1625	1500 to 1575	1450 to 1550	Water[c]-Oil
1080	1525 to 1625		1450 to 1550	Water[c]-Oil
1085	1525 to 1625	1500 to 1575[b]	1450 to 1550	Water[c]-Oil
1095	1525 to 1625		1450 to 1550	Water[c]-Oil

(a) For explanation of this temperature range, see discussion of Group I.
(b) For spheroidizing, anneal at 1250 to 1375 F.
(c) Brine or caustic is frequently used. See text.
(d) Soluble oil solution is used for hardening bolts.
(e) Mineral oil is used when quenching for machinability.

The process treatment of these steels is applied principally to sheet and strip at the mills, to prepare it for forming and drawing. These treatments have been specialized to a very high degree; the details depend on the intended application of the material and the available equipment. The temperatures used are near the lower transformation temperature, and are somewhat higher for hot finished than for cold finished material. The time cycles and cooling rates vary widely. Detailed discussion is beyond the scope of this article.

It is often necessary to process anneal drawn products between operations, thus relieving work strains in order to permit further working. This operation is normally carried out at temperatures between the recrystallization temperature and the lower transformation temperature. The effect is to soften by recrystallization and grain growth of ferrite. It is desirable to keep the recrystallized grain size relatively fine; for that reason rapid heating and short holding time at temperature are used. The low temperatures also reduce scaling. The customary practice is to discharge the parts from the annealing temperature into air; thereafter it is usually necessary to remove scale. If surface protection is desired, the material should be heated in liquid baths or in furnaces having a controlled atmosphere.

A similar practice may be used in the treatment of low-carbon cold headed bolts made from cold drawn wire. Sometimes the strains introduced by cold working so weaken the heads that they break through the most severely worked portion under slight additional strain. Process annealing, as described previously, is used to overcome this condition. Since the temperatures used are close to the lower transformation temperature, this treatment results in considerable reduction of the normal mechanical properties of the shank of the cold headed bolt. A more suitable treatment is stress relieving at about 1000 F, in order to retain much of the strength acquired in cold working and to provide ample toughness. A common practice is to combine a stress-relieving treatment with a quench from the upper transformation temperature or slightly above, producing mechanical properties that approach those of the cold drawn stock. A common quenching medium is a water solution of soluble oil, the use of which produces two desirable results: (1) the surface of the parts acquires a pleasing black color accepted as a commercial finish, and (2) the speed of the quench is slowed to the point where fully quenched hardness is not produced, so it is not necessary to temper the parts.

Heat treatments are frequently employed to improve machinability. The generally poor machinability of the low-carbon steels, except those containing sulfur or other special alloying elements, results principally from the fact that the proportion of free ferrite to carbide is high. This situation cannot be changed fundamentally, but the machinability can be improved by putting the carbide in its most voluminous form, pearlite, and dispersing fine particles of this pearlite evenly throughout the ferrite mass. Normalizing is commonly used with success, but best results are obtained by quenching the steel in oil from 1500 to 1600 F. With the exception of steel 1025, no martensite is formed and the parts do not require tempering.

Group II, Steels 1030 to 1050. Because of the higher carbon content, quenching and tempering become of increasing importance when steels of this group are considered. They are the most versatile of the carbon steels, because their hardenability (that is, their response to quenching) can be varied over a wide range by suitable control. This important subject is discussed on pages 489 to 502.

It should be pointed out that in this group of steels there is a continuous change from water-hardening to oil-hardening types; as a result, the hardenability is very sensitive to changes in chemical composition, particularly to the content of manganese, silicon and residual elements, and to grain size. In addition, these steels are very sensitive to changes in section. In evaluating the results of heat treatment, careful consideration must be given to the effect of prior structure and to surface condition at the time of quenching.

The rate of heating parts for quenching has a marked effect on hardenability under certain conditions. If the structure is nonuniform, as a result of severe banding or lack of proper normalizing or annealing, extremely rapid heating, such as may be obtained in liquid baths, will not allow sufficient time for diffusion of carbon and other alloying elements in the austenite. As a result, nonuniform or low hardness will be produced unless the duration of heating is extended. In heating the steels that contain free carbide (for example, spheroidized material) sufficient time must be allowed for the solution of the carbides; otherwise the austenite at the time of quenching will have a lower carbon content than is represented by the chemical composition of the material, and disappointing results may be obtained. This condition may be produced deliberately; see Group III, below, for an example.

These medium-carbon steels should be either normalized

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or annealed before hardening, in order to obtain the best mechanical properties after hardening and tempering. Parts made from bar stock are frequently given no treatment prior to hardening, but it is common practice to normalize or anneal forgings.

Although these steels do not possess the machinability of screw stock, they machine reasonably well. Most bar stock, both hot finished and cold finished, is machined as received, except in the higher carbon grades and small sizes that require annealing to reduce the as-received hardness. Forgings are usually normalized, since this treatment avoids the extreme softening and consequent reduction of machinability that result from annealing. In some instances a "cycle treatment" is used. In this practice the parts are heated as for normalizing, and are then cooled rapidly in the furnace to a temperature somewhat above the nose of the S-curve; that is, within the transformation range that produces pearlite. Then the parts are held at temperature or cooled slowly until the desired amount of transformation has taken place; thereafter they are cooled in any convenient manner. Specially arranged furnaces are usually required. Details of the treatments vary widely and are frequently determined by the furnace equipment available.

Cold headed products are commonly made from these steels, especially from the ones containing less than 0.40% C. Process treating before cold working is usually necessary because the higher carbon decreases the workability. For certain uses, these steels are normalized or annealed above the upper transformation temperature, but more frequently a spheroidizing treatment is used. The degree of spheroidization required depends on the application. After the mechanical operations are finished, the parts are heat treated by quenching and tempering.

These medium-carbon steels are widely used for machinery parts for moderate duty. When such parts are to be machined after heat treatment, the maximum hardness is usually held to 320 Brinell, and is frequently much lower.

The following list gives the range within which the hardness of representative parts is usually found.

Part	Grade of Steel	Hardness Number
Crankshafts	1040 to 1045	228 to 286
Connecting rods	1040 to 1045	187 to 241
Wheel flanges	1035 to 1040	302 to 444
Steering arms	1035 to 1040	207 to 269
Shafts	1045 to 1050	228 to 402
Couplings	1030 to 1045	207 to 321
Thrust washers	1040 to 1045	341 to 514
Wheel lugs	1040 to 1045	364 to 477

The selection of a quenching medium will vary with the steel composition, the design of the part, the hardenability of the steel and the hardness desired in the finished part. When the design of the part permits, the best combination of strength and toughness results from full hardening (martensitization) of the part, followed by suitable tempering. For these steels, this procedure nearly always means quenching in water, brine or caustic soda, except for parts of light or complicated section. The lower carbon steels, if fine-grained and abnormal, are shallow hardening even when quenched in caustic; while the higher carbon steels, when coarse-grained and normal, will give hardnesses of 450 Brinell when small sections are quenched in oil and will exhibit satisfactory hardening in pieces as large as 1 in. in diam.

Water is the quenching medium most commonly used because it is best known and is usually cheapest and easiest to install. Caustic soda solution (5 to 10% NaOH by wt) is used in many instances with improved results. Compared with water, it is a faster and, therefore, a more thorough and more uniform quench, producing better mechanical properties in all but light sections. Because of its rapid action, more scale is removed from the parts. When used hot (130 to 160 F), caustic soda solution frequently makes possible drastic quenching of parts that could not be water quenched without breakage. The disadvantages of caustic soda are that it can be used only in a closed system in which provisions are made for cooling; operators must be protected against contact with it; the solution must be checked constantly and the proper strength maintained; and wool clothing disintegrates rapidly after contact with it. Cotton clothing is not affected.

Salt solutions (brine) are often successfully used. Up to 100 F they produce almost as good results as caustic, but are much less effective when hot. Therefore, they cannot be used when breakage is a problem, combined with the necessity for a drastic quench. Like caustic, they require a closed system. Salt solutions are not dangerous to operators but their corrosive action on iron or steel parts of equipment is very serious.

When the section is light or the properties required after heat treatment are not very high, oil quenching is often used. This nearly always eliminates the breakage problem and is very effective in reducing distortion.

The wide range shown in the quenching temperatures in Table I is made necessary by the fact that a wide range of conditions must be met. It is not intended that such a temperature range should be used on any one part or under any given set of conditions. General practice is to use suitable temperatures plus or minus 10°F. The lower temperatures should be used for the higher manganese steels, light sections, coarse-grained material and water quenching; higher temperatures are required for lower manganese, heavy sections, fine grain and oil quenching.

A type of treatment finding considerable use is the light case hardening of many machinery parts. The material is heated to its normal hardening temperature in an activated bath or in a suitable atmosphere and is then quenched. This treatment produces a thin, hard skin for wear resistance. Only low-temperature tempering can be done on such parts; otherwise the surface hardness will be impaired. It is necessary to choose the degree of hardenability in relation to section size so as to obtain the required degree of toughness in the product tempered at a low temperature. In using such parts, it must be borne in mind that the presence of the hard skin reduces notch toughness below that which would be found if the skin were absent.

From these steels are made many common hand tools, such as pliers, open-end wrenches, screw drivers, and a few edged tools—for example, tin snips and brush knives. The cutting tools are necessarily quenched locally on the cutting edges, in water, brine or caustic, and are subsequently given suitable tempering treatments. In some instances the edge is suitably time quenched; then the remainder of the tool is oil quenched for partial strengthening. When made of these grades of steel, pliers, wrenches and screw drivers are usually quenched in water either locally or completely and are then suitably tempered.

Group III, Steels 1055 to 1095. Steels of this group are used chiefly for heavy machinery parts, hand tools, agricultural cutting tools, and springs. The subject "Heat Treatment of Springs" is discussed on page 644.

Forged parts should be annealed for these reasons: (1) because refinement of the forging structure is important in producing a high-quality hardened product, and (2) because the parts come from the hammer too hard for cold trimming of the flash or for any machining operations. Ordinary annealing practice, followed by furnace cooling to 1100 F, is satisfactory for most parts as given in the table.

Most of the parts made from steels in this group are hardened by conventional quenching. However, special technique is necessary at times; a few examples are described. Both oil and water quenching are used—water, for heavy sections of the lower carbon steels and for cutting edges; oil, for general use. Austempering and martempering (*see* page 629) are often successfully applied to parts made of steels in this group. The principal advantages from such treatments are considerably reduced distortion, elimination of breakage, in many instances, and greater toughness at high hardness.

For heavy machinery parts, such as shafts, collars and the like, steels 1055 and 1061 may be used, either as-normalized and tempered for low strengths or as-quenched and tempered for moderate strengths. Other steels in the list may be used, but the combination of carbon and manganese in the two mentioned makes them particularly well adapted for such applications. It must be remembered that even with all hardenability factors favorable, including the

use of a drastic quench, these steels are essentially shallow hardening as compared with alloy steels, because carbon alone, or in combination with manganese in the amounts involved here, does not promote deep hardening to any great extent. Therefore, the sections for which such steels are suited will be definitely limited. In spite of this limitation the danger of breakage is real and must be carefully guarded against when such parts are being treated, especially when changes in section are involved.

Hand tools made from steels in this group include open-end wrenches, Stillson wrenches, hammers, mauls, pliers and screw drivers; and cutting tools, such as hatchets, axes, mower knives and band knives. The combination of carbon and manganese in the steels used may vary widely for the same type of tool, depending partly on the equipment available for manufacture and partly on personal experience with or preference for certain combinations. A manganese content lower than listed will be used in some tools. This is justified when it makes a particular carbon range easier to handle, but it should be understood that for many applications, a combination of lower carbon and higher manganese would serve just as well. Hand cutting tools, discussed later, are an exception.

For hardening wrenches (except the Stillson type), screw drivers, pliers and similar tools, oil quenching is generally used, followed by tempering to the required hardness range. Even when no reduction of as-quenched hardness is desired, stress-relieving at 300 to 375 F is desirable, to reduce residual strain and so help prevent sudden service failures. In Stillson-type wrenches the jaw teeth are really cutting edges and are nearly always quenched in water or brine to produce a hardness of 50 to 60 Rockwell C. Either the jaws may be locally heated and quenched or the parts may be heated all over and the jaws locally time-quenched in water or brine. The entire part is then quenched in oil for partial hardening of the remainder. In this way considerable structural strength is obtained.

Hammers must possess high hardness on the striking face and somewhat lower hardness on claws. They are usually locally hardened and tempered on each end, depending on their type. The striking face is always quenched in water or brine. Satisfactory service depends on getting the proper depth of fully hardened (martensitic) surface on this face, and following with stress relieving at about 350 F. Final hardness on the striking face is usually Rockwell C 50 to 58; on claws, 40 to 47.

Hand cutting tools, particularly axes and hatchets, must possess high hardness and high relative toughness in their cutting edge, as well as the ability to hold a keen edge. Since nothing is so effective as carbon in imparting the latter property, the carbon content is always higher than if hardness and toughness alone were to be considered. Many such tools are given an ordinary furnace anneal following forging, but high-quality tools are prepared for hardening by spheroidization, which may be performed as a separate operation following regular annealing. Most frequently, however, the refining and spheroidizing treatments are accomplished by quenching in oil from 1600 F, and then tempering at 1250 to 1375 F. The quench keeps the carbide in a finely divided state and from this condition spheroidization takes place rapidly at the temperatures specified.

For hardening, the cutting edges of such tools are usually heated in liquid baths to the lowest temperature at which the piece can be hardened, and are then quenched in brine. The quick heating of the liquid bath plus the low temperature fail to put all the spheroidal carbon into solution. As a result the cutting edge of the tool consists of martensite containing less carbon than indicated by the chemical composition of the steel and containing many embedded particles of cementite. In this condition the tool is at its maximum toughness, relative to its hardness, and the embedded carbides promote long life of the cutting edge. Final hardness is 55 to 60 R_c.

Manufacturers of agricultural implements make much use of the steels in this group. Braces, control rods, shafts and similar parts are often made of high-carbon steels, untreated in order to obtain increased strength at low cost. The principal heat treated parts are plowshares, moldboards, coulters, cultivator shovels, disks for harrows and plows, mower and binder knives, ledger plates and band knives. Those parts used for cutting or turning soil must be moderately tough and must have the ability to resist abrasion. They are made with various combinations of carbon and manganese that will permit full hardening.

Plowshares and cultivator shovels are usually quenched in water or brine to obtain 500 to 600 Brinell. Plowshares, moldboards and cultivator shovels are often made from "soft center steel", which consists of a layer of dead soft material between two equally thick layers of high-carbon steel. This material is rolled from specially cast composite ingots. Such parts are heat treated to produce high hardness in the outer layer, leaving the relatively soft interior layer to provide toughness. The final product is similar in physical properties to a case hardened part; in fact, these parts are sometimes case hardened.

The grass-cutting and grain-cutting tools are usually made of 1090 or 1095, because of the effect of carbon in providing the desired edge that will last long in service. These parts are made from strip stock by blanking, and no annealing is done, except probably some process annealing performed in the rolling mills, at or below the transformation range. Spheroidization is, therefore, only occasionally obtained. Local hardening is done either by induction heating or in continuous furnaces provided with fixtures that permit the pieces to be heated on the cutting edges only. Upon discharge, the parts are quenched all over in oil and are tempered at a low temperature. Final hardness on the cutting edges is in the neighborhood of 55 to 60 Rockwell C.

The Heat Treatment of Steel Castings

By the Subcommittee on Heat Treatment of Steel Castings*

THIS article applies generally to commercial castings for ordinary construction purposes and not for special uses. Where authoritative specifications exist (for example, ASTM specifications), the practice listed conforms to such specifications.

Chemical Composition.

Carbon Steels	C	Percentage Mn max	Si max	P max	S max
Low-carbon steels	less than 0.20	1.00	0.60	0.05	0.05
Medium-carbon steels	0.20 to 0.50	1.00	0.60	0.05	0.05
High-carbon steels	more than 0.50	1.00	0.60	0.05	0.05

* The members of this subcommittee are R. A. Gezelius. *Chairman* (General Steel Castings Corporation), John Juppenlatz (Lebanon Steel Foundry) and David Zuege (Sivyer Steel Casting Company).

Alloy Steels. Only the so-called "low-alloy" steels are considered in this section. The actual compositions involved are too numerous to list here. Typical steels and the properties obtainable are listed in Table I. These steels contain a maximum of 0.60% C and additions of one to four alloying elements. However, the total alloy content is usually less than 5%.

Specific data concerning hardenability and transformation are unavailable for certain cast steels. In these instances the information on wrought steels can be used. The cast steels will usually possess slightly higher hardenability than wrought steels of a comparable composition because of the higher manganese and silicon content of cast steels. These variations, as well as those in the "S-curves", are minor in nature and should cause no difficulty in the heat treatment of commercial castings.

Preliminary Care After Casting. After being poured, the castings should be allowed to cool in the molds to a temperature below the transformation range. When they have cooled to room temperature, they will have a coarse "as-cast" structure. While the castings are in this condition, residual stresses from uneven cooling may be sufficient to cause rupture in the higher carbon and alloy steels during handling. Therefore, when the hardness is high or the castings are of such design as to be conducive to high residual stresses, a preliminary stress relieving or an annealing treatment may be required to obviate breakage in handling. These treatments, described below, should be started before the casting has cooled to less than 500 F.

Table I. Typical Compositions and Mechanical Properties of Cast Steels

Type of Steel	Approximate Composition, percentage								Heat Treatment, deg Fahr				Mechanical Properties			
	C	Mn	Si	Ni	Cr	Mo	Cu	V	Anneal	Normalize	Quench	Temper	Tensile Strength, psi	Yield Strength, psi	Elongation, %	Reduction of Area, %
Low C	0.17	0.74	0.40	...	...	...	...	...	1650	....	....	....	65,900	35,000	34	61
Low C	0.17	0.74	0.40	...	...	...	...	...	....	1650	....	....	66,000	39,000	34	■
Low C	0.17	0.74	0.40	...	...	...	...	...	....	1650	....	1250	64,500	38,500	35	■
Low C	0.17	0.74	0.40	...	...	...	...	...	....	1650	1550	1250	67,000	38,000	34	61
Med C	0.30	0.60	0.36	...	...	...	...	...	1650	....	....	....	74,200	37,600	29	45
Med C	0.30	0.60	0.36	...	...	...	...	...	....	1650	....	1250	73,000	43,500	30	48
Med C	0.30	0.60	0.36	...	...	...	...	...	....	1650	1550	1250	78,800	53,200	31	56
Med C	0.30	0.60	0.36	...	...	...	...	...	....	1650	1550	1100	89,400	62,500	26	51
High C	0.42	0.72	0.41	...	...	...	...	...	1650	....	....	....	84,250	41,500	26	40
High C	0.42	0.72	0.41	...	...	...	...	...	....	1650	....	1250	83,900	48,700	27	42
High C	0.42	0.72	0.41	...	...	...	...	...	....	1650	1550	1250	93,800	63,900	26	55
High C	0.42	0.72	0.41	...	...	...	...	...	....	1650	1550	1100	105,500	74,200	21	41
1330	0.30	1.50	0.35	...	...	...	...	...	....	1650	....	1200	95,000	55,200	28	54
1330	0.30	1.50	0.35	...	...	...	...	...	....	1650	....	1000	100,000	60,200	26	52
1330	0.30	1.50	0.35	...	...	...	...	...	....	1650	1575	1200	103,250	81,000	25	55
1330	0.30	1.50	0.35	...	...	...	...	...	....	1650	1575	1000	126,200	102,000	18	41
8030	0.30	1.25	0.35	...	...	0.15	...	...	....	1650	....	1200	97,000	68,000	24	48
8030	0.30	1.25	0.35	...	...	0.15	...	...	....	1650	....	1000	100,000	70,000	20	44
8030	0.30	1.25	0.35	...	...	0.15	...	...	....	1650	1575	1200	115,000	90,000	21	50
8030	0.30	1.25	0.35	...	...	0.15	...	...	....	1650	1575	1000	160,000	145,000	12	22
8430	0.30	1.50	0.35	...	...	0.35	...	...	....	1650	....	1200	105,000	75,000	24	47
8430	0.30	1.50	0.35	...	...	0.35	...	...	....	1650	....	1000	112,000	80,000	22	44
8430	0.30	1.50	0.35	...	...	0.35	...	...	....	1650	1575	1200	120,000	100,000	20	46
8430	0.30	1.50	0.35	...	...	0.35	...	...	....	1650	1575	1000	165,000	148,000	14	35
8630	0.30	0.80	0.35	0.50	0.50	0.15	...	...	....	1650	....	1200	97,000	68,000	24	48
8630	0.30	0.80	0.35	0.50	0.50	0.15	...	...	....	1650	....	1000	100,000	70,000	20	44
8630	0.30	0.80	0.35	0.50	0.50	0.15	...	...	....	1650	1575	1200	115,000	90,000	21	50
8630	0.30	0.80	0.35	0.50	0.50	0.15	...	...	....	1650	1575	1000	160,000	145,000	12	22
2% Ni	0.25	0.75	0.35	2.00	...	...	...	...	....	1650	....	1200	92,500	57,000	26	54
2% Ni	0.19	0.75	0.35	2.00	...	...	...	...	....	1650	....	1200	82,000	55,000	30	55
2% Ni	0.19	0.75	0.35	2.00	...	...	...	...	....	1650	1650	1200	96,000	76,000	25	62
2% Ni	0.19	0.75	0.35	2.00	...	...	...	...	....	1650	1650	1000	110,000	87,000	21	55
Ni-Mo	0.20	0.75	0.35	1.90	...	0.35	...	...	1750	....	....	....	78,000	46,000	26	50
Ni-Mo	0.20	0.75	0.35	1.90	...	0.35	...	...	....	1750	....	1200	84,000	60,000	27	52
Ni-Mo	0.20	0.75	0.35	1.90	...	0.35	...	...	....	1750	1550	1200	90,000	70,000	26	53
Ni-Mo	0.30	0.75	0.35	1.50	...	0.30	...	...	....	1650	....	1200	90,000	60,000	22	45
Ni-Mo	0.40	0.75	0.35	1.80	...	0.28	...	...	....	1650	....	1200	110,000	82,000	18	40
Ni-V	0.30	0.75	0.35	1.50	...	...	...	0.15	1650	....	....	....	97,500	62,250	24	47
Ni-V	0.30	0.75	0.35	1.50	...	...	...	0.15	1650	1525	....	....	97,000	68,000	27	55
C-V	0.30	0.75	0.35	...	...	...	...	...	....	1650	....	1200	81,000	55,000	27	40
Cu	0.16	0.90	0.40	...	...	...	1.15	...	....	1650	1575	1250	84,700	71,000	24	50
Cu	0.20	0.65	0.35	...	...	...	1.25	...	1650	1575	....	930	107,750	89,500	21	45
Cu	0.30	0.75	0.35	...	...	...	1.25	...	....	1650	....	1150	94,000	67,000	22	47
Cu	0.30	0.80	0.40	...	...	...	1.30	...	....	1650	1650	1200	99,000	70,000	25	55
Cu	0.30	0.75	0.40	...	...	...	1.75	...	....	....	1650	1200	113,000	99,000	19	47
Cr-Mo	0.25	0.75	0.35	...	0.75	0.30	...	...	....	1650	....	1250	86,300	58,850	23	40
Cr-Mo	0.35	0.75	0.35	...	0.75	0.40	...	...	....	1700	....	1200	96,000	63,500	22	42
Cr-Mo	0.35	0.75	0.35	...	0.75	0.35	...	...	....	1650	1600	1250	111,500	85,800	17	36
Mo	0.25	0.75	0.35	...	...	0.55	...	...	....	1650	....	1250	77,500	48,000	30	56
Mo	0.30	0.70	0.30	...	...	0.50	...	...	....	1650	....	1250	82,000	52,500	24	46
Mo	0.40	0.80	0.35	...	...	0.50	...	...	....	1650	....	1250	90,000	60,000	20	33
Mo	0.28	0.83	0.35	...	...	0.50	...	...	....	....	1650	1200	94,200	65,950	26	59

For local heating of castings with high hardenability, any treatment such as burning, cutting and welding should be performed only on castings preheated to minimize the danger of excessive air hardening, which often results in cracks. This preheating for welding and for similar operations requires higher temperatures and greater care as the hardenability increases. Temperatures of 200 to 300 F are sufficient for the low-carbon steels; as high as 700 to 800 F may be required for high-carbon alloy steels.

Equipment for Heat Treatment. For best results in heat treating operations, controlled furnaces are required so that uniform temperatures and heating rates can be maintained. When air or liquid quenching is involved, the quenching equipment is important if rates of cooling are to be controlled. *See* the articles on pages 615 to 629.

Full Annealing. The castings are heated above the transformation temperature range at a rate that will obtain a reasonable degree of uniformity of temperature within each casting. A rate of 150 to 200°F per hr is usually satisfactory for this purpose. The casting should be held at temperature long enough for the very large crystals formed during freezing to be broken up by recrystallization, and for a more homogeneous material to be produced by the diffusion of elements from regions of microsegregation formed during solidification.

Recrystallization is completed as soon as the temperature rises above the transformation range. Within this range the rate of diffusion is rather slow but it increases rapidly with increasing temperature; consequently temperatures approximately 200°F higher than the transformation temperature range are usually employed.

Very small carbon steel castings can be homogenized in a comparatively short time; for larger carbon steel castings experience has indicated that 1 hr per in. of maximum section is satisfactory. This rule may be modified for extremely heavy sections, since 10 to 12 hr at temperature is usually the maximum time required.

After soaking at the proper temperature for the required length of time, the castings are permitted to cool slowly in the furnace to a temperature of 1000 F or less; then the rate of cooling may be accelerated.

Full annealing ordinarily produces good ductility values accompanied by tensile and yield strengths lower than those produced by the other methods of heat treatment. Impact values are also usually low. A coarse grain structure results when high annealing temperatures are employed. Usually only carbon steels are fully annealed.

Normalizing. In this treatment the castings are heated above the transformation temperature range and are held at that temperature for the proper length of time, in the same manner as for full annealing. Thereafter they are removed from the furnace and permitted to cool in still air.

Although normalizing is not a drastic hardening process, variations in the rates of cooling through the transformation range will influence the resulting mechanical properties. A 1-in. section will cool faster and yield higher strengths than a 2-in. section cooled under similar conditions. Therefore, because of these variations in cooling rates, lower strengths and hardnesses may be expected within the heavier sections of a casting that contains both light and heavy sections. Also, in batch-type furnaces the cooling rate is normally retarded in the central portion of the load, so the method of furnace loading must be considered carefully if uniform results are to be obtained.

Cooling in an air blast is not considered normalizing, since this treatment produces cooling rates more like those employed in conventional quenching operations.

Homogenizing. The castings are heated uniformly, as in annealing or normalizing, to some temperature well above the upper transformation range for at least 1 hr per in. of maximum thickness, and are then cooled from that temperature, usually in still air.

Homogenizing is important only for higher alloy steels prior to quenching operations for hardening. It is usually not required for carbon or low-alloy steels produced to meet ordinary commercial specifications. Quenching temperatures are usually too low to promote effectively a complete diffusion of carbon, particularly in alloy steels, and to break up the as-cast structure. These homogenizing temperatures range usually from 1750 F to considerably more than 2000 F, with time at temperature decreasing as the temperature increases. Air-cooling from these temperatures seems to be beneficial in preventing reversion of segregates found after cooling in the furnace.

Liquid Quenching. This treatment is required when mechanical properties are desired that cannot be produced by annealing, normalizing, or normalizing and tempering.

The castings are heated above the transformation temperature range, are held above that range for a proper period of time, and are then cooled rapidly in a liquid bath to a temperature lower than that associated with the maximum rate of austenite transformation.

Both heating and quenching equipment should be accurately controlled for uniformity of results. Water or oil may be used, depending on the rate of cooling required.

The holding temperatures for quenching are usually about 100 F above the transformation range. The time at temperature is 30 min to 1 hr or more per in. of maximum cross section, depending on the sluggishness of the alloy used and the time required for carbides to go into solution.

When the castings have been properly and uniformly heated, prompt transfer to a suitable quenching tank is essential. Quenching tanks should be of sufficient size, or the quenching medium should be sufficiently cool, to prevent a rise in temperature of more than 20 F in the quenching medium during the quenching operation. Adequate circulation is needed to obtain uniform cooling rates. Castings that are treated simultaneously must be arranged in the furnace and on the quenching racks in such a way that the hot furnace gases and the quenching medium may circulate freely.

Quenching should be continued until the temperature of the entire casting is lower than 500 F, or until a temperature is reached within the martensite range, thus hindering the formation of intermediate transformation products that might be undesirable.

Proper quenching may be hampered by the presence of various thicknesses within one casting. Since the heavier sections cool more slowly than the lighter sections, a liquid quenching treatment may not be suitable for some castings. This uneven cooling may cause cracking in the lighter sections; however, methods are available to minimize the danger. Some of the methods that may be used are differential quenching, spray quenching, "mudding up" lighter sections, or protecting them with plates to prevent excessively rapid cooling.

Tempering. This treatment, which follows normalizing or hardening operations, removes stresses set up in castings during nonuniform cooling. Tempering also increases ductility and impact resistance and decreases the tensile and yield strengths of the hardened material.

The castings are heated uniformly to the proper tempering temperature, are held at temperature for approximately 1 hr per in. of section (minimum usually ½ hr) and are then cooled. The temperatures employed may range from 400 to 1275 F, depending on the hardness and other mechanical properties desired. It is considered good practice to increase the time at temperature from the usual 1 hr per in. of effective cross section when temperatures of less than 850 F are employed, in order to insure the complete removal of residual stresses.

Temperatures higher than 1275 F are rarely employed, since austenite may form and hardening may be encountered in certain types of alloy steels. Obviously, low temperatures are employed for maximum hardness and high temperatures for maximum ductility. When tempering quenched castings, it is important to permit the casting to cool to a temperature low enough to complete the martensite transformation before reheating. This temperature may be as low as 250 F, depending on the composition of the alloy involved. However, it is important that castings of high hardness be tempered promptly after quenching, in order to relieve stresses and obviate cracking.

It is a common practice to cool castings in the furnace from the tempering temperature to some intermediate temperature between tempering and room temperature, and then to cool further in still air. Cooling in still air from the tempering temperature or even quenching in water from the tempering temperature is desirable when temper brittleness may be encountered and when good impact resistance is required at low temperatures.

Stress Relieving. If the relief of stresses is the only consideration, temperatures lower than 500 F are of little value and temperatures higher than 1000 F are usually not required. Experimental work has indicated that a temperature of 750 F will reduce stresses approximately 50% and that temperatures of 1000 F will reduce stresses more than 90%.

Tempering quenched steels at temperatures as low as 350 to 450 F will relieve excessive stresses and induce little or no softening or loss in strength. However, tempering temperatures lower than 700 F are seldom used in the treatment of commercial steel castings; in fact, temperatures higher than 900 F are usually employed. Increased temperatures for tempering will cause a progressive loss in strength, along with progressive improvement in ductility and impact resistance.

In normalized steels, temperatures lower than 1000 F will have little effect on strength or ductility.

Time-Temperature Quenching. When the size and design are such that quenching might cause cracking if the castings were kept in the water or oil until cold, the castings may be removed from the quenching bath when the heaviest section has cooled to about 500 F. The temperature should then be permitted to equalize in the various sections by conduction. For complete martensite formation, higher alloy steels may require additional cooling in still air, but low-alloy steel and carbon steel will usually be properly hardened when quenched to 500 F and will then be ready for tempering.

To ascertain the time required for quenching, in order to produce the desired temperature in heavier sections, thermocouples or temperature sticks (Tempil) may be used on pilot castings or test specimens of similar thickness.

Delayed Quenching (Subcritical). When the alloy content is sufficient, the castings may be heated and held at a temperature above the transformation temperature

range, then cooled in air in such a manner that no part of the casting reaches a temperature lower than 1000 F. The temperature of the castings may then be equalized at 1000 F in a furnace, and the steel may be quenched to about 300 F. This treatment serves to reduce the stresses, since the temperature differentials are less than those obtained during quenches from higher temperatures and the danger of cracking is thus greatly reduced.

Quenching in Heated Baths. Martempering may be accomplished by quenching castings in liquid baths at 300 to 800 F. The effectiveness of this heat treatment is governed by the composition and by the S-curve involved. In martempering, the rate of cooling in the quenching bath is highly important. The time in the quenching bath determines the mechanical properties obtained. Many small castings are now being treated by this method without subsequent tempering.

Case Hardening. The several methods of case hardening described on pages 677 to 702, are applied to steel castings in the same manner as to wrought steels.

The Heat Treatment of Heavy Forgings

BY THE SUBCOMMITTEE ON LARGE FORGINGS*

HEAVY FORGINGS comprise masses that weigh substantially more than those encountered in the usual large-volume, repetitive heat treating operations employed in the production of parts for automobiles, trucks and tractors, and in other practice involving similar sections. The class may be considered to include parts from approximately four inches in thickness or diameter to the largest dimensions forged.

The heat treatment of heavy forgings may consist of annealing, normalizing, quenching and tempering, or various combinations of these treatments to produce the mechanical and metallurgical properties required in a given part. The treatment of heavy sections is subject to a number of controlling factors that are more important than with smaller sections of steel. Many of these factors vary with the size of section and are further affected by shape, chemical composition, and the desired mechanical properties. The procedure that is followed in the heat treatment of heavy forgings will be determined to a large extent by experience in handling each specific part. The mechanical and metallurgical properties that can be obtained are affected by the mass, which limits the rate of heating and increases the period required for holding at soaking temperature. Likewise, the mass reduces the possible rate of cooling. Consequently the possibility of obtaining fully martensitic structures may be remote, even when the sections involved have been quenched. Therefore the normal expectancy is lower values for mechanical properties with increased size of section, a fact that is recognized in nearly all specifications for heat treated forgings. In many instances multiple treatments are required in developing high, uniform values for any composition, especially when the steel has been heated repeatedly during the forging operation.

Furnaces. Furnaces for heating heavy sections are necessarily large, yet they must be capable of heating uniformly and yielding to varying time-temperature cycles within prescribed temperature variation. Oil, gas and electricity are satisfactory sources of heat, provided the above requirements can be met.

Heating. In treating heavy forgings it is good practice to avoid charging a cool forging into a hot furnace. Ordinarily a furnace temperature is recommended that does not exceed 300 to 500 F for alloy steel and 300 to 800 F for carbon steel. After being placed in the furnace, the forging should be permitted to equalize at furnace temperature before heat is applied. When forgings have been transported hot from the forge to treatment shops, they should be allowed to transform in the proper temperature range under controlled conditions in the furnace—a precaution that tends to prevent flakes and thermal cracks—before reheating for subsequent treating operations. The rate of heating should be uniform and is governed by the size and shape of the part being heated. Too rapid heating of heavy sections should be avoided because of deleterious results in central areas. In general, the time allowed for heating to temperature should be 45 to 60 min per in. of cross section. The forging should then be held at temperature long enough to obtain uniform temperature throughout the mass.

Annealing. The purpose of annealing forgings is to refine the grain structure, increase the ductility, or soften the steel for ease of machining. Annealing consists of heating the metal to a temperature above the transformation range, holding it a sufficient length of time at that temperature, and then cooling it in the furnace or under other suitable conditions for uniform, retarded cooling.

Normalizing. The purpose of normalizing forgings is to refine the grain structure or to secure the highest combination of mechanical properties without resorting to quenching in a liquid medium. This treatment consists of heating the parts to a temperature above the transformation range, holding long enough to ensure uniform temperature throughout the mass, and cooling in still or agitated air. However, for uniformity in forgings of complicated shape and variable section, it is often desirable first to normalize the forgings at a temperature well above the transformation range, and to follow this treatment with one or more additional normalizing treatments at successively lower temperatures all above the transformation range. Varying reductions by plastic forging are usually associated with varying thermal histories, which may produce a nonuniform grain structure. Therefore, more than one normalizing treatment may be required for producing the desired refinement.

Quenching. For the larger sizes and for most alloy steels, the usual practice is to rough machine before quenching, in order to bring the size reasonably close to the finished dimensions and to ensure freedom from surface defects and scale. It is customary for the designer to provide large radii or fillets at sharp changes in section so as to reduce the hazard of cracking. Usually as sections increase in size, or as shapes become more irregular, the hazard of quench cracking is increased. It is recommended that liquid quenching be restricted ordinarily to parts 10 in. or less in diameter or thickness and, where possible, that forgings more than 7 in. in diameter be bored. The effectiveness of quenching a bored forging depends to a great extent on the ratio of the wall thickness to the diameter of the hole, and to the length. More highly alloyed steel is recommended for heavy-walled forgings where desired properties can be developed by cooling cycles conducted in air or in the furnace.

For developing higher mechanical properties if they are required, and also for realizing the effects of alloy additions, heavy sections are quenched after a suitable pretreatment. As composition and size become more critical, forgings are usually given a normalizing or annealing treatment, or both, to develop a uniform prestructure and machinability before heating for quenching. Forgings may be quenched in air blasts, oil or water. Decisions concerning liquid quenching procedure, however, must be based on proper consideration of the part to be quenched—that is, the shape and composition; on facilities for handling hot heavy sections; and on available quenching tanks of suitable size, with necessary circulation or agitation, and arrangements for liquid cooling.

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Care must be used in choosing the time and temperature at which the forging should be removed from the quenching medium. If removed while too hot or too cold, the piece may crack. Experience in quenching heavy sections should govern the temperature at which the forging is to be removed from the quenching medium. Large sections do not cool uniformly throughout; central areas cool more slowly and require more time. Forgings are usually permitted to reach uniformity in temperature after being removed from the quenching medium before tempering. If the sections are large or irregular, this equalizing can be done best in a furnace with temperature controlled at the point desired. Quenched forgings should never be allowed to become cold before tempering. However, after liquid quenching, especially with alloy steels, it is advisable to equalize at some temperature below the transformation range so as to complete transformation and ensure stability. This same procedure may be employed after normalizing or air quenching.

Tempering. Normalizing is usually followed by tempering to improve ductility or to adjust the mechanical properties otherwise to meet specifications. Quenching is always followed by tempering, partly for the same reasons and also to remove quenching stresses. Tempering after either normalizing or quenching, will follow the same procedure as described above under Heating, except that the holding time will be increased for quenched parts to ensure adequate toughness. Forgings that do not have abnormal variations in size may be cooled in air. If size and shape cause complications, controlled cooling rates may be necessary to ensure stability. Here again experience is an important guide in determining how forgings should be cooled from the tempering temperature.

Stress Relief. When maximum dimensional stability is required in the finished machined condition on quenched and tempered, or normalized and tempered large forgings, the part may be stress relieved before the last light tool cut. This cycle is similar to the tempering procedure, except that the temperature for stress relieving is usually about 50 F or more below the tempering temperature.

Straightening. When straightening is necessary it is usually performed slightly below the tempering temperature. Often a part is straightened during the cooling after tempering, at a temperature above 400 F.

Mechanical Properties. Space does not permit a full discussion of the complex subject of mechanical properties of large forgings. Mass is the principal complicating factor. Most data available to the average metallurgist, concerning mechanical properties, have been obtained from metal heat treated as specimens 1 in. in diam. However, the heavier masses involved in large forgings, introduce greatly changed and varied rates of heating and cooling. These factors, in turn, affect the reaction rates of austenite formation and decomposition, and the temperatures at which these reactions take place, with resulting variation in the microstructure of the steel forging. This variation in structure naturally makes the mechanical properties obtainable from heavy masses different from those exhibited by test specimens 1 in. in diam. Optimum mechanical properties are usually developed in the outer areas of large forgings, decreasing in the inner portions—rather rapidly with carbon steel and less rapidly with steels of increasingly greater alloy content. In general, as the size of section increases, the values of mechanical properties may decrease within the forging. In the mechanical testing of large forgings the effect of mass on the properties of the steel is fully recognized. Test specimens are cut from locations in the forging (or in a prolongation of the forging) selected carefully to ensure that the property values obtained will be representative of the forging. (*See* "Mechanical Testing of Forgings", page 135.)

The American Society for Testing Materials offers several specifications for steel forgings. For general work, the ASTM Specifications A 235-46 (for carbon steel forgings) and A 237-46 (for alloy steel forgings) may be used. In applying these specifications, the engineer can usually benefit from consultation with a metallurgist experienced in production and heat treatment of heavy forgings.

Properties, Composition and Heat Treatment of Steel Gears

BY THE SUBCOMMITTEE ON HEAT TREATMENT OF STEEL GEARS*

THE PURPOSE of this article is to describe the properties and requirements that should be considered in the design and production of gears and sprockets, as well as to list the more commonly used steels and heat treatments for them. In addition, information is given concerning the application and limitations of processes used in treating gears.

Properties and Corrective Measures to Eliminate Failures. The primary purpose of gears and sprockets is to transmit power. The most important properties required in such parts are these: adequate load-carrying capacity, resistance to wear, to scoring, to pitting fatigue, to bending fatigue, and to chipping.

Adequate Load-Carrying Capacity. If gears are to perform satisfactorily, they must be designed and processed with great care, because poor design and processing can more than offset the best metallurgical practices. In general, the better the design, the smaller the gear required to do a satisfactory job. Design is important with respect not only to the form of the gear teeth, but also to the form of the entire supporting assembly, in order to avoid excessive localized loading of the teeth as a result of the shifting of the contact area under high service loads.

Area of tooth contact is very important in the life of a gear. In the cutting of gears intended for heavy-duty service, it is possible to compensate to some extent for distortion incident to heat treatment. In many plants, it is common practice to cut the gears after heat treatment. This practice, limited to gears that do not require high surface hardness, permits better control of tooth contact.

Resistance to Wear. Smooth abrasive wear is the normal type encountered in gears that have been in service long. This very slow removal of surface metal is not corrected by the use of EP (extreme-pressure) lubricants; in fact such lubricants might, under some conditions, produce slightly increased wear. High surface hardness is required for withstanding this type of wear.

Resistance to Scoring. Scoring or scuffing is rapid abrasive wear and results from the metal-to-metal contact of the gears and the subsequent welding of one contacting surface on another. Produced particularly at high speed and with heavy loading, scoring is usually considered to be the result of failure of the oil film, rather than of the metallurgical properties of the gear. For changing the chemical properties of the surface of the gear so that the surface will not weld, sulfur, sulfur chloride or other suitable material may be added to the lubricant in order to react chemically with the surface of the gear. Such lubricants are referred to as EP lubricants.

In some instances, treatment of gears to produce oxide, phosphate, or sulfide surfaces may give satisfactory results. This treatment prevents seizing and scuffing during the run-in period only; however, if conditions of operation are not too severe, such a treatment may be sufficient. Under very severe conditions, the EP lubricants are required. These lubricants are particularly needed for hypoid pinions and gears used in pleasure cars and trucks.

Resistance to Pitting Fatigue. Pitting of teeth, particularly at the pitch line, is a compression-fatigue type of

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failure. Repeated compressive stresses produce shear failure slightly below the surface, and eventually a small flake comes off, leaving a pit. Compressive-fatigue strength and resistance to pitting are approximately proportional to hardness. Case hardened gears are better in this respect than through-hardened gears of the oil-hardening type, since the surface layers of case hardened gears are usually harder. Structure may have some influence on resistance to pitting. Depth of case and hardness of core are also factors. If the case is too thin or the core is too soft to support the case, the tendency toward failure of the surface is increased.

Resistance to Bending Fatigue. Resistance to bending-fatigue failure is greatly influenced by the quality of finish on the surface of the fillets at the base of the teeth. Consequently, the machining practice employed in cutting a gear may have an important bearing on the suitability of a gear for a particular application. If the gear teeth have been finished by shaving, lapping, or grinding operations that do not include the fillet, it is essential for the initial machining of the fillet to leave a smooth surface.

Breaking of the tooth at the root is a bending-fatigue type of failure in which the rupture originates at the surface. The properties of the case are probably the most important as far as this type of failure is concerned. Soft spots in the fillet at the root of the tooth are conducive to very low fatigue strength. The fatigue resistance of the fillet may be increased appreciably by surface peening.

Resistance to Chipping. Chipping of clash-gear points is a type of failure frequently attributed to improper hardness or structure. In nitrided gears, chipping may be caused by the concentration of the white nitride layer at the edges. However, mechanical design has a great deal of influence on chipping. The engaging ends of teeth should be designed in such a way that tooth corners cannot be the first points of contact.

Classification of Gear Steels. Metallurgical practices on gears, with respect to the severity of service for which they are best suited, may be classified as follows:

Very heavy duty. Carburized low-carbon alloy steel with case depth more than 0.060 in.
Heavy duty. Carburized low-carbon alloy steel with case depth 0.040 to 0.060 in.
Medium duty. Carburized low-carbon alloy steel with case depth 0.020 to 0.040 in.
Medium duty. Carburized 0.30% C alloy steel with case depth 0.010 to 0.015 in.
Medium duty. Carburized 0.40% C alloy steel with case depth 0.005 to 0.010 in.
Medium duty. Cyanide-treated, medium-carbon alloy steel with case depth 0.003 to 0.010 in.
Medium duty. Oil-hardened, medium-carbon alloy steel, hardened from neutral or slightly carburizing atmosphere
Light duty. Cyanide-treated, low-carbon plain carbon steel with case depth 0.005 to 0.010 in.
Light duty. Medium-carbon plain carbon steel, heat treated to 250 Bhn
Extremely light duty. Free-machining type of steel from cold finished bar stock
Extremely light duty. Medium-carbon or low-carbon plain carbon steel, not heat treated

The steels for these various types of services are listed in the following tables. Table I shows the composition of the steels suitable for carburizing to obtain great wear resistance and load-carrying capacity. The hardenability rating of these steels is in the following order, beginning with the steel of lowest hardenability and using the hardenability of the uncarburized core as an index: AISI, A4027, A4620, A8620, A8720, A4820, A4320, A3312.

Table I. Steels Suitable for Carburizing in Order to Obtain High Wear Resistance and Load-Carrying Capacity

SAE Steel No.	AISI Steel No.	Composition, percentage C	Mn	Cr	Si	Ni	Mo	Al	P max	S max
3312	A3312	0.08 to 0.13	0.45 to 0.60	1.40 to 1.75	0.20 to 0.35	3.25 to 3.75	.....	.....	0.040	0.040
4027	A4027	0.25 to 0.30	0.70 to 0.90	.....	0.20 to 0.35	.....	0.20 to 0.30	.....	0.040	0.040
4320	A4320	0.17 to 0.22	0.45 to 0.65	0.40 to 0.60	0.20 to 0.35	1.65 to 2.00	0.20 to 0.30	.....	0.040	0.040
4620	A4620	0.17 to 0.22	0.45 to 0.65	.....	0.20 to 0.35	1.65 to 2.00	0.20 to 0.30	.....	0.040	0.040
4820	A4820	0.18 to 0.23	0.50 to 0.70	.....	0.20 to 0.35	3.25 to 3.75	0.20 to 0.30	.....	0.040	0.040
....	A8620	0.18 to 0.23	0.70 to 0.90	0.40 to 0.60	0.20 to 0.35	0.40 to 0.70	0.15 to 0.25	.....	0.040	0.040
....	A8720	0.18 to 0.23	0.70 to 0.90	0.40 to 0.60	0.20 to 0.35	0.40 to 0.70	0.20 to 0.30	.....	0.040	0.040
Nitralloy		0.38 to 0.43	0.40 to 0.70	1.40 to 1.80	0.20 to 0.40	.....	0.30 to 0.45	0.90 to 1.35	0.040	0.040

These steels for the most part are the most commonly used. It is generally accepted, however, that steels suitable for gears should contain 0.10 to 0.25% C, and should have sufficient alloy content to allow hardening in the section sizes in which they are used. Higher-carbon steels with shallower cases are sometimes used. Several types of nitralloy composition may be used in addition to the one listed in the table. McQuaid-Ehn grain size of 5 to 8 is usually specified.

The steels in Table II are suitable for gears that require medium wear resistance and load-carrying capacity.

Table II. Steels Suitable for Gears That Require Medium Wear Resistance and Load-Carrying Capacity

SAE Steel No.	AISI Steel No.	Composition, percentage C	Mn	Cr	Si	Ni	Mo	V	P max	S max
....	A1345	0.43 to 0.48	1.60 to 1.90	.....	0.20 to 0.35	.....	.....	.....	0.040	0.040
2345	A2345	0.43 to 0.48	0.70 to 0.90	.....	0.20 to 0.35	3.25 to 3.75	.....	.....	0.040	0.040
4145	A4145	0.43 to 0.48	0.75 to 1.00	0.80 to 1.10	0.20 to 0.35	.....	0.15 to 0.25	.....	0.040	0.040
4340	A4340	0.38 to 0.43	0.60 to 0.80	0.70 to 0.90	0.20 to 0.35	1.65 to 2.00	0.20 to 0.30	.....	0.040	0.040
4640	A4640	0.38 to 0.43	0.60 to 0.80	.....	0.20 to 0.35	1.65 to 2.00	0.20 to 0.30	.....	0.040	0.040
....	A5145	0.43 to 0.48	0.70 to 0.90	0.70 to 0.90	0.20 to 0.35	.....	.....	.....	0.040	0.040
6145	A6145	0.43 to 0.48	0.70 to 0.90	0.80 to 1.10	0.20 to 0.35	.....	.....	0.15 min	0.040	0.040
....	A8645	0.43 to 0.48	0.75 to 1.00	0.40 to 0.60	0.20 to 0.35	0.40 to 0.70	0.15 to 0.25	.....	0.040	0.040
....	A8745	0.43 to 0.48	0.75 to 1.00	0.40 to 0.60	0.20 to 0.35	0.40 to 0.70	0.20 to 0.30	.....	0.040	0.040
....	A9845	0.43 to 0.48	0.70 to 0.90	0.70 to 0.90	0.20 to 0.35	0.85 to 1.15	0.20 to 0.30	.....	0.040	0.040

These steels are the types most commonly used for gears, However, any steel that has the proper characteristics of hardenability, with carbon content from 0.35 to 0.50%, is suitable for gears of this class. It is now possible to purchase a number of types of alloy steels to meet specifications for hardenability. These steels have slightly broader chemical limits for the individual elements but the range of hardenability is controlled more closely. To designate these steels the regular SAE or AISI specification numbers are used with the suffix H. With regard to hardenability these steels are rated in the following order, beginning with the steel of lowest hardenability: AISI, A1345, A4640, A5145, A2345, A6145, A8645, A8745, A4145, A9845, A4340.

The steels listed in Table III are suitable for gears and sprockets that require only a moderate degree of strength.

SAE 1141 is suitable for gears to be subjected to very light service; this steel can be machined from cold finished bar stock and, used in the machinable hardness ranges, is one on which good surface finish can be produced and high cutting speeds employed. SAE 1050 steel is usually hardened by quenching in oil from 1475 to 1525 F. The

other steels in Table III are commonly quenched in water, brine, or caustic solution from 1500 to 1575 F. The design may determine whether the gear can be quenched in water. For instance, in very large gears the cooling rate may be so slow, even with water quenching, that satisfactory freedom from distortion can be obtained. With other designs, the distortion may not be of sufficient importance to offset the advantage of water quenching. The mill practice and grain size of the steel affect the hardness and the hardness penetration with any given speed of cooling. The residual elements, such as chromium, nickel, molybdenum and copper, have a marked effect on the plain carbon steels and may cause them to crack during water quenching. It is important to determine the quantities of residual elements present and the resulting hardenability.

Table III. Composition of Carbon Steel for Gears

SAE Steel No.	AISI Steel No.	Composition, percentage C	Mn	P max	S max
1035	C-1035.....	0.32 to 0.38	0.60 to 0.90	0.045	0.055
1040	C-1040.....	0.37 to 0.44	0.60 to 0.90	0.045	0.055
1045	C-1045.....	0.43 to 0.50	0.60 to 0.90	0.045	0.055
1050	C-1050.....	0.48 to 0.55	0.60 to 0.90	0.045	0.055
1141	C-1141.....	0.37 to 0.45	1.35 to 1.65	0.045	0.08 to 0.13

NOTE: Silicon content of 0.15 to 0.30% is desired. Steels may be purchased that have carbon ranges other than those listed in Table III.

Forging. The steels listed in Table I may be heated between 2100 and 2325 F for forging. The temperature of the forging furnace should be controlled automatically with pyrometers, and the finish forging temperature should not be lower than 1800 F.

The steels listed in Table II may be heated between 2100 and 2300 F, and the forging should be finished at a temperature not lower than 1800 F.

The steels listed in Table III may be heated between 2100 and 2350 F. The finishing temperature for these steels should be in the range from 1600 to 1850 F.

The upset method of forging is preferred because it permits proper grain flow. It is desirable to obtain uniform grain flow so that the direction of loading will be perpendicular to the direction of the grain. Uniform grain flow, which helps to minimize distortion in heat treatment, may be obtained by upsetting or by hammer forging. Where strength and minimum distortion are not essential, other methods of forging are permissible. When the section of a forging is large, particularly when made of deep-hardening steel, such as SAE 4340, it is necessary to cool the forging very slowly to prevent internal bursts.

Normalizing and Annealing. In general all forgings should be normalized and annealed. This treatment will refine the coarse structure produced by the forging temperature, minimize the distortion in subsequent heat treating operations, and improve the machinability. When gears are to be cut from bar stock, annealing or normalizing the bar stock may be advisable but is often unnecessary.

Table IV

Normalizing and Annealing of Steels Listed in Table I

Steel	Normalizing Temperature, deg Fahr	Cooling	Tempering Temperature, deg Fahr
3312	1650 to 1750	Air	950–1100
4027	1675 to 1750	Cool at maximum of 600 °F per hr to 900 F.	None
4320	1650 to 1750	Cool either in air or rapidly in furnace to 1200 F. Hold at 1200 F for 4 hr and cool in air.	None
4620	1650 to 1750	Cool in air or rapidly in furnace to 1000 F. Hold at 1000 F for 1 hr and furnace cool to 500 F.	None
4820	1625 to 1725	Cool either in air or rapidly in furnace to 1200 F. Hold at 1200 F for 4 hr and cool in air.	None
A8620	1650 to 1750	Cool either in air or rapidly in furnace to 1000 F. Hold at 1000 F for 1 hr and cool in furnace to 500 F.	None
Nitralloy	1750 to 1850	Cool either in air or rapidly in furnace to 1400 F. Hold at 1400 F for 3 to 4 hr. Cool in 1 hr to 1250 F. Hold at 1250 F for 1 hr and cool in air.	None

Normalizing and tempering or cycle annealing are commonly applied to steels listed in Table I. The hardness desired in these operations depends on the machining operations and the type of finish required for the particular gear. The hardness obtained depends on the cooling rate, which in turn depends on the size of the gear. The treatments given in Table IV are for gears of moderate size common in automotive and aircraft applications.

The normalizing temperature should be at least 25 F higher than the carburizing temperature.

For steel 3312, the desired hardness for cutting will be between 229 and 262 Bhn, although the type of finish required and whether or not broaching is to be used enter into the selection of this hardness range. The 4027 steel should have a Brinell hardness of 150 to 180. The remaining steels should machine well from 187 to 217 Bhn.

Table V

Normalizing and Annealing of Steels Listed in Table II

Steel	Normalizing Temperature, deg Fahr	Cooling	Tempering Temperature, deg Fahr
A1345	1600 to 1700	Cool in air or rapidly in furnace to 1200 F. Hold at 1200 F for 3 to 4 hr and cool in air.	None
A2345	1600 to 1700	Cool in air or rapidly in furnace to 1150 F. Hold at 1150 F for 2 to 3 hr, cool in furnace to 1100 F and cool in air.	None
A4145	1650 to 1750	Cool in air or rapidly in furnace to 1250 F. Hold at 1250 F for 2½ to 3½ hr. Cool to 900 F in 3½ to 4½ hr. Then cool in air.	None
A4340	1600 to 1700	Air	1200 F
A4640	1650 to 1750	Cool in air or rapidly in furnace to 1250 F. Hold at 1250 F for 2½ to 3½ hr. Cool to 900 F in 3½ to 4½ hr. Then cool in air.	None
A5145	1650 to 1750	Cool in air or rapidly in furnace to 1250 F. Hold at 1250 F for 2½ to 3½ hr. Cool to 900 F in 3½ to 4½ hr. Then cool in air.	None
A6145	1650 to 1750	Cool in air or rapidly in furnace to 1330 F. Hold at 1330 for 2 to 3 hr. Cool in furnace to 1250 F and then cool in air.	None
A8645	1650 to 1750	Cool in air or rapidly in furnace to 1250 F. Hold at 1250 F for 2½ to 3½ hr. Cool to 900 F in 3½ to 4½ hr. Then cool in air.	None
A8745	1650 to 1750	Cool in air or rapidly in furnace to 1250 F. Hold at 1250 F for 2½ to 3½ hr. Cool to 900 F in 3½ to 4½ hr. Then cool in air.	None
A9845	1600 to 1700	Cool in air or rapidly in furnace to 1200 F. Hold at 1200 F for 4 to 5 hr and then cool in air.	None

After these treatments, the Brinell hardness number should be between 187 and 229, except that for SAE 4340 the range will be 217 to 241. However, the Brinell hardness is not always indicative of good machining qualities. Microscopic inspection should show lamellar pearlite with a minimum of free ferrite or spheroidization.

If furnaces are not available for cycle annealing as listed in the tables, the gears may be annealed after normalizing, by heating to 1550 F, cooling in the furnace to about 900 F, and then cooling in air.

Normalizing of the Plain Carbon Steels Listed in Table III. For the plain carbon steels listed in Table III, heating from 1650 to 1750 F and then cooling in air will provide the desired hardness for machining. If the parts are unusually small, it may be necessary to cool in air to around 1300 F, to hold at this temperature for 2 hr and then to cool in air to room temperature.

Carburizing. When made from steels listed in Table I, gears may be carburized to any desired depth and treated as shown in Table VI. An activated salt bath, carburizing compound, gas or vaporized oil may be used in carburizing these steels. Salt is used for shallow cases.

Carburizing compound, most widely used, affords fair control of case depth. Accurate control of case depth and of carbon concentration at the surface, may be obtained by carburizing with gas or vaporized oil, using test specimens to determine the length of the carburizing cycle. The time required for carburizing is shorter when gas or

vaporized oil is used. Control of carbon content at the surface is desired, and in general, eutectoid composition is considered most satisfactory. When the work material has been cooled slowly after carburizing, it is then reheated and quenched instead of being quenched directly from the carburizing temperature. The reheating method is usually chosen in order to minimize distortion or to obtain greater surface hardness. This greater surface hardness results from the formation of martensite with less retained austenite than is formed when deep-hardening steels are quenched directly. Distortion may be increased because of excessive cold working with dull tools on the surface of green gear teeth. If the gears are reheated and quenched after carburizing, care should be taken to avoid decarburization during the operation.

Table VI. Carburizing Treatments

Steel	Carburizing Temperature, deg Fahr	Method of Cooling	Reheating Temperature, deg Fahr	Quenching Medium	Tempering Temperature, deg Fahr
3312	1650 to 1700	Pit or box	1475 to 1500	Oil	250 to 300
4027	1650 to 1700	Oil quench	.....	...	250 to 300
4320	1650 to 1700	Pit, box or oil quench	1500 to 1525	Oil	250 to 300
4620	1650 to 1700	Oil quench	.....	...	250 to 300
4820	1650 to 1700	Pit, box or oil quench	1475 to 1500	Oil	250 to 300
A8620	1650 to 1700	Oil quench	.....	...	250 to 300

Gas carburizing with the addition of ammonia gas is sometimes used for obtaining a hard, wear-resistant case.

Nitralloy steel is nitrided at 950 to 980 F for a sufficient time to give the desired depth of case. Before the nitriding process, the steel must be free from decarburization at the surface and must be in the quenched and tempered condition. The usual practice is to quench from 1700 to 1750 F in oil, and to temper at 1100 to 1300 F. After nitriding, 0.001 to 0.003 in. of metal should be removed from the contacting surfaces of the teeth to avoid surface flaking. Locations on carburized gears, where it is desirable to stop off the carburizing, may be copper-plated to a minimum thickness of 0.0007 in. On nitrided gears, the stop-off is accomplished by using tin 0.0003 to 0.0005 in. thick, or bronze with a minimum thickness of 0.0005 in.

Hardening and Tempering. The steels listed in Table II may be hardened by the treatments listed in Table VII.

Heating for Quenching. The gears are heated slowly and uniformly to the quenching temperature given in Table VII and are held long enough to ensure complete and thorough penetration of heat. The heating medium should be selected carefully to hold scaling to a minimum and to prevent decarburization. These purposes may be accomplished when the work is heated in a cyanide salt bath or in an atmosphere that will produce a light carburized case.

Quenching. The best results are obtained by free circulation of oil around the gear being quenched. Formation of gas pockets should be avoided. Special quenching fixtures are commonly used to minimize distortion. The speed of cooling depends somewhat on the rapidity of the circulation of oil. It is good practice to keep the temperature of the oil constant and between 110 and 130 F.

Water Quenching. Generally water quenching is used only on plain carbon steels containing less than 0.40% C. Quenching in cold water produces higher hardness but increases the danger of distortion and cracking. The heavier and more uniform the section and the lower the carbon and manganese contents, the more drastic may be the quench.

Quenching in warm water produces results intermediate between the effects of cold water and of oil quenching. Bath temperatures above 130 F are not recommended.

Brine or Soda Solution. Brine quenching is generally carried on in a solution of sodium hydroxide (caustic soda), or sodium chloride (common salt). The cooling rate of sodium hydroxide is higher. Sodium chloride solutions quench more slowly than sodium hydroxide and are corrosive to work pieces and equipment, but are safer to use. A ▮ to 10% solution of either of the materials is generally used. Higher concentrations are not much more effective. Temperature changes of brine solutions alter the cooling rate less than similar changes in water.

Below the temperature of martensite formation, quenching in brine is more drastic than quenching in water. Time quenching or quenching from brine into hot water or oil, may reduce the likelihood of distortion or cracking in parts of irregular shape.

The quenching of gears in brine, is not generally recommended because of the stresses induced by such drastic cooling.

Fused Salt Quenching. When the design makes special treatment necessary to avoid distortion, gears may be quenched in hot fused salt. Martempering, the process for hardening steel by this means, is discussed on page 629.

Time Quenching. Time quenching in water is used for those parts that cannot be completely quenched in water because of their composition or design. The operation is carried out by allowing the immersed section to remain in the quenching liquid only until the metal contains enough residual heat in the center of the heavier sections, to reheat the entire part to a temperature approaching that used for tempering. At this point, the part is withdrawn from the quench and allowed to cool in air until the residual heat has been distributed as evenly as possible throughout. After this, cooling may be carried on in any convenient manner. Automatic devices are desirable for timing the quench and ejecting the gear. If the time quenching is controlled carefully and the hardness range on the finished gear is not too narrow, the tempering operation may be omitted; but it is safer to temper the gear as though it had been completely quenched. Other variations of time quenching involve quenching in water and transferring to oil.

Cyanide Treatment of Gears. Sodium cyanide baths are used in the heat treatment of gears for cases less than about 0.008 to 0.010 in. deep. Treatment in cyanide is not favored for producing cases deeper than 0.010 in. The depth of the cyanide case, in many instances, varies from 0.003 to 0.005 in. Cyanide cases are used chiefly in connection with low-carbon plain carbon steels; the concentration of sodium cyanide in the bath is maintained at 18 to 30%. High surface hardness with correspondingly high resistance to wear, is obtained from treatment in cyanide. The light case obtained makes it necessary to finish the gears completely before cyaniding.

One distinct advantage of a cyanide treatment is that the work material comes out of the bath nearly as clean as before treatment. Cyanide baths are used extensively in hardening higher-carbon materials, such as the oil-hardening types of alloy steels (0.35 to 0.50% C), commonly used in gears. An appreciable volume of gears of this type have been treated in cyanide to keep the surface free from scale or decarburization. When cyanide baths are used primarily as a medium for clean heating, somewhat lower concentrations of sodium cyanide are maintained, although the concentration should not be less than 8%. Because greater emphasis is now placed on the improved wear resistance that can be produced by treatments in cyanide, the 18 to 30% concentration is preferred in most operations.

Tempering. In tempering, all sections should be brought to the proper temperature and held for 30 min to several hours, depending on the size and type of gear. One purpose of tempering is to relieve stress; therefore the lower the temperature used, the longer the gear should be held at that temperature.

Table VII. Hardening and Tempering

AISI Steel No.	Austenitizing Temperature, deg Fahr	Tempering Temperature, deg Fahr	Quenching Medium
A1345	1460 to 1510	425 to 475	Oil
A2345	1450 to 1500	425 to 475	Oil
A4145	1500 to 1540	425 to 475	Oil
A4640	1480 to 1530	425 to 475	Oil
A5145	1490 to 1540	425 to 475	Oil
A6145	1515 to 1565	425 to 475	Oil
A4340	1475 to 1525	425 to 475	Oil
A8645	1480 to 1530	425 to 475	Oil
A8745	1480 to 1530	425 to 475	Oil
A9845	1490 to 1540	425 to 475	Oil

Local Hardening. Teeth of gears and sprockets may be hardened locally by rapid heating and quenching of the surface. Both electrical induction and flame heating methods are employed. In both methods, the application of heat is so rapid that the surface layers reach the desired hardening temperature before the center of the gear tooth has become hot. These methods have proved particularly advantageous, with regard to cost, for the heat treatment of very large gears and sprockets, because a considerable proportion of the weight of the gear is not heated.

The objective of local hardening is to produce the desired surface hardness, the desired pattern of hardened and unhardened areas in the tooth section, and generally a good serviceable gear, free from distortion and harmful entrapped stresses. The pattern of hardened and unhardened areas in the tooth section can be examined readily by cutting and etching both longitudinal and cross sections in this area. The nature of the application determines the type of pattern required. Obviously the wearing surfaces of the gear teeth should be hardened. This hardening may be all that is required if bending and crushing stresses are very low. On the other hand, if bending stresses are high, the fillets at the roots of the teeth should also be hardened. When crushing stresses near the pitch line are high, it is desirable to have either a relatively deep hardened area, a fairly high core hardness, or both.

In carburizing and hardening, the hardened area naturally follows the contour of the surface—though not always, if induction or flame hardening is employed. The factors that govern the pattern of the hardened area include the size and shape of the gear, frequency of the induction circuit, power input, time of heating, degree of preheat, if any, and the period of delay before quenching. The shorter the heating time, the better the heated zone follows the contour of the surface. Very large gears are heated successfully with 9600-cycle circuits that will contour-harden gear teeth as small as 2-pitch. Contour hardening of fine-pitch gears may require 500,000 cycles or more. At present contour hardening of gears finer than 5-pitch is not done commercially. With finer pitch, the upper part of the tooth is hardened through and contour hardening ceases.

In flame hardening large gears, heat is usually applied progressively to one tooth at a time. The flame travels across the face of the tooth, and is followed immediately by a pressure quenching spray. This method is discussed in the article entitled "Flame Hardening" on page 647, where mention is made of the use of straddle-type heads that heat both faces of a tooth simultaneously.

The photograph on page 647 shows the cross section of a tooth hardened in this manner. It will be noted that the faces of the tooth are hardened down to the working depth, but that the fillets at the roots of the teeth are untreated and consequently soft. If there is sufficient distance between consecutive teeth, it may be possible to include the fillet in the heated and quenched area.

Large gears may be induction hardened, one tooth at a time. In small and medium-sized gears, the entire gear is usually placed in the induction field and the whole periphery is heated almost simultaneously.

In general, gears should be tempered below 450 F after local hardening to relieve stresses. The steel used for flame hardened and induction hardened gears usually contains 0.40 to 0.55% C. Either plain carbon or alloy steels may be employed, though the tendency is toward the use of plain carbon steels. Oil quenching is often used.

Both the induction and the flame heating methods are subject to a number of variations. The best results will be obtained only by careful study of these methods and by modification of the practice to fit a particular product.

Grinding. If gear teeth are ground after hardening, care should be taken to avoid the formation of grinding checks; overheating during grinding, which softens the surface of the gear tooth; and taking off too much of the case, if the gear is carburized or nitrided. It is good practice to etch the gear teeth in an alcohol solution containing 10% nitric acid to reveal any effects of overheating from grinding.

Hardness Testing. Hardness is generally tested with the Rockwell machine, using the 15-N scale for cases 0.010 to 0.015 in. deep, the 30-N scale for 0.015 to 0.025 in., and the C scale for deeper cases or for oil-hardened gears that are not carburized. It is recognized that production hardness tests cannot be made at the location where the hardness is most important—at the base of the gear tooth, for instance, or at the pitch diameter—but must be made at some location that indicates whether the gear has been properly hardened. A file test may be used for determining the presence of a soft skin on carburized and hardened gears. It is necessary occasionally to cut sections from production gears and make a thorough check on hardness at various locations.

Magnetic Particle Inspection. In the inspection of gears by the magnetic particle method, it is common practice to reject all that contain grinding checks, quenching cracks, straightening cracks, forging defects or seams.

Nonmetallic inclusions are judged by their severity and location in relation to stressed areas, but any true indications on the tooth surfaces are considered cause for rejection. It should be noted that indications at the roots of the teeth are likely to be overlooked because of powder build-up in this area and because of the tooth shape.

The Composition and Heat Treatment of Splined Shafts

By the Subcommittee on Heat Treatment of Splined Shafts*

THIS ARTICLE summarizes the processes to be followed for the heat treatment of splined shafts. A splined shaft is constructed so that it interlocks, either rigidly or with sliding, with another part or parts, such as gears. A splined shaft may have one or more keyways or one or more keys, but ordinarily the same shaft does not have both keys and keyways. Splined shafts are used in two general classes of work, automotive parts and machine-tool parts; examples are transmission shafts, axle shafts and propeller shafts. Any distinctions as to relative length or diameter would be rather arbitrary. Although steels other than those listed and discussed later, may be used successfully in splined shafts, the selections made are believed to be representative and adequate.

Design. Splined shafts are subjected to alternating stresses; hence their endurance limit in fatigue is important. The shaft should be designed to eliminate unnecessary necks and sharp corners where stresses might be concentrated. Fillets and machined grooves in splines should always be gradually rounded.

Stiffness is one of the necessary properties of some types of splined shafts, particularly of long shafts. Shaft designs should provide for sufficient section so that harmful deflection will not occur under the applied load. Shafts not properly designed may twist or bend, thus causing undesirable effects from alternating stress, vibration and the like, which will be manifested in the gears or other moving parts, as well as in the shaft. Heat treatment may raise the elastic limit of the steel, but it will not change the modulus of elasticity. For this reason, heat treated shafts are no stiffer than untreated shafts when operating below the elastic limit.

Distortion. This is the trouble most commonly encountered in the heat treatment of splined shafts. To avoid distortion, care must be used in all operations. Distortion

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includes volume changes as well as twisting or warping. Stresses induced by preliminary or roughing operations may need to be relieved by normalizing, annealing or stress-relief tempering before the final machining.

The carburizing and heat treating operations should all be carried out with extreme care. With some carburized splined shafts it may be necessary to avoid the "double treatment" (Method III of Table I), and to carburize at a lower temperature to minimize distortion.

Many splined shafts are made of bar stock having either a black, hot rolled finish, or a bright, cold drawn finish. Material treated in either way is more likely to be distorted later, than a properly normalized forging; therefore when minimum straightening is essential, splined shafts made of bar stock should be normalized in the same way as forgings, unless the straightening operation is considered absolutely necessary on the finished shaft. If hot rolled or cold drawn bar stock is used, it is essential that 1/64 to 1/32 in. should first be machined from the outer surface to insure a clean surface for hardening.

Keyways in a splined shaft may cause distortion in quenching. Unless designed with ample section, a shaft with a keyway has less stiffness than one carrying keys integral with the shaft. To minimize distortion in quenching, it is advantageous to have more than one integral key. These keys are equally spaced about the shaft to facilitate equal cooling and to balance the section.

Martempering will also minimize distortion; both Table I and Table II include this method of heat treatment.

Table I. Carburizing and Heat Treating of Carburized Splined Shafts

Carburizing Temperature, 1600 F and 1700 F (1650 F minimum preferred by many)
After carburizing, alternate methods
I Quench directly and temper.
II Cool in box, reheat once, quench in oil, temper.
III Cool in box, reheat (to refine core), quench in oil, reheat, quench, temper.

Steel[b]	Method II[a] Reheating Temperature, deg Fahr	Method III First Reheating[c] Temperature, deg Fahr	Method III Second Reheating Temperature, deg Fahr	For Any Method Tempering Temperature,[d] deg Fahr
1020	1400 to 1450	1550	1400 to 1450	350 to 425
1022	1400 to 1425	1575	1400 to 1425	300 to 400
2320	1325 to 1375	1540	1375 to 1400	350 to 500
2520	1350 to 1450	1525	1350 to 1400	275 to 400
3120	1375 to 1425	1550	1400 to 1425	350 to 500
3310	1375 to 1425	1525	1375 to 1400	350 to 500
3415	1350 to 1400	1525	1375 to 1400	350 to 500
4620	1420 to 1470	1525	1375 to 1425	275 to 400
4815	1375 to 1425	1600	1375 to 1425	275 to 400
8620	1425 to 1450	1575	1400 to 1450	300 to 400
8720	1425 to 1450	1575	1400 to 1450	300 to 400
9315	1375 to 1425 or 1500 to 1525	1525	1375 to 1400	350 to 500

(a) Many find it desirable to quench from 1450 to 1550 F.
(b) Only typical steels are listed from each type. The carbon range can be varied slightly without affecting recommended temperatures.
(c) An alternate treatment for alloy steels, which may minimize distortion, is to quench from the austenitizing temperature into salt at 400 F, hold according to cross section, cool to room temperature, and temper to requirements (martempering).
(d) Opinions differ considerably as to the tempering temperature that should be used for various steels. For some steels a lower tempering temperature, but not less than 275 F, may be desirable.

Chemical Composition of Steels for Splined Shafts. Two types of steel are commonly used for splined shafts. These are the carburizing and the direct-hardening types and include the following steels:

Carburizing Steels. 1020, 1022, 1320, 8620, 8720 2320, 2520, 3120, 3310, 3415, 4620, 4815 and 9315.

Direct-Hardening Steels. 1045, 1052, 1335, 8635, 8735, 2340, 3140, 3250, 3450, 4140, 4340 and 6150.

Selection of Steels for Splined Shafts. Splined shafts that are not to be highly stressed, can be made satisfactorily from steels 1020, 1022 or 1320. For sufficient stiffness, the shaft is sometimes designed large enough so that these steels may be used instead of alloy steels.

For small shafts that are to be carburized, steels 3120, 2520, 3310, 2320, 4620 and 4815 are satisfactory. If the diameter is more than 1½ in., the carbon content can be increased slightly without resulting in brittleness during quenching. For large shafts, steels 3415, 3120, 2320, 2520, 4620 and 4815 are satisfactory. Some users report favorably on the 9300 series for highly stressed splined shafts that have heavy sections.

Although the water-hardening steels can be used, it should be pointed out that water quenching may result in cracking, particularly if the design is such that the shaft will be susceptible to cracking. Steel 1045 is used for splined shafts but is not entirely satisfactory. It does not always respond uniformly to heat treatment, whereas 1335 does.

Steels 1022 and 1335, and others of this general type are used successfully in splined shafts. They machine freely, have good mechanical properties, and harden without difficulty.

In addition to these manganese steels, steels 1340 and 1345 are used to some extent for splined shafts. They machine less readily than the manganese steels listed, but have excellent mechanical properties and are of the oil-hardening type.

Almost any structural steel can be made into satisfactory splined shafts if the factors of *design, hardenability* and methods of *heat treatment* are properly correlated. Even the free-machining steels can be used, though conditions of surface stress and wear must be considered carefully if these steels are chosen, so they are not listed in the tables of recommended steels.

Table II. Hardening and Tempering of Direct-Hardening Splined Shafts

Quenching may be done in water,[a] oil[b] or salt,[c] as discussed in footnotes. Temper to requirements.[d]

Steel[e]	Quenching Temperature,[f] deg Fahr	Steel[e]	Quenching Temperature,[f] deg Fahr
1045	1475 to 1550	3140	1500 to 1550
1052	1475 to 1550	3250	1475 to 1525
1335	1475 to 1525	3450	1475 to 1525
8635	1475 to 1550	4140	1525 to 1575
8735	1475 to 1550	4340	1475 to 1550
2340	1425 to 1550	6150	1525 to 1625

(a) Steels 1045, 1335, 8630, 8730, 2330 and 4130 may be quenched in water.
(b) All the steels except those listed in Note (a), are classed as oil-hardening steels, and even those listed in Note (a) may be oil-quenched in small sections.
(c) *Martempering.* Any of the steels may be quenched in a salt bath at 400 F, held until equalized at that temperature (according to section), cooled in air to room temperature, and tempered.
(d) No exact tempering temperatures can be listed. *See text.*
(e) Only representative steels are listed. Carbon content may be varied to suit requirements; the usual upper and lower limits are 0.30 and 0.50%. For example, in the 8600 series, 8630 may be chosen for some uses; for other uses, 8650 may be chosen.
(f) Most of the fine-grained oil-hardening steels will harden in oil when quenched from within the range 1475 to 1550 F; some authorities express a preference for the range from 1525 to 1550. The range of carbon content selected may influence the exact temperature range chosen. Some prefer to heat the steels in a cyanide bath to the hardening temperature.

Normalizing and Annealing of Carburizing Steels. For normalizing, the carburizing steels should be heated to a temperature between 1650 and 1825 F. For best results in machining, the temperature should be at least 50 F above the carburizing temperature. Holding too long at elevated temperature causes excessive scaling if the furnace atmosphere is not properly controlled. The steel should be cooled slowly, to give the machining qualities desired.

Careful annealing of helical splined shafts is essential in order to minimize the movement of the helical angle or load in subsequent heat treatment.

Carburizing. The depth of carburized case is selected in accordance with the individual requirements. The methods of carburizing as given in this Handbook (pages 677 to 693) may be followed. The conventional pack carburizing process is satisfactory. Shafts should either stand vertically in the box or be supported to prevent sagging under heat. Uniform heating is essential; in some furnaces this may require horizontal heating at a possible sacrifice of straightness. In box carburizing, it is also important to be careful that the box is heated uniformly. The carburizing temperatures and the heat treatments for carburized splined shafts are given in Table I.

Quenching Treatments for Carburized Splined Shafts. There are several quenching treatments that may be given: (1) a direct quench from the box, (2) a single or (3) a double quench after cooling in the box, or (4) martempering. The factors that govern the choice of methods are: (*a*) shock resistance desired, (*b*) grain growth characteristics of the steel, (*c*) distortion. In some plants, experience has shown that suitable impact values and minimum distortion are obtained for certain steels by quenching directly from the box. However, it is common practice to use a single quench when the steel has cooled in the box after carburizing. (*See* Method II in Table I.)

In the single quenching treatment, it is advisable to use lower carburizing temperatures, and if the structure is coarse after carburizing, it is advisable to use the higher reheating temperature listed in Method II, Table I. It is, of course, desirable to hold distortion to a minimum. When steels are selected that do not coarsen at the carburizing temperature used, distortion is held to a minimum by direct quenching from the box, by a single reheating after cooling in the box, or particularly by martempering.

The double quench, as given in Table I, Method III, will produce refinement of case and core and resistance to shock and impact. While this treatment can be given without the need for such great care in the control of grain size as is necessary in single quenching, it has the serious disadvantage that the added reheating is almost certain to cause serious distortion. Thus it may be preferable in many instances to control the grain size and to use only the single quench.

For hardening, it is suggested that the splined shafts be hung vertically from eyebolts in the furnace, and also quenched vertically from the same eyebolts for both single-quenched and double-quenched shafts. Splined shafts are always distorted somewhat in relation to the keyway. It may be necessary to quench in a fixture or on a machine after the final heating, so that the shafts will be so little distorted that they will be straight after grinding, when an ample amount of grinding stock is allowed. If this method is used, the straightening operation may be unnecessary in some instances.

Splined shafts can also be heated in a horizontal position in a continuous furnace, provided the supports are properly spaced. The shafts come out fairly straight, although they usually require some straightening.

Tempering Carburized Splined Shafts. In tempering, the highest temperature should be used that will give the desired hardness.

Normalizing and Annealing Direct-Hardening Steels. For normalizing or annealing, the direct-hardening steels for splined shafts should be heated openly, exposing maximum surface area, to a temperature of 1600 to 1700 F. Closer temperature limits, but within this range, may be desirable for certain steels. For this treatment the steels should be held at temperature only long enough to insure complete penetration of heat. From these temperatures the steels may be cooled in the air or cooled at a rate that will produce the desired machining qualities. A retarded cooling rate through certain temperature ranges, may be desirable in order to produce good machining qualities; for example, for steels 1335, 1340, 2345 and 6150.

Hardening and Tempering Direct-Hardening Steels. The quenching temperatures for the splined shafts made from direct-hardening steels are given in Table II, with notes concerning the quenching mediums that can be used.

Low temperatures, usually in the range from 300 to 475 F, are employed for stress relieving. The time will be longer than that required when a tempering range of 900 to 1000 F is used. For every type of steel there will be a "blue brittleness" temperature range that should not be used in tempering. The lower limit of this undesirable temperature range for tempering is usually about 500 F. If it is desired to temper at a temperature higher than 500 F and lower than 900 F, the tempering ranges suitable for the steel in question should be determined by reference to other sections of this Handbook, or by consultation with the maker of the steel. Selection of the tempering temperature is influenced by several factors: whether machining is to be done after hardening, what procedures are to be followed in straightening, and what final hardness is desired.

As an example, some of the hardening and tempering variations possible for steel 3145, may be considered, in their correlation with machinability. This steel may be quenched from the temperature range 1425 to 1450 F and tempered between 900 and 1000 F. The shaft is hardened vertically, with spline or keyway not cut, leaving ample stock for grinding. The keyway is then milled after the heat treatment. If the steel has been properly normalized and properly handled, straightening is rarely needed, but if necessary, straightening can be done at the tempering temperature. After tempering, the shaft is rough-ground to 0.010 in. oversize; then the spline is milled and the splined shaft is finish-ground.

If, however, the tempering range selected for steel 3145 is 650 to 750 F after quenching from the range 1525 to 1550 F, the difficulties in machining after heat treatment will be increased, as compared with results from tempering between 900 and 1000 F. The Brinell hardness number will be considerably more than 300, but if no machining is needed after hardening, this tempering temperature will be quite satisfactory for this steel. If steel 3145 is tempered in the range from 300 to 475 F, the hardness will be still higher. It should be noted that although a tempering temperature as low as 650 F is possible for this steel, many steels cannot be tempered in this range for reasons previously discussed.

Most medium-carbon alloy steels, when tempered to Rockwell C 35, can be machined at a reasonable cost. Although higher mechanical properties can be obtained, machining costs mount rapidly when the hardness is above Rockwell C 35. Somewhat higher hardness values can be tolerated on steel 4340, still maintaining machinability.

Splined shafts may be difficult to straighten after quenching. If the tempering temperature is to be in the low range, straightening is usually performed before tempering and immediately after quenching; that is, while the steel is still hot. If the tempering temperature is in the high range, straightening may be done after tempering, if desired, although it can be done with less difficulty at the tempering temperature. Care should be taken in the design of splines and keyways (if more than one is present) to keep them balanced about the shaft, thus minimizing distortion. Even with a single spline, it may be possible to jig-quench or machine-quench so that distortion will be held within grinding allowance. The use of vertical retort furnaces with controlled atmospheres also tends to minimize the amount of straightening and grinding necessary. Although all the steels listed will distort unless extra precautions are taken, steels requiring the higher quenching temperatures may have a greater tendency to distort. Straightening is easier if the grain size is controlled. Grain size from 5 to 7 is preferred.

Most of the steels listed are ordinarily quenched in oil, although steels 1045, 1335, 8630, 8730, 2330 and 4130 are usually classed as water-hardening steels. Steels having higher carbon content, or shafts of very small cross section, regardless of composition, should not be quenched in water.

The coolant is not specified in Table II. The coolant and quenching rate must be co-ordinated with the design and with the hardenability of the steel. This often requires experimentation before the best methods for a particular job are developed. For a further consideration of hardenability and its relation to size of section and rates of cooling, reference may be made to pages 489 to 502.

Finally, the use of martempering is recommended as a heat treating procedure to minimize distortion and to secure satisfactory properties. The procedure is listed in footnotes to Table I and Table II, and reference may be made to page 629 for further details.

The Composition and Heat Treatment of Steel Springs

BY THE SUBCOMMITTEE ON HEAT TREATMENT OF STEEL SPRINGS*

IN this article the composition and heat treatment of four types of steel springs are discussed. The products considered are small flat springs, large flat and leaf springs, small helical springs, and large helical springs.

Small Flat Springs

This section describes the heat treatment of small flat springs used for miscellaneous purposes. The practice discussed here includes only springs cold formed from strip or from blanks less than ⅛ in. thick.

Imperfections. Flat stock of the compositions listed is furnished commercially in various grades. The price varies with the care used during processing in order to insure freedom from defects. The best grades should be free from surface cracks, hairline seams, surface decarburization, slag inclusions, die scratches, localized segregations, slivers and cuts. Such defects are starting points for fatigue failures and may cause early fracture; thus they are detrimental to highly stressed springs or to those operating rapidly over a great number of stress cycles.

Carbon steel 1045 is used in a hard cold rolled condition, not hardened and tempered, for flat springs in light sections $\frac{1}{16}$ in. thick or less, which are not highly stressed and in which low cost is a major consideration. All the carbon steels from 1045 to and including 1095 can be obtained in the form of cold rolled strip, either annealed or pretempered, while 1060, 1074 and 1095 can be had in the pretempered condition in several ranges of Rockwell hardness, held to a mean, plus or minus two points. All these steels can also be obtained hot rolled in strips or flat bars, or hot rolled, pickled and oiled. This material is supplied in the "as-rolled" condition, not tempered and not annealed. It varies considerably more in thickness than cold rolled strip, but may be used when low cost is desired and inaccuracy of loading can be tolerated.

The alloy steels, 6150, 9260 and 8650, are ordinarily supplied in the annealed condition for hardening and tempering after forming, but these materials are used occasionally in a pretempered condition. They may also be obtained hot rolled in thicknesses of $\frac{1}{16}$ in. or more.

Table I. Chemical Composition of Flat Material Used for Small Cold Formed Springs

Steel	C	Mn	Cr	Si	V, min	Mo	Ni
Carbon Steels							
1045	0.43 to 0.50	0.60 to 0.90					
1060	0.55 to 0.65	0.60 to 0.90					
1074	0.70 to 0.80	0.50 to 0.80					
1080	0.75 to 0.88	0.60 to 0.90					
1095	0.90 to 1.05	0.30 to 0.50					
Alloy Steels							
6150	0.48 to 0.53	0.70 to 0.90	0.80 to 1.10	0.20 to 0.35	0.15		
9260	0.55 to 0.65	0.70 to 1.00	.....	1.8 to 2.2	...		
8650	0.48 to 0.53	0.75 to 1.00	0.40 to 0.60	0.20 to 0.35	...	0.15 to 0.25	0.40 to 0.70

NOTE: Phosphorus, 0.04% max in all steels. Sulfur, 0.05% max in carbon steels, 0.04% max in alloy steels

Heat Treatment. Small springs made from cold rolled or pretempered materials should be given only a "stress-relief" heat treatment to relieve forming strains. This treatment consists of holding the springs for 20 to 30 min at temperatures between 450 and 550 F for light springs of carbon steels, and as high as 725 F for alloy steels.

Springs made from carbon steels in the annealed or as-rolled condition should be heated uniformly to a temperature between 1450 and 1525 F and then quenched rapidly in circulating quenching oil held to a temperature of 110 to 140 F. Springs will scale when heated in an open furnace. If no scaling is desired, they must be heated for quenching in a furnace that has a controlled atmosphere free from oxygen or in a salt bath of suitable composition. As quickly as possible after quenching in oil, springs should be tempered at a temperature ranging from 680 to 800 F, depending on the hardness desired. When some permanent set is allowable, the hardness should be 40 to 44 Rockwell C. When maximum resistance to set is desired, the range should be 44 to 48 Rockwell C. Carbon steel springs should never exceed Rockwell C 50, because material harder than that tends to be brittle.

Alloy steel springs made from 6150, 9260, or 8650 should be similarly treated from a quenching temperature of 1575 to 1625 F, and tempered at 725 to 900 F, depending on hardness. These steels can be about four points Rockwell harder than the carbon steels because of the alloying elements they contain. They should be held at the tempering temperature long enough to permit complete penetration of the heat. The method of cooling after tempering is not important.

Other Kinds of Material. Certain grades of stainless steel, notably the 18-8 type (for example, AISI type 302), are used for applications where springs are subjected to moderately elevated temperatures.

Phosphor bronze, beryllium copper and brass are used when electrical conductivity is desired.

High speed steels are used where springs are subjected to temperatures as high as 850 F.

Large Flat and Leaf Springs

This section discusses the heat treatment of hot formed flat springs made of carbon or alloy steels. It includes only springs hot formed from bars ⅛ in. or more in thickness, of the type used for railway, automotive and agricultural equipments, and also for miscellaneous applications.

Imperfections. Because of the nature of the production process, flat hot rolled bars cannot be free from such imperfections as pits, rolled-in scale, hairline surface seams and surface decarburization. Round bars can be rolled oversize and centerless ground, removing enough material in obtaining the finished size to eliminate such defects, but surface grinding processes developed so far for flat bars are too expensive, unless low cost is not essential.

Defects should be held to the minimum obtainable by the best mill practice. All bars should be free from pipes or laps, and as nearly free as possible from carbide segregations or inclusions that might cause quench cracking.

Hardness. The steel as received from the manufacturers should be soft enough to permit the simple cold working operations of shearing, punching, trimming and bending without cracking.

Chemical Composition. Steels 1074, 1095, 6150, 9260 and 8650 are used for hot formed flat springs ⅛ in. thick or more, as well as for small flat springs (*see* Table I). Steels 5150 (0.48 to 0.53% C, 0.70 to 0.90% Mn, 0.20 to 0.35% Si, 0.70 to 0.90% Cr) and 4068 (0.63 to 0.70% C, 0.75 to 1.00% Mn, 0.25 to 0.35% Si, 0.20 to 0.30% Mo) are also used for flat springs ⅛ in. thick or more.

* The members of this subcommittee are E. H. Stilwill, *Chairman* (Chrysler Corporation), D. C. Green (Muelhausen Spring Corporation), N. E. Hendrickson (The Mather Spring Company), L. R. Steele (Eaton Manufacturing Company), E. W. Stewart (The William D. Gibson Company), J. R. Thompson (American Steel & Wire Company), R. S. Thompson (Washburn Wire Company) and F. P. Zimmerli (Barnes-Gibson-Raymond, Inc.).

Heating for Slotting, Nibbing, Spear-Pointing and Tapering. For these operations the bars should be heated uniformly no higher than 1800 F, in a suitable furnace.

Heating for Forming. For forming, the bars should be heated uniformly in a suitable furnace to the lowest temperature at which the steel will work satisfactorily; this temperature should never exceed 1750 F for carbon steels nor 1800 F for alloy steels. After forming, the springs should be air cooled until they become distinctly black.

Annealing. When annealing is necessary for machining, the steel may be heated to between 1250 and 1400 F with rate of cooling controlled according to requirements.

Table II. Heat Treatment of Hot Formed Large Flat and Leaf Springs

Steel	Normalizing(a) Temp, deg Fahr	Quenching(b) Temp, deg Fahr
1074	1525 to 1575	1450 to 1525
1095	1575 to 1625	1475 to 1525
4068	1550 to 1600	1500 to 1525
6150	1600 to 1650	1600 to 1650
9260	1600 to 1650	1600 to 1650
5150	1600 to 1650	1475 to 1525
8650	1600 to 1650	1600 to 1650

(a) These normalizing temperatures should be used as the forming temperature whenever feasible.
(b) Quench in oil at 110 to 140 F.

Heating for Quenching. When springs have been allowed to cool to a distinct black after forming, they should be uniformly reheated in a suitable furnace to the quenching temperatures given in Table II. The soaking time in minutes in the furnace, after the springs are heated to temperature, may be determined by multiplying the thickness in inches by 60. This is equivalent to a soaking time of 1 hr per in. of section thickness. The springs should then be quenched, preferably in a suitable fixture in an ample volume of circulating oil that is held at a temperature of 110 to 140 F. The springs should be held in the oil until they have cooled to a temperature no higher than 300 F.

Tempering. As soon as possible after quenching, the springs should be tempered at a temperature ranging from 680 to 800 F for carbon steels, and from 725 to 900 F for alloy steels, depending on the hardness desired. They should be held at the tempering temperature long enough to insure complete penetration of the heat. The method of cooling after tempering is not important. If a salt bath is used for tempering, a hot water dip will remove the salt film from the springs.

When some permanent set is allowable in carbon steels the hardness of these steels should be about 352 to 388 Brinell, and when maximum resistance to permanent set is necessary, the hardness should be about 388 to 444. For alloy steels under the same circumstances, the hardness should be 375 to 415 Bhn and 415 to 461 Bhn respectively.

Small Helical Springs

This section discusses the heat treatment of cold coiled small helical springs designed to be used for miscellaneous purposes. The practice includes only springs made from wire ½ in. or less in diam.

Imperfections. The various materials furnished for small helical springs are supplied commercially in several grades; the prices vary according to the care used during processing, in order to insure freedom from defects. The best grades should be free from surface cracks, hairline seams, surface decarburization, slag inclusions, localized segregations, die scratches, slivers, pits and cuts. Such defects are detrimental to highly stressed springs, or those operating over a great number of stress cycles, because they are starting points for fatigue failures and may cause early fracture.

Hardness. The wire as received from the manufacturer, whether carbon or alloy steel, pretempered or soft, should have uniform hardness in order to hold uniform dimensions in coiling or forming. All spring wire of $\frac{3}{16}$-in. diam or less, whether pretempered or soft, should coil on its own diameter as an arbor, and in larger sizes should coil on an arbor twice as large in diameter, without breaking or cracking the surface.

Chemical Composition. The chemical compositions of steel wires generally used for cold coiled small helical springs made from wire ½ in. in diam or less are given in Table III.

Hard Drawn Wire. Hard drawn wire is not pretempered, but, as the name implies, obtains its physical properties from the cold work of die drawing. This type of wire is made into springs that are given no heat treatment except for heating a short time to relieve coiling strains. In drawing, this wire is "process annealed" by heating to a temperature considerably lower than the transformation range, at intervals during the reduction. This treatment reduces the tensile strength enough to permit further reduction in diameter, but retains part of the cold work previously imparted to the wire without changing the structure. Hard drawn wire is of comparatively low quality and is not guaranteed to be free from surface imperfections such as hairline seams, and not guaranteed to harden without quench cracks. The wire is used ordinarily for low-stressed springs not subjected to severe duty.

Music Wire. Music wire is a cold worked wire supplied to the spring manufacturers for making into small springs without further heat treatment except heating to remove coiling strains. Commercial sizes range from 0.004 to 0.135 in. in diam, but this material may be obtained in sizes increasing to a maximum of about 0.250-in. diam. Music wire is drawn to higher tensile strengths and to higher torsional elastic limits than any other material available. These high mechanical properties are obtained by a combination of the high carbon content and many continuous passes or reductions in the drawing dies. Toughness is obtained from a process called "patenting", which consists of heating the rods just before the drawing process, by passing them rapidly through a furnace. The material is heated to a temperature somewhat above the transformation range and is then quenched in lead or air at a speed that produces a sorbitic structure. The wire will then stand a great reduction in diameter without developing brittleness, if the number of passes is sufficient and the reduction at any one pass is not too great. Music wire is supplied in a bright smooth finish and the best grades are quite free from surface imperfections. Such wire is purchased according to tensile properties, not hardness.

Table III. Chemical Composition of Steel Wire Used for Cold Coiled Small Helical Springs

Designation	C	Mn	P, max	S, max	Si	Cr	V
Hard Drawn ASTM A227-41	0.45 to 0.75	0.60 to 1.20	0.045	0.050	0.10 to 0.30		
Music Wire ASTM A228-41	0.70 to 1.00	0.20 to 0.60	0.030	0.030	0.12 to 0.30		
Oil Tempered ASTM A229-41 (A)	0.55 to 0.75	0.80 to 1.20	0.045	0.050	0.10 to 0.30		
Oil Tempered ASTM A229-41 (B)	0.55 to 0.75	0.60 to 0.90	0.045	0.050	0.10 to 0.30		
Tempered Valve Spring ASTM A230-41	0.60 to 0.70	0.50 to 0.80	0.030	0.030	0.12 to 0.30		
Chromium-Vanadium ASTM A231-41	0.45 to 0.55	0.60 to 0.90	0.040	0.050	0.15 to 0.30	0.80 to 1.10	0.15 min
Chromium-Vanadium Valve Spring ASTM A232-41	0.45 to 0.55	0.60 to 0.90	0.030	0.030	0.12 to 0.30	0.80 to 1.10	0.15 to 0.25
SAE 9260	0.55 to 0.65	0.70 to 1.00	0.04	0.04	1.80 to 2.20	.....	.....

Oil-Tempered Wire. This wire is furnished to spring manufacturers in a heat treated condition. No further heat treatment is necessary after the material has been coiled into springs except heating for a short time to relieve coiling strains. The composition ASTM A229-41 (A) is used for the sizes larger than $\frac{3}{16}$ in. or $\frac{7}{32}$ in., varying with the practice in individual mills; and the composition ASTM A229-41 (B) is used for diameters as small as 0.020 in., the usual minimum for this grade. In commercial quality, this material is in the lower price range and is not guaranteed to be free from seams. It is widely used for commercial springs that are not in the class of "high-duty" springs where fatigue life is of paramount importance. Oil-tempered wire varies in tensile strength according to diameter. The smaller the wire, the higher the tensile strength; wire 0.020 in. in diam has a minimum tensile strength of about 295,000 psi while wire ½ in. in diam has a minimum of about 175,000 psi. The elastic limit in torsion varies somewhat with composition and with variations in manufacturing procedure, but is usually at least 40% of the ultimate tensile strength.

Oil-tempered valve-spring wire, ASTM A230-41, is the best quality of carbon steel wire available for "high-duty" springs. It is not possible to produce even this wire so that every foot of material is free from pits, slight seams or similar defects. For extremely high-grade springs, such as valve springs for aircraft engines, the finished springs are subjected to a magnetic particle inspection to eliminate any springs with seams, and are also inspected visually at a magnification of about 8 or 10 diam to eliminate any springs that show pits or similar defects. Except for such special springs, this costly inspection is seldom used.

High-grade springs are usually shot blasted. This process has proved very beneficial for increasing the resistance to fatigue, because of the compressive stress trapped in the surface layers of the material by the shot peening.

Annealed Wire. Wire is supplied to spring manufacturers in an annealed condition, and is used for making springs that are to be hardened and tempered after coiling. After being process annealed to produce partial or complete spheroidization, the wire is drawn to finished size.

Most commercial springs of wire diameters less than ⅜ in. are made from hard drawn wire, music wire or one of the grades of tempered wire. Some of the larger springs that have wire diameters from ⅜ to ½ in. are made from annealed wire and are heat treated after coiling, particularly when the ratio of coil diameter to wire diameter is small, resulting in difficulty in coiling the oil-tempered material. Experience has shown that more uniform springs can be obtained by using the pretempered materials than by hardening and tempering after coiling. This is because the desirable properties of uniform hardness, toughness, freedom from surface decarburization and from quenching cracks, are more easily obtained by hardening the wire as a continuous strand than by hardening the springs after coiling.

Close-coiled or extension springs are usually made with a property called "initial tension", which is a preload or pressure between adjacent coils when free. Initial tension cannot be obtained in springs that are hardened and tempered after coiling, because the condition is one of residual stress, later eliminated by heating the springs above the transformation temperature for hardening.

Chromium-Vanadium and Silicon-Manganese Steel Wire. The commercial grade and the select grade of these materials are supplied in both oil-tempered and annealed conditions. They are subject to the comments previously made about carbon steels, concerning the desirability of the oil-tempered material for springs in preference to annealed material heat treated after coiling. Both of these kinds of steel wire are used chiefly in springs that are very highly stressed and are subjected to moderately elevated temperatures, in which an alloy steel will operate for a satisfactory life but carbon steels soften too much.

Other Kinds of Wire. Certain nonferrous materials, such as brass, phosphor bronze and other bronzes, are used to some extent in springs when electrical conductivity or resistance to corrosion is a consideration. Some high-nickel alloys and copper-nickel alloys are used for special purposes.

Certain grades of stainless steel have found a rather wide application in small springs, notably the 18-8 Cr-Ni type (for example, AISI type 302). This material can be drawn to tensile strengths almost equal to those of music wire, size for size. However, the elastic limit, as well as the endurance limit in fatigue, is unfortunately considerably lower than the corresponding properties in music wire. This 18-8 material is resistant to many acids and alkalies, and to ordinary atmospheric conditions. It is used at temperatures no higher than 600 F.

Beryllium copper has been used to some extent, particularly in electrical applications in which a spring must act as a conductor of current, because this alloy has higher conductivity than any other spring material.

High speed steels are used for springs that are subjected to operating temperatures lower than 850 F.

Stress Relieving. The hardening and tempering of springs after coiling should not be confused with the low-temperature heat treatment after coiling, which is applied for the purpose of relieving coiling strains. Stress relieving a spring formed from hard drawn oil-tempered wire or music wire, will increase resistance to permanent deformation.

Heating and Quenching. Springs made from carbon steels in the annealed condition should be heated uniformly to a temperature between 1450 and 1525 F, and should then be quenched rapidly in circulating quenching oil held at a temperature between 110 and 140 F. As quickly as possible after quenching in oil, springs should be tempered by raising to a temperature between 680 and 800 F, depending on the hardness desired. When some permanent set is allowable, the hardness should be 40 to 44 Rockwell C. When maximum resistance to set is desired, the range should be 44 to 48 Rockwell C. Carbon steel springs should never exceed Rockwell C 50, because brittleness may result.

Alloy steel springs should be similarly treated from a quenching temperature of 1575 to 1625 F and should be tempered at 725 to 900 F, depending on the hardness desired. This material can be about four points Rockwell harder than carbon steel with corresponding toughness and mechanical properties.

All springs made of carbon or alloy steels should be held at the tempering temperature long enough to permit complete penetration of the heat. The method of cooling after tempering is not important.

Spring of hard drawn music wire or oil-tempered wire should be heated to relieve coiling strains, and experience has indicated that 350 to 750 F is the most desirable range for these materials. After heating to temperature, the springs should be held in this range long enough to permit complete penetration of the heat.

Large Helical Springs

This section discusses the heat treatment of hot coiled helical springs of both plain carbon and alloy steels. The practice includes only large springs made from bar stock ½ in. in diam or more and of the type generally used for railway, automotive and agricultural equipment, but also used extensively for miscellaneous applications.

Imperfections. The bars should be as nearly free as possible from surface cracks, rolling seams, surface decarburization, pits, rolled-in scale, inclusions, carbide segregations, pipes and laps. Commercial bars in the as-rolled condition may not be free from these surface defects. If complete freedom from surface defects is necessary, centerless-ground bars must be used.

Hardness. The steel as received from the manufacturers must be soft enough to permit the cold working operations of shearing, trimming and bending without cracking.

Chemical Composition. Steels 1085, 1095, 6150, 9260, 4068 and 8650 are used for hot coiled helical springs made from bars ½ in. or more in diam. The compositions of these steels are given above. Steel 9262, which is the same as 9260 but with 0.25 to 0.40% Cr, is also used.

Most hot coiled springs are made from carbon steel. The alloy steels are used for special applications, requiring springs that are highly stressed or that must operate at elevated temperatures with little or no set. Alloy steels have been used largely in bar diameters wider than ⅝ in., because of greater hardenability and resistance to fatigue.

Heating for Tapering and for Coiling. For tapering, the bars should be heated in a suitable furnace to a temperature not exceeding 1850 F. For coiling, the bars should be heated uniformly in a furnace to the lowest temperature at which the steel will work satisfactorily. This temperature should never exceed 1750 F for carbon steels, nor 1800 F for alloy steels. After coiling, the springs should be cooled in air until they become distinctly black, except in special instances.

Annealing. When annealing is necessary for machining, the steel may be heated to the range between 1250 and 1400 F. The rate of cooling should be controlled according to the requirements.

Heat Treatment. The heat treatments for steels 1095, 4068, 6150, 9260 and 8650 are given in Table II. Steels 1085 and 9262 are heat treated in the same way as 1095 and 9260, respectively. The recommendations given for heating and for tempering large flat springs apply also to large helical springs.

Many large helical springs are produced successfully by quenching directly from the coiling operation. This involves careful controls, and the practice must be limited to springs large enough in bar diameter and short enough in bar length to maintain a proper quenching temperature immediately after coiling. In direct quenching, the bar should never be heated above the normalizing temperature shown in Table II.

Shot Peening. Shot peening is distinctly beneficial as a means of increasing the endurance limit of all of the spring steels in the sizes commonly used. Data concerning the effects of shot peening on the properties of helical springs are given in the article on page 243 of this Handbook.

Flame Hardening

BY THE SUBCOMMITTEE ON FLAME HARDENING*

FLAME HARDENING can be defined as a process of heating the surface layer of an iron-base alloy above the transformation temperature range by means of a high-temperature flame, and then quenching. In this process the fuel gas flames impinge directly on the work piece.

The treated layer can be varied from a thin skin obtained by heating quickly, to a substantial layer obtained by "soaking heat". The usual depth for most purposes is $\frac{3}{32}$ to $\frac{1}{8}$ in. of nearly fully hardened material. Because there is no alteration of the chemical composition of the work piece, a hardenable material must be used. This method must not be confused with carburizing, cyaniding or nitriding, since these processes require the addition or absorption of other elements.

Comparison of Furnace and Flame Hardening. Because of uniform heating, furnace hardening produces parts that are hardened all over. Flames permit selective hardening because they can be directed to localized areas. Small parts to be hardened all over and produced in large quantities can usually be hardened more economically in the furnace. In many instances where the parts are large or where only certain areas are to be hardened, flame hardening can be used.

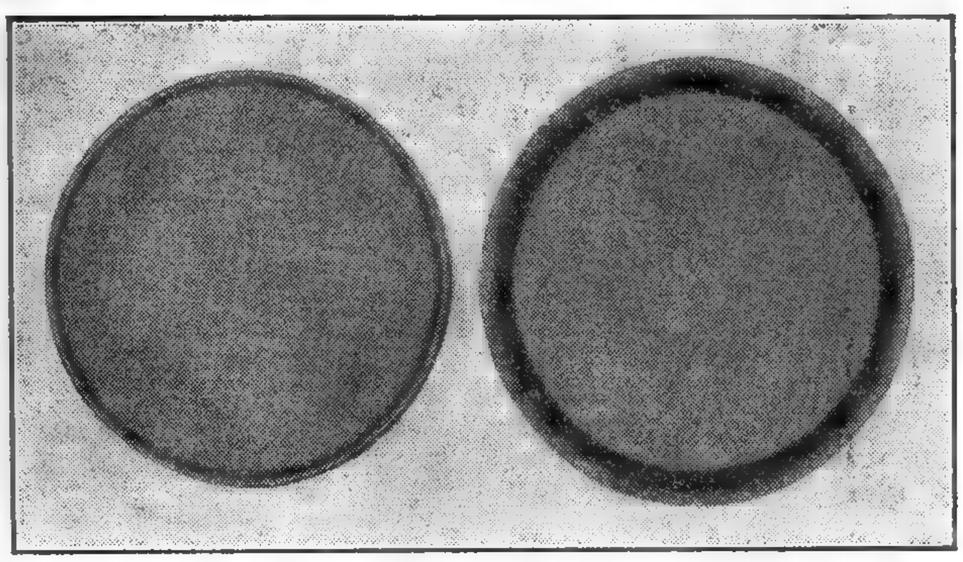

Fig. 1 Round bars flame hardened by the combination method. Light case and medium case. SAE 1045 steel.

Distortion. Flame hardening tends to minimize or eliminate objectionable distortion on many designs. However, thin pieces that are long in proportion to the cross section will distort, sometimes excessively, when hardened on one side. Often the procedure may be altered to reduce this effect. Pieces hardened symmetrically or on two sides have the least distortion. Long round bars should be annealed virtually free from stress. A water bath can sometimes be used to compensate for heating that is uneven or on one side only. Distortion is a problem in itself and must be studied, sometimes by experiment, to determine the best method for correction. Sometimes a change in design that does not affect the utility of the part will aid in the elimination of distortion.

Materials. *Steels.* Any type of hardenable steel, including stainless, can be flame hardened if the proper procedures are followed. The carbon content should be 0.35% or more for appreciable hardening. The best range for most flame hardening methods is 0.40 to 0.50%. The alloy content will determine the type of quench to be used. Straight carbon steels in the range indicated can usually be given a rapid quench. The quench for alloy steels can be varied from a rapid quench to air cooling, depending on the hardenability of the steel. Sometimes a quench using compressed air immediately behind the flames is followed by a quench using water. Full hardness cannot always be expected with the slower cooling rates. Typical hardness patterns in a flame hardened steel bar and in a gear tooth are shown in Fig. 1 and 2, respectively.

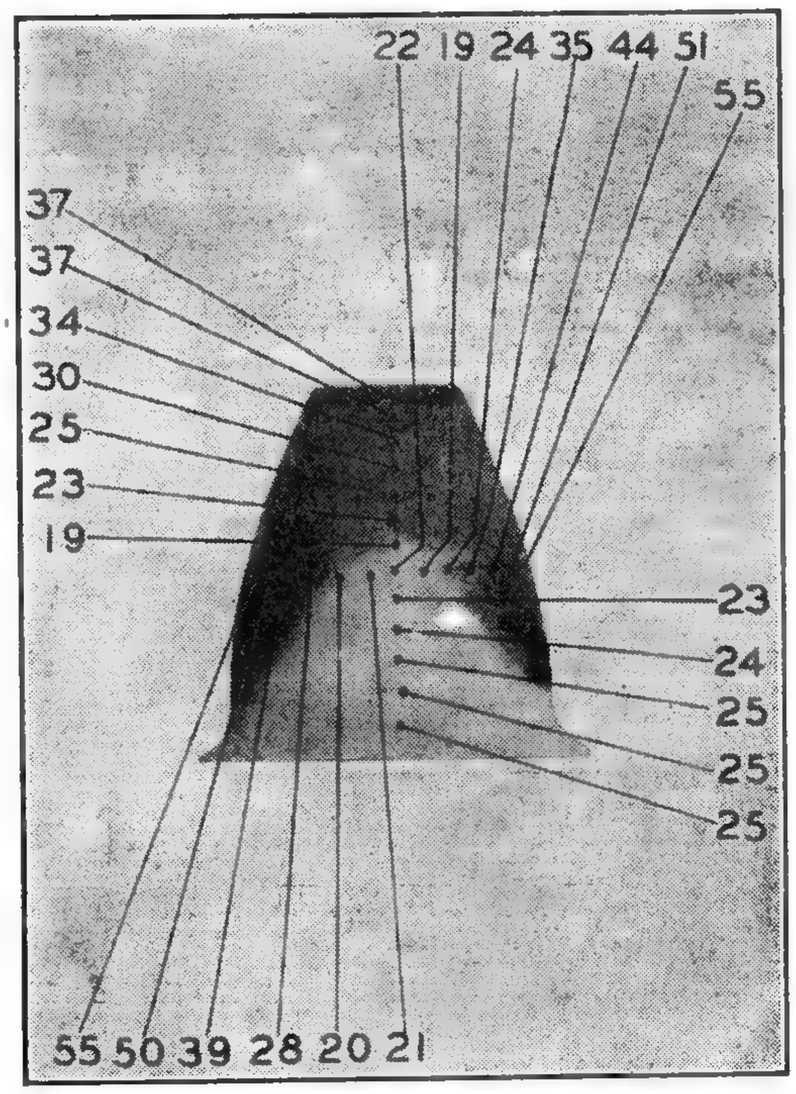

Fig. 2 Distribution of hardness in a gear tooth. SAE 4640 steel, progressively hardened without quenching.

Cast Iron. Pearlitic cast irons offer a broad field for the flame hardening process. Chilled cast iron has high resistance to wear, but chilled castings cannot be machined.

* The members of this subcommittee are H. V. Inskeep, *Chairman* (The Linde Air Products Company), Paul F. Berg (Selas Corporation of America), Carl E. Ernst (Gleason Works), A. L. Hartley (Cincinnati Milling Machine Co.) and Stephen Smith (Air Reduction Sales Co.)

Pearlitic cast iron can be machined to dimension and then flame hardened, greatly increasing the resistance to wear. In general, gray cast iron should have about 0.40 to 0.80% combined carbon for satisfactory hardening. Alloying elements such as nickel, chromium, molybdenum and vanadium, in the amounts used in cast iron, have little effect on the results. Cast iron is easily overheated and in general should be hardened at lower temperatures than steel. Any specific cast iron should be tested for hardenability, since poor results can be obtained even though the chemical composition may be correct. It has been found that the rebound type of device for measuring hardness gives more consistent and accurate results than the penetrator types on flame hardened cast iron. The penetrator types produce crushing of the matrix, causing scatter and low readings. Figures 3, 4 and 5 illustrate the results of flame hardening cast iron.

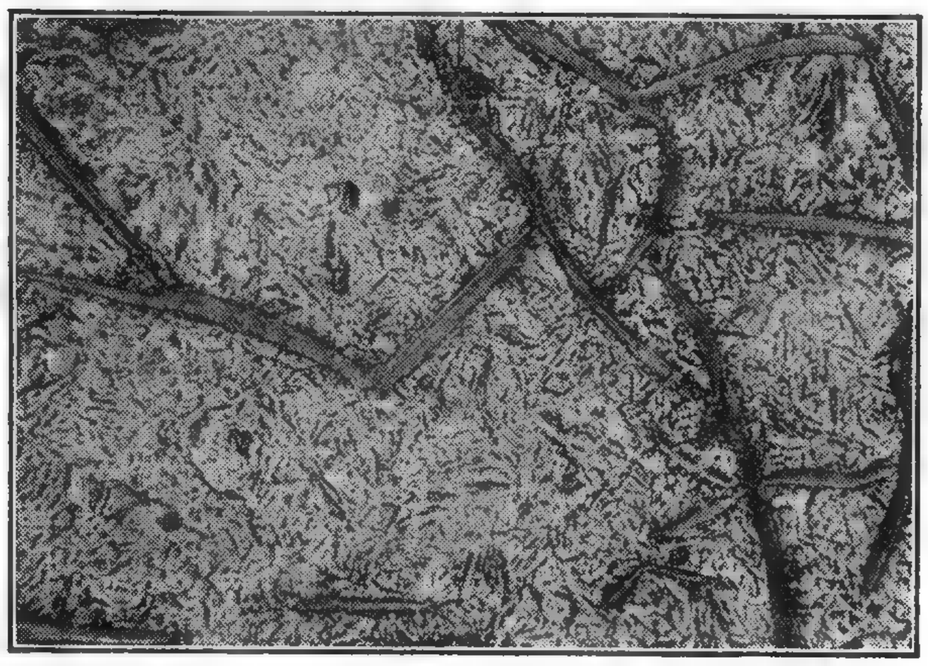

Fig. 3 Microstructure of cast iron, flame hardened by the progressive method. Composition 3.46% total C, 0.76% combined C, 1.58% Si, 0.76% Mn. Maximum hardness, 600 Brinell (converted from scleroscope). *Above,* case immediately below surface (× 500). *Below,* unhardened material.

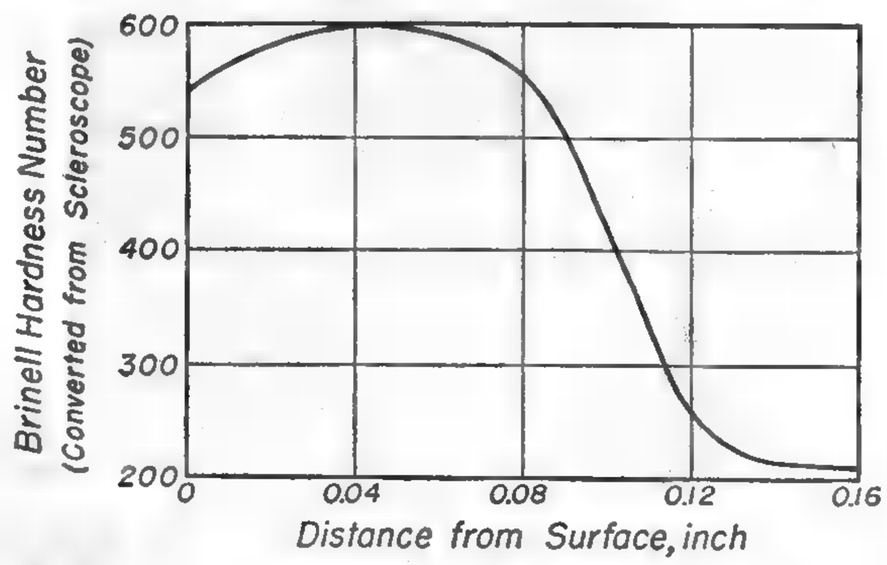

Fig. 4 Hardness penetration for the cast iron shown in Fig. 3.

Properties. This method of heat treatment can produce the optimum hardness on the surfaces subject to wear but leaves the core in its original condition; thus it is possible to treat the core for desired properties and then impart a hard surface layer without altering the core.

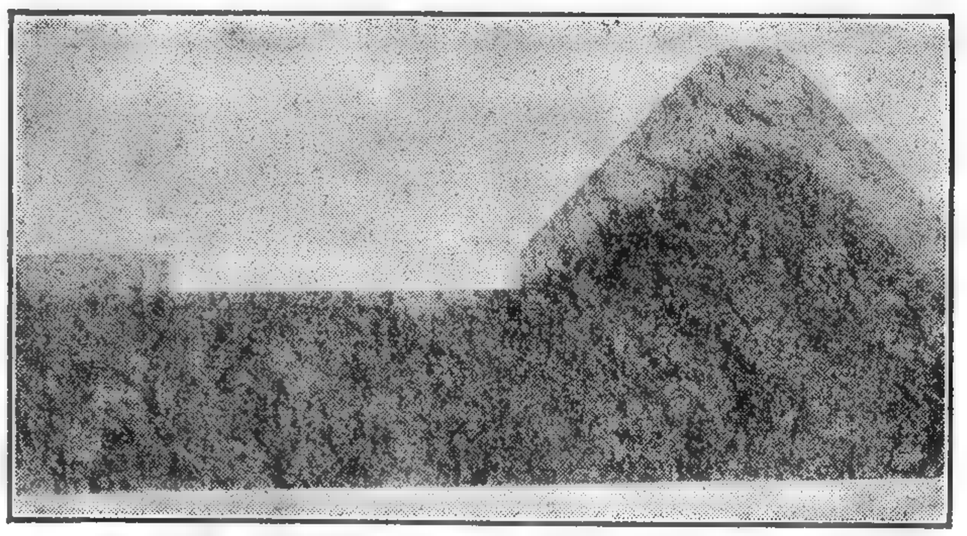

Fig. 5 Flame hardened sliding way section illustrating corner hardening. Cast iron.

Hardness. Flame hardening can produce the maximum hardness possible with any given type of steel if a rapid quench is used. In straight carbon steels, almost full hardness exists in 50% or more of the total layer affected by heat. The transition zone gradually reduces in hardness until core hardness is reached. Alloy steels, if water quenched, have a sharper gradient of hardness in the transition zone. If an air-hardening steel is quenched in air, the transition zone is deepened and the gradient of hardness is more gradual. Under some conditions of service, the deeper transition zone is desirable. Hardness on the surface is likely to be slightly lower when the hardened layer is thick. Thinner cases produce higher hardness at the surface, as illustrated by the curves in Fig. 6. By adjusting the rate of heat input and rate of quench, the relationship between fully hard and transition zone material can be varied.

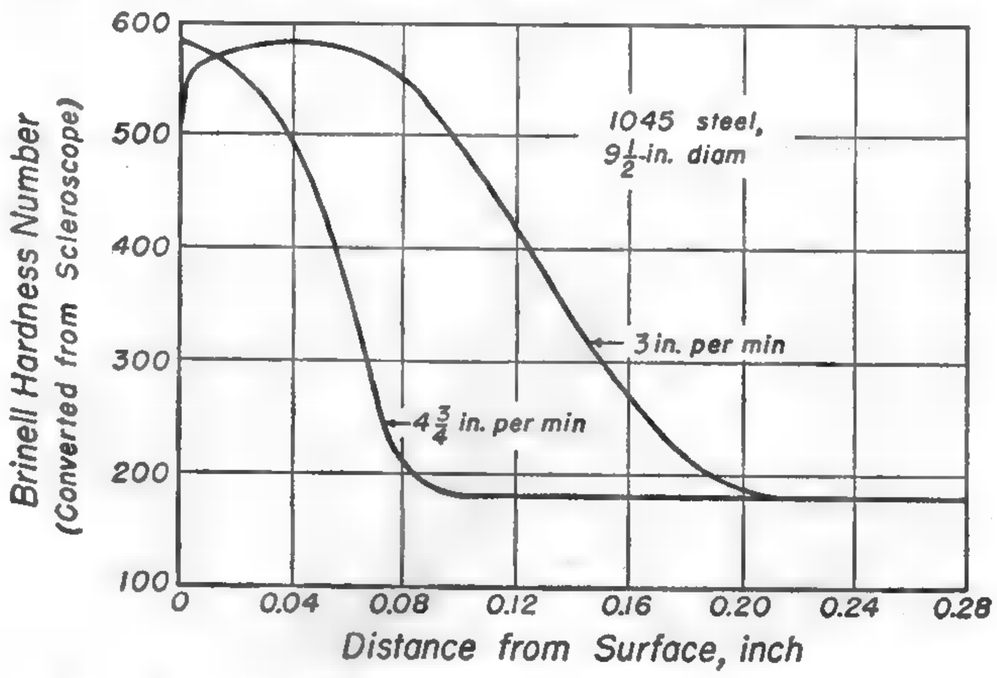

Fig. 6 Effect of progressive speed on the hardness penetration in a 9½-in. diam bar of SAE 1045 steel after flame hardening.

Methods. *The Stationary or Spot Hardening Method.* This method of flame hardening will accomplish hardening in spots or patterned areas. The work piece and the heating head are stationary. The size and shape of the desired hardened area will determine the design and number of flames in the heating head. For instance, stems for automotive engine valves require a single flame, and tractor-tread side bars that have a hardened area of 19 sq in. require a heating head with many flames distributed in an unusual pattern. The type of quench can be varied greatly by this method, easily utilizing still air, water spray and water or oil immersion.

Progressive Method. The progressive method implies a relative motion between the heating head and the work; either may move. The heating head is followed by a quench, usually a water spray. However, a quench in still air or a combination of compressed air and water spray may be used. The path of travel can be straight or of some other form—for instance helical on a large round bar. A slightly softer zone may exist at overlap points, as when the finish of a run meets the starting point on a round, or at the side of the heated path when parallel runs are made. Several mechanisms can be used for head or work travel, such as tractor-type flame-cutting machines, lathes or boring mills for rotary motions, or special types such as gear-hardening machines. Figures 2, 7 and 8 illustrate the result of progressive hardening.

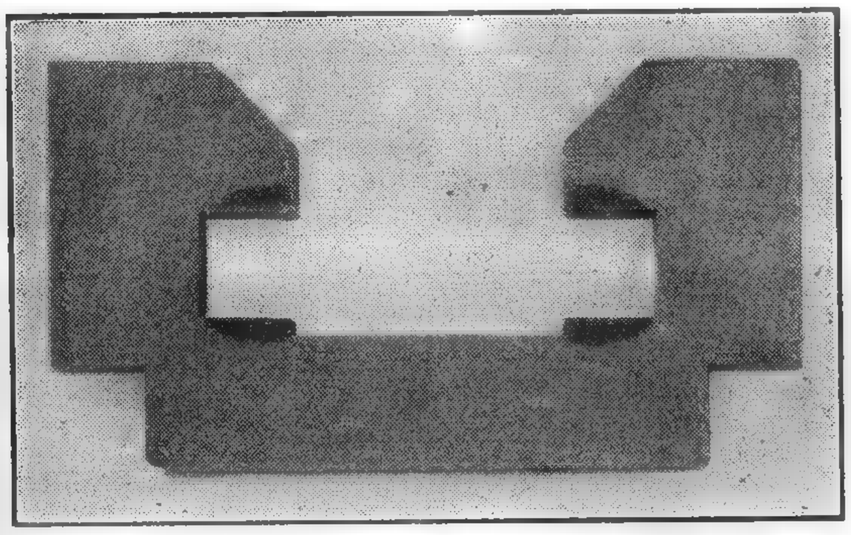

Fig. 7 T-bolt slot ½ in. wide, progressively hardened in two passes. Because of the narrow slot two heads were required. Bottom sides were hardened on the first pass, top sides on the second pass.

Spinning Method. The spinning method is used to harden areas on round sections, such as crankshaft bearings. The work piece spins in contact with flames from stationary heating heads. When the heating cycle ends, the quench is applied either by water spray or by immersion in a quench bath if the piece can be dropped from the chuck. Gears with 4DP teeth and smaller can be hardened by this method. Areas 7 in. wide on rounds 7½ in. in diam have been hardened by spinning. Parts hardened by this method are shown in Fig. 9 and 10.

Progressive Spinning. Round pieces of considerable length can be hardened by heating with a ring of heating flames followed by a ring of quench sprays. The cylindrical piece is revolved on its axis while the heating heads and quench move axially along the piece. The work piece is best placed vertically and revolved at a speed as high as is practical (at least 60 revolutions per inch of travel of the heating head), if the dimensions and balance of the article will permit. The higher revolving speeds produce the most homogeneous case. The diameters being hardened currently by this method vary from ¾ to 19 in. Internal surfaces such as mud-pump liners are also treated.

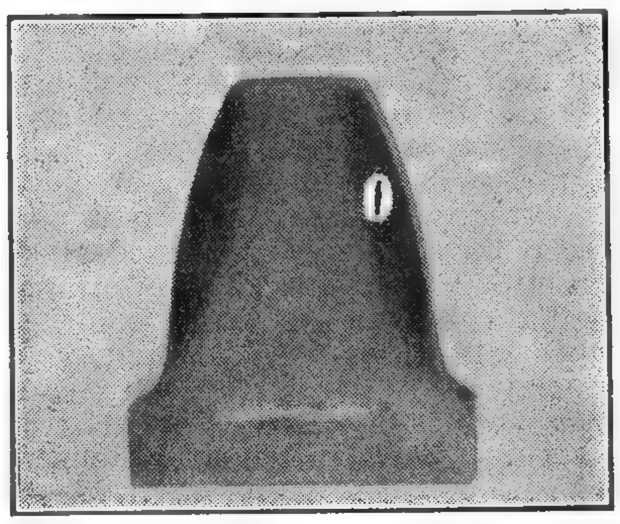

Fig. 8 Gear tooth progressively hardened with quenched SAE 1045 steel.

Equipment. Where production is limited and the areas to be flame hardened are small, the heating and quenching operations can be done by hand. A spot can be heated by a heating blowpipe with a single tip, held in the hand. When the temperature is raised sufficiently, heating is stopped and a stream of quenching medium is directed on the spot. Progressive flame hardening can be done by this simple method. The quench-spray tube is usually attached to the heating tip and the flame and spray are advanced over the path to be hardened. Hand operation is to be avoided if possible; a mechanized procedure is not influenced by the personal factor.

Heating Heads and Blowpipes. Most flame hardening applications involve areas that cannot be covered by a single flame. Multiflame heating heads are used, of the screw-in tip type or the drilled-face type. Both types are

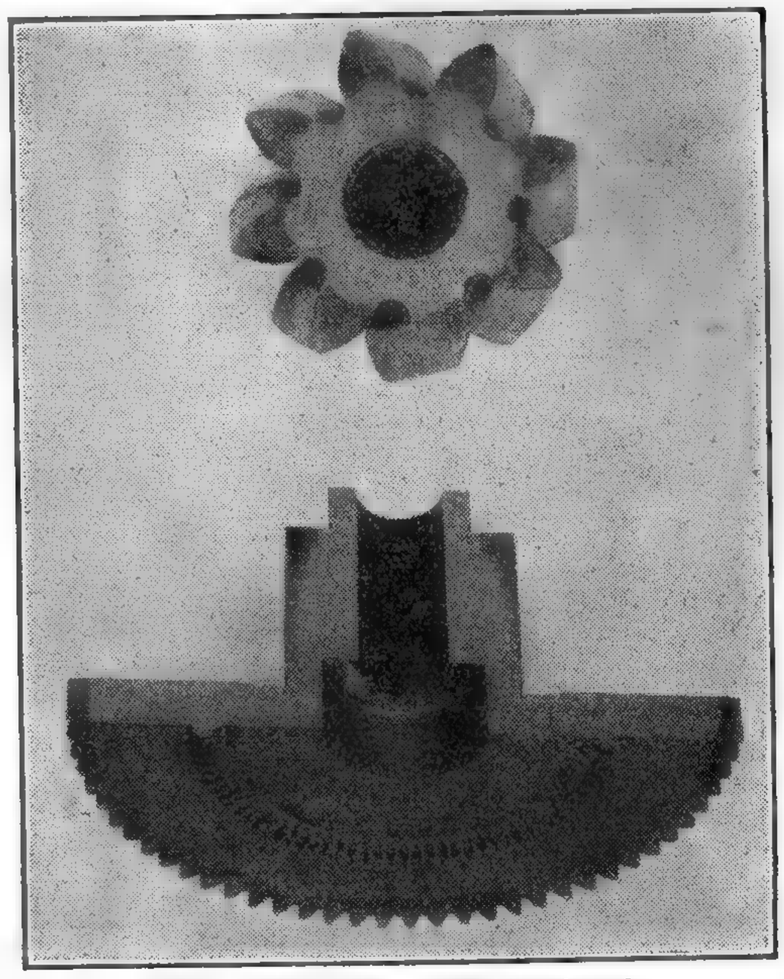

Fig. 9 Small gears, spin hardened.

available in standard sizes. To vary the coverage, tips are removed and plugs inserted. Heads with drilled faces are usually designed for specific applications and often the quench-spray holes are drilled in the same head. Water cooling of the heads is essential since operating conditions result in high temperatures.

The fuel gases are supplied to the heating heads by means of blowpipes designed to mix the fuel gas and oxygen properly and provide resistance to flashback. Blowpipes may have water-cooled connections to the heads.

Quenching Equipment and Mediums. *Equipment.* The design of quenching equipment is influenced by the type of heating head used and the type of steel to be hardened. Progressive operations must have full quench coverage over the heated band. This type of quench is designed to spray the quenching medium on the work ¾ to 1¼ in. behind the last row of flames when hardening 1045 steel. The spray should issue from the head at a 20-deg angle away from the flames. More sensitive steels will require a greater spacing between the flames and the quench. The principle involved is to obtain the maximum hardness without danger of cracking the steel. It should be remembered that the mass of steel underneath the heated layer aids the quenching action by withdrawing heat.

When a spray quench is used for the spinning method of flame hardening, the quench blocks should be in normal position while the heating cycle takes place. As soon as the flames are extinguished, the quench is turned on. The quench blocks should cover the heated band and provide enough quenching liquid to obtain full hardness. There should be enough quench points around the periphery to envelop the area completely with the quenchant. When the nature of the work piece is such that it can be removed easily from the heating position, dropping the part into a quench bath is sometimes advisable. This quench bath may be of any suitable composition.

Quenching Mediums. Water is the preferable quenching medium for all spray quenches. The use of oil in any form is to be strictly avoided in the vicinity of heating equipment that uses oxygen. If the quench blocks are designed for a maximum rate of cooling, variation in the rate can be obtained by reducing the water pressure supplying the quench. Increasing the distance between the last row of flames and the point where the quench impinges will allow the mass of metal to extract heat and further slow down the quench.

Compressed air passed through a quench block will further slow down the quenching rate and is useful in some applications. A quench in still air can be used with some types of air-hardening steels to provide a case that is shock resistant and particularly suited to gear teeth.

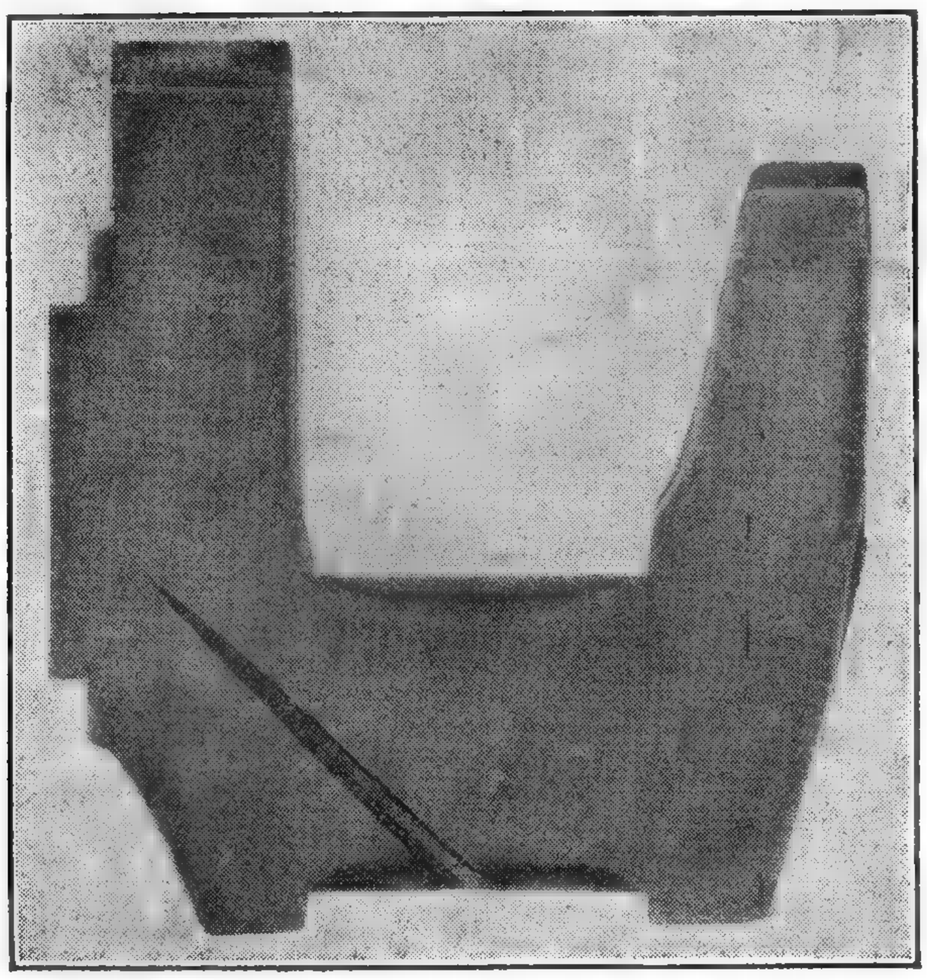

Fig. 10 Automotive crankshaft, spin hardened SAE 1045 steel.

Immersion quenches can vary in type in relation to the hardness desired and the type of steel used. The mediums usually are water, water and soluble oil, or oil.

Tempering. Flame hardened steel will respond to a tempering treatment as it would if hardened to the same degree by any other method. Standard procedures, mediums and temperatures can be used. However, since the flame hardening process can be applied to articles of considerable size, it is often difficult to find tempering equipment that has sufficient capacity.

Large articles are usually hardened by the progressive method and can be tempered at the same time by the simultaneous flame hardening and tempering process. This process consists of hardening progressively with a heating head and quench, and simultaneously reheating the hardened surface with a heating head spaced a short distance behind the quench. The reheating or tempering head must be designed correctly in regard to number and size of flame ports to produce the desired temperature in the flame hardened case at the flame hardening speed. Exact and final adjustment can be made by varying the flow of gas through the head. This simultaneous hardening and tempering process finds its greatest value in treating the larger articles, but it can be applied economically to smaller pieces as well.

Controls. Manufacturers of heating heads and blowpipes can furnish valves and regulators for the control of gas pressures and flows. Manual operation of valves is satisfactory for many applications, but where timing must be precise or production large, devices can be used for the control of cycles. Such controls are best applied to the spinning method. Progressive or progressive spinning methods require motivating equipment to move the heads over the work at a constant speed. Gases are usually turned on and off manually in these operations.

Machines. Progressive flame hardening usually requires a constant relation between the speed of the heating head and that of the work. Cutting machines are very suitable, since they have good regulation of speed and a wide range of speed. The larger sizes can carry considerable equipment without overloading. Machines for cutting shapes can be used to follow paths that are not straight, as is necessary for die hardening. A lathe can be used if the cross slide travel is adequate.

Progressive spinning requires special machines that will hold and turn the round in a vertical position. A platform is necessary that is movable at proper speeds to carry the heating heads and quench. The size can vary.

Lathes or special machines can be used for spinning operations. Production spot or pattern hardening is best done by machines built for the purpose. These machines usually consist of a rotating table carrying the work piece. The table is loaded at one point and the pieces are carried successively under the heating and quenching positions, or the piece may be kicked off into a quenching bath.

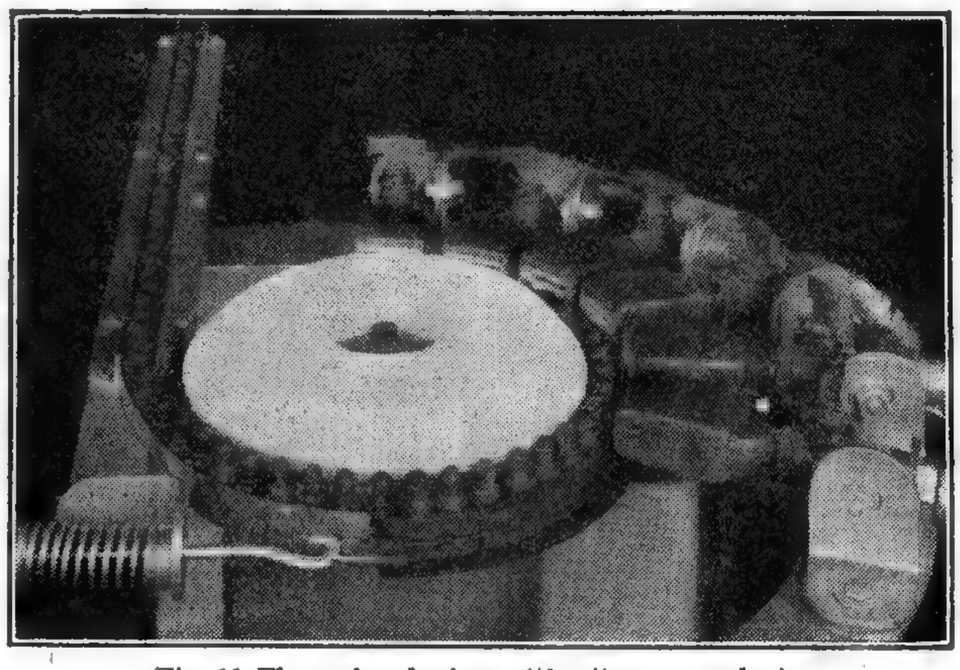

Fig. 11 Flame hardening with city gas and air.

Gear hardening can be done by hardening each tooth individually with special heating heads operating in pairs and heating and quenching both sides of the tooth simultaneously. The heads can be moved along the tooth by one of the cutting machines mentioned above. However, gears with 4DP teeth or smaller can be heated and quenched by the spinning method. One of the commercial gear-hardening machines will harden gears progressively without quenching when an air-hardening steel is used. Another gear-hardening machine will harden gears up to 12 in. in diam by the spinning method. Quenching is obtained by the immersion method.

Fuel Gases. Acetylene is the fuel gas most widely used for flame hardening. Mixing with oxygen at nearly a one to one ratio gives a neutral flame of high temperature, about 5630 F. Other fuel gases can be used for certain applications, provided equipment is designed for their use. The fuel gases can be mixed with oxygen or with air to produce flames of varying temperatures.

One combustion system in use today employs petroleum and natural or manufactured gas mixed with air and burned in special burners for flame hardening. One type of burner transmits heat to the work by means of convection and radiation; another type burns the fuel in a combustion chamber and issues the hot products of combustion (at approximately 3000 F) through a blast opening onto the work. The comparatively low-temperature burners supply a soaking heat that is advantageous for some spot hardening and spin hardening operations. Full hardness of the steel can be obtained by a suitable quench. The process can be used to spin harden gears of considerable diameter and to spot harden parts such as rocker arms for automotive engine valves, push-rod ends for airplane engine valves and ball peen hammers. Figure 11 shows a machine for hardening ball ends for push rods in airplane engines. Fuel gas costs for this process are negligible.

Gas Consumption and Speeds. Gas consumption for flame hardening will vary with the thickness of the case obtained. For example, when acetylene and oxygen are being used, thin cases about ⅛ in. thick will require about 0.14 cu ft each of acetylene and oxygen per sq in. Cases ½ in. thick will require 0.4 cu ft of each gas. For intermediate case thicknesses, the gas consumption is approximately proportional to the thickness of the case. Case thickness is the total zone affected by heat, as revealed by an ammonium persulfate or other suitable etch.

The speed of travel of the flame hardening head over the work material, or the time of heating for the spot or spinning method will vary with the thickness of case desired and the rate of gas combustion in the heads. The proximity of the quench spray to the last row of flames will affect the speed somewhat in the progressive method. Progressive and progressive spinning speeds can vary between 2 and 10 in. per min for most applications. The time required for the spot or spin method can vary from 10 sec for a thin case on small pieces to 1½ min for a ½-in. case on a rail end. The normal time for average operations is 30 to 40 sec.

Precautions. The flame hardening process is basically simple, but like all heat treating operations, certain variables are encountered. Speed of travel or time of heating should be held constant for uniform results. In the progressive method, the flames gradually heat the work piece in front of the heating head, and sometimes this effect must be compensated for by gradually increasing the speed of travel or by precooling. Pressures of fuel gas and oxygen should be controlled closely for uniform input of heat. Overheating of the surface should be avoided, since this condition accounts for most cracking problems. For precise work, it is advisable to examine test pieces metallurgically, altering speed, time or heat input for desired results.

Because flame hardening treats the surface of the steel, this surface and material underneath to the depth of heat treatment should be in the proper condition to respond to the operation. Decarburized areas will not harden. The surfaces to be hardened must be clean and free from scale, since scale interferes with both heating and quenching. Pits, blowholes, seams and laps at or near the surface will cause uneven heating, melting, or cracking during quenching.

Pieces properly flame hardened will have no scale or pitting. The discoloration produced on the surface can be removed by using an alkaline oxide-remover.

Stress relieving at approximately 400 F is recommended for all flame hardened articles except when the piece is quenched in still air.

Hardening temperatures can be judged by competent operators, but to the inexperienced the heated metal will appear colder than it actually is, because of the light from the burning gases; the consequent tendency is to overheat. It is difficult to see any temperature color when cast iron is treated properly by the progressive method. Metallurgical examination is the best method for establishing operating conditions. Overheated spots may appear under individual flames but, with properly designed heating heads, this effect is minimized and not readily detectable by microscopic examination.

Flame Softening

By H. V. Inskeep*

OXYGEN is commonly used to sever steel. A stream of oxygen projected from a suitable cutting tip attached to a cutting blowpipe is a useful tool that will sever steel either in sheet or in forms of considerable thickness. Every severing tool, whether saw, grinder or milling cutter, affects the surface that it cuts. The oxygen stream likewise has its effect and leaves the cut surface characteristically different from the base metal.

The chemical reaction of oxygen and steel during flame cutting evolves a great amount of heat. This heat raises the temperature of the cut edge to the melting point on the surface and above the transformation temperature for a shallow depth. The depth of the zone that is heated above the transformation point depends on the speed of cutting, the thickness of the piece and the amount of preheat emitted by the flames of the cutting tip. If this zone is cooled rapidly, hardening results when the carbon content of the steel is sufficiently high. This hardness can result in the cracking of the cut edge.

Straight carbon steels containing 0.30% C or less, do not harden sufficiently to prevent the use of flame-cut pieces in structures or in subsequent fabrication where bending is involved. However, steels containing alloying elements and steels containing more than 0.30% C may harden sufficiently, when cut by flames, to prevent the use of flame-cut pieces for some purposes.

When undesirable hardening occurs along a cut edge, oxyacetylene flames, applied by suitable equipment, can be used either to prevent hardening or to temper an already hardened cut surface. The term "flame softening" is applied to this process.

Some steels, such as the high speed types, certain highly alloyed ferrous materials, and several of the tool steels, will crack during flame cutting or very soon after, especially if they are in the bloom, billet or slab form. Total preheating, in a furnace or otherwise, before cutting, will prevent cracking in these instances. Preheat temperatures may vary from 400 to 800 F; the higher temperatures are used for the more sensitive steels.

The point where flame cutting produces a hardened surface that will be detrimental subsequently has not been determined for all steels and all uses of the flame-cut parts. To complicate matters, there is no one standard that can be used to meet all requirements. For structural uses, the flame-cut edges should meet satisfactorily the tests prescribed for the parent metal. These tests require liberal ductility and other properties within specified limits. In other applications, machinability is the only desired property. Where the flame-cut piece is to be heat treated and the edges are not bent during handling operations, the edges must not crack or check either during cutting or during cooling after cutting. Where the question of hardness or lack of ductility is important, examination or tests of the cut surfaces should be made. When material for test specimens is being cut, the lowest atmospheric temperature at which cutting will be done and the size and thickness of the piece should be duplicated, since these conditions all influence the results.

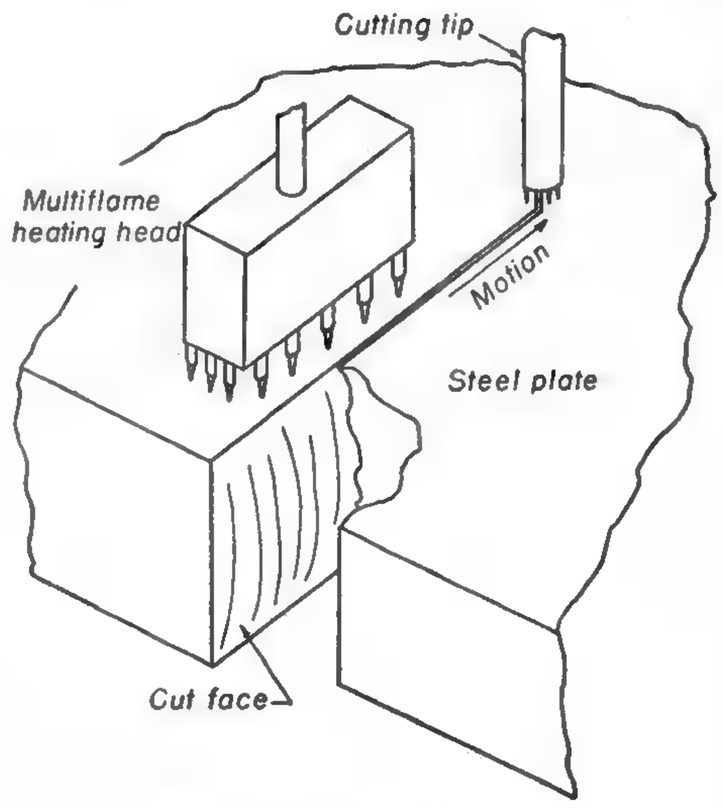

Fig. 1 Type I flame softening.

* The Linde Air Products Company, Newark, N. J.

Methods. Where excessive hardness or lack of ductility of a flame-cut surface indicates the need for softening, one of the following methods of flame softening may be used:

Type I. This type is used simultaneously with the cutting operation and the relationship of heating head and cutting tip is shown in Fig. 1. When the heating head is operated behind the cutting tip, the operation is known as "postheating". If the heating head operates in front of

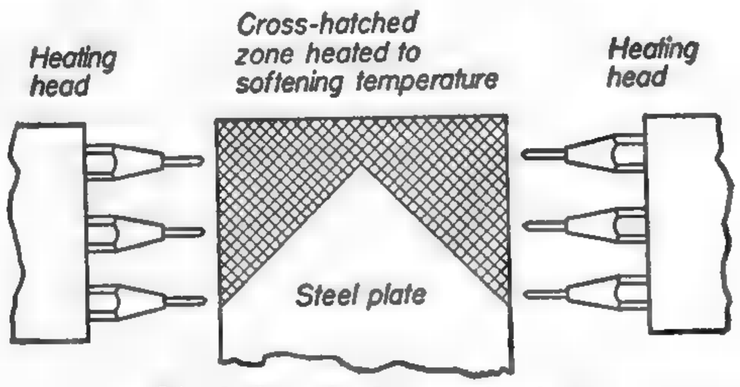

Fig. 2 Type II flame softening.

the cutting tip, the operation is called "preheating". The practical limit of plate thickness to which this type can be applied is 1½ in.

Type II. This type of flame softening is the same as type I except that heating heads are placed above and below the plate, as shown in Fig. 2. The plate can be preheated or postheated by this method. The practical limit of thickness is 3 in.

Type III. At times it is not possible or convenient to flame treat and flame cut simultaneously. When simultaneous treatment cannot be applied, the cut edge can be tempered by heating, as illustrated in Fig. 3. This tempering operation may be performed at any time after the cut has been made, providing the material does not crack during or after cutting. Cut surfaces 12 in. wide have been softened by this type of treatment, but even this thickness is not the limit, because heating heads can be made to cover even wider surfaces.

Choice of Methods. The choice of the flame softening method will depend on the type of steel being cut, thickness, economy, and whether or not it is expedient to cut and flame soften simultaneously.

There is a difference between the consumption of oxygen and acetylene in type I and that in type III. The consumptions are approximately 0.20 cu ft of each gas per sq in. of cut edge for type I treatment and approximately 0.06 cu ft of each gas per sq in. of cut edge for type III treatment. Type I treatment is accomplished simultaneously with cutting and there is almost no additional labor charge for softening. Type III treatment is separate from the cutting operation and requires a separate labor charge. The speed of travel for type III treatment, when using equipment that is available commercially, is 8½ in. per min along the cut edge. With these data, an approximate idea of the relative costs can be obtained.

To flame soften simultaneously with the cutting operation, results in considerable advantages when structural work is being done. Type I can easily be applied to any location on a plate where a cut is to be made. Type II is limited in scope to cutting applications where it is possible to carry the underside heating head on a bracket suspended

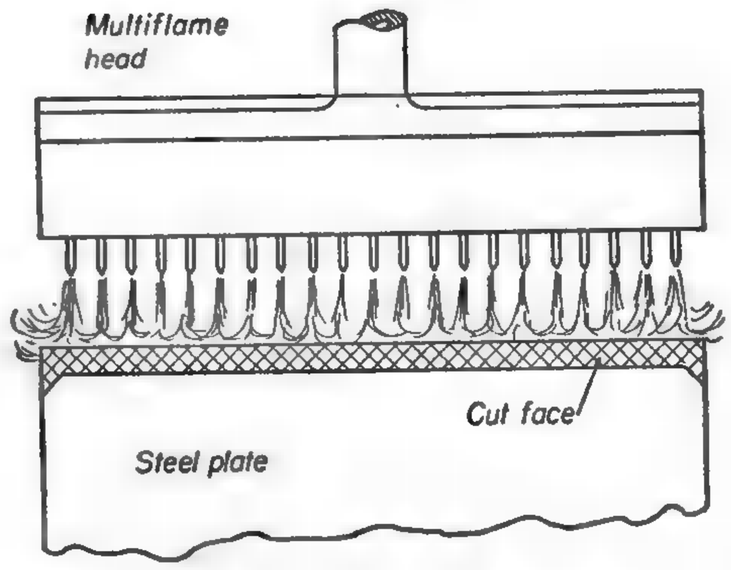

Fig. 3 Tempering the hardened zone on a cut face with a multiflame head that has a single row of flames.

from the main cutting machine. Care must be taken to see that the scrap from cutting does not drop on the equipment. Type III is used only after the cutting operation.

Temperatures. On straight carbon steels, the temperature of the surface during treatment is not critical except that it must be high enough to accomplish softening. Heating above the transformation range does not result in appreciable rehardening, since the cooling rate is slow. However, if an air-hardening steel is treated, care must be taken not to heat it above the transformation range. Overheating will reharden and underheating will not soften appreciably. Overheating of the plate surface under the heating heads must be avoided with air-hardening steels when type I and type II methods are used.

Effects of Flame Softening. Figure 4 shows the effect of flame cutting and softening on the hardness and ductility of the eight steels listed. Adequate softening has been obtained by the type I treatment.

Miscellaneous. Flame softening by means of a manually operated single or multiflame oxyacetylene blowpipe can be used in many ways. Spot softening can be done for machine work, such as cutting keyways, drilling holes, altering hardened dies, cutting threads and removing hard spots encountered in various machinmg operations on large castings. Temperature for hand operation is usually estimated visually. The softened surface can be tested by indenting with a small center-punch or chisel.

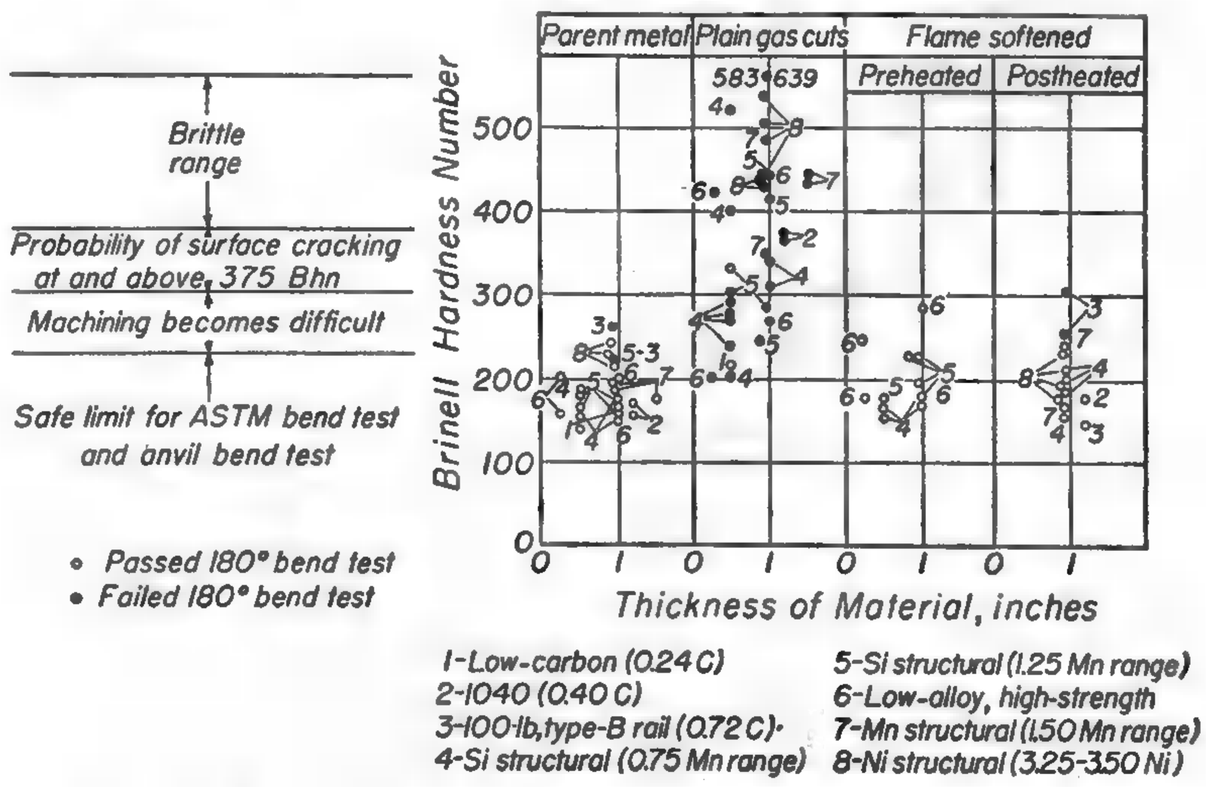

Fig. 4 Graphic presentation of data from hardness and bend tests performed on eight types of steels, flame cut and flame softened. Type I treatment (H. H. Moss, Iron Age, Dec 30, 1937 and Jan 20, 1938)

TOOL STEELS

Prepared by the

SUBCOMMITTEE ON TOOL STEEL

S. C. SPALDING, *Chairman*
The American Brass Company

W. L. BADGER
General Electric Company

A. D. BEEKEN
Vulcan Crucible Steel Company

J. P. BINDYKE
Heppenstall Company

G. E. BRUMBACH
The Carpenter Steel Company

W. R. FRAZER
Union Twist Drill Company

W. H. MACMILLAN
Remington Arms Company, Inc.

W. E. MAHIN
Armour Research Foundation

J. H. MCCADIE
National Twist Drill & Tool Company

J. E. MCCAMBRIDGE
U. S. Navy Yard, Philadelphia

H. E. REPLOGLE
Universal-Cyclops Steel Corporation

G. A. ROBERTS
Vanadium-Alloys Steel Company

R. SCHEMPP
Crucible Steel Company of America

A. G. SPENCER
Chevrolet-Flint Division of General Motors Corporation

W. H. WILLS
Allegheny Ludlum Steel Corporation

G. P. WITTEMAN
Bethlehem Steel Company

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The Forging and Heat Treating of Tool Steels

BY THE SUBCOMMITTEE ON TOOL STEEL

THE purpose of this article is to outline the general procedures for the forging and heat treating of tool steels. This outline is given to avoid repetition in articles which follow, concerning the composition and heat treatment of particular types of tool steels.

Even when correct equipment and temperature are used, many hardening failures result from improper manipulation during heat treatment. Failures may also occur as a result of improper design. Some of the factors involved in such failures are discussed in the article on page 243.

Forging. The object of forging is to change the shape or size, improve the physical properties, refine the structure or reduce the waste of material in machining.

Heating for Forging. The temperature ranges to be used are given on page 657. The heating should be done with a minimum of decarburization and at a rate that will insure complete penetration through the steel. This requires a good control of the atmosphere in good equipment. Some of the high-alloy compositions, such as the molybdenum high speed steels, require extra precautions; for example, coating the surface with borax or some other suitable protecting material. For highly alloyed tool steels, such as high speed and high-carbon high-chromium, the heating time is about twice that required for carbon tool steel. Overheating and excessive soaking at forging temperatures must be avoided.

Forging Operation. Forging should start with light blows which can be increased as the metal starts to flow.

When to increase the force of the blows and when to stop and reheat are decisions chiefly at the discretion of the operator. Care must be taken to keep the steel within the proper temperature range and to effect a sufficient reduction to insure proper grain refinement. The steel can be reheated as often as necessary to complete the forging, provided the above conditions are observed.

Cooling. Slow cooling in an inert insulating material, such as lime or mica, is recommended to prevent possible cracking from forging strains. This type of cooling is not always required for carbon steels but becomes increasingly important as the alloy content increases; for the air-hardening steels cooling of this type is essential. It is advisable to begin the normalizing or annealing treatment before the steel cools to atmospheric temperature, but not before it has cooled well below the transformation range.

Normalizing. Normalizing involves heating steel far enough above the transformation range to dissolve all excess constituents and then cooling the steel in air. This treatment results in a more uniform grain size and tends to break up nonuniform structures. Normalizing is more important on pieces that have been forged. It should not be necessary on steel that has been annealed by the manufacturer, unless it has been forged subsequently. Steels that tend to air harden, such as high speed steel, are generally not normalized.

Rate of Heating. Heating for normalizing should be done in a manner similar to that described under heating for hardening. Correct soaking time is proportional to the size of the piece. Prolonged soaking will coarsen the grain, rendering subsequent refinement difficult.

Rate of Cooling. The material is cooled from normalizing temperatures in still air.

Annealing. Tool steel is annealed to soften it for machining or further processing and to put it in condition for further heat treatment. If it is necessary to reharden a tool for any reason, the tool should be thoroughly annealed before rehardening.

Packing. Steel to be annealed should be placed in a sealed container to keep out furnace gases. When pieces are small, they should be packed in cast-iron chips, lime, mica or other neutral material to prevent scaling, decarburizing, and too rapid changing of temperature. Care must be taken to keep the steel from contact with the container and to avoid the presence of scale.

Heating. The steel should be heated slowly and uniformly to the temperature desired (*see* page 657).

Holding at Temperature. The steel should be held at the annealing temperature long enough for complete penetration of heat and transformation. The time will increase with the weight of the charge and the alloy content of the steel; generally 1 to 4 hr will be sufficient.

Cooling. The steel should be cooled slowly, preferably in the furnace, or in mica or other good heat-insulating material. In general, the slower the cooling, particularly through the transformation range, the softer the steel. The higher the alloy content, the more slowly the steel must be cooled. The cooling rate varies from 10 to 50°F per hr, depending on the composition of the steel and the structure desired.

Stress-Relief Annealing. This process, sometimes called subcritical annealing, is useful in removing residual stresses induced by heavy machine work or other cold working. As indicated, stress-relief annealing is usually carried out at temperatures below the transformation range (1000 to 1200 F). In many cases it is safely done without surface protection, but for some tools packing is necessary to prevent scaling and decarburization. Air cooling may be used safely. This treatment often aids in minimizing warpage as well as breakage during hardening.

Tools are usually stress relieved after machining and before hardening, but it is often desirable to rough machine, then stress relieve before finish machining.

Hardening. *Heating for Hardening.* The rate of heating for alloy tool steels should be slower than for plain carbon steels and should be slower, the higher the alloy content. In general, the slower and more uniform the heating, the less the warping or change in size or shape, provided other factors are unchanged.

Heating for hardening is most rapid in molten baths, somewhat slower in open or semimuffle fuel-heated furnaces, and slowest in electric or complete muffle-type furnaces.

To avoid sudden changes in temperature, large or intricate tools should be charged at low furnace temperature (below 1000 F). During heating, the tool should be manipulated so as to heat all parts at as nearly the same rate as possible. It is often advisable to support the tool on jigs or fixtures in order to reduce warpage and give better heat circulation. It is good practice to turn or move frequently pieces that have a tendency to heat unevenly. When practical, it is advisable to heat long slender sections while they are suspended vertically.

Large Sizes. A range of temperature is usually given in recommendations of heating for hardening. This does not imply that satisfactory results can be obtained on any tool if held anywhere within that range. Generally the larger pieces are heated to the high side of the range and the small pieces are heated to the low side.

Holding at Temperature. Care should be taken to hold the tool at temperature long enough to insure uniform heating throughout the section of the piece. As noted in the specific tool steel articles, certain steels of higher alloy content will require more time at temperature to obtain comparable solution of the carbides. Excessive time at temperature may cause some grain growth and surface decarburization, particularly at temperatures well above the transformation range.

Furnace Atmosphere. Proper control of furnace atmosphere is important and varies somewhat with the type of steel and the temperature used. Certain types of steel, such as the manganese oil-hardening grades, tend to have a soft skin on the surface after quenching. A slightly oxidizing atmosphere will prevent this condition. On the other hand, the best results for hardening high speed and high-carbon high-chromium steels are obtained in a reducing atmosphere with high CO and minimum CO_2. Neutral liquid baths also give good results.

Effect of Scale. If tool steel is heated above a dull red heat while in contact with scale, even though in a neutral or reducing atmosphere, it will decarburize. Therefore, care should be taken to keep steel, furnace hearth and containers as free from scale as possible.

Thermocouples. For specific instructions see the article "Pyrometry", page 174 in this Handbook.

Quenching Medium. The quenching medium employed depends on the speed of cooling necessary to harden the particular steel. Sufficient volume of coolant should be provided to maintain the quenching medium at proper temperature for uniform results. The use of air is not recommended for agitating and cooling liquid baths.

Brine. Tools quenched in brine (10% salt by weight) will throw their scale more readily, producing a cleaner surface of more uniform hardness. Brine is a more uniform and more drastic quench than water, when used in still or mildly agitated baths. On pieces having considerable mass or requiring definite flow directions, sprays or geysers are necessary. Brine should be maintained at a fairly constant temperature, ranging from 60 to 80 F.

Water. When water is used for quenching, it should be held at a fairly constant temperature (usually 60 to 80 F). Fresh water is often aerated and may produce soft spots; therefore, water that has been previously boiled or has been frequently used is recommended. Using sprays or geysers is a great help in obtaining the desired hardness, by eliminating gas pockets and washing away any scale that may be present. Tools quenched in water should be agitated so as to cool as quickly as possible through the transformation range, and should be removed from the bath while still warm (below 200 F).

Oil. Oils generally give best results when used between the temperatures of 100 and 150 F. Quenching in cold oil of improper fluidity should be avoided. Some oils deteriorate faster than others; consequently, they should be reconditioned as often as necessary. Oil baths should be checked frequently for the presence of water. For quenchings tools from a cyanide or other salt bath a straight mineral oil should be used because this kind of oil will not decompose under such conditions.

Air. Certain types of tool steels harden during air cool-

ing. Air cooling may be accomplished in three ways: (1) air blast, which is the discharge from a high-pressure line; (2) fan air, which is the current of air discharged from a fan; and (3) still air, which is atmospheric air undisturbed by artificial circulation. When any one of the three methods is used, the tool should be held or supported so as to allow as nearly uniform cooling as possible. In the use of an air blast, care must be taken to apply the blast through a properly designed device and to avoid the presence of water in the blast.

Special Quenching Mediums. Unusual conditions often require special quenching mediums; for example, a solution of 5 to 10% sodium hydroxide in water, which has a tendency to overcome soft spots and nonuniform hardening of carbon tool steels. Mixtures of water and glycerin will produce rates of cooling intermediate between those of oil and water. For oil-hardening steels the glycerin content is comparatively high (60 to 90% glycerin) whereas for water-hardening steels the glycerin content is low (10 to 40% glycerin).

Quenching. Tools should be quenched in such a manner that warping is at a minimum. When tools are immersed, the formation of gas pockets can be avoided by vigorous agitation of the piece or by the use of sprays or geysers. It is important to have the cooling medium come in contact with all parts of the work to be hardened. Usually tools should not be removed from the quenching bath until they are below 200 F or the point where water boils on them, nor should they become cold in the quench. A good time to remove the tool is when all the surface is approximately 125 to 150 F. Then, if a rather large mass is involved, the tool should be held at this temperature until it becomes uniform in temperature throughout. This may be accomplished by placing the tool in an oil bath for the required length of time, after which it may be transferred to the tempering furnace.

Tempering. After removal from the quenching bath and before tempering, tools are always in a highly and nonuniformly strained condition and danger of cracking is most pronounced. Tools should not become cold before tempering, but should not be too hot to be held in the bare hands. Satisfactory tempering results are obtained by heating slowly and uniformly in a freely circulating medium. If a liquid is used, the tools should be placed in a wire basket for immersion, thus preventing contact with the sides or bottom of the tempering pot. When charging tools for tempering, the heating medium should be at a low temperature and the tools still warm.

Rate of Heating. Tools should be brought to temperature slowly to prevent rapid release of hardening stresses and warpage. Better results are obtained by holding at a lower temperature for a longer time. Generally the length of time should not be less than one hour at temperature. For recommendations on specific steels, reference should be made to the other articles on tool steel in this Handbook. Repeated tempering at the same temperature is usually more effective than one long tempering operation.

Rate of heat transfer will vary in different heating mediums. It is most rapid in metallic baths, less rapid in salt and oil baths and slowest in still-air furnaces.

Cooling from Tempering. Cooling from the tempering operation should be in still air because rapid cooling may induce strains in the steel.

Tempering by Color. Temper colors are the result of slight oxidation of the surface of steel when heated at low temperatures, and depend on time, temperature and composition of the steel. They indicate only the temperature of the surface and do not indicate that the steel has been heated uniformly throughout. Tempering by color is not conducive to uniformity. When necessity requires that tools be tempered by color, they should be heated slowly as in other operations and the temperature should be raised progressively to the point or color desired, after which further tempering is usually prevented by quenching or withdrawing from the heating medium. The quenching should be done preferably in oil.

Interrupted Quenching. High speed and other highly alloyed steels frequently are given an "interrupted" quench. consisting of cooling in oil to about 1000 to 1200 F, removing from the oil and cooling in still air to a temperature at which the steel can be handled with bare hands. A molten salt or lead bath, operating at 1000 to 1200 F, can be used instead of oil. The part is held in the bath a sufficient time to allow the steel to reach bath temperature, after which it is cooled in oil or air.

If the temperature of the steel, when removed from the quenching medium, is just above the temperature at which martensite begins to form during cooling (400 to 600 F), the method is called "martempering". Martempering generally aids in minimizing distortion and cracking in irregularly shaped parts of medium- or high-alloy steels. The cooling rates obtainable in the molten bath for martempering restrict this quenching method to steels that can be hardened in oil or air with conventional quenching.

Some tools, especially those made from oil-hardening steels, can be quenched into the low-temperature bath and allowed to transform isothermally. This method (austempering), as applied to oil-hardening steels, is limited to section sizes smaller than about 1 in. and tools which do not require a hardness greater than Rockwell C 60.

General Notes. *Salt Baths.* The salt bath method of hardening tools—particularly high speed steel tools—has greatly expanded with the increased use of molybdenum steels. This method is especially useful in hardening tools that cannot be ground after hardening. With good operating conditions tools can be produced free from decarburization and scale. The surface will be fully hard with very little distortion. For additional information, see the article "Salt Baths", page 283 in this Handbook.

Nitride Case. A nitride case will often give greater tool life and can be applied to any type of high speed steel. Such a case is produced by heating the finished tool in a cyanide bath at 1050 F for 15 min to 2 hr. The time at temperature depends on the depth of case desired. The usual time is about 30 min.

Cold Treatment. The purpose of cold treatment is to complete the transformation from austenite to martensite. The usual practice is to cool the steel to at least minus 90 F after quenching and before tempering, and to hold long enough to insure complete penetration.

Warping. The amount of warping during hardening depends on the shape of the tool, the kind of steel, the conditions of heating and the severity of the quench. In general, water-hardening steels warp more than oil-hardening, whereas air-hardening steels show the least distortion. Long thin tools warp more than short heavy ones.

Causes of excessive warpage include poor tool design, the use of the wrong type of steel, nonuniform or too rapid heating, improper support of the steel while heating, heavy machining, or cold working strains (*see* Stress-Relief Annealing under Annealing), insufficient removal of surface, nonuniform quenching and nonuniform or too rapid tempering.

Soft Spots. Common causes of soft spots are: decarburization; improper heating, quenching or bath agitation; gas pockets; tong contact; adhering scale; insufficient removal of surface; or defective furnace bottoms.

Straightening. When it is necessary to straighten a tool, the operation is best performed during cooling (on the "descending heat"). Straightening is done by peening, or bending in a vise or on a suitable press with an adjustable control and knife-edge rests, so that if one load does not satisfactorily straighten the tool, another load can be applied immediately. For straightening during cooling, the tools should be withdrawn from the quenching bath at a temperature from 500 to 600 F, which is just below the point where the oil ceases to flash, or for water-quenched tools, just where the water steams or dries off the tools immediately. Straightening may be continued to just above the M_s point (about 400 F for most grades). Air-hardening steels may be straightened at any time while cooling from the quenching temperature, preferably before they reach 400 F.

Classification and Approximate Compositions of Principal Types of Tool Steels

BY THE SUBCOMMITTEE ON TOOL STEEL

The purpose of this table is to give the reader a condensed list of the principal steels used by industry in each group. It should be understood that other steels have been found satisfactory for the specific applications covered in the chart, but they are not used generally. Except for the carbon tool steels, the quantity of each element present is given as a nominal percentage. This is done to simplify the chart and indicate the type of steel only. These figures cannot be used as a specification. In some instances optional (†) elements are listed. This means that these steels have found satisfactory application either with or without the element present, and generally no change of treatment is required.

The numerical designations employed in this table (IA, IIB2, VC3, etc.) are used to identify the same steels in the articles on heat treatment of tool steels in this Handbook (pages 660 to 676).

	C	Mn	Si	Cr	V	W	Mo	Co	Ni
I Carbon Tool Steels									
A Straight-Carbon	0.60–1.40	0.25	0.25	....	....	....	....	....	....
B Carbon-Chromium	0.60–1.40	0.25	0.25	0.20–0.75	....	....	....	....	....
C Carbon-Vanadium	0.60–1.40	0.25	0.25	....	0.20–0.50	....	....	....	....
II "Nondeforming" Tool Steels									
A Oil-Hardening Low-Alloy									
1. Low-Manganese	0.90	1.20	0.25	0.50	0.20†	0.50	....	....	....
2. High-Manganese	0.90	1.60	0.25	0.35†	0.20†	....	0.30†	....	....
3. Tungsten	1.20	0.25	0.25	0.50	0.25	1.75	0.25†	....	....
B Air-Hardening Low-Alloy									
1. Manganese	0.90	2.50	0.30	1.50	....	....	1.00	....	....
2. Chromium	1.00	0.50	0.25	5.00	0.50†	....	1.00	....	....
C Oil-Hardening High-Alloy									
1. High-Carbon High-Chromium	2.15	0.35	0.35	12.00	1.00†	1.00†	....	....	0.50†
D Air-Hardening High-Alloy									
1. 1.00 Carbon, High-Chromium	1.00	0.35	0.35	12.00	0.50†	....	0.80	....	1.00†
2. 1.50 Carbon, High-Chromium	1.50	0.35	0.35	12.00	0.50†	....	0.80	3.50†	....
3. 2.15 Carbon, High-Chromium	2.15	0.35	0.35	12.00	0.50†	....	0.80	....	....
III Shock-Resisting Tool Steels									
A Chromium-Vanadium	0.50	0.60	0.25	1.00	0.20	....	....	....	....
B Low-Silicon, Manganese	0.55	0.40	1.00	....	0.25†	....	0.50	....	....
C High-Silicon, Manganese	0.55	0.80	2.00	0.30†	0.25†	....	0.40†	....	....
D Tungsten	0.55	0.25	0.25	1.25	0.25†	2.50	0.50†	....	....
E Tungsten-Silicon	0.55	0.25	1.00	1.25	0.25†	2.50	0.50†	....	....
IV Hot Work Tool Steels									
A Chromium									
1. 0.65 Carbon	0.65	0.30	0.30	4.00	0.75	....	0.50	....	....
2. 0.90 Carbon	0.90	0.30	0.30	4.00	0.75†	....	0.50†	....	....
B Chromium-Molybdenum	0.35	0.30	1.00	5.00	0.40†	1.25†	1.50	....	....
C 5 Chromium, 5 Tungsten	0.40	0.30	1.00	5.00	0.40†	5.00	....	....	....
D 7.5 Chromium, 7.5 Tungsten	0.45	0.60	1.50	7.50	0.40†	7.50	....	....	....
E Molybdenum									
1. Low	0.40	0.25	0.50	3.75	0.75	1.00	5.75	....	....
2. High	0.60	0.25	0.25	3.75	1.10	1.50	8.50	....	....
F Tungsten									
1. 9%	0.30	0.25	0.25	3.50	0.50†	9.00	....	....	....
2. 12%	0.40	0.25	0.25	2.50	0.50	12.00	....	....	....
3. 15%	0.40	0.25	0.25	3.00	0.50	15.00	3.00†	....	2.00†
4. 18%	0.50	0.25	0.25	4.00	1.00	18.00	....	....	....
V High Speed Tool Steels									
A Molybdenum									
1. Molybdenum-Vanadium	0.85	0.30	0.25	4.00	2.00	....	8.00	....	....
2. Molybdenum, Low-Tungsten, 1 Vanadium	0.80	0.30	0.25	4.00	1.00	1.50	8.50	....	....
3. Molybdenum, High-Tungsten, 2 Vanadium	0.85	0.30	0.25	4.00	2.00	6.25	5.00	....	....
4. Molybdenum, High-Tungsten, 4 Vanadium	1.20	0.30	0.25	4.00	4.00	6.00	4.50	....	....
B Molybdenum-Cobalt									
1. Molybdenum, Low-Tungsten, 5 Cobalt	0.85	0.30	0.25	4.00	1.00	1.50	8.50	5.00	....
2. Molybdenum, Low-Tungsten, 8 Cobalt	0.85	0.30	0.25	4.00	2.00	1.50	8.50	8.00	....
3. Molybdenum, High-Tungsten, 5 Cobalt	0.85	0.30	0.25	4.00	2.00	6.25	5.00	5.00	....
4. Molybdenum, High-Tungsten, 8 Cobalt	0.85	0.30	0.25	4.00	2.00	6.25	5.00	8.00	....
C Tungsten									
1. 18 Tungsten, 1 Vanadium	0.70	0.30	0.25	4.00	1.00	18.00	....	....	....
2. 18 Tungsten, 2 Vanadium	0.85	0.30	0.25	4.00	2.00	18.00	0.75	....	....
3. 18 Tungsten, 3 Vanadium	1.00	0.30	0.25	4.00	3.00	18.00	....	....	....
D Tungsten-Cobalt									
1. 14 Tungsten, 2 Vanadium, 5 Cobalt	0.80	0.30	0.25	4.00	2.00	14.00	0.75	5.00	....
2. 18 Tungsten, 1 Vanadium, 5 Cobalt	0.75	0.30	0.25	4.00	1.00	18.00	0.75	5.00	....
3. 18 Tungsten, 2 Vanadium, 9 Cobalt	0.80	0.30	0.25	4.00	2.00	18.00	0.75	9.00	....
4. 20 Tungsten, 2 Vanadium, 12 Cobalt	0.80	0.30	0.25	4.00	2.00	20.00	0.75	12.00	....
VI Miscellaneous Tool Steels									
A Die Iron	0.05	0.10	0.03	....	....	....	....	....	....
B Low-Chromium, Nickel	0.10	0.45	0.25	0.60	....	....	....	....	1.25
C High-Chromium, Nickel	0.12	0.45	0.25	1.50	....	....	....	....	3.50
D High-Chromium	0.35	0.35	0.20	12.00	....	....	....	....	....
E Nickel-Chromium	0.75	0.60	0.20	1.00	0.10†	....	....	....	1.75
F Nickel-Chromium-Molybdenum									
1. 0.70 Carbon, 0.30 Molybdenum	0.70	0.70	0.20	0.80	0.10†	....	0.30	....	1.60
2. 0.50 Carbon, 0.30 Molybdenum	0.50	0.65	0.25	1.00	0.10†	....	0.30	....	1.60
3. 0.55 Carbon, 0.75 Molybdenum	0.55	0.60	0.85	1.00	0.10†	....	0.75	....	2.00
G Chromium-Molybdenum	0.55	0.80	0.25	1.00	0.10	....	0.45	....	....
H Chromium-Manganese	1.25	0.60	0.20	0.50	....	....	....	....	....
I Chromium-Manganese-Molybdenum	1.25	0.85	0.20	0.50	....	....	0.50	....	....
J Chromium	1.00	0.30	0.20	1.40	0.20†	....	0.30†	....	....
K Finishing	1.35	0.25	0.20	0.75†	....	3.50	....	....	....

† Optional element. Steels have found satisfactory application either with or without the element present.

Forging, Normalizing and Annealing Treatments for Principal Types of Tool Steels

BY THE SUBCOMMITTEE ON TOOL STEEL

Steel[a]	Forging[b]			Normalizing[c]		Annealing[d]		
	Heat Slowly to	Start Forging at	Do Not Forge below	Heat Slowly to	Hold at	Temperature, deg Fahr	Rate of Cooling	Approximate Hardness, Brinell
	Temperature, deg Fahr			Temperature, deg Fahr				
IA	1450	1800–2000	1500	1450	1450–1800	1360–1450	Slowly in Furnace	159–197
IB	1450	depending	1500	1450	depending	depending	Slowly in Furnace	159–197
IC	1450	on carbon content[e]	1500	1450	on carbon content[e]	on carbon content[e]	Slowly in Furnace	159–197
IIA1	1500	1800–1950	1550	1500	1600	1400–1450	50°F max per hr	183–212
IIA2	1500	1800–1900	1550	1500	1550	1375–1425	50°F max per hr	183–212
IIA3	1500	1800–2000	1600	1500	1650	1450–1500	50°F max per hr	192–217
IIB1	1600	1850–2000	1650	Do Not Normalize		1360–1400	25°F max per hr	207–241
IIB2	1600	1850–2000	1650	Do Not Normalize		1550–1600	40°F max per hr	201–229
IIC1	1650	1800–2000	1650	Do Not Normalize		1600–1650	50°F max per hr	212–235
IID1	1650	1800–2000	1650	Do Not Normalize		1600–1650	50°F max per hr	207–229
IID2	1650	1800–2000	1650	Do Not Normalize		1600–1650	50°F max per hr	207–229
IID3	1650	1800–2000	1650	Do Not Normalize		1600–1650	50°F max per hr	217–241
IIIA	1500	1900–2100	1550	1500	1600	1400–1450	Slowly in Furnace	152–179
IIIB	1500	1900–2100	1600	1500	1600	1400–1450	Slowly in Furnace	192–217
IIIC	1500	1900–2100	1600	1500	1600	1400–1450	Slowly in Furnace	192–229
IIID	1500	1900–2100	1600	Do Not Normalize		1450–1500	Slowly in Furnace	183–207
IIIE	1500	1900–2100	1600	Do Not Normalize		1450–1500	Slowly in Furnace	207–229
IVA1	1600	1800–2000	1650	Do Not Normalize		1475–1525	50°F max per hr	187–217
IVA2	1600	1800–2000	1650	Do Not Normalize		1475–1525	50°F max per hr	187–217
IVB	1650	1950–2150	1650	Do Not Normalize		1550–1600	50°F max per hr	197–229
IVC	1650	1950–2150	1700	Do Not Normalize		1600–1650	50°F max per hr	207–235
IVD	1650	1950–2150	1700	Do Not Normalize		1600–1650	50°F max per hr	212–241
IVE1	1550	1900–2100	1650	Do Not Normalize		1550–1600	50°F max per hr	207–229
IVE2	1550	1900–2100	1650	Do Not Normalize		1600–1650	50°F max per hr	212–235
IVF1	1600	2000–2200	1650	Do Not Normalize		1600–1650	50°F max per hr	207–235
IVF2	1600	2000–2200	1650	Do Not Normalize		1600–1650	50°F max per hr	207–235
IVF3	1650	2000–2200	1700	Do Not Normalize		1600–1650	50°F max per hr	217–241
IVF4	1650	2000–2200	1750	Do Not Normalize		1600–1650	50°F max per hr	217–241
VA1	1500	1900–2100	1700	Do Not Normalize		1500–1600	50°F max per hr	207–235
VA2	1500	1900–2100	1700	Do Not Normalize		1500–1600	50°F max per hr	207–235
VA3	1500	1950–2150	1700	Do Not Normalize		1600–1650	50°F max per hr	217–241
VA4	1500	2000–2150	1700	Do Not Normalize		1600–1650	50°F max per hr	223–248
VB1	1500	1950–2150	1750	Do Not Normalize		1600–1650	50°F max per hr	235–269
VB2	1500	1950–2150	1750	Do Not Normalize		1600–1650	50°F max per hr	235–269
VB3	1500	1950–2150	1750	Do Not Normalize		1600–1650	50°F max per hr	235–269
VB4	1500	1950–2150	1750	Do Not Normalize		1600–1650	50°F max per hr	235–269
VC1	1600	1950–2200	1750	Do Not Normalize		1600–1650	50°F max per hr	217–248
VC2	1600	2000–2200	1750	Do Not Normalize		1600–1650	50°F max per hr	223–255
VC3	1600	2000–2250	1750	Do Not Normalize		1600–1650	50°F max per hr	228–255
VD1	1600	2000–2200	1750	Do Not Normalize		1600–1650	50°F max per hr	228–255
VD2	1600	2000–2200	1750	Do Not Normalize		1600–1650	50°F max per hr	228–255
VD3	1600	2000–2200	1800	Do Not Normalize		1600–1650	50°F max per hr	235–262
VD4	1600	2000–2200	1800	Do Not Normalize		1600–1650	50°F max per hr	248–293
VIA	....	2200–2350	1900	Not Required		1350–1600	Slowly in Furnace	81–100
VIB	....	1900–2200	1550	Not Required		1350–1500	Slowly in Furnace	109–137
VIC	....	1900–2100	1550	Not Required		1350–1500	Slowly in Furnace	131–170
VID	1600	1950–2150	1600	Do Not Normalize		1550–1600	Slowly in Furnace	170–207
VIE	1500	1900–2100	1550	1500	1600	1400–1450	Slowly in Furnace	183–212
VIF1	1500	1900–2100	1550	1500	1600	1400–1450	Slowly in Furnace	183–212
VIF2	1500	1900–2100	1550	1500	1600	1400–1450	Slowly in Furnace	179–207
VIF3	1500	1900–2100	1550	1500	1600	1400–1450	Slowly in Furnace	183–212
VIG	1500	1900–2100	1550	1500	1650	1425–1475	Slowly in Furnace	183–212
VIH	1500	1800–2000	1550	1500	1650	1425–1475	50°F max per hr	174–201
VII	1500	1800–2000	1550	1500	1650	1450–1500	50°F max per hr	174–201
VIJ	1500	1800–2000	1550	1550	1650	1450–1500	50°F max per hr	174–201
VIK	1550	1800–2000	1650	1550	1650	1450–1500	50°F max per hr	207–235

(a) These numbers are the ones used in the table of principal types of tool steels on page 656.

(b) The temperature at which to start forging is given as a range, the higher side of which should be used for large sections and heavy or rapid reductions, and the lower side for smaller sections and lighter reductions. As the alloy content of the steel increases, the time of soaking at forging temperature increases proportionately. Likewise, as the alloy content increases, it becomes more necessary to cool slowly from the forging temperature. With very high-alloy steels, such as high speed steels and air-hardening steels, this slow cooling is imperative in order to prevent cracking and to leave the steel in a semisoft condition. Either furnace cooling or burying in an insulating medium such as lime, mica, or silocel, is satisfactory.

(c) The length of time the steel is held, after being uniformly heated through at the normalizing temperature, varies from about 15 minutes for a small section to about one hour for large sizes. Cooling from the normalizing temperature is done in still air. The purpose of normalizing after forging is to refine the grain structure and to produce a uniform structure throughout the forging. Normalizing should not be confused with low-temperature (about 1200 F) annealing used for the relief of residual stresses resulting from heavy machining, bending and forming.

(d) The annealing temperature is given as a range, the upper limit of which should be used for large sections and the lower limit for smaller sections. The length of time the steel is held, after being uniformly heated through at the annealing temperature, varies from about one hour for light sections and small furnace charges of carbon or low-alloy tool steel, to about four hours for heavy sections and large furnace charges of high-alloy steel.

(e) Forging, normalizing and annealing temperatures of carbon tool steels are given as ranges because they vary with carbon content. The following temperatures are recommended:

Forging
0.60 to 1.25% C: the range given
1.25 to 1.40% C: the low side of the range

Normalizing
0.60 to 0.75% C: 1500 F
0.75 to 0.90% C: 1450 F
0.90 to 1.10% C: 1600 F
1.10 to 1.40% C: 1600 to 1800 F
For explanation, see Fig. 2, page 661.

Annealing
0.60 to 0.90% C: 1360 to 1400 F
0.90 to 1.40% C: 1400 to 1450 F

The Selection of Tool Steels

BY THE SUBCOMMITTEE ON TOOL STEEL

SIMPLIFICATION of the problems connected with the selection of tool steels has long been an aim of both producers and consumers. However, it is difficult to establish a workable yet simple set of rules which will serve as a solution to this problem. If it is to be complete, a tabulation of tools in common use and of recommended steels must be highly detailed and must include a large number of different tool steels for each application. As a result, such a tabulation loses much of its practical significance for the user. This article, therefore, will be restricted to a discussion of the general principles involved in selection and will include a tabulation of the metallurgical characteristics of the principal tool steel types, as an aid in selection. A correlation of these metallurgical characteristics with the requirements of the tool in operation should form the basis of a sound approach to the selection of a steel for any application.

Practical experience indicates that in the majority of instances the choice is not limited to a single type of tool steel or even to a particular family of tool steels for a workable solution to an individual tooling problem. Because it is desirable to select the steel that will give the most economical over-all performance, the tool life obtained with each steel under consideration should be judged by weighing such factors as expected productivity, ease of fabrication, and cost.

The majority of tool steel applications can be divided into a small number of groups or types of operations: cutting, shearing, forming, drawing, extrusion, rolling and battering. Cutting tools include drills, taps, broaches, hobs, lathe tools and the like. Shearing tools include shears, blanking and trimming dies, punches and such. Forming tools include forging dies, cold heading dies, die-casting dies. Battering tools include chisels and all forms of tools involving heavy shock. Many of these classifications can be further divided into cold working and hot working tools.

For each of these groups certain metallurgical characteristics are of utmost importance. Cutting tools must possess high hardness, high resistance to the softening effect of heat, and high wear resistance. Shearing tools require high wear resistance combined with fair toughness, and these characteristics must be properly balanced, depending on the tool design, thickness of the stock being sheared, and temperature of the shearing operation. Forming tools must possess high toughness and high strength and many require maximum resistance to heat softening. In battering tools high toughness is most important.

Hardness, strength, toughness, wear resistance and resistance to heat softening are, therefore, prime selective factors for tool steel applications. Many other properties must be seriously considered in individual applications; these include permissible distortion in hardening, permissible surface decarburization, hardenability or depth of hardness desired, resistance to heat checking, machinability and grindability, as well as heat treating requirements, including temperatures, atmospheres and equipment.

Table I is presented as an aid in the relative evaluation of these properties for the tool steels listed in the classification table on page 656 and discussed in the various articles on tool steel in this Handbook. The various tool steels have been combined into logical groups where possible, and the following properties have been rated as Good, Fair, or Poor: nondeforming properties, safety in hardening, toughness, resistance to softening effect of heat, wear resistance, machinability, and resistance to decarburization. Depth of hardening is rated as Shallow, Medium or Deep.

An attempt has been made to rate *all the steels in the table relative to one another,* rather than to rate them within any one particular class. All high speed steels have therefore been rated Poor in toughness, despite the fact that small differences exist in this property among the high speed steel types in question. These differences may be important when selecting a particular high speed steel for a cutting application. Similarly, the majority of the hot work steels have been rated as Good in resistance to the softening effect of heat; whereas significant differences exist in the "hot hardness" and "hot strength" of these types, requiring careful study when a steel must be selected for hot die work.

"Nondeforming" Properties. The first column in Table I rates the tool steels on the basis of the distortion normally obtained in hardening the respective grades from the normally recommended hardening temperatures. Unless otherwise specified, the quenching medium is the one that is standard for the grade. The steels of Class III and Steel VIJ are quenched either in oil or in water and a rating has been given for each type of quenching medium. This property is important in intricately designed tools which must maintain their shape after hardening. The steels rated Good or Best in this column can be machined very close to size prior to heat treatment so that little grinding will be required after the hardening operation. In general, water-hardening steels exhibit the most distortion and air-hardening steels exhibit the least. It is important to note, however, that carbon tool steels and other shallow-hardening types distort very little in heat treatment when the hardened case is small in comparison with the unhardened core for any particular tool or die design.

Safety in Hardening. The second column in Table I deals with the over-all freedom from heat treating difficulties which may be experienced in handling the tool steel grades in question. The ratings apply particularly to freedom from cracking when complicated or intricate sections are being hardened. It will be noted that the air- and oil-hardening steels prove superior to the water-hardening steels in this respect.

Toughness. The term "toughness", when applied to tool steels, is subject to several interpretations. In general, high-carbon steels will be found to have lower toughness than low-carbon steels. This is reflected in the good ratings given in the third column in Table I to the medium- and low-carbon tool steels of Classes III and IV. Carbon tool steels and other shallow-hardening steels which harden with a case and a core may, however, be rated Good in toughness, since the high compressive stresses existing at the surface enable them to withstand high tensile loads and repeated impact without early failure, regardless of the carbon content. The hardness of the tool itself will also have a considerable bearing on the toughness of the steel. The ratings given in Table I are based on use of the tool steels at their regular working hardness. In tool steels the concept of toughness is best expressed as the ability to resist breaking, rather than the ability to deform plastically before breaking, since most tools must be rigid articles which do not deform in service. Generally, slight plastic deformation renders these steels unfit for use.

Resistance to Softening Effect of Heat. This property, also called "hot hardness" or "red hardness", and reflected to some extent in the resistance of the material to tempering, is an important selective factor, especially for tools used for hot work. As the alloy content of the steel increases, especially in those alloying elements which form hard, stable carbides, the resistance to softening at elevated temperatures is improved. In the hot working tool steels of Class IV, rated Good to Very Good in Table I, the resistance to softening increases as the tungsten, chromium, molybdenum and vanadium contents increase. High speed steels have the best rating in this column.

Wear Resistance. Wear resistance, a property difficult to measure, increases as the carbon and alloy contents increase. A fair correlation can be made between the wear resistance of steels and their content of hard, undissolved carbide particles; other factors being equal, wear resistance is greatest in steels that have the most carbide particles. The hardness of the steels likewise affects the wear resistance markedly; the steels in Table I have been compared according to their behavior after hardening to the normal working hardness.

Machinability. The machinability ratings given are qualitative and are intended to show the relative difficulty

Table I. Approximate Comparison of Principal Types of Tool Steels on the Basis of Some Metallurgical Characteristics

Steel[a]	"Nondeforming" Properties[b]	Safety in Hardening[b]	Toughness	Resistance to Softening Effect of Heat	Wear Resistance	Machinability	Quenching Medium	Hardening Temperature Range[c] deg Fahr	Depth of Hardening	Resistance to Decarburization[d]
IA, B & C	Poor	Fair	Good[e]	Poor	Fair to Good	Best	Water	1400–1650	Shallow	Best
IIA	Very Good	Very Good	Fair	Poor	Good	Good	Oil	1400–1625	Medium	Good
IIB	Best	Best	Fair	Fair	Very Good	Fair	Air	1450–1800	Deep	Good to Fair
IIC	Very Good	Good	Poor	Fair	Best	Poor	Oil	1700–1825	Deep	Fair
IID	Best	Best	Poor[f]	Fair	Best	Poor	Air	1750–1900	Deep	Fair
IIIA	W Poor O Fair	W Poor O Good	Very Good	Poor	Fair	Good	Water Oil	1500–1550 1600–1700	Medium	Good
IIIB & C	W Poor O Fair	W Poor O Good	Best	Fair	Fair	Fair	Water Oil	1550–1650 1600–1700	Medium	Poor
IIID & E	Fair	Good	Very Good	Fair	Fair	Fair	Oil	1650–1800	Medium	Fair to Good
IVA, B, C & D	Good	Good	Good	Good	Fair	Fair	Air	1650–2150	Deep	Fair
IVE	Good	Good	Good	Good	Fair	Fair	Air, Oil	1950–2250	Deep	Poor
IVF	Good	Good	Good to Fair	Good to Very Good	Fair to Good	Fair	Air, Oil	1850–2350	Deep	Fair
VA	Good	Fair	Poor	Very Good	Very Good	Fair	Oil, Air, Molten Salt	2125–2275	Deep	Poor
VB	Good	Fair	Poor	Best	Very Good	Fair	Oil, Air, Molten Salt	2125–2275	Deep	Poor
VC	Good	Good	Poor	Very Good	Very Good	Fair	Oil, Air, Molten Salt	2150–2375	Deep	Good
VD	Good	Fair	Poor	Best	Very Good	Fair	Oil, Air, Molten Salt	2250–2400	Deep	Poor
VIA	Fair	Fair	Good	Poor	Good	Poor	Water	Carburize 1450–1550	Shallow	Best
VIB	Fair	Fair	Good	Poor	Good	Fair	Water	Carburize 1450–1550	Shallow	Good
VIC	Good	Good	Good	Poor	Good	Fair	Oil	Carburize 1400–1550	Shallow	Good
VID	Good	Good	Very Good	Fair	Fair	Poor	Oil	1750–1900	Medium	Fair
VIE, F & G	Good	Good	Very Good	Fair	Fair	Fair	Oil	1500–1700	Medium	Fair
VIH & I	Fair	Good	Fair	Poor	Good	Good	Oil	1450–1525	Shallow	Good
VIJ	W Poor O Fair	W Poor O Good	Fair	Poor	Good	Good	Oil Water	1500–1600 1475–1550	Medium	Good
VIK	Poor	Poor	Poor	Poor	Very Good	Fair	Water	1475–1550	Shallow	Good

(a) These numbers are the ones used in the table of principal types of tool steels on page 656.

(b) See the article on "Composition and Heat Treatment of Nondeforming Tool Steels" (page 661). The letter "W" means "when quenched in water"; the letter "O", "when quenched in oil".

(c) The purpose of this column is to show the broad ranges of temperature employed in hardening. This information may serve to indicate the heat treating equipment required; it is not to be used as a specification. For more exact data on the hardening temperatures used for each type of steel, see the individual articles which follow in this Handbook (pages 660 to 676).

(d) Some steels decarburize much more than others on heating. This is important in many applications and has an influence on the type of heat treating equipment to be selected. This column is intended to show relative resistance to decarburization.

(e) Toughness decreases with increasing carbon content and depth of hardening.

(f) The lower carbon grades may be rated as Fair.

which might be experienced in machining the steels in question, during the manufacture of tools or dies. In addition to the hardness in the annealed condition, two factors affect the machinability of tool steels: (1) the quantity of hard excess carbides, which add wear resistance to the steels and decrease the life of the tools used to cut them, and (2) the microstructure of the steel itself, which is known to have a marked effect on certain machining operations. Low-carbon irons and stainless irons are very difficult to machine, presumably because of the preponderance of a soft ductile phase. Fine surface finish is difficult to achieve on tool steels of this nature.

Hardening Temperature Range. The hardening temperature ranges listed in Table I are necessarily very broad in most instances because of grouping several types of tool steels into one classification. For more accurate information on recommended hardening treatments the reader is referred to the individual articles covering the particular type of steel in question. The selection of tool steels may be influenced to some extent by the hardening temperature range, since this range must lie within the possibilities of the furnace equipment available. Resistance to decarburization, last column of Table I, will naturally be considered with the hardening temperature range.

Depth of Hardening. This column relates to the depth of hardening or hardenability of the individual tool steels. The hardenability ratings are given on the basis of the use of the particular quenching medium recommended in the previous column. Carbon tool steels in Class I and several of the carburizing grades in Class VI, as well as the tungsten finishing steel (Type VIK), are very shallow-hardening steels. These steels are generally quenched in water. The hardenability increases in tool steels as the alloy content increases, and for large tool or die sections it is imperative that a high-alloy steel be selected if high strength is to be developed throughout the section in the finished part.

Resistance to Decarburization. A study of this column is important in the selection of tool steels, since it influences the type of heat treating equipment to be selected, as well as the amount of material which should be removed from the surface after hardening. Both of these factors are important since they concern the economies of tool steel use. The ratings are intended to apply at the hardening temperature normally recommended. Those steels which are rated Poor must be protected in some way from decarburization during the heating cycle.

The Composition and Heat Treatment of Carbon Tool Steels

By the Subcommittee on Tool Steel

THIS article covers the processes to be followed in heat treating carbon tool steel for general purposes. For information regarding the heat treatment of specific types of tools, reference should be made to the articles in this Handbook on the particular tools in question.

Composition and Application. Carbon tool steel hardens with a hard case and tough core, except in small sizes. Sections smaller than about ½ in. will harden all the way through. Sections about $\frac{3}{32}$ in. will harden well in oil from 1500 F. (Hardenability testing of tool steels is discussed on page 412 of this Handbook.) For material such as drill rod and ground flat stock, oil quenching is often used to minimize distortion and secure greater safety in hardening.

By variation of the carbon content, a wide range of physical properties can be obtained. Increasing the carbon content increases hardenability, up to about 0.85% C. As the carbon content increases beyond 0.85%, its effect is to decrease hardenability. This is an important consideration in applications involving shock, such as cold header dies or tools operating under heavy pressure. A case that is too shallow may fail by sinking.

Types containing 0.20 to 0.75% Cr and others containing 0.20 to 0.50% V, while not carbon steels strictly speaking, are usually classed with the carbon tool steels.

Chromium in the range from 0.20 to 0.75% serves two functions. All other factors being equal, chromium-bearing carbon steels have greater depth of case and slightly more wear resistance than chromium-free steels of the same carbon content.

The addition of vanadium to carbon steels will decrease the depth of case and slightly increase toughness as compared with vanadium-free steels of the same carbon content; and will allow a wider hardening range with a wider range of case depths obtainable, and with little effect on grain size.

After a standardized heat treatment, case depth can be varied in steels of approximately the same composition, by variations in melting practice and prior treatment. This fact should not be confused with the influence of carbon content and of alloy additions, such as chromium and vanadium.

Table I. Approximate Chemical Compositions of Carbon Tool Steels[a]

Steel No.[b]	C	Mn	Si	Cr	V
IA	0.60 to 1.40	0.25	0.25	....	....
IB	0.60 to 1.40	0.25	0.25	0.20 to 0.75	....
IC	0.60 to 1.40	0.25	0.25	....	0.20 to 0.50

(a) The compositions given are type compositions only. Actual analyses of the steels they represent will vary a reasonable amount from these averages. It should be remembered that the more the composition of any steel varies from these averages, the more the treatment may differ from that recommended.

(b) These numbers are the ones used in the table of principle types of tool steels on page 656.

Lower carbon ranges are used for tools where toughness and resistance to shock are of primary importance; the higher carbon ranges are used where the main requirements are hardness, resistance to abrasion, or ability to hold a keen edge.

Thus, factors such as carbon content, alloy additions, melting practice and prior treatment have made available a class of steels with predetermined physical properties for a wide range of applications. Generally carbon steels are the easiest tool steels to machine and form. Frequently these steels are the only types that will serve successfully for specialized applications.

The type compositions are given in Table I. The ranges for the carbon content and a few of the more common applications for the steels listed are as follows:

Carbon Content, 0.60 to 0.75%. Hot forming or heading dies for short runs, machinery parts, hammers (sledges and pinch bars), concrete-breakers and rivet sets.

Carbon Content, 0.75 to 0.90%. Hot and cold sets, chisels, dies, shear blades, mining drill steel, smiths' tools, set hammers, swages and flatteners.

Carbon Content, 0.90 to 1.10%. Hand chisels, small shear blades, large taps, granite drill steel, trimming dies, drills, cutters, slotting and milling tools, mill picks, circular cutters, threading dies, cold header dies, jewelers' cold striking dies, blanking, forming and drawing dies and punches.

Carbon Content, 1.10 to 1.40%. Small cutters, small taps, drills, reamers, slotting and planing tools, wood-cutting tools, turning tools and razors.

Forging, Normalizing and Annealing. See table, page 657, and the article on page 653 of this Handbook.

Hardening. The steel should be heated uniformly to the temperature given in Table II and should be quenched in brine or water, preferably in a brine solution of 10% by weight, held at a temperature of 70 to 80 F. The tool should be removed from the bath while still warm, but not before it has cooled below 200 F.

The temperatures given in Table II are average for most tools. Small or intricate sections should be quenched from the lower side of the range. A fully hardened carbon steel

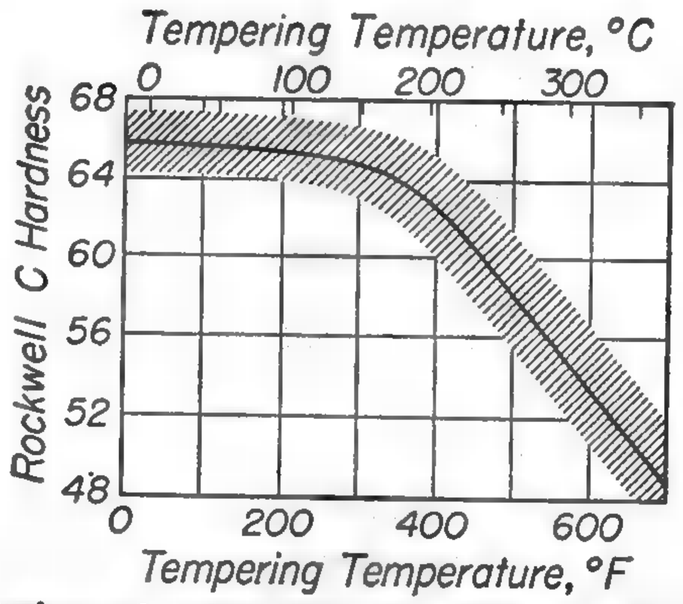

Fig. 1 Hardness of carbon tool steel containing 0.90% C or more, after quenching from the recommended temperature and tempering at 100 to 700 F

tool of 0.90% C or higher will have a Rockwell C hardness of 64 to 67, as shown in Fig. 1.

Tempering. After the steel has been quenched and allowed to cool below 150 F, it should be reheated to the tempering temperature, held for at least one hour, and then cooled in still air. The hardness resulting from tempering at these temperatures is shown in Fig. 1.

Suitable Tempering Temperatures for Various Tools. 300 to 375 F. Lathe tools and milling cutters for brass and copper alloys, scraper and cutting tools for soft metals, drawing mandrels and dies, bone-cutting tools, steel-engraving tools, gages, cutting tools for iron and steel, and threading dies for brass.

375 to 500 F. Hand taps and dies, hand reamers, drills, bits, cutting dies, penknives, milling cutters, chasers, inserted sawteeth, press dies for blanking and forming, rock

Table II. Hardening and Tempering Treatments for Carbon Tool Steels

Steel No.	Carbon, per cent	Rate of Heating for Hardening	Hardening Temperature, deg Fahr	Quenching Medium	Tempering Temperature, deg Fahr
IA, IB, IC	0.60 to 0.80	Slowly	1450 to 1550	Brine or water	300 to 650
IA, IB, IC	0.85 to 1.05	Slowly	1425 to 1550	Brine or water	300 to 650
IA, IB, IC	1.10 to 1.40	Slowly	1400 to 1525	Brine or water	300 to 650

drills, taps and dies, dental and surgical instruments, twist drills, hammer faces, wood-carving tools, forming dies, shear blades, reamers and hacksaws.

500 to 650 F. Bending dies, shear blades, chuck jaws, forging dies, drifts, tools for wood cutting, hammers and drop dies, axes, cold chisels, coppersmith tools, screwdrivers, molding and planing tools, hacksaws, butcher knives and saws.

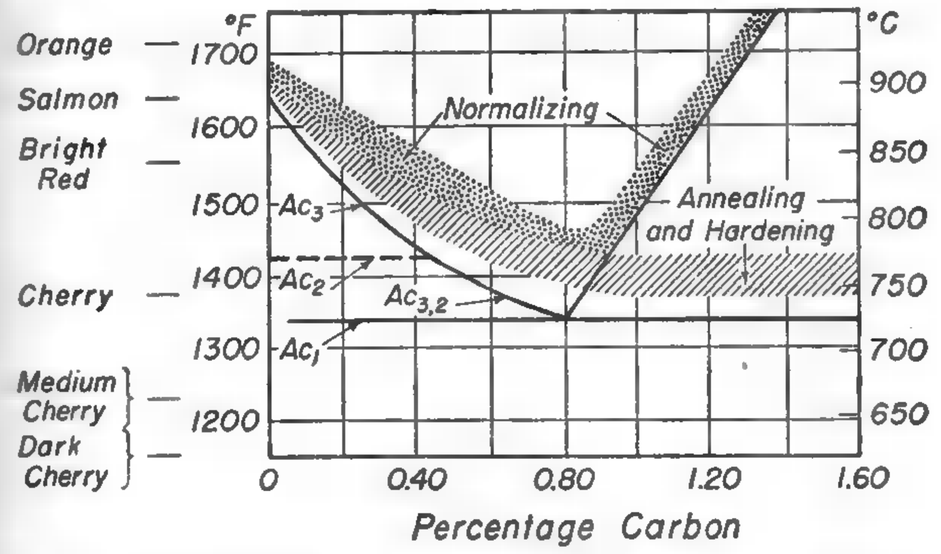

Fig. 2 Transformation temperature range for iron-carbon alloys, showing normalizing, annealing and hardening ranges

Notes About the Process. *Normalizing.* A normalizing treatment after forging and before annealing is recommended for all carbon tool steels to obtain a uniform and refined grain structure.

The proper normalizing ranges are shown in Fig. 2. Heating to temperatures much above the lowest which will give all austenite is conducive to austenitic grain growth and intergranular weakness.

A low normalizing temperature for high-carbon steels (1.25 to 1.50% C) fails to break up massive cementite and results in a brittle structure. The solubility of carbon in austenite increases with increasing temperature.

Quenching. The quenching temperatures given are average for most tools. Small or intricate sections should be quenched from the lower side of the range. However, some classes of tools, such as cold heading and cold striking dies, require higher temperatures.

The quenching temperature influences the hardness, hardenability and final grain size. Since these factors have marked effects upon the physical properties, uniformity of tool life cannot be obtained if the quenching temperature is not closely controlled. Since absolute uniformity of heating cannot be obtained, the best practice is to use temperatures about 50 to 75 F above Ac_1 (Fig. 2).

Brine or water is the usual quenching medium for carbon tool steels. For details concerning quenching, see the articles on pages 615 and 620.

Microstructure. The microstructure of the annealed steel should consist of carbide particles of a uniform and small size in a background of ferrite. Pearlite may be present in amounts less than 25%. The microstructure should be free from large carbide particles in network form. When tools are forged and subsequently normalized and annealed, full consideration should be given to producing the proper microstructure.

The Composition and Heat Treatment of "Nondeforming" Tool Steels

BY THE SUBCOMMITTEE ON TOOL STEEL

THIS article covers the heat treatment of the "nondeforming" types of tool steels, including the manganese oil-hardening, the tungsten oil-hardening, the chromium air-hardening, the manganese air-hardening, and the high-carbon high-chromium steels shown in Table I.

The word "nondeforming" is enclosed in quotation marks because no tool steel is absolutely nondeforming; during hardening, all steels change more or less in size and shape. The steels given in Table I deform less than other types of tool steel.

Application. These "nondeforming" steels are used for tools and dies having a design that prohibits the use of water-hardening steels because of the hazard of distortion or cracking during hardening. The oil-hardening steels (IIA and IIC) usually hold their dimensions less closely than the air-hardening steels (IIB and IID).

All the steels of this group are rather deep hardening and are often selected, where deep hardening offers an advantage, instead of carbon steels or other steels having shallow-hardening characteristics. In fully hardened small sections, these steels give approximately Rockwell C 63 to 65, but as the size of the section increases, the hardness decreases. This is particularly noticeable in steels of Group IIA.

The wear resistance of these "nondeforming" steels is roughly proportional to the amount of carbide present, and therefore is a function of both the carbon content and the alloy content. On this basis, steels IIC1 and IID3 have the greatest wear resistance, and steels IIA1, IIA2 the least. The chromium air-hardening steel IIB2 has wear resistance midway between the manganese oil-hardening grades (IIA1 and IIA2) and the high-carbon high-chromium steels, but at high hardness levels, chromium air-hardening steel has greater toughness than either of the others.

Selection among steels of the high-chromium type is generally on a basis of toughness, wear resistance and machinability. The 1.50% C type and the 1.00% C type are tougher and more readily machinable, but the 2.15% C type has better properties of wear resistance.

The steels in these groups, particularly the high-carbon high-chromium and the air-hardening steels, are well suited for tools, such as blanking, forming and trimming

Table I. Approximate Chemical Compositions of "Nondeforming" Tool Steels[a]

Steel No.[b]	C	Mn	Si	Cr	V	W	Mo	Co	Ni
IIA1	0.90	1.20	0.25	0.50	0.20 opt	0.50	....	....	....
IIA2	0.90	1.60	0.25	0.35 opt	0.20 opt	....	0.30 opt	....	....
IIA3	1.20	0.25	0.25	0.50	0.25	1.75	0.25 opt	....	....
IIB1	0.90	2.50	0.30	1.50	....	....	1.00	....	....
IIB2	1.00	0.50	0.25	5.00	0.50 opt	....	1.00	....	....
IIC1	2.15	0.35	0.35	12.00	1.00 opt	1.00 opt	....	....	0.50 opt
IID1	1.00	0.35	0.35	12.00	0.50 opt	....	0.80	....	1.00 opt
IID2	1.50	0.35	0.35	12.00	0.50 opt	....	0.80	3.50 opt	....
IID3	2.15	0.35	0.35	12.00	0.50 opt	....	0.80	....	....

(a) The compositions given are type compositions only. Actual analyses of the steels they represent will vary a reasonable amount from these averages. It should be remembered that the more the composition of any steel varies from these averages, the more the treatment may differ from that recommended.

"Opt" indicates that the element so marked is optional in the composition. Steels have been found satisfactory either with or without the element present.

(b) These numbers are the ones used in the table of principal types of tool steels on page 656.

dies, deep-drawing dies, wire-drawing dies, plug gages, burnishing broaches, thread-rolling dies, woodworking knives, shear blades and lathe centers.

Forging, Normalizing and Annealing. *See* table on page 657 and the article on page 653 of this Handbook.

Hardening. In order to hold distortion to a minimum and to secure maximum and uniform hardness, it is advisable to preheat slowly and uniformly to the temperatures indicated in Table II. This is recommended especially for the high-carbon high-chromium steels (IIC and IID) and for the chromium air-hardening steel IIB2, since the absorption of heat and the solution rate of the carbides are slower in these materials than in lower-alloy tool steels.

After being held at the preheating temperature for complete uniformity, the steel should be transferred to the hardening temperature shown in Table II. The actual temperature selected will depend on the mass, as will the holding time at this temperature prior to quenching. Steel IIA2 should be quenched as soon as uniformity has been obtained, while steels IIA1 and IIA3 may be held at temperature for ½ hr if desired. In steels IIA1 and IIA3 maximum hardness will result after soaking for up to ½ hr, but no soak should be given if minimum distortion is of greater importance. The holding time for the 5.00% or 12.00% Cr steels and the air-hardening manganese steel should be approximately twice as long as for carbon tool steel of similar size, but must be balanced against possible danger of decarburization.

The manganese oil-hardening, manganese air-hardening and tungsten oil-hardening grades are not particularly susceptible to decarburization and may be handled like carbon tool steels in hardening. Slightly oxidizing atmospheres are satisfactory. Salt baths or controlled-atmosphere furnaces are desirable but not necessary. The high-carbon high-chromium steels, however, partly because of the relatively high temperatures required for hardening, tend to decarburize and should be heated in a protective manner, by using salt baths, controlled-atmosphere furnaces or pack-hardening methods. This also applies to the 5.00% Cr air-hardening steel, IIB2; although with a somewhat lessened susceptibility to decarburization, small sections of this steel may be treated in semimuffle-type furnaces using a slight excess of fuel to air. When these chromium steels are to be pack-hardened, spent pitch coke is recommended, especially where edge strength is desired. Charcoal, which carburizes at the temperatures recommended, may be used where parts are required only to resist wear.

Attention should be called to the fact that large quantities of austenite may be retained after the high-carbon high-chromium steels or the 5.00% Cr air-hardening steel have been quenched from temperatures above those recommended in Table II. Low hardness (Fig. 1) may result, and in exceptional instances the steels are essentially nonmagnetic. Austenite retained in this way may produce secondary hardness since it transforms in subsequent tempering at about 1000 F. The high quenching temperature and the accompanying coarsened austenitic grain size may be of value in dies which must resist heat or in tools and dies which are to be nitrided after hardening. High-carbon high-chromium steels are readily nitrided either by the ammonia gas process or by tempering at 1000 F in cyanide bath mixtures.

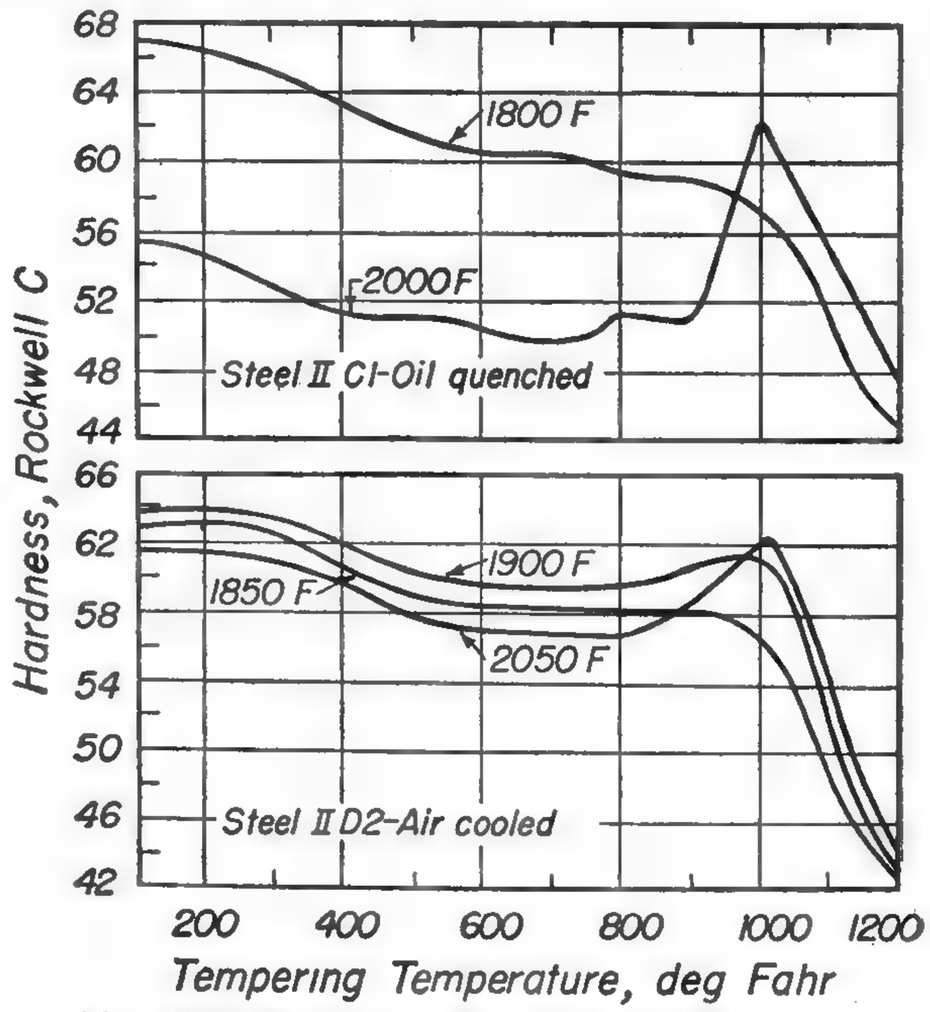

Fig. 1 Hardness and tempering curves for high-carbon high-chromium steels.

Tempering. These steels should be reheated slowly to the desired tempering temperature in order to prevent cracking. Tempering of the high-carbon high-chromium steels below 350 F is rarely advisable on account of the lack of toughness that results. Because of the possible large variation in composition from the averages shown in Table I, the user should consult published information on the particular steel in question, for determining the relation between hardness and tempering temperature.

Notes About the Process. For the oil-hardening steels listed, it is important to avoid heating the quenching oil to a temperature approaching the flash point, during prolonged and continuous quenching. The best oil temperature is generally 100 to 150 F. The ratio of bath volume to mass of steel is an important factor.

The edges and corners of any piece of steel harden more readily than large flat areas because of the difference in the rate of heat extraction. This is particularly noticeable with large flat sections of the IIA steels of Table I. In order to crack off the scale and harden the broad flat surface properly, it is advisable to force plenty of oil against this surface, ordinarily by means of a pump under good pressure, and to use the higher side of the hardening range.

Table II. Hardening and Tempering Treatments for "Nondeforming" Tool Steels

Steel No.	Preheat Temperature, deg Fahr	Rate of Heating for Hardening	Hardening Temperature, deg Fahr	Time at Temperature, minutes	Quenching Medium	Tempering Temperature, deg Fahr
IIA1	1200	Slowly	1450 to 1500	30[a]	Oil	325 to 500
IIA2	1200	Slowly	1400 to 1475	Do not soak	Oil	325 to 500
IIA3	1200	Slowly	1575 to 1625	30[a]	Oil	350 to 550
IIB1	1250	Slowly	1450 to 1600	15 to 30	Air	300 to 500
IIB2	1450	Slowly	1700 to 1800	15 to 30	Air	350 to 1000[b]
IIC1	1500	Very Slowly	1750 to 1825	15 to 45	Oil	350 to 1000[b]
IID1	1500	Very Slowly	1775 to 1850	15 to 45	Air	350 to 1000[b]
IID2	1500	Very Slowly	1800 to 1900	15 to 45	Air	350 to 1000[b]
IID3	1500	Very Slowly	1900 to 1975	15 to 45	Air	350 to 1000[b]

(a) Soak 30 minutes for maximum hardness. Do not soak for minimum distortion.
(b) The higher tempering temperatures are used when the quenching temperature is high. It is sometimes considered undesirable to temper these steels between 600 and 800 F.

High-carbon high-chromium steels may fail differently from low-alloy or carbon tool steels. Where the latter steels generally require regrinding because of becoming dull, the high-carbon high-chromium steels may wear so long that deep chipping of the edges results from fatigue. More frequent sharpening of such tools will be beneficial in preventing this type of failure. In redressing tools or dies after such failure, it is advisable to anneal, remachine and reharden, rather than resort to grinding.

Grinding of the high-carbon high-chromium steels in the hardened condition is difficult because of their high resistance to abrasion. Unless proper grinding wheels are used, heat checks may form. Soft wheels of self-dressing character are recommended.

The so-called "martempering" treatment, involving quenching in a bath at 250 to 400 F, has been applied successfully to oil-hardening tool steels, with consequent reduction in distortion and cracking.

The Composition and Heat Treatment of Shock-Resisting Tool Steels

BY THE SUBCOMMITTEE ON TOOL STEEL

THE tool steels used for industrial applications in which resistance to shock is of prime importance are of the medium-alloy type and include the chromium-vanadium, the low silicon-manganese, the high silicon-manganese and the chromium-tungsten steels, although the plain carbon steels with 0.80 to 0.90% C are also used. The nominal compositions of these steels are given in Table I.

Table I. Approximate Chemical Compositions of Shock-Resisting Tool Steels[a]

Steel No.[b]	C	Mn	Si	Cr	V	W	Mo
IA	0.80 to 0.90	0.25	0.25	....	....	....	....
IC	0.80 to 0.90	0.25	0.25	....	0.20 to 0.50	....	....
IIIA	0.50	0.60	0.25	1.00	0.20	....	....
IIIB	0.55	0.40	1.00	....	0.25 opt	....	0.50
IIIC	0.55	0.80	2.00	0.30 opt	0.25 opt	....	0.40 opt
IIID	0.55	0.25	0.25	1.25	0.25 opt	2.50	0.50 opt
IIIE	0.55	0.25	1.00	1.25	0.25 opt	2.50	0.50 opt

(a) The compositions given are type compositions only. Actual analyses of the steels they represent will vary a reasonable amount from these averages. It should be remembered that the more the composition of any steel varies from these averages, the more the treatment may differ from that recommended.

"Opt" indicates that the element so marked is optional in the composition. Steels have been found satisfactory either with or without the element present.

(b) These numbers are the ones used in the table of principal types of tool steels on page 656.

Application. Shock-resisting steels are generally used for pneumatic chisels and calking tools, rivet busters, concrete breakers, track chisels, punches, rivet sets, and other tools requiring a tough hard steel having good fatigue resistance. Steels IIIA, IIIB and IIIC may also be used successfully for hand chisels, beading tools, flue expanders, nail sets, screw drivers, drift pins, sledges and other tools requiring a steel hard enough to resist spalling, upsetting or galling.

Forging, Normalizing and Annealing. *See* table, page 657, and the article on page 653 of this Handbook.

Hardening and Tempering. The temperatures and quenching mediums to be used in the hardening and tempering of these steels are given in Table II. In determining the portion of the quenching temperature range to be used in the hardening treatment, consideration should be given to the size (cross-sectional area) of the tool and to the as-quenched hardness desired. Generally the quenching temperature is increased as the size of the tool increases or as it is desired to produce higher as-quenched hardness. All steels should be tempered within the range given in Table II to obtain the desired hardness. Ordinarily, tools of higher hardness that have been tempered in the lower portion of the tempering temperature range will exhibit greater resistance to wear, abrasion, galling and upsetting, with a sacrifice of toughness; while those of lower hardness, tempered at higher temperatures within the range, will be tougher, with a sacrifice of wear resistance but with less tendency to spall, chip and break.

Table II. Hardening and Tempering Treatments for Shock-Resisting Tool Steels

Steel No.	Hardening Temperature,[a] deg Fahr	Quenching Medium	Tempering Temperature, deg Fahr	Hardness, Rockwell C
IA, IC	1425 to 1475	Brine or Water	400 to 700	62 to 48
	1500 to 1550	Brine or Water	300 to 800	60 to 50
IIIA	1600 to 1700	Oil	300 to 800	55 to 45
IIIB	1550 to 1600	Brine or Water	300 to 800	60 to 52
	1550 to 1650	Brine or Water	300 to 800	60 to 50
IIIC	1600 to 1700	Oil	300 to 800	58 to 50
IIID	1700 to 1800	Oil	400 to 1000	58 to 50
IIIE	1700 to 1800	Oil	400 to 1000	58 to 48

(a) Soaking at the hardening temperature should be avoided except for steels IIID and IIIE. Large tools or tools in which decarburization may be harmful should be preheated.

Double heat treating procedures are occasionally used to develop different properties in different parts of a tool. Chisels may be hardened all over in oil and then tempered at 800 to 900 F to a hardness of approximately Rockwell C 42 to 50, after which the cutting edge only is heated to the hardening temperature, quenched in brine or water and tempered, as indicated in Table II. By this method, maximum resistance to spalling is developed in the chisel shank and maximum hardness is obtained at the cutting edge.

Some types of tools may be either differentially heated in liquid baths or differentially quenched in fixtures. Such treatments cause a gradation of hardness and a combination of resistance to cutting, galling, abrasion, shock, upsetting and spalling. Rivet sets, for example, may be held in a fixture and quenched, shank end down, in a vertically rising stream of water. This will produce a differential rate of cooling between the shank end and the head end. As a result, the shank will have high hardness to withstand upsetting and the head, lower hardness to resist spalling.

The Composition and Heat Treatment of High Speed Steel Cutting Tools

BY THE SUBCOMMITTEE ON TOOL STEEL

THIS article covers the heat treatment of molybdenum and tungsten high speed steels as listed under Group V of the tool steel classification table on page 656. The composition types are repeated here in Table I.

Molybdenum High Speed Steels

Application. The first three steels of Group VA in Table I can be classified as general-purpose steels for average tool application under normal operating conditions. Steel VA4, an alloy highly resistant to abrasion, is ideally suited for light cuts or for machining abrasive materials. The molybdenum-cobalt steels listed under Group VB in Table I are special-purpose alloys for uses requiring high hardness at elevated temperatures ("red hardness"), particularly for cutting hard, gritty or scaly material such as hard cast alloys and heat treated steels.

Forging. All these steels are forgeable but they must be

heated carefully to prevent excessive decarburization during the heating cycle. This is particularly true with types VA1, VA2 and the cobalt grades. They should all be heated slowly to a uniform temperature of about 1500 F in a slightly oxidizing atmosphere, before being heated to the forging temperatures recommended on page 657. These steels, particularly VA1, VA2 and the cobalt series, can be protected from excessive decarburization by coating with borax (*see* below). After forging, all pieces should be slowly cooled to at least 300 F either by cooling in the furnace or by burying in silocel, lime, mica or dry sand before annealing.

Table I. Approximate Chemical Compositions of High Speed Tool Steels[a]

Steel No.[b]	C	Mn	Si	Cr	V	W	Mo	Co
VA1	0.85	0.30	0.25	4.00	2.00	....	8.00	....
VA2	0.80	0.30	0.25	4.00	1.00	1.50	8.50	....
VA3	0.85	0.30	0.25	4.00	2.00	6.25	5.00	....
VA4	1.20	0.30	0.25	4.00	4.00	6.00	4.50	....
VB1	0.85	0.30	0.25	4.00	1.00	1.50	8.50	5.00
VB2	0.85	0.30	0.25	4.00	2.00	1.50	8.50	8.00
VB3	0.85	0.30	0.25	4.00	2.00	6.25	5.00	5.00
VB4	0.85	0.30	0.25	4.00	2.00	6.25	5.00	8.00
VC1	0.70	0.30	0.25	4.00	1.00	18.00	....	....
VC2	0.85	0.30	0.25	4.00	2.00	18.00	0.75	....
VC3	1.00	0.30	0.25	4.00	3.00	18.00	....	....
VD1	0.80	0.30	0.25	4.00	2.00	14.00	0.75	5.00
VD2	0.75	0.30	0.25	4.00	1.00	18.00	0.75	5.00
VD3	0.80	0.30	0.25	4.00	2.00	18.00	0.75	9.00
VD4	0.80	0.30	0.25	4.00	2.00	20.00	0.75	12.00

(a) The compositions given are type compositions only. Actual analyses of the steels they represent will vary a reasonable amount from these averages. It should be remembered that the more the composition of any steel varies from these averages, the more the treatment may differ from that recommended.

(b) These numbers are the ones used in the table of principal types of tool steels on page 656.

Annealing. These steels must be fully annealed after forging or when rehardening is required. Pack annealing in tightly closed containers is recommended to decrease the amount of decarburization. The packing material can be dry sand or lime to which a small amount of charcoal has been added; burned cast-iron chips are also satisfactory. The container should be filled in such a way with the steel to be annealed that a minimum amount of packing material is required, since this material acts to insulate the box and will slow down the heating cycle. After the steel has reached the temperature specified, it should be held at temperature, as recommended in the table on page 657, depending on the size and weight of the boxes or pipe; and should then be slowly cooled in the furnace at a rate not exceeding 50 °F per hr, until a temperature of 1200 F is reached, when a faster rate of cooling is permissible.

Hardening. During the hardening of molybdenum high speed steels necessary precautions should be taken to minimize decarburization. Salt baths are excellent for hardening these steels but since, for efficiency, salt baths should be operated continuously, they are not practical unless large quantities of tools are to be hardened (*see* article on "Salt Baths", page 283). For intermittent hardening, controlled-atmosphere furnaces will produce satisfactory results if proper atmospheres are maintained, or if the tools are coated with borax or copper paint (*see* Notes about the Process, below).

Preheating. Preheat the tools uniformly to between 1350 and 1500 F in a semimuffle or controlled-temperature furnace or to between 1500 and 1550 F in a salt bath. For very large tools, a good practice is to use a double preheating by keeping one furnace at 1000 to 1100 F and the second furnace at 1500 to 1550 F. Some preheating salts have such a high melting point that, to keep the high-temperature furnace running continuously, a double preheating setup is required because of the thick layer of salt that freezes on the work. A preheating salt with a lower melting point will eliminate this condition.

Heating for Hardening. After thorough preheating, the tools should be placed quickly in the high-temperature furnace or salt bath, operating at a temperature within the range given in Table II. In controlled-atmosphere furnaces with reducing atmospheres, the heat transfer is rather slow, particularly at these temperatures, so the tools will come to temperature much more slowly and, for obtaining suitable solution of carbides, will require a longer time at temperature than is necessary in salt baths. For comparable results, tools can be heated in a salt bath at a somewhat lower temperature.

Table II. Hardening and Tempering Treatments for Molybdenum High Speed Steels

Steel No.	Hardening Temperature,[a] deg Fahr
VA1	2150 to 2225
VA2	2150 to 2225
VA3	2200 to 2275
VA4	2200 to 2250
VB1	2200 to 2250
VB2	2200 to 2250
VB3	2200 to 2250
VB4	2200 to 2275

(a) Heating for hardening should follow preheating at 1350 to 1550 F. When the high-temperature heating is carried out in a salt bath, the temperature should be about 25 F lower than those given in this table.

Quenching Medium. Oil, air or molten bath.

Tempering Temperature. 1000 to 1150 F.

Quenching. These steels can be quenched in air, oil or a molten bath. Except for thin tools, air-quenched between plates to keep them straight, it is customary to quench in oil from muffle or semimuffle furnaces and in molten salt from a high-temperature salt bath. After its temperature has been equalized in the salt quench, the tool is air-cooled. To minimize quenching strains and prevent cracking of large cutters hardened from furnace, an interrupted oil quench is often used, wherein the cutter is cooled in the oil until just when it loses color (about 1000 F); then it is cooled in air. All tools should be cooled sufficiently for handling without gloves, after which they should be tempered immediately.

Straightening. When straightening is required, it should be done immediately after quenching, while the tool is between 800 and 400 F. Tools can be kept in this range with a torch and then cooled in air before tempering.

Tempering. After hardening (and straightening, if necessary) the tools should be placed in the tempering furnace or salt bath, as soon as they can be held with bare hands. There they should be reheated to a temperature within the range specified in Table II and should be held at temperature a minimum of 2 hr. Then they should be cooled in air until they can be handled again, and the same cycle is repeated. This double tempering is recommended to obtain maximum toughness along with the hardness produced by the treatment.

Tungsten High Speed Steels

Application. Steel VC1 is the general-purpose 18–4–1 type of high speed steel, steel VC2 is the 18–4–2 type and VC3 is the 18–4–3 type. The higher vanadium contents of the VC2 and VC3 steels make them more resistant to wear and abrasion and ideal for cutters taking fine cuts, such as broaches and reamers. The tungsten-cobalt steels listed in Group VD are all special-purpose steels for use where conditions require high "red hardness" and resistance to abrasion. The cobalt series steels are more brittle than those not containing this element; therefore they are not recommended for fine-edged tools or tools for finishing cuts. Cobalt tool steels are used in tools for heavy-duty operations, such as lathe tools and cutters for heavy cuts.

Forging and Annealing. See discussion of molybdenum high speed steels, above.

Hardening. Since the tungsten high speed steels are more resistant than the molybdenum steels to decarburization during hardening, they can be successfully hardened in a wider range of furnaces, but controlled-atmosphere furnaces or salt baths are considered best. Because high temperatures are required for hardening the tungsten-

cobalt types, and because cobalt will diffuse from the surface, a reducing atmosphere or salt bath is recommended.

Preheating. All tools should be preheated thoroughly and uniformly to within the temperature range given in Table III. It is advisable to use a double preheating for very large cutters with gashes or sharp angles at the base of the teeth. When the tool has been thoroughly heated in a furnace that is being held at 1100 to 1200 F, it is then placed in the second furnace, operating at the higher temperatures given in Table III.

Table III. Hardening and Tempering Treatments for Tungsten High Speed Steels

Steel No.	Hardening Temperature,(a) deg Fahr
WC1	2300 to 2375
WC2	2325 to 2375
WC3	2250 to 2325
WD1	2325 to 2375
WD2	2350 to 2400
WD3	2350 to 2400
WD4	2350 to 2400

(a) Heating for hardening should follow preheating at 1500 to 1600 F. When the high-temperature heating is carried out in a salt bath, the temperatures should be about 50 F lower than those given in this table.

Quenching Medium. Oil, air or molten bath.

Tempering Temperature. 1000 to 1100 F.

Heating for Hardening. After thorough preheating, the tools should be placed quickly in the high-temperature furnace or salt bath, operating at a temperature within the range given in Table III. Because of the higher temperatures and the leaner atmospheres used, tools made of tungsten high speed steels will come to temperature faster and will require slightly less time at temperature than tools made of the molybdenum steels. The tools should not be kept at the high temperature long enough to cause excessive grain growth or heavy scaling of the surface. For comparable results, salt bath hardening can be done at a somewhat lower temperature.

Quenching, Straightening and Tempering. See discussion of molybdenum high speed steels, above.

Surface Treatments of High Speed Steel Tools

In some tool applications the development of an extremely hard surface on the tool is advantageous, particularly for light cutting, as in reaming, or for machining material of an abrasive nature, such as aluminum, copper, cast iron, hard rubber or plastics. A hard skin effect can be produced by treating the finished tool in a cyanide bath (a salt mixture containing about 28 to 30% cyanide and having a low melting point). This treatment is carried out by preheating the tools to 800 or 900 F, immersing them in the casing salt bath operating at 1000 to 1050 F, and leaving them there for a length of time determined by the size and nature of the tool being treated. A tool is seldom treated for more than an hour, which is enough time to produce a case depth of approximately 0.001 in. Because this surface case is inherently brittle, more delicate tools are immersed for shorter periods. For example, small drills and taps of fine pitch may require only 10 or 15 min treatment, whereas a larger tool may take an hour to develop sufficient case for obtaining the desired results. After the tools have cooled to room temperature, the adhering salt is washed off in hot water. (*See also* the article "Salt Baths", page 283.)

Although many tools are used as treated in the cyanide bath, it has been recommended by some to retemper at 950 to 1000 F for an hour, in order to toughen the case without affecting its hardness. This should be done in a tempering salt bath so that no heavy oxide is produced.

Another surface treatment used for both cased and uncased tools, after the final grinding operation, is tempering in a salt bath to produce a surface film of iron oxide, or tempering in steam in a furnace, giving similar results and a blue color to the surface. The oxide film is supposed to be porous, so cutting oil will be absorbed and will present a lubricated surface to the chip.

Notes About the Process

Protection of Surfaces During Heating (Other Than by Salt Bath). Because of the tendency of molybdenum high speed steels to decarburize when heated to the forging or hardening temperature range, the use of a borax film or proper furnace atmosphere is helpful in minimizing decarburization. Borax may be lightly sprinkled over the steel at a low temperature (1000 to 1400 F). When reheating is necessary during forging, more borax should be applied. Small tools, heated as above, can be rolled in a box of borax.

A method more suitable for finished tools is to apply the borax in the form of a saturated water solution. The unheated tools can be immersed in the solution at 180 to 212 F, or the solution can be applied with a brush or spray. Pieces so treated are heated as usual; care must be taken not to scrape off the borax during the handling.

When borax is used in a furnace with a Carborundum bottom, it is necessary to use a metal pan, preferably of stainless iron, to prevent the borax from fusing with the Carborundum. Such fusion produces a glasslike insoluble coating impossible to remove from a tool without damage to the cutting edge.

Another method of protecting finished tools for hardening is to apply a coating of copper paint which can be brushed or sprayed on. After drying, a protective coating of copper is left on the tool.

Controlled-Atmosphere Furnaces. Controlled-atmosphere furnaces can be used successfully if care is taken to maintain an atmosphere that is neutral in chemical reactions with the surface of the steel. Both electric and fuel-heated furnaces are available in which the atmosphere is independent of the source of heat. Some furnaces have a built-in combustion chamber, wherein the products of combustion of gas and air are circulated through a drying system to eliminate water vapor, and are then returned to the hardening chamber for protecting the work. A second type of furnace is designed with an inner retort, which is heated to the furnace temperature. The retort is filled with charcoal, and air is passed through. The charcoal burns, producing a gas high in carbon monoxide, which is used as a protecting atmosphere. Other furnaces are made with special external gas-making units, whence the prepared gas is pumped into the furnace for controlling decarburization. Most of these furnace atmospheres are high in carbon monoxide so that a carburizing reaction can take place.

Another method for producing an atmosphere that will protect the surface is to heat the tools in a block or muffle of suitable carbonaceous material, wherein an atmosphere high in carbon monoxide is generated at the hardening temperature. However, the size of the muffle is limited, so this method is adapted only to small tools.

Salt Baths. For tools that cannot be ground after hardening, or for tools that require the best possible surface condition and edges kept sharp, salt bath heating will give the best results. The only appreciable change in dimensions will be expansion or contraction caused in quenching the tool or caused by the change in structure of the steel while hardening. Three salt baths are generally used—the preheating, high-temperature, and quenching baths. The function of the quenching bath is to equalize the temperature as well as to assure a clean surface after heat treatment. A discussion of the composition and use of salt baths is given in the article on page 283 of this Handbook.

The Composition and Heat Treatment of Die Blocks and Hot Die Inserts

By the Subcommittee on Tool Steel

THIS article covers the processes to be followed in the heat treatment of die blocks and die inserts generally used in forging hammers and presses.

Many users purchase die blocks in the heat treated or prehardened condition, ready for the sinking of the initial impression. Subsequent resinking and service may be had without annealing or rehardening the dies after each operating service. This applies to dies of commercially machinable hardness. Such die blocks are usually furnished with a uniformity of five points of scleroscope hardness and in a range of 40 to 60 scleroscope (265 to 426 Brinell). Ordinarily, the shallower the impression, the greater is the hardness. Users can also purchase prehardened die blocks of specially treated, free-machining steel, in a range of 60 to 70 scleroscope hardness (426 to 514 Brinell) with only moderately increased machining resistance.

Composition. The approximate chemical compositions of carbon and alloy steels generally used in die blocks and die inserts are given in Table I.

Forging, Normalizing and Annealing. In heating for forging, normalizing and annealing, the steel should be brought slowly and uniformly to the temperature given in the table on page 657. Steels VIF2 and VIF3 should be cooled very slowly between 900 and 600 F.

Hardening. The die block should be warmed in front of the furnace to remove the chill, then charged into the furnace at not more than 500 F. Heating for hardening should be slow and uniform at a rate of approximately 150 to 250 °F per hr, depending on the size. The greater the size, the slower should be the rate of heating; also, the more highly alloyed the steel, the slower should be the heating. The time for holding at temperature should be approximately ¼ hr for carbon steels and ½ hr for alloy steels per inch of average cross-sectional dimension. The hardening temperatures are given in Table II.

Carbon steel die blocks are usually quenched in water (60 to 70 F) or, under certain conditions, in brine, and should be completely immersed, face down, for ½ to 2 min, depending on size. Then the shank is withdrawn until the block is immersed to a depth of 1 to 1½ in. below the deepest impression. To develop full hardness, a geyser of ample volume should be directed against the center of the die impression. The face of the die block should be cooled to 400 F, or to a point where reheating from the inside is not likely to occur to a sufficient degree to cause softening.

Die blocks that require oil quenching are entirely immersed in an oil bath (100 to 150 F) circulated to give maximum heat dissipation. The volume of the oil bath should be sufficient to keep it at proper temperature for uniform results. When large die blocks are being quenched, a strong geyser should be directed toward the center of the impression to insure a uniformly high hardness. The die blocks should be held beneath the surface of the oil until they have cooled to approximately 400 F.

Tempering. After quenching in oil, water or brine, the die blocks should not be allowed to stand in the as-quenched condition, but should be placed immediately in a suitable furnace or bath or on a hot plate (shank down), and should be equalized and heated slowly and uniformly to the desired tempering temperature, as given in Table II. Die blocks should be charged into a furnace or bath maintained at 400 F, and never above 500 F. The rate of heating to the tempering temperature should be the same as for hardening; when the die block is of intricate design or the thickness is very uneven, a slower rate is suggested in order to heat the heavy sections with a minimum of temperature difference between the thinnest and thickest portions. The time at temperature should be about:

¾ hr per in. of average thickness—up to 8 in.—but in no instance less than 2 hr.
⅞ hr per in. of average thickness—8 to 10 in.
1 hr per in. of average thickness—more than 10 in.

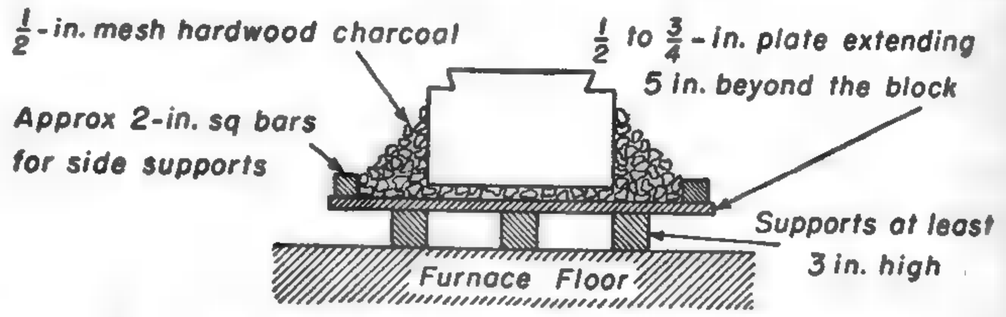

Fig. 1 Method of protecting surface of die block during heating for hardening

The dies should be cooled in still air from the tempering temperature.

Die-Block Inserts. The term "insert" may refer to a die block used to form the entire forging. It frequently has less thickness than a regular die block, because it is held in a die-block holder. On the other hand, "inserts" usually refers to the small sections set in a die block to strengthen or minimize the wear at one or more points in the die-block impression. These inserts are generally made from a more expensive die steel and will last as long as the other portions of the impression, thus considerably improving the life of the die block.

Hot die steel inserts may be made from a variety of types of steel; the more common steels used are listed in Table I and the heat treatments in Table II.

Notes About the Process. *Protection of Surface of Die Blocks When Heating for Hardening.* To reduce scaling

Table I. Approximate Chemical Compositions of Steels for Die Blocks and Hot Die Inserts[a]

Steel No.[b]	Purpose	C	Mn	Si	Cr	V	W	Mo	Ni
				Steels for Die Blocks					
IB	Hot forging	0.60	0.25	0.25	0.25	....	....	....	....
IC	Hot forging	0.70	0.25	0.25	....	0.20	....	....	....
IC	Cold forging	0.85	0.25	0.25	....	0.20	....	....	....
VIG	Drop hammer	0.55	0.80	0.25	1.00	0.10	....	....	....
VIF2	Drop hammer	0.50	0.65	0.25	1.00	0.10 opt	....	0.45	....
VIF3[c]	Press	0.55	0.60	0.85	1.00	0.10 opt	....	0.30	1.60
IVB[c]	Press	0.35	0.30	1.00	5.00	0.40 opt	1.25 opt	0.75	2.00
								1.50	....
				Steels for Hot Die Inserts					
IIIE		0.55	0.25	1.00	1.25	0.25 opt	2.50	0.50 opt	....
IVF1		0.30	0.25	0.25	3.50	0.50 opt	9.00	....	....
IVF2		0.40	0.25	0.25	2.50	0.50	12.00	....	....
IVF3		0.40	0.25	0.25	3.00	0.50	15.00	3.00 opt	2.00 opt

(a) The compositions given are type compositions only. Actual analyses of the steels they represent will vary a reasonable amount from these averages. It should be remembered that the more the composition of any steel varies from these averages, the more the treatment may differ from that recommended.
"Opt" indicates that the element so marked is optional in the composition. Steels have been found satisfactory either with or without the element present.
(b) These numbers are the ones used in the table of principal types of tool steels, on page 656.
(c) These steels are also used for hot die inserts.

Table II. Hardening and Tempering Treatments for Steels for Die Blocks and Hot Die Inserts

Steel No.	Preheat Temperature, deg Fahr	Rate of Heating for Hardening	Hardening Temperature, deg Fahr	Time at Temperature	Quenching Medium	Tempering Temperature, deg Fahr	Approximate Hardness[c] Brinell	Approximate Hardness[c] Scleroscope
IB (0.60%C)	....	Slowly and uniformly	1450 to 1500	Approx ¼ hr per in. of avg cross section	Water or brine	600 to 1000	514 to 311	70 to 46
IC (0.70%C)	....	Slowly and uniformly	1450 to 1500	Approx ¼ hr per in. of avg cross section	Water or brine	600 to 1000	514 to 302	70 to 45
IC (0.85%C)	....	Slowly and uniformly	1425 to 1475	Approx ¼ hr per in. of avg cross section	Water or brine	350 to 600	601 to 514	80 to 70
VIG	1250	Slowly and uniformly	1525 to 1575	Approx ½ hr per in. of avg cross section	Oil	600 to 1100	534 to 363	72 to 53
VIF2	1250	Slowly and uniformly	1500 to 1550	Approx ½ hr per in. of avg cross section	Oil	600 to 1100	514 to 311	70 to 46
VIF3	1250	Very slowly	1525 to 1575	Approx ½ hr per in. of avg cross section	Oil	600 to 1100	578 to 429	78 to 60
VIF3	1250	Very slowly	1625 to 1675	Approx ½ hr per in. of avg cross section	Dry air blast	600 to 1100	534 to 415	72 to 58
IVB	1500	Moderately from preheat	1800 to 1875	Approx ½ hr per in. of avg cross section	Still air	1000 to 1150	555 to 375	75 to 54
IIIE	1450	Moderately from preheat	1650 to 1750	Approx ½ hr per in. of avg cross section	Oil Oil	350 to 650[a] 1000 to 1250[b]	555 to 514 461 to 311	75 to 70 64 to 46
IVF1[d]	1500	Rapidly from preheat	2000 to 2150	Heat to slight sweat but do not soak	Oil Air	1100 to 1250 1100 to 1250	514 to 352 495 to 331	70 to 51 68 to 49
IVF2[d]	1500	Rapidly from preheat	2000 to 2200	Heat to slight sweat but do not soak	Oil Air	1100 to 1250 1000 to 1250	555 to 388 534 to 363	75 to 55 72 to 53
IVF3[d]	1500	Rapidly from preheat	2000 to 2200	Heat to slight sweat but do not soak	Oil Air	1050 to 1200 1050 to 1200	601 to 514 578 to 495	80 to 70 78 to 68

(a) When die is to be used for cold work.
(b) When die is to be used for hot work.
(c) Composition, size, time at tempering temperature and other processing variations tend to give slight variations in resulting hardness.
(d) The hardness values given result from the use of a quenching temperature of 2100 F. When greater toughness is desired, use 2000 F quenching temperature. This results in Brinell impression diameters 0.05 to 0.10 mm larger than those corresponding to the Brinell hardness numbers given. When higher hardness is desired, quench from 2200 F. This will result in a sacrifice of toughness and will give Brinell impression diameters 0.05 to 0.10 mm smaller than those corresponding to the Brinell hardness numbers given in this table.

and decarburization of the impression, it is recommended that die blocks and inserts be heated in a controlled-atmosphere furnace or with the impression placed face down in charcoal or packed in spent pitch coke (Fig. 1).

Air-Blast Hardening. When die blocks or inserts are hardened in air, the blast must be dry and so directed as to strike the impression face uniformly. An air pressure of 12 to 24 oz with ample volume is suggested.

Tempering. Carbon steel die blocks are sometimes tempered on a hot plate. The die block is placed shank down on the hot plate and heated until the desired color or scleroscope hardness is obtained on the face. When hot die blocks are tested with the scleroscope, the readings will be 4 to 5 points lower than in testing subsequently at room temperature. Accordingly, proper allowance must be made to insure final desired hardness. When relying on temper color to indicate hardness, the following is suggested as a guide: faint straw, 400 F; straw, 440 F; deep straw, 475 F; bronze, 520 F; peacock, 540 F; full blue, 590 F; light blue, 640 F.

The Composition and Heat Treatment of Tools for Hot Forging Machines

By the Subcommittee on Tool Steel

THE composition and heat treatment of steels used for tools in hot forging machines (gripper dies, header dies, piercers, crowners, punches and such) depend on the conditions and operating temperatures encountered in actual service.

Hot forging machine operations usually require tools having a combination of the following characteristics:

1 Resistance to wear and to washing at elevated temperatures, that is, "red hardness"
2 Resistance to "heat checking"
3 Resistance to softening from repeated or continuous heating at elevated temperatures, that is, "thermal stability"
4 Sufficient toughness to prevent breakage.

The compositions of steels commonly used as tools for hot forging machines are given in Table I.

These steels may be divided into three groups in accordance with their alloy contents.

Group I. Low-Alloy Steels (Steels VIF3 and IIIE). Used for short runs and general applications where operating temperatures are not very high and where "red hardness" and high thermal stability are, therefore, not the chief requisites. As a group, these steels have high toughness and water cooling is permissible.

Group II. Medium-Alloy Steels (Steels IVA2, IVB and IVC). This group of steels includes primarily either straight chromium steels or chromium steels with additions of silicon, tungsten or molybdenum.

These steels are probably the most widely used for general hot working applications where operating temperatures are not excessively high and where rapid cooling of the working surfaces may be encountered. Steels of this group have good toughness and may be water-cooled in service.

Group III. High-Alloy Steels (Steels IVD, IVF1, IVF2 and IVE1). These steels contain substantial amounts of tungsten or molybdenum or both. They are useful under high-temperature operating conditions requiring maximum "red hardness" and resistance to softening. Water cooling is generally not recommended.

Forging and Annealing. The recommendations for forging and annealing are given in the table on page 657 and in the article on page 653.

Table I. Approximate Compositions of Steels for Tools for Hot Forging Machines[a]

Steel No.[b]	C	Mn	Si	Cr	V	W	Mo	Ni
VIF3	0.55	0.60	0.85	1.00	0.10 opt	....	0.75	2.00
IIIE	0.55	0.25	1.00	1.25	0.25 opt	2.50	0.50 opt	....
IVA2	0.90	0.30	0.30	4.00	0.75 opt	....	0.50 opt	....
IVB	0.35	0.30	1.00	5.00	0.40 opt	1.25 opt	1.50	....
IVC	0.40	0.30	1.00	5.00	0.40 opt	5.00	....	....
IVD	0.45	0.60	1.50	7.50	0.40 opt	7.50	....	....
IVF1	0.30	0.25	0.25	3.50	0.50 opt	9.00	....	....
IVF2	0.40	0.25	0.25	2.50	0.50	12.00	....	....
IVE1	0.40	0.25	0.50	3.75	0.75	1.00	5.75	....

(a) The compositions given are type compositions only. Actual analyses of the steels they represent will vary a reasonable amount from these averages. It should be remembered that the more the composition of any steel varies from the average, the more the treatment may differ from that recommended.

"Opt" indicates that the element so marked is optional in the composition. Steels have been found satisfactory either with or without the element present.

(b) These numbers are the ones given in the table of principal types of tool steels on page 656.

Hardening and Tempering. Temperatures for hardening and tempering are given in Table II. The usual precautions should be taken to avoid carburization, decarburization or excessive scaling. The soaking time at the specified hardening temperature depends on the size of the tool as well as on the available heat treating equipment. The tempering temperature to be used depends on the hardness desired. The tempering should continue at least 3 to 4 hr. Rather large tools should be held at temperature for a minimum of 1 hr per in. of thickness.

Whenever possible, the surface oxide remaining after heat treatment should be left on the tools unless scaling has been excessive. Such an oxide on the surface retards seizing and galling. If grinding or polishing exposes bare metal, it is recommended that the tools be reoxidized at a temperature about 50 F below the tempering temperature. About 30 min at temperature is all that is required for this operation.

The usual working hardnesses of these steels in various applications are shown in Table III.

Table II. Hardening and Tempering Treatments for Tools for Hot Forging Machines

Steel No.	Preheat Temperature, deg Fahr	Hardening Temperature, deg Fahr	Quenching Medium	Tempering Temperature, deg Fahr
VIF3	1250	1525 to 1575	Oil	900 to 1125
VIF3	1250	1625 to 1675	Air blast	800 to 1100
IIIE	1250	1700 to 1800	Oil	800 to 1200
IVA2	1450	1750 to 1850	Air	1000 to 1150
IVA2	1450	1650 to 1750	Air blast	1000 to 1150
IVB	1450	1800 to 1900	Air	1050 to 1150
IVC	1500	1800 to 1900	Air	1100 to 1175
IVD	1500	2050 to 2150	Air or Oil	1100 to 1250
IVF1	1500	2050 to 2150	Air or Oil	1150 to 1225
IVF2	1500	2050 to 2150	Air or Oil	1175 to 1250
IVE1	1500	2150 to 2250	Air or Oil	1175 to 1225

Table III. Usual Working Hardnesses of Tools for Hot Forging Machines

Steel No.	Application	Usual Working Hardness, Rockwell C
IIIE, IVA2, IVB, VIF3	Gripper dies	43 to 50
IIIE, IVA2, IVB, IVC, VIF3	Header dies	43 to 48
IVB, IVF1, IVF2, IVD, IVE1	Piercers	43 to 48
IIIE, IVB	Crowners	40 to 45
IVD, IVF2	Cutoff tools	45 to 50
IVB, IVF1, IVF2, IVE1	Nut dies	43 to 48

The Composition and Heat Treatment of Tools for Hot and Cold Trimming

BY THE SUBCOMMITTEE ON TOOL STEEL

TOOLS for hot and cold trimming include punches and dies used in removing the flash from forgings. The chemical composition of trimming-tool steels generally depends on the type of trimming operation, the mass of the forging involved, the thickness of the flash, the trimming temperature, the chemical composition and hardness of the material trimmed, and the amount of production expected. When trimming is done hot, "red hardness" of the tool is required in addition to resistance to abrasion from the scale present. Compositions of steels for trimming tools are given in Table I.

Cold trimming usually involves severely abrasive conditions and requires tools sufficiently tough not to break or chip. Toughness is secured by placing tools in service at intermediate hardness ranges (Rockwell C 52 to 60).

Punches and trimming dies are usually, but not always, made from the same type of tool steel. Very abrasive or tough forgings may require more highly alloyed steels for trimming dies than are necessary for punches.

The forging, normalizing and annealing temperatures are given in the table on page 657.

Data on the heat treating of tools for hot and cold trimming are given in Table II.

Care should be used to obtain good alignment in mounting both dies and punches. Dies that are not flat on the bottom should be ground to assure firm and even seating.

Trimming dies should not be used after they are noticeably worn or dull, because when dies are in this condition, much higher pressures are developed in the trimming operation, and chipping or breaking may result.

In the resharpening of cutting edges the usual precautions should be used to avoid grinding stresses or cracks.

Table I. Approximate Chemical Compositions of Steels for Trimming Tools[a]

Steel No.[b]	C	Mn	Si	Cr	V	W	Mo	Co
Tools for Hot Trimming								
IIID	0.55	0.25	0.25	1.25	0.25 opt	2.50	0.50 opt	...
IVA2	0.90	0.30	0.30	4.00	0.75 opt	...	0.50 opt	...
IVC	0.40	0.30	1.00	5.00	0.40 opt	5.00	...	...
IVF2	0.40	0.25	0.25	2.50	0.50	12.00	...	...
IVF4	0.50	0.25	0.25	4.00	1.00	18.00	...	...
Tools for Cold Trimming								
IA, IC	0.90	0.25	0.25	...	0.25 to 0.50 opt	...	...	...
IIB2	1.00	0.50	0.25	5.00	0.50 opt	...	1.00	...
IID2	1.50	0.35	0.35	12.00	0.50 opt	...	0.80	3.50 opt

(a) The compositions given are type compositions only. Actual analyses of the steels they represent will vary a reasonable amount from these averages. It should be remembered that the more the composition of any steel varies from these averages, the more the treatment may differ from that recommended.

"Opt" indicates that the element so marked is optional in the composition. Steels have been found satisfactory either with or without the element present.

(b) These numbers are the ones used in the table of principal types of tool steels, page 656 in this Handbook.

Table II. Hardening and Tempering Treatments for Trimming Tools

Steel No.	Preheating Temperature,(a) deg Fahr	Hardening Temperature,(a) deg Fahr	Time at Temp, min	Quenching Medium	Tempering Temperature, deg Fahr	Hardness,(b) Rockwell C
IIID	1200	1700 to 1800	15 to 30	Oil	900 to 1150	50 to 45
IVA2	1300	1700 to 1800	15 to 30	Air	800 to 1000	50 to 45
IVC	1450	1800 to 1875	15 to 30	Air	1025 to 1100	50 to 45
IVF2	1550	2050 to 2150	2 to 5	Oil or air	1150 to 1225	50 to 45
IVF4	1550	2150 to 2250	2 to 5	Oil or air	1200 to 1250	50 to 45
IA(c), IC(c)	1200	1450 to 1500	10 to 20	Water	450 to 750	60 to 52
IIB2(c)	1450	1750 to 1800	10 to 20	Air	450 to 1100	60 to 52
IID2(c)	1500	1800 to 1875	15 to 45	Air	450 to 1050	60 to 52

(a) Heat rapidly from the preheating temperature to the hardening temperature.

(b) For cold trimming, a hardness of Rockwell C 55 to 57 is recommended for average trimming work involving larger forgings made of carbon, low-alloy, or intermediate-alloy steels. A hardness of Rockwell C 52 to 54 is recommended for trimming high-alloy steel forgings, intricate in design and having deep sections, or for trimming forgings at high hardnesses.

(c) A hardness of Rockwell C 58 to 60 is recommended for small simple tools used in cold trimming carbon and low-alloy steels.

The Composition and Heat Treatment of Solid Shear Blades

By the Subcommittee on Tool Steel

THIS article covers the heat treatment of solid shear blades and the steels most commonly used for hot and cold shearing of ferrous and nonferrous metals.

Chemical Composition. The approximate chemical compositions of the steels generally used for solid shear blades are given in Table I. Table II shows a grouping of the steels according to the nature of the work to be done and the service life desired.

In selecting a steel for heavy and extra heavy cold shearing, proper consideration must be given to the fact that shallow-hardening steels tend to spall on the cutting edge and that highly alloyed steels, which harden through, are likely to break out deeply or break in two.

Forging, Normalizing and Annealing. Recommendations for the forging, normalizing and annealing of the steels listed in Table I are given in the table on page 657 and in the article on page 653 of this Handbook.

Hardening. Hardening treatments are given in Table III. Reference should be made also to the article on page 653 of this Handbook, where the general methods and precautions are discussed.

Table II. Steels for Solid Shear Blades

Shearing Application	Steel
Cold Shearing	
Extra heavy and heavy materials (bars, billets and plate)	IA, IC, IIC (0.55% C), VIF3
Medium materials (bars, shapes, plate and strip)	IA, IC, IIC (0.55% C), VIF1, VIF3, IID1, IIB2
Light materials (strip, sheet and tin plate)	IA, IC, IIC (0.65% C), VIF1, IIB1, IIB2, IIC1, IID1, IID2, IID3, VC1
Hot Shearing	
Extra heavy materials (billets, blooms and slabs)	VIF2, IIID (0.40% C), IVB
Heavy materials (bars, billets and sheet bar)	IIC, IIID, IIIE, IVB, IVF1
Medium and light materials (bars, strip and sheet)	IID1, IVB, IVF3

Notes. The designation "light material" refers to stock no larger than ¼ in. in diam or thickness; "medium material", more than ¼ in. but no larger than ¾ in. in diam or thickness; "heavy material", ¾ to 4 in.; and "extra heavy material", more than 4 in.

For cold shearing, the carbon content of steels IA and IC is about 0.75% for heavy, 0.85% for medium and 1.0% for light work. For hot shearing, the carbon content is usually about 0.65% for heavy work and 0.75% for medium work.

Table I

Approximate Compositions of Steels for Solid Shear Blades(a)

Steel No.(b)	C	Mn	Si	Cr	V	W	Mo	Co	Ni
IA(c)	0.73	0.25	0.25	....	....	....	....	....	....
IC(c)	0 75	0.25	0.25	....	0.20–0.50	....	....	....	....
IIB1(d)(e)	1.00	2.00	0.30	1.00	....	....	1.00	....	....
IIB2(e)	1.00	0.50	0.25	5.00	0.50 opt	....	1.00	....	....
IIC1(f)	2.15	0.35	0.35	12.00	1.00 opt	1.00 opt	....	....	0.50 opt
IID1(d)(e)(g)(k)	0.85	0.35	0.35	12.00	0.50 opt	....	0.80	....	....
IID2(f)(g)	1.50	0.35	0.35	12.00	0.50 opt	....	0.80	....	....
IID3(f)(g)	2.15	0.35	0.35	12.00	0.50 opt	....	0.80	....	....
IIIC(e)	0.55	0.80	2.00	0.30 opt	0.25 opt	....	0.40 opt	....	....
IIID(e)	0.55	0.25	0.25	1.25	0.25 opt	2.50	0.50 opt	....	....
IIIE(e)	0.55	0.25	1.00	1.25	0.25 opt	2.50	0.50 opt	....	....
IVB(h)(i)	0.35	0.30	1.00	5.00	0.40 opt	1.25 opt	1.50	....	....
IVF1(i)	0.30	0.25	0.25	3.50	0.50 opt	9.00	....	....	....
IVF3(j)	0.40	0.25	0.25	3.00	0.50	15.00	3.00 opt	....	2.00 opt
VC1(f)	0.70	0.30	0.25	4.00	1.00	18.00	.. .	....	....
VIF1(d)(e)	0.70	0.55	0.25	0.60	....	....	0.20	....	1.25
VIF2(d)(e)	0.45	0.75	0.25	1.00	0.10 opt	....	0.45	....	1.75
VIF3(j)	0.55	0.60	0.85	1.00	0.10 opt	....	0.75	....	2.00

(a) The compositions given are type compositions only. Actual analyses of the steels they represent will vary a reasonable amount from these averages. It should be remembered that the more the composition of any steel varies from these averages, the more the treatment may differ from that recommended.

"Opt" indicates that the element so marked is optional in the composition. Steels have been found satisfactory either with or without the element present.

(b) These numbers are the ones used in the table of principal types of tool steels, on page 656 in this Handbook. When note (d) follows the designation, the composition is a slight modification of that shown in the table of principal types.

(c) For limited service involving high shock but low abrasion.

(d) A slight modification of the composition given for this steel in the table of principal types of tool steels, page 656.

(e) For service involving intermediate amounts of shock and abrasion.

(f) For long-run service involving low shock and high abrasion.

(g) May contain optional amounts of cobalt or nickel or both.

(h) For long-run service involving shock and abrasion at elevated temperatures.

(i) For long-run service involving low shock but high abrasion at elevated temperatures.

(j) For long-run service, involving intermediate amounts of shock and abrasion and where the stock being sheared has a temperature as high as 1200 F.

(k) For flying pinch strip shearing. Used for hot shearing but not recommended for use at temperatures above 1500 F.

(l) In the absence of tungsten, it may be advisable to increase the molybdenum content to 2.00% when shearing temperatures are higher than 1900 F.

When it is practical, long thin blades should be heated and quenched in a vertical position to minimize sagging during heating and warping during quenching. Long heavy blades should be heated on a smooth, horizontal furnace floor to minimize sagging, and should be turned over frequently to permit uniform and thorough heating.

When quenching long heavy blades, it is recommended that the quenching bath be agitated, that the blades be quenched with the edge down, rather than with a flat side down, and that the blades be turned over, during the quench, to minimize warping.

Tempering. The temperatures given in Table III cover a wide range to indicate the hardening capacity of any steel. The type of material to be sheared determines the hardness requirement of the blade. For shearing thin material, the hardness should be on the higher side, and for heavy material and hot shearing, on the lower side.

Notes About the Process. Shear blades should be straightened during cooling from the hardening temperatures. A quick-acting straightening press, such as a hydraulic press with knife-edge supports, should be available to apply a quick, uniform pressure at the desired locations along the knife. For straightening during cooling from the hardening temperature, the shear blades should be withdrawn from the quenching bath at a temperature from 400 to 500 F, which is just below the point where the oil ceases to flash; or with water-quenched blades, just where the water steams or dries off the blades immediately. A shear blade should be straightened, if necessary, as soon as possible after tempering, while still hot.

Table III

Hardening and Tempering Treatments for Solid Shear Blades

Steel No.		Preheat Temperature, deg Fahr	Rate of Heating for Hardening[a]	Hardening Temperature,[b] deg Fahr	Time at Temperature, minutes	Quenching Medium	Tempering Temperature, deg Fahr	Range of Hardness, Rockwell C	Usual Working Hardness, Rockwell C[c]
IA, IC	0.65 C	....	Slow & uniform	1450 to 1500	30 to 90	Oil	300 to 1050	45 to 30	30 to 45
	0.75 C	....	Slow & uniform	1425 to 1475	15 to 60	Brine or water	300 to 800	64 to 67	47 to 55
	0.85 C	....	Slow & uniform	1400 to 1450	15 to 60	Brine or water	300 to 800	64 to 47	47 to 55
	1.00 C	....	Slow & uniform	1400 to 1450	15 to 60	Brine or water	300 to 800	64 to 67	54 to 62
IIB1 Mod		1250	Slow & uniform	1500 to 1600	15 to 90	Still air	300 to 800	63 to 55	55 to 62
IIB2		1450	Moderate from preheat	1725 to 1775	20 to 80	Still air	300 to 1050	63 to 50	50 to 60
IIC1		1450	Moderate from preheat	1750 to 1800	20 to 80	Oil	300 to 1000	62 to 55	55 to 62
IID1 Mod		1450	Moderate from preheat	1750 to 1800	20 to 80	Still air	300 to 1050	58 to 46	46 to 58
IID2		1450	Moderate from preheat	1800 to 1850	20 to 80	Still air	300 to 1050	62 to 50	50 to [illegible]
IID3		1450	Moderate from preheat	1800 to 1850	20 to 80	Still air	400 to 1000	64 to 56	56 to 62
IIIC[d]	0.55 C	1250	Slow & uniform	1575 to 1625	15 to 60	Water	300 to 800	60 to 49	49 to 58
		1250	Slow & uniform	1600 to 1650	15 to 60	Oil	300 to 800	58 to 46	46 to 56[e]
	0.65 C	1250	Slow & uniform	1575 to 1625	15 to 60	Oil	300 to 850	60 to 49	49 to 60
		1250	Slow & uniform	1550 to 1600	15 to 60	Water	300 to 850	62 to 50	50 to 60
IIID & IIIE		1250	Moderate from preheat	1650 to 1750	15 to 60	Oil	300 to 1000	58 to 46	46 to 52
IVB		1500	Rapid from preheat	1800 to 1875	20 to 80	Still air	1000 to 1150	54 to 42	42 to 52
IVF1		1500	Rapid from preheat	2000 to 2150	Do not soak	Air or oil	1000 to 1200	52 to 42	42 to 50
IVF3		1500	Rapid from preheat	2100 to 2200	Do not soak	Air or oil	1000 to 1250	56 to 45	45 to 50
VC1		1550	Rapid from preheat	2200 to 2300	Do not soak	Air or oil	1025 to 1150	62 to 57	57 to 62
VIF1		1250	Slow & uniform	1500 to 1550	15 to 60	Oil	300 to 800	60 to 48	48 to 60
VIF2 Mod		1250	Slow & uniform	1600 to 1650	30 to 90	Oil	300 to 1020	45 to 30	30 to 45
VIF3		1250	Slow & uniform	1550 to 1625	30 to 90	Oil	400 to 900	59 to 48	48 to 55

(a) Steels preheated to 1450 F and higher may be transferred directly into the higher hardening temperature.

(b) The lower temperature of the range is intended for small cross sections, and the higher temperature for larger cross sections.

(c) The hardness requirements will vary with the cross section of the blade, gage or thickness and with the temperature of the metals sheared. Generally, the thinner the materials sheared, the higher should be the hardness of the blade. Also, the higher the temperature of the metals sheared, the lower should be the hardness. Ordinarily shear blades for shearing nonferrous metals should be 2 to 4 numbers (Rockwell C) lower in hardness than for corresponding gages of ferrous metals.

(d) Steel IIIC, when not containing molybdenum, may be water-quenched; when containing molybdenum, this steel should be oil-quenched.

(e) Steel IIIC (0.55% C), when intended for hot shearing, should be oil-quenched and tempered to Rockwell C 46 to 52, depending on the service temperature.

The Composition and Heat Treatment of Press Tools for Cold Shearing, Blanking, Punching, Forming and Coining

By the Subcommittee on Tool Steel

THE approximate chemical compositions of the steels generally used for dies and punches for cold shearing, blanking, punching, forming and coining, are given in Table I. Other steels less common than these may sometimes be used. Solid shear blades, forging press tools and trimming tools are discussed in other articles.

uniformly to the temperature specified and then bringing up to the hardening temperature more rapidly. However, very slow and uniform heating from room to hardening temperature is more helpful in preventing distortion.

Where pack hardening is suggested, refer for instructions to the general article on Forging and Heat Treating of Tool Steels, on page 653 in this Handbook.

Table I

Approximate Chemical Compositions of Press Tools for Shearing, Blanking, Punching, Forming and Coining[a]

Steel No.[b][f]	C	Mn	Si	Cr	V	W	Mo
IA	0.85 to 1.10	0.25	0.25	...	...	...	...
IB	1.10	0.25	0.25	0.20 to 0.75	...	...	...
IC	0.85 to 1.10	0.25	0.25	...	0.20 to 0.50	...	...
IIA1	0.90	1.20	0.25	0.50	0.20 opt	0.50	...
IIA2	0.90	1.60	0.25	0.35 opt	0.20 opt	...	0.30 opt
IIA3	1.20	0.25	0.25	0.50	0.25	1.75	0.25 opt
IIB1	0.90	2.50	0.30	1.50	...	...	1.00
IIB2	1.00	0.50	0.25	5.00	0.50 opt	...	1.00
IIC1[d]	2.15	0.35	0.35	12.00	1.00 opt	1.00 opt	...
IID2[e]	1.50	0.35	0.35	12.00	0.50 opt	...	0.80
IIIB	0.55	0.40	1.00	...	0.25 opt	...	0.50
IIIC	0.55	0.80	2.00	0.30 opt	0.25 opt	...	0.40 opt
IIID	0.55	0.25	0.25	1.25	0.25 opt	2.50	0.50 opt
VA3[c]	0.85	0.30	0.25	4.00	2.00	6.25	5.00
VC1[c]	0.70	0.30	0.25	4.00	1.00	18.00	...

(a) The compositions given are type compositions only. Actual analyses of the steels they represent will vary a reasonable amount from these averages. It should be remembered that the more the composition of any steel varies from these averages, the more the treatment may differ from that recommended.

"Opt" indicates that the element so marked is optional in the composition. Steels have been found satisfactory either with or without the element present.

(b) These numbers are the ones used in the table of principal types of tool steels on page 656.

(c) The carbon content may be lower for special purposes.

(d) 0.50% Ni optional.

(e) 3.50% Co optional.

(f) These steels are used both for dies and for punches, with the exception of steels IIIB, IIIC and IIID, which are used for punches only.

Forging, Normalizing and Annealing. The temperatures for these operations are given in the table on page 657. Instructions as to procedures may be noted in the article on page 653 or in articles dealing with the various types of steels under consideration.

Hardening and Tempering. The heat treatments are given in Table II.

Notes About the Process. Ordinarily both the punch and the die are made from the same steel. When the design of a die is intricate or when distortion is a factor, an air- or oil-hardening steel should be used, but for more simple designs a water-hardening steel may be used.

Steels IIA1, IIA2, IIA3, IIB1 and IIB2 can be preheated without the use of two furnaces, by heating slowly and

Steels IIC1 and IID2 absorb heat at a slower rate than the other steels. They should therefore be heated much more slowly. Steels IIB2, IIC1 and IID2 are sometimes pack hardened, especially if the die cannot be ground.

Most cold coining dies must have a deep hardness to prevent sinking under the high pressures developed, and also to permit redressing by grinding of flat dies. Press-coining dies usually are either flat or have relatively shallow impressions, and steels like IIA1, IIA2, IIA3, IIB1, IIB2, and IID2 are the most widely used.

For long-run tools and tools working on hard, abrasive materials, the more highly alloyed steels (the high-carbon high-chromium type and the high speed type) are used.

Table II

Hardening and Tempering Treatments for Press Tools

Steel No.	Preheat Temperature, deg Fahr	Rate of Heating for Hardening	Hardening Temperature, deg Fahr	Time at Temperature, minutes	Quenching Medium	Tempering Temperature, deg Fahr
IA, IB, IC	....	Slow	1425 to 1500	10 to 30	Brine or water	325 to 550
IIA1	1200	Very slow	1450 to 1500	10 to 30	Oil	325 to 500
IIA2	1200	Very slow	1400 to 1475	Do not soak	Oil	325 to 500
IIA3	1300	Very slow	1575 to 1625	Do not soak	Oil	350 to 550
IIB1	1300	Very slow	1450 to 1600	20 to 120	Still air or mild fan	350 to 700
IIB2	1450	Very slow	1700 to 1800	30	Still air or mild fan	350 to 700
IIC1	1400	Very slow	1775 to 1825	15 to 45	Oil	400 to 1000
IID2	1400	Very slow	1800 to 1900	15 to 45	Air	400 to 1000
IIIB	....	Slow	1525 to 1575	10 to 30	Brine or water	350 to 700
IIIC	....	Slow	1550 to 1650	10 to 30	Brine or water	350 to 700
IIIC	....	....	1600 to 1700	....	Oil	350 to 700
IIID	....	Slow to 1400	1650 to 1750	10 to 30	Oil	500 to 650
VA3	1500	Rapid from preheat	2125 to 2225	Do not soak	Air or oil	1025 to 1200
VC1	1500	Rapid from preheat	2150 to 2300	Do not soak	Air or oil	1050 to 1200

The Composition and Heat Treatment of Cold Heading Dies

By the Subcommittee on Tool Steel

THIS article covers the processes to be followed in the heat treatment of cold heading dies made from the steels shown in Table I. The cold heading operation is discussed in the article on page 43.

Table I

Approximate Chemical Composition of Steels for Cold Heading Dies[a]

Steel No.[b]	C	Mn	Si	Cr	V	W	Mo	Co
IA, IB, IC	0.90	0.25	0.25	0.25 opt	0.20 to 0.50 opt	...	...	...
IA, IB, IC	1.10	0.25	0.25	0.25 opt	0.20 to 0.50 opt	...	...	...
IIB2[c]	1.00	0.50	0.25	5.00	0.50 opt	...	1.00	...
IID2[c]	1.50	0.35	0.35	12.00	0.50 opt	...	0.80	3.50 opt
VA2[c]	0.80	0.30	0.25	4.00	1.00	1.50	8.50	...
VC1[c]	0.70	0.30	0.25	4.00	1.00	18.00	...	...

(a) The compositions given are type compositions only. Actual analyses of the steels they represent will vary a reasonable amount from these averages. It should be remembered that the more the composition of any steel varies from these averages, the more the treatment may differ from that recommended.
"Opt" indicates that the element so marked is optional in the composition. Steels have been found satisfactory either with or without the element present.
(b) These numbers are the ones used in the table of principal types of tool steels on page 656.
(c) Used primarily for inserts.

Stress Relieving. Dies and headers that are cold hubbed should be heated to between 1250 and 1350 F and slowly cooled before hardening. If much metal is moved in hubbing, alternate stress relieving and hubbing operations are necessary.

Forging, Normalizing and Annealing. See table on page 657, and the article on page 653 of this Handbook.

Hardening. Preheating is often advantageous in order to insure thorough heating and to shorten the time required in the hardening furnace. Preheating and hardening temperatures are shown in Table II. Dies should be heated slowly and uniformly.

Solid dies of relatively small cross section are usually quenched through the hole only. Large dies may be immersed in the quenching solution while the coolant is forced under pressure through the hole.

When hardening open dies, care must be taken to avoid gas pockets in the die impressions. This is done best by a jig that forces the quenching medium against the surface to be hardened.

When hardening heading dies, it is essential that a uniform and sufficient depth of hardness be obtained to resist the pressures developed in the heading operation.

Some small, solid cold heading dies are made from steels IIB2 and IID2, but these steels are generally used for inserts.

Table II

Hardening and Tempering Treatments for Cold Heading Dies

Steel No.	Preheat Temperature, deg Fahr	Hardening Temperature, deg Fahr	Quenching Medium	Tempering Temperature, deg Fahr
IA, IB, IC (0.90% C)	1000	1500 to 1650[a]	Brine or water[b]	300 to 600
IA, IB, IC (1.10% C)	1000	1450 to 1600[a]	Brine or water[b]	300 to 600
IIB2	1450	1700 to 1750	Air	400 to 600
IID2	1450	1800 to 1850	Air	400 to 600
VA2	1500	2150 to 2200	Oil, air or molten bath[c]	1000 to 1150
VC1	1500	2200 to 2300	Oil, air or molten bath[c]	1000 to 1150

(a) The size and shape of the die, the character of the impression and the character of the stock to be headed will determine whether the high or low temperature is better.
(b) For quenching open dies without a jig, brine is preferable to water.
(c) Air or molten bath quench is preferable to minimize distortion.

Tempering. Tempering should be started immediately after quenching. Time at temperature should not be less than one hour and longer periods are advisable.

The tempering temperature is governed by the type of die and the material to be headed. For extrusion dies and inserts, a minimum hardness of Rockwell C 59 is usually necessary.

Notes About the Process. If decarburized surfaces cause difficulty, a light coating of boric acid during the heating period may help to overcome the trouble. This coating is applied by quickly dipping the preheated die into a hot, saturated solution or by sprinkling the powder on the preheated die.

When hardening solid dies and headers with deep impressions, it is essential to quench in a jig that forces the coolant, under pressure, into the impression or through the hole in such a way that the forming of all gas pockets is avoided and plenty of fresh coolant impinges against the surfaces to be hardened.

High speed steels have been given considerable recognition as a material suitable for cold heading die inserts, particularly for that class of cold heading work requiring close tolerances and a die steel that will withstand high abrasive action.

Parts of rather intricate design can be cold formed with favorable production performance from dies made with high speed or chromium air-hardening die steel inserts. The inserts are suitably shrunk or fastened into a holder made from a medium-carbon low-alloy steel to provide the necessary support. It is very important that such an insert be fitted carefully into a holder; otherwise cracking in service will result.

The Composition and Heat Treatment of Thread-Rolling Dies

BY THE SUBCOMMITTEE ON TOOL STEEL

THIS article covers the heat treatment of thread-rolling dies made from steels of the approximate compositions shown in Table I. Other grades of steel are sometimes used for such dies, but in relatively small amounts. The thread-rolling operation is discussed on page 44.

Machining. In preparing the steel for the milling operation, it is essential that sufficient stock should be machined off to insure the removal of all surface defects and traces of decarburization. The steel must be uniformly annealed to prevent injury to the expensive thread-milling hobs. Speed of milling should be adjusted to obtain the smoothest possible finish on the threads, since this is helpful in increasing die life. After the thread form has been milled on the die face, all traces of oil and chips should be removed from the die before hardening. After the dies have become worn in use, they are often annealed and planed off. Thereafter new threads are milled and the dies are hardened and tempered for further use. For annealing, the dies should be carefully packed in sealed containers, along with suitable packing material. For annealing temperatures, see the table on page 657 and the article on page 653. Some thread-rolling dies are ground from solid hardened blanks.

Stress Relieving. After machining, a stress-relieving treatment at 1100 to 1200 F is often beneficial in preventing distortion of the teeth during subsequent heat treatment.

Hardening. In order to minimize distortion it is essential to heat all thread-rolling dies slowly throughout the heating cycle and to hold until heated through. This is particularly important with the more highly alloyed steels. The die should be tempered as soon as it is cool enough to hold in the bare hands.

Dies made from steels IIB2 and IID2 are usually pack hardened or heated in controlled-atmosphere furnaces to prevent decarburization. Burnt cast-iron chips, or pitch coke that has been heated to approximately 2000 F to remove all volatile matter, may be used for the packing medium. The box should be heated slowly to between 1250 and 1300 F, held until a uniform temperature is reached throughout the box, then heated gradually to the hardening temperature (*see* Table II), and held until a uniform temperature obtains in the charge. When hardening in controlled-atmosphere furnaces, the dies should be soaked for 15 to 30 min. Then the dies should be removed from the pack and air-cooled to room temperature, after the adhering particles are brushed off.

Table II. Hardening and Tempering Treatments for Thread-Rolling Dies

Steel No.	Preheating Temperature, deg Fahr	Hardening Temperature, deg Fahr	Quenching Medium	Tempering Temperature, deg Fahr
IIB1	1250	1450 to 1600	Air	300 to 500
IIB2	1450	1750 to 1800	Air	400 to 600
IID2	1500	1800 to 1875	Air	400 to 950
VA3	1500	2150 to 2225	Oil or molten bath	1050 to 1150
VC1	1600	2250 to 2300	Oil or molten bath	1050 to 1150

Tempering. In tempering, dies should be heated slowly to the temperature shown in Table II, preferably in a circulating-air type of furnace, and held at temperature for a minimum of 2 hr. Longer tempering times are desirable. In general, a hardness of Rockwell C 58 to 59 is satisfactory on softer materials and about 60 to 61 on harder stock.

Table I

Approximate Chemical Compositions of Steels for Thread-Rolling Dies[a]

Steel No.[b]	C	Mn	Si	Cr	V	W	Mo	Co
IIB1	0.90	2.50	0.30	1.50	...	...	1.00	...
IIB2	1.00	0.50	0.25	5.00	0.50 opt	...	1.00	...
IID2	1.50	0.35	0.35	12.00	0.50 opt	...	0.80	3.50 opt
VA3	0.85	0.30	0.25	4.00	2.00	6.25	5.00	...
VC1	0.70	0.30	0.25	4.00	1.00	18.00	...	...

(a) The compositions given are type compositions only. Actual analyses of the steels they represent will vary a reasonable amount from these averages. It should be remembered that the more the composition of any steel varies from these averages, the more the treatment may differ from that recommended.

"Opt" indicates that the element so marked is optional in the composition. Steels have been found satisfactory either with or without the element present.

(b) These numbers are the ones used in the table of principal types of tool steels on page 656.

The Composition and Heat Treatment of Die-Casting Dies and Permanent Molds

BY THE SUBCOMMITTEE ON TOOL STEEL

METALLIC molds are used exclusively in die casting and permanent mold casting. Some applications of centrifugal casting also use metallic molds.

Detailed information on the methods of casting may be found in the NONFERROUS METALS SECTION of this Handbook.

Table I lists the steels in common use for die-casting dies and permanent molds. Certain preferences are indicated but other steels may be used.

The composition and heat treatment will depend principally on the operating temperature. In dies for casting zinc- and lead-base alloys — relatively low-temperature work—carbon steels may be used without heat treatment. Aluminum- and magnesium-base alloys require heat treated alloy steels. Copper alloys require special steels and heat treatments. For die casting zinc-base alloys, high-grade carbon steel may be used; but certain alloy steels of the chromium-vanadium and chromium-molybdenum types are particularly popular, and these are heat treated for long runs. Nitralloy and nitrided alloy steels are desirable in uses where resistance to wear and erosion is important.

Chemical Composition. The chemical compositions given in Table I are representative of the steels commonly used for die-casting dies and permanent molds. The usual applications for these steels are indicated in Table II.

Forging, Normalizing and Annealing. See the table on page 657 and the article on page 653 of this Handbook.

Hardening. Table III presents the accepted hardening heat treatments for these steels. Dies should be heated for hardening in furnaces with atmosphere suitably controlled or in salt baths—particularly dies for die casting, where the maintenance of dimensions and freedom from scaling and pitting of the working surface are desired. When the other methods are not available, pack hardening is used on steels requiring temperatures higher than

Table I

Approximate Chemical Compositions of Steels for Die-Casting Dies and Permanent Molds[a]

Steel No.[b]	C	Mn	Si	Cr	V	W	Mo	Co	Ni
IIIA	0.50	0.60	0.25	1.00	0.20	...	...	...	...
IVB	0.35	0.30	1.00	5.00	0.40 opt	1.25 opt	1.50	...	...
IVF1	0.30	0.25	0.25	3.50	0.50 opt	9.00	...	...	...
VIF1	0.70	0.70	0.20	0.80	0.10 opt	...	0.30	...	1.60
VIG mod[c]	0.35	0.70	0.50	0.80	...	...	0.30	...	...
Nitralloy G	0.30	0.50	0.25	1.20	...	...	0.50	1.10%Al	
Stainless 410	0.10	0.80	0.80	12.00	...	...	...	...	...

(a) The compositions given are type compositions only. Actual analyses of the steels they represent will vary a reasonable amount from these averages. It should be remembered that the more the composition of any steel varies from these averages, the more the treatment may differ from that recommended.
"Opt" indicates that the element so marked is optional in the composition. Steels have been found satisfactory either with or without the element present.
(b) The first five steels are designated according to the numbers used in the table of principal types of tool steels, page 656.
(c) A modification of the composition given for steel VIG on page 656.

1650 F. Many die failures are caused by carburized or decarburized surfaces, resulting from the use of improper packing compounds or atmospheres. Carburization is probably the most dangerous and common result of pack hardening, because carbonaceous materials are ordinarily used.

Packing for Pack Hardening. New cast-iron chips are carburizing at temperatures above 1650 F, but this effect diminishes with use. Mixtures of new and spent chips have been used successfully as high as 1800 F. The chips must be clean.

Table II

Applications of Steels for Die-Casting Dies and Permanent Molds

Steel No.	Application
IIIA	Long-run dies for die-casting zinc-base alloys; permanent molds for gravity casting aluminum or magnesium. Used in the heat treated condition.
IVB	Dies for die-casting copper-, aluminum-, and magnesium-base alloys; permanent molds for gravity-casting alloys that have higher melting points. Used in the heat treated condition.
IVF1	Permanent molds for gravity casting. Dies for die-casting brass. Used in the heat treated condition.
VIF1	Permanent molds for gravity casting low-melting alloys. Used in the normalized and tempered condition at a hardness of about 300 Brinell.
VIG mod	Dies for die casting zinc-, tin-, and lead-base alloys. Used in the normalized or quenched and tempered condition, depending on casting conditions. For zinc-base alloys, usually quenched and tempered.
Nitralloy G	Used in nitrided condition for moving parts of dies, such as cores or slides.
Stainless 410	Permanent molds.

Note. Meehanite and gray cast iron are also used for permanent molds and SAE 1020 to 1045 for die-casting dies for low-melting alloys.

Aluminum oxide of mesh size 8 to 12 has been found safe for temperatures between 1750 and 2050, if the aluminum oxide is burned out prior to use. An addition of a small amount of spent charcoal has been found beneficial. At the higher temperatures indicated, a slight, easily removable scale may be formed.

Pitch coke of mesh size 6 to 8 is highly satisfactory in the range from 1700 to 2100 F when properly prepared. This preparation consists of holding the pitch coke at 2000 F in a closed chamber until the volatile matter is removed. Double heating is recommended when high-temperature packing is desired. Below 1700 F spent pitch coke is decarburizing in action.

Regardless of what material is used for packing, the packing box should be well sealed to prevent the admission of furnace gases.

Rates of Heating. Warping and change of size and shape may be reduced to a minimum by slow rates of heating. For this reason large dies should not be heated at a rate exceeding that which will give a total heating time of 1½ hr per in., measuring the greatest thickness of the die plus packing material. Frequently it is necessary to heat more slowly to minimize distortion.

Tempering. Table III gives temperature ranges for the tempering of these steels. After quenching, the steels should be tempered as soon as they are cool enough to be held in the bare hands. Tempering furnaces should be reduced in temperature to between 200 and 400 F before the dies are placed inside; this precaution will avoid excessive heating rates and uneven heating. Dies should not be quenched from the tempering temperature.

Tempering temperatures are selected to produce the hardness that gives the best results, according to experience. Dies are frequently tempered on the low side of the temperature range. The hardness is then determined and a second tempering treatment is given, at a slightly higher temperature if necessary, to produce the desired hardness. This process eliminates the chance of overtempering and provides the benefit of a double temper in higher alloy steels.

Notes About the Process. For aluminum-base or copper-base die castings, the alloy steel dies are water-cooled in service and should be preheated (usually to about 350 F) with water flowing slowly through the die. This practice prevents the serious damage likely to result from introducing cold water into a hot die.

Table III. Hardening and Tempering Treatments for Die-Casting Dies and Permanent Molds

Steel No.	Hardening Temperature, deg Fahr	Time at Temperature, minutes	Quenching Medium	Tempering Temperature,[a] deg Fahr	Hardness, Rockwell C
IIIA	1600 to 1700	30 to 60	Oil	800 to 1000	45 to 40
IVB	1800 to 1850	30 to 60	Air	1100 to 1200	45 to 35
IVF1	2000 to 2150[b]	Do not soak	Air or molten bath	1150 to 1250	45 to 37
VIF1	1500 to 1550	30 to 60	Oil	1200 to 1300	35 to 30
VIG mod	1550 to 1600	30 to 60	Oil	500 to 900	35 to 25
Nitralloy G	See the article on nitriding, page 697 of this Handbook				
Stainless 410	1800 to 1850	15 to 30	Air	800 to 950	40 to 35

(a) Time at the tempering temperature is usually about 2 hr per in. of greatest thickness. It is not uncommon to allow a total time of 10 to 12 hr for heating die blocks.
(b) Preheat at 1500 F.

The Composition and Heat Treatment of Plastic Molds

By the Subcommittee on Tool Steel

THIS article deals with the composition and heat treatment of the steels generally used for plastic molds and hubbing. Plastic materials, derived from phenol, urea, rubber, casein and other bases, are molded to shape in steel molds. Usually this forming is done at an elevated temperature. The dimensions and surface condition of the finished article are governed by the corresponding surfaces of the mold. Cleanliness, ease of fabrication, resistance to abrasion and to deformation, and uniform heat treating properties are necessary in the mold materials.

The die impression is formed by hubbing, by a machining operation or by a combination of the two. Hubbing consists of sinking the die impression cold with a master hub. This is often done in several operations with intermediate annealing. Low-carbon steels fully annealed are used for hubbed molds, subsequently carburized. Where the conditions are such that hubbing steels cannot be used, the dies are cut by machine.

Cleanliness. In order to insure freedom from internal defects that might mar the surface of the finished mold, the deep-etch test and magnetic particle inspection are used. Under operating pressures and temperatures, internal defects tend to open up and leave ridges or imperfections on the surface of the mold.

Fabrication. Some molds are shaped largely by hubbing, some by machining, and others by a combination of both processes. The depth to which a hub can be driven, as well as the power needed for the operation, depends largely on the hardness of the mold steel when annealed. This in turn depends on composition; a carbon steel can be annealed considerably softer than an alloy steel of the same carbon content. Consequently the steels that hub easily do not usually make so strong a mold as steels more difficult to hub. The selection of the steel will therefore be a compromise among final strength, wear resistance and hubbing properties.

Free-machining properties and good finish are desirable in mold steels that must be machined to shape. Since cleanliness is an important factor, the high-sulfur types are not desirable; therefore it is necessary to depend on careful annealing for the required machining properties.

Resistance to Abrasion and Deformation. Wear resistance is of great importance on long-run dies. Resistance to abrasion is increased by the addition of carbon and alloying elements. Strength is vital in dies that have thin sections, or in large dies where an entire surface may sink under heat and pressure. In large dies of this sort, when a case-hardening steel is used, core hardness is of considerable importance.

Uniform Heat Treating Properties. In the cost of producing dies for plastics, an important factor is stoning, machining or grinding to size after heat treatment. These operations are minimized by several precautions, such as protection from scaling by heat treatment in a controlled atmosphere, use of borax or copper plating, pack hardening and salt bath hardening. The use of air- or oil-hardening steels to minimize distortion, and the use of stress relieving to minimize machining stresses after rough machining are other methods of reducing final cost. Care must be taken in water- or oil-quenching to flush the impression thoroughly, in order to avoid soft spots. In steels subject to temper brittleness, the tempering range from 400 to 800 F should be avoided.

Composition and Heat Treatment. The approximate compositions of mold and hub steels are given in Table I. Forging, normalizing and annealing data are listed in the table on page 657. If annealing is required between hubbing operations, subcritical temperatures should be used. Hardening and tempering treatments are indicated in Table II.

Notes About the Process. Steel VIA is used for molds when ease of hubbing the impression is of primary importance. This steel is carburized and heat treated to give a surface hardness of Rockwell C 58 to 64. It is generally applied to molds for short-life applications, and to molds that have small or medium-sized cavities, involving low molding temperatures and pressures. Steel VIA is low in cost, distorts a moderate amount in hardening and has fair strength and wear resistance as well as considerable toughness. It machines with difficulty in the annealed condition but machines somewhat better after cold working by hubbing.

Steel VIB is a good general-purpose mold steel, applicable to the manufacture of almost all types of molds. It can be hubbed easily, although less easily than steel VIA. Steel VIB is case hardened and used at about the same hardness as steel VIA. It can be used for medium-life applications, for molds that have small or medium-sized cavities, involving moderate molding pressures and temperatures. It is quite low in cost, distorts moderately in hardening, has slightly more strength and wear resistance and greater toughness than steel VIA. Steel VIB can be hardened in either brine or oil without danger of soft spots.

Steel VIC is used for severe service conditions. Molds made from this steel can be hubbed or machined and are used after case hardening to about Rockwell C 55 to 62. The case and core strength and toughness exceed that ob-

Table I

Approximate Chemical Compositions of Mold and Hub Steels[a]

Steel[b] No.	Purpose	C	Mn	Si	Cr	V	W	Mo	Ni	Max hardness (annealed), Bhn
VIA	Hubbing mold	0.05	0.10	0.05	...	...	...	...	...	101
VIB	Cut die & hubbing mold	0.10	0.45	0.25	0.60	...	...	...	1.25	131
VIC	Cut die & hubbing mold	0.12	0.45	0.25	1.50	...	...	...	3.50	152
VIG	Cut die	0.55	0.80	0.25	1.00	0.10	...	0.45	...	201
IIA1	Cut die	0.90	1.20	0.25	0.50	0.20 opt	0.50	...	...	201
IIA2	Cut die	0.90	1.60	0.25	0.35 opt	0.20 opt	...	0.30 opt	...	201
IIB2	Cut die & hubs	1.00	0.50	0.25	5.00	0.50 opt	...	1.00	...	229
IID2	Cut die & hubs	1.50	0.35	0.35	12.00	0.50 opt	...	0.80 Co	3.50 opt	229
IVF4	Cut die	0.50	0.25	0.25	4.00	1.00	18.00	...	...	229
VID	Cut die	0.35	0.35	0.20	12.00	...	...	...	...	229
VIG[c]	Cut die	0.30	0.75	0.25	0.80	...	...	0.25	...	201
IIIC	Hubs	0.55	0.80	2.00	0.30 opt	0.25 opt	...	0.40 opt	...	229
IIIE	Hubs	0.55	0.25	1.00	1.25	0.25 opt	2.50	0.50 opt	...	229
VIF3	Hubs	0.55	0.60	0.85	1.00	0.10 opt	...	0.75	2.00	241

(a) The compositions given are type compositions only. Actual analyses of the steels they represent will vary a reasonable amount from these averages. It should be remembered that the more the composition of any steel varies from these averages, the more the treatment may differ from that recommended.

"Opt" indicates that the element so marked is optional in the composition. Steels have been found satisfactory either with or without the element present.

(b) These numbers are the ones used in the table of principal types of tool steels, page 656.

(c) A modification of steel VIG.

Table II. Hardening and Tempering Treatments for Molds and Hubs

Steel No.	Carburizing Temperature, deg Fahr	Hardening Temperature, deg Fahr	Time at Temperature, minutes	Quenching Medium	Tempering Temperature, deg Fahr	Hardness, Rockwell C
VIA	1650 to 1700	1450 to 1475	15	Brine	300 to 500	64 to 58
VIB	1650 to 1700	1450 to 1500	15	Oil or brine	200 to 500	64 to 58
VIC	1650 to 1700	1400 to 1425	15	Air or oil	300 to 500	62 to 55
VIG	....	1500 to 1550	15	Oil	350 to 550	57 to 50
IIA1	....	1450 to 1500	15	Oil	325 to 500	63 to 57
IIA2	....	1400 to 1475	15	Oil	325 to 500	62 to 57
IIB2	....	1750 to 1800	15	Air	400 to 800	62 to 58
IID2	....	1800 to 1850	15 to 45	Air	400 to 1000	62 to 58
IVF4	....	2200 to 2300	2	Molten bath at 1000 F	1050 to 1150	62 to 58
VID	....	1825 to 1900	15 to 30	Oil	300 to 400	55 to 50
VIG[a]	1650 to 1700	1500 to 1550	15	Oil	350 to 550	62 to 58
IIIC	1650 to 1700	1600 to 1650	Quench	Oil	350 to 450	62 to ■
IIIE	1650 to 1700	1650 to 1700	from box	Oil	350 to 450	62 to 57
VIF3	....	1550 to 1625	15	Oil	400 to 500	60 to 58

(a) A modification of Steel VIG.

tainable with steel VIA. The life of molds made from this steel is long; the pressures may be high; distortion during heat treatment is low.

Steels IIA1 and IIA2 are used for making machined molds. These steels are more expensive, initially, but because of their "nondeforming" properties, savings are often made in finishing operations after heat treating. These steels harden to about Rockwell C 60 to 63, have very high abrasion resistance, resist high pressures and have moderate toughness.

Steel VID is commonly used where corrosion resistance is desired. This steel is used at lower hardnesses than the steels previously mentioned. It has extremely high strength and good toughness and gives moderate resistance both to abrasion and to the softening effect of high temperatures.

Steel IID2 is used where high abrasion and heat resistance are desired. It has excellent "nondeforming" properties and moderate shock resistance. The cost of this steel is high and machining and grinding properties are poor. High speed steel has similar properties and has been used for similar applications. The use of steel IID2 is justified only for long-run applications.

Dies cast to shape are sometimes used with saving of time and labor. Such dies usually have a composition similar to that of steel IID2.

In certain applications where large impressions are involved, heat treated die blocks can be purchased at hardnesses as high as 400 Brinell, and the impression can be machined without subsequent heat treating. Steel VIG is typical of material processed in this manner. Material of this type is also available in specially treated free-machining die blocks, heat treated to a hardness of Rockwell C 45 to 52 with only moderately increased machining resistance.

CASE HARDENING

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Carburizing Methods

BY R. B. SCHENCK*

IN modern practice, the process of carburizing is applied to ferrous metal with the object of increasing the carbon content of the surface and in some cases the nitrogen content as well, so that when subjected to suitable heat treatment, the surface portion thus carburized will be substantially harder than the underlying metal. The combined processes of carburizing and hardening have long been known as "case hardening".

This combination of hard surface and softer interior, made possible by case hardening, is of inestimable value in modern engineering practice. By the use of alloy steels, great strength and toughness in the core can be combined with extreme surface hardness, resulting in a composite structure capable of withstanding certain kinds of stress to a high degree. For less exacting requirements, there are many applications where low or moderate core properties, together with a high degree of surface hardness, can be obtained with cheaply fabricated, low-priced carbon steels.

Commercial carburizing may be accomplished by any one of the following methods: (1) pack carburizing, (2) gas carburizing, (3) carbonitriding, or (4) liquid carburizing.

For pack carburizing, the work material is heated in contact with a solid carburizing compound in a closed container. In the gas method, the metal is exposed to a carburizing gas in a heated chamber. For carbonitriding, the metal is heated in the presence of a gaseous mixture containing both carburizing gas and ammonia. In liquid carburizing, the work material is immersed in a fused carburizing salt. Methods (1) and (2) add only carbon in producing the case; methods (3) and (4) add both carbon and nitrogen.

A choice of the method to be used depends on so many factors that it becomes very difficult to set up any definite rules to be followed. The design of the part, composition of the steel, type and depth of case, permissible distortion, production volume, initial investment, and operating cost must all be considered; and together these factors present such an involved picture that the only correct procedure is to judge each situation on its own merits.

Pack Carburizing. The pack method is the oldest and for years has been the one most extensively employed. Modified in various ways, pack carburizing has been used for virtually every kind of article that could be carburized, ranging from typewriter parts to armor plate. Ordinarily this is considered the most foolproof of the four methods, and the safest to use in the absence of trained supervision.

The usual form of the pack method, commonly referred to as "box carburizing", lends itself readily to either batch or continuous furnace operation. The principal disadvantages are the time consumed in heating the charge, the high cost of labor for packing and unpacking, and the preclusion of automatic quenching.

The only other form of pack carburizing that deserves mention here is the "rotary retort" method, suitable only for batch operation. For parts that can withstand rough handling, it is probably the most economical method yet devised.

Gas Carburizing. Gas carburizing, for both batch and continuous operation, has recently undergone intensive development and, according to present indications, may eventually replace other methods to a great extent.

Noteworthy improvements have been made in equipment for continuous gas carburizing with either automatic quenching, hand quenching, or slow cooling. Batch furnaces for gas carburizing have likewise been greatly improved. Better sealing, more positive controls and forced circulation of the gas around the work material, have contributed greatly to the dependability of the process.

An important characteristic of gas carburizing is that the carbon content of the case can be controlled effectively by suitable adjustment of the gas composition.

One of the oldest commercial forms of gas carburizing is the rotary retort method, very similar to the one described under Pack Carburizing, but using gas instead of solid carburizing compound. In general, the same advantages and limitations apply to both.

Carbonitriding. From a commercial standpoint this process is relatively new. It is used principally for light cases (usually not more than 0.020 in. deep) produced at moderate temperatures. Like gas carburizing, it is readily adapted to either batch or continuous operation. Continuous furnaces are in use at temperatures between 1500 and 1550 F, producing large quantities of carbonitrided parts with case depths from 0.003 to 0.010 in. Many of these parts were formerly hardened by cyaniding. If the gas contains a sufficient percentage of ammonia, carbon steel parts can be made file-hard without quenching.

Liquid Carburizing. Progress in the technique of liquid carburizing, with respect to both the carburizing agent and the equipment, has been extremely rapid in the last few years. The new activated baths with their higher rate of penetration and better quality of case, together with im-

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Prepared for the Subcommittee on Carburizing, with membership as follows: R. B. Schenck, *Chairman;* J. A. Dow (The Dow Furnace Co.), F. E. Harris (Buick Motor Division), H. W. McQuaid (Consultant, Cleveland), R. G. Peters (Warner Gear Division, Borg-Warner Corporation) and G. T. Williams (Pratt & Whitney Aircraft Division of United Aircraft Corporation).

proved methods of heating and control, are extensively replacing the old cyanide pot in the more progressive plants. Continuous operation and automatic handling have been used successfully in a number of installations. Liquid carburizing is used mostly for light cases at moderate temperatures. For case depths of more than 0.030 in. other methods are usually employed. The process is extremely flexible, easily controlled and particularly well adapted to small units. An important use of liquid carburizing is for local hardening by immersing only the portion to be hardened. The largest single item of operating expense is ordinarily the carburizing salt.

The Mechanism of Carburization

By F. E. Harris*

THE CARBURIZATION of steel may be considered on the basis of two fundamental concepts. The first is diffusion, influenced by the properties of the steel, and concerned with the movement of carbon in the steel itself; the second deals with the source supplying the carbon, and with the transfer of carbon to the steel surface.

These two general concepts may be described briefly:

1 Fick's law of diffusion is

$$\frac{dm}{dt} = -SD\frac{dc}{dx},$$

where dm/dt may be taken as the time rate of flow of the solute, carbon, through the area S. This rate is proportional to the area itself, where D is the proportionality factor or diffusion coefficient. The rate is also proportional to another factor, dc/dx, which expresses the rate at which the carbon concentration c varies with the depth x. The flow of carbon in gamma iron is in part analogous to the flow of heat in solids, and to some extent expressions developed for the conduction of heat are applicable.[1, 2]

2 The equilibrium state for chemical reactions may be represented by numerical constants, K_p, derived from the general expression

$$\log K_p = \frac{A}{T} - B$$

where K_p is a numerical factor termed the "equilibrium constant", which is derived from the values for the concentrations of the reactants and products of a chemical reaction. The subscript p denotes the dependency of the chemical reaction on pressure. T is the absolute temperature at which the reaction takes place. A and B are constants derived for the particular reaction.

Instead of being developed in a formal way from the basic principles, the mechanism of carburization may be analyzed from the viewpoint of carbon flow, by stating the controlling factors. These factors may be divided for discussion into two distinct classifications: (1) factors that control the flow of carbon in steel and (2) factors that influence the transfer of carbon to the steel surface.

The mechanism will be explained in that order.

The Flow of Carbon in Steel. A solution has been defined as any phase of which the composition may vary continuously within certain limits. Carburizing is concerned with the solid solution of carbon in austenite. The limits of carbon content of this phase depend on the temperature and the composition of the steel.

The rate of flow of carbon in austenite depends on values for the diffusion coefficient and characteristics of the concentration gradient. The diffusion coefficient is in turn a function of temperature and carbon concentration. The diffusion of carbon proceeds from the higher concentration, developed from the supply source, to the lower concentration of the core; when the concentration limits (surface and core) are maintained consistently, the form of the gradient may be predicted for any given and constant temperature of operation. The form of the gradient, under certain known and standard operating conditions, is described by a simple function of the elapsed time.

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Prepared for the Subcommittee on Carburizing

Concentration Limits. The iron-carbon phase diagram as commonly drawn represents, by the A_{cm} line, the variation of solubility of carbon in austenite with variation of temperature in plain carbon steels. The common alloying elements tend to move the cementite line to the left. Figure 1, derived from carburizing experiments, shows the approximate limits of surface concentrations for eight common carburizing steels.[3]

Carbon Gradients. The general form of the carbon gradient is influenced only by the range of concentration, from surface to core. For a given temperature, the rate

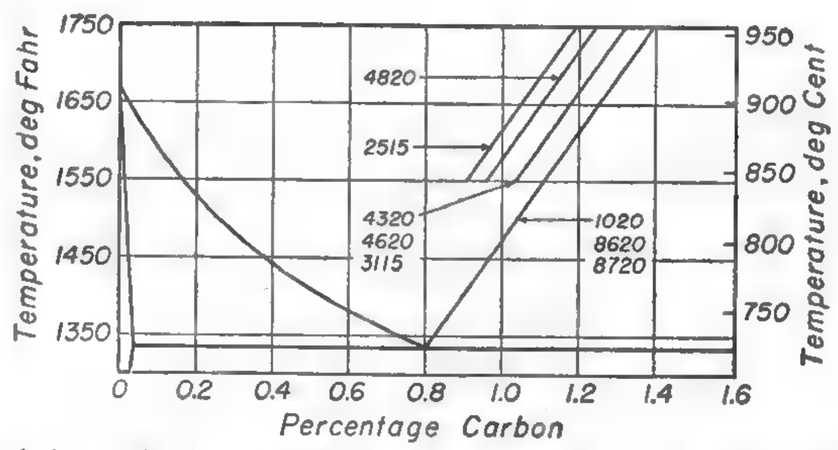

Fig. 1 Approximate solubility of carbon in austenite for eight steels

of diffusion increases with increasing carbon concentration. For the common carburizing steels and practice, the surface concentration limits are from 1.0 to 1.3% C with core concentrations usually from 0.12 to 0.25% C. For this range of concentrations, a single gradient form may be derived without great error. This is done by adopting a special standard for the co-ordinate scales on which any C-X (concentration-depth) curve is plotted. Thus the unit of concentration may be taken as the difference between the actual percentage of carbon at the surface and the per-

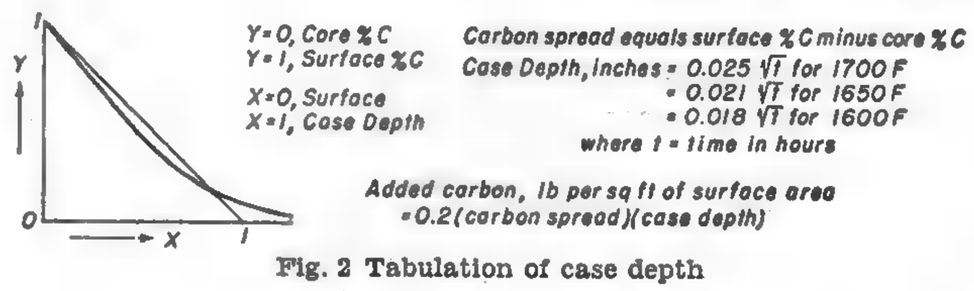

Fig. 2 Tabulation of case depth

centage of carbon in the core. This difference is called "carbon spread". A similar treatment for the depth or X ordinate brings out the significance of the term, "case depth", so that, for the standard gradient, the C-X curve becomes the plot for carbon spread versus case depth. The concept aids materially in evaluating and comparing carbon gradients.

For its attainment, the standard carbon gradient obviously requires a constant temperature of operation and a sufficient supply of carbon to the steel surface.

Case Depth. A straight line may be drawn, closely simulating a given gradient, so that the area enclosed between the line and the co-ordinates equals the area between the actual gradient and the axis.[3] Such a line intersects the concentration axis at a point representing the surface concentration. The point where this line intersects the depth axis designates the total case depth.

The slope of this line is a function of the scale chosen

for the carbon spread compared with the scale taken for case depth. The choice of equal units on the scale is taken arbitrarily as a standard, and the general form of the actual gradient may be represented (Fig. 2). Since the rate of diffusion increases with temperature, the case depth must be expressed for given and constant temperatures. For the conditions stipulated, the case depth will be directly proportional to the square root of the time factor.

Readings of case depth, when thus determined, closely approach the measurements obtained from the etch test, and for ordinary operations will represent a point about 0.07% C higher than the actual concentration of the core. From the representation of the gradient in Fig. 2, a relative depth can be estimated readily for any desired minimum of carbon concentration (or effective case). The particular value of this definition of total case depth is found in facilitating evaluations of gradients.

Added Carbon. From the construction of the case depth, the amount of carbon added through a unit surface area may be readily derived. Thus for an area of 1 sq ft or 144 sq in., the effective volume of steel expressed in cubic inches is 144 × (case depth in inches). The weight of this volume in pounds is 144 × 0.28 × (case depth) or 40 × (case depth). The average increase in percentage concentration is represented by one-half the carbon spread, and the numerical factor for carbon added during carburi-

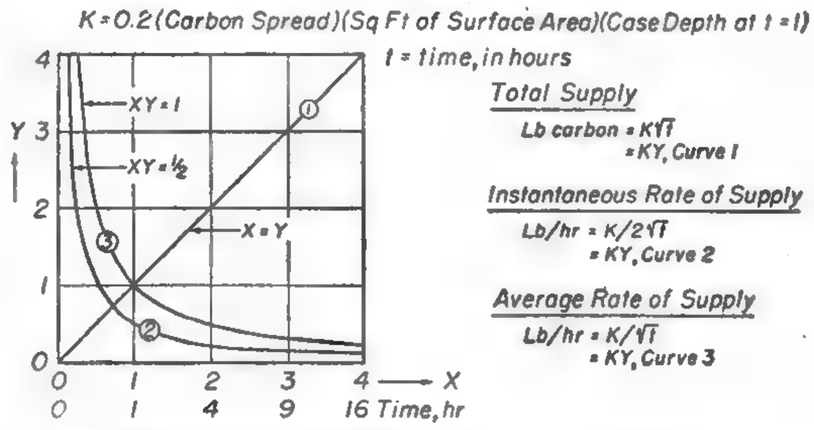

Fig. 3 Rates of carbon demand for standard gradient

zation becomes ½ × 1/100 × (carbon spread). Thus the amount of carbon in pounds added through each square foot of surface area is

$$\frac{40\ (\text{case depth})\ (\text{carbon spread})}{200}$$

or 0.2 (case depth) (carbon spread) where the case depth is expressed in inches and where the carbon concentrations from which the value for carbon spread is derived are expressed in weight percentages.

Rates of Carbon Demand. The carbon added through the surface area is directly proportional to the case depth, and thus is also a function of the square root of the elapsed time of carburization. The number of pounds of carbon added in the first hour for a given area may be designated by K. The total number of pounds of carbon added for a given time t then becomes $K\sqrt{t}$, where t is the time in hours. The instantaneous rate at which the surface demands carbon to maintain the surface concentration, at a given elapsed time t, is then $K/(2\sqrt{t})$; the rate is expressed in pounds per hour. The average rate for a given elapsed time is twice the instantaneous rate.

Figure 3 shows the graphs and presents the derivation for the rates of demand that must be matched by the source of the carbon supply in order to obtain the standard gradient. The rate curves may be readily interpreted for any given time or time interval on the X ordinate; the scale unit is the square root of the time in hours. The corresponding Y value from the graph, multiplied by the K factor, will give the rate of demand for carbon in pounds per hour.

Diffusion Coefficients. Although the concentration gradient may be standardized without great error for the surface and core concentrations commonly found in carburization, the actual concentrations that limit the gradient have a pronounced effect on the form of the gradient. This phenomenon is explained by the dependency of the diffusion coefficient, and thus the diffusion rate, on the concentration itself. This coefficient increases with increasing carbon concentration.[4] The influence of concentration on the form of the gradient may be shown by comparing the gradients for carburizing and decarburizing, obtained at equal temperatures and times, with the limiting concentrations approximately equal for both operations. The rate of diffusion as affected by concentration will have little variation when the concentrations bounding the gradient are close together. When the carbon spread is low, the gradient

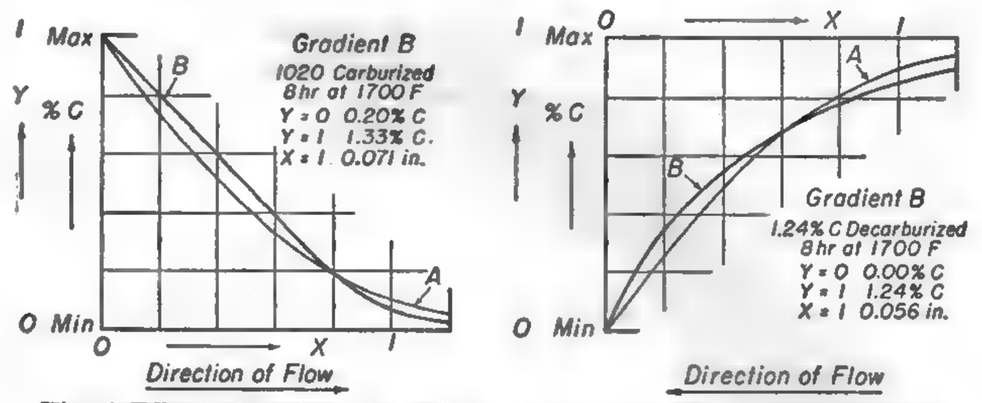

Fig. 4 Effect of carbon spread on gradients in the austenite phase

is represented by curves A in Fig. 4. These curves are shown to be identical in form. The actual gradients for fairly wide carbon spreads are shown in curves B. It will be noted that the divergence from curve A is opposite in direction for the two operations. The reason for this is apparent since, for decarburization, the rate of diffusion at the surface, where the larger portion of the total carbon is abstracted from the steel, is low because of the low value of concentration; for the carburizing operation, the concentration at the surface is high, and thus a high rate of diffusion is found where the larger portion of the total carbon is added to the steel.

The Ferrite Phase. The factors that limit the flow of carbon may also require a consideration of the ferrite phase and the interface between ferrite and austenite.[8,9] Except at very low carburizing temperatures, the minimum concentration of carbon in austenite is usually exceeded by the core concentration and, in general, carburization is concerned solely with the austenite phase. For temperatures between the A_3 and A_1 points, when the supply depletes the surface carbon (decarburization) to a concentration value below that of saturated ferrite (the maximum

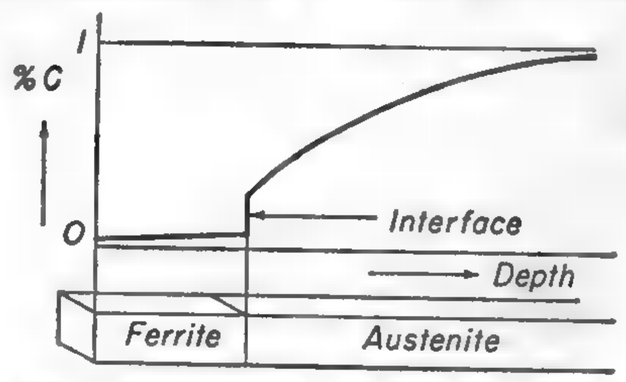

Fig. 5 Decarburizing 1.0% C steel at 1500 F (schematic)

solubility of carbon in ferrite is 0.025% C) the ferrite phase may be the controlling factor in carbon flow. At 1500 F it is possible to abstract more carbon from the surface of a 1.0% C steel by decarburization than can be added to a bar of equivalent surface area by the carburization of a 0.24% C steel for equal conditions of time and temperature. These data are consistent with the recent calculations of Polder,[5] which indicate that, at a given temperature, the coefficient of diffusion of carbon in ferrite is greater than that of carbon in austenite. A schematic gradient for the decarburization of a high-carbon steel is shown in Fig. 5, for ferrite and austenite. The ferrite-austenite interface is also illustrated (Fig. 6) by carburizing ■ sample of very low carbon content at a temperature slightly above A_1.

The Cementite Phase. The decarburization of cast iron can be used to demonstrate the equilibrium (lack of flow) between cementite and saturated austenite. The micrograph of Fig. 7 shows the interface between austenite and cementite in a decarburized white cast iron.

Flow of Carbon from the Supply Source. The primary function of carburizing mediums is to furnish an adequate

supply of carbon to the steel surface. The transfer of carbon from the source of supply to the steel is involved with reactions occurring at this surface. The carburizing agent responsible for the actual transfer of carbon is a carbon compound. The extent to which various carbon compounds may supply carbon is related to the conditions that determine the equilibrium with the surface carbon of the steel. The equilibrium composition of the reactants and products is a function of temperature and also of the carbon concentration at the surface.

The equilibrium composition is a condition involving no transfer or flow of carbon. The maximum availability of carbon in a given carbon compound is represented by the excess above the composition in equilibrium with the steel surface. The availability of a given agent decreases with increasing surface concentration and is lowest at the upper limit of carbon solubility (saturated austenite).

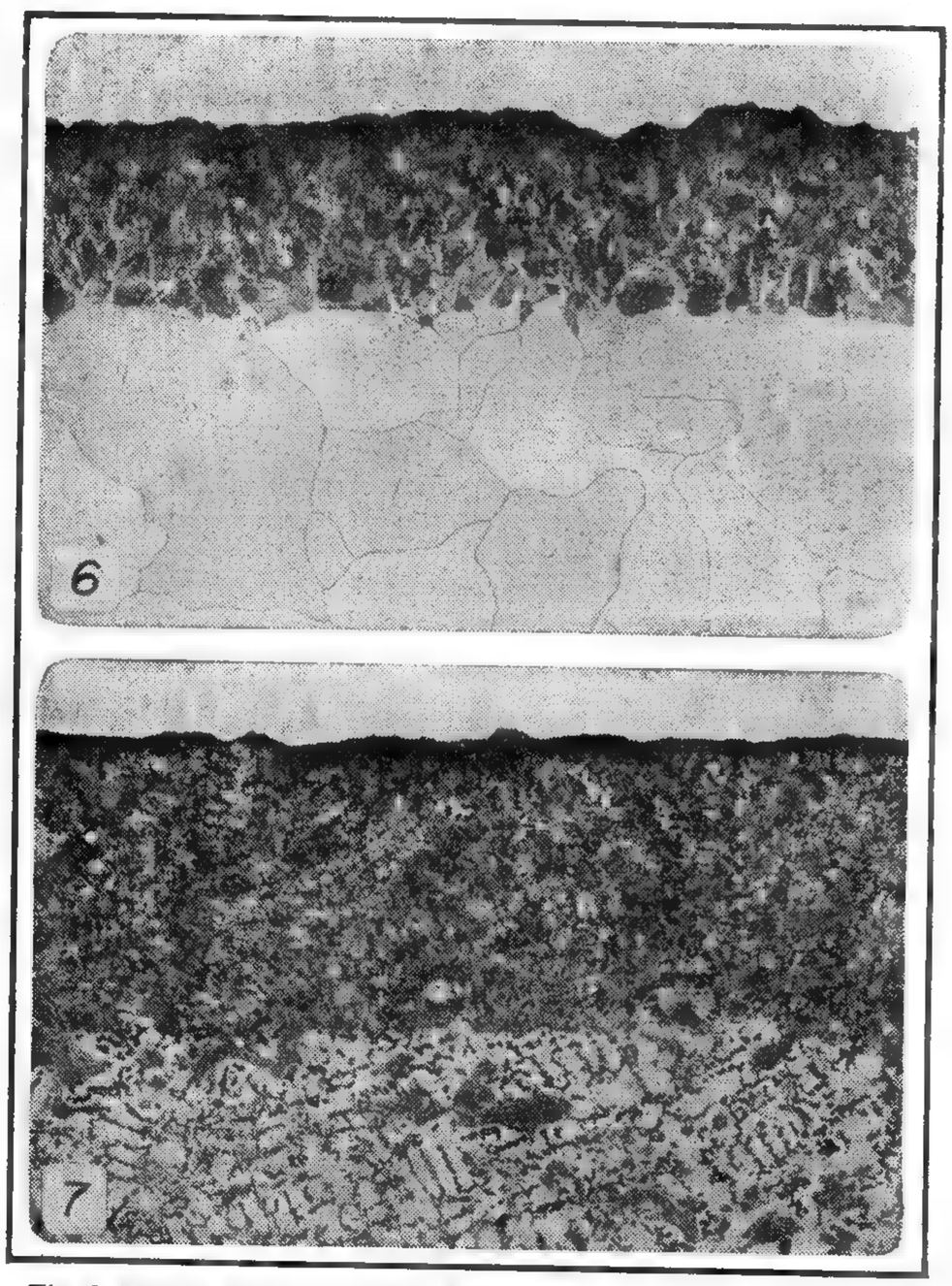

Fig. 6 Magnet iron containing 0.03% C, after carburizing at 1400 F for 5 hr. Etched with nital (× 100)

Fig. 7 White cast iron containing 3.5% C, after decarburizing for 2 hr and then carburizing for ■ hr at 1700 F. Etched with nital (× 100)

The Carburizing Reaction. The reaction involving the actual transfer of carbon occurs at the steel surface (interface) and the reactants, which are carbon compounds, may be considered independently. The interface reactions for two common carbon compounds, carbon monoxide and methane, may be written:

$$2CO = (C) + CO_2 \qquad (1)$$
$$CH_4 = (C) + 2H_2 \qquad (2)$$

where the symbol (C) represents the carbon dissolved in iron at the steel surface. Considering the reactions that occur for the same compounds, away from the interface, the reactions for deposition of carbon are expressed:

$$2CO = CO_2 + C \text{ (solid carbon)} \qquad (3)$$
$$CH_4 = 2H_2 + C \text{ (solid carbon)} \qquad (4)$$

These reactions may be compared from the viewpoint of the availability of carbon for the interface reactions (1 and 2) and of the stability of the carbon compounds at elevated temperatures (3 and 4). Figure 8 represents the equilibrium percentages of the gaseous reactants and products for saturated austenite, and for surface concentrations representing one-half the saturated value for a given steel at the temperatures illustrated. The curves for the decomposition reactions can be considered identical with those for saturated austenite (Curve *A*). For the gas dilution assumed, where the total volume of the gas reactant and gas product is taken as 20% of the total volume of gases, and where the total pressure is one atmosphere, it will be noted that the decomposition of methane is almost complete at equilibrium. Thus the carbon available for transfer from methane at the interface will be high. Carbon monoxide, on the contrary, is very stable and becomes increasingly so as the temperature and degree of dilution increase. The availability of carbon in this gas, under the conditions noted above, will be extremely low.

Equilibrium data may also be used to evaluate capacities for decarburization. Since CO is a very stable gas at high temperatures and high dilution, the presence of CO_2, even in small amounts, requires such a high percentage of CO for equilibrium that CO_2 may be called a strong decarburizing gas. Similarly, hydrogen may be considered a neutral gas or, when present in very large amounts, a weak decarburizing component.

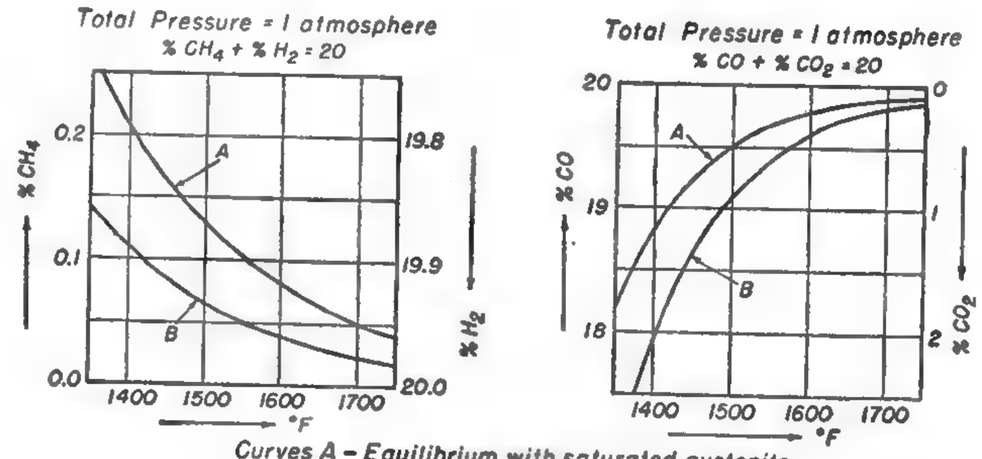

Fig. 8 Equilibrium relations for CH_4-H_2 and CO-CO_2

Intermediate reactions may occur that influence the carbon supply. For gaseous mediums, the concentration of hydrogen is important in re-forming carbon dioxide:

$$H_2 + CO_2 = CO + H_2O$$

For solid carburizers, an important reaction is

$$C \text{ (in charcoal)} + CO_2 = 2CO$$

Liquid carburizing may be aided by the reaction

$$2NaCN + BaCl_2 = Ba(CN)_2 + 2NaCl$$

These reactions illustrate the formation of carbon compounds for the actual transfer reactions at the interface.

The rate at which reactions proceed and the conditions that affect the speed of reaction must be considered in the practical application of equilibrium data. The equilibrium data are invaluable, however, in determining the point beyond which a reaction may not proceed.

Gas Carburizing. Gas carburizing practice consists in furnishing a continuous flow of prepared gases to the reaction chamber. The principal carburizing agent is generally a hydrocarbon and, as has been shown, gases of this type are relatively unstable. The use of ■ carrier gas of high stability permits the requirements for purging and the conditions of pressure to be maintained without deposition of soot. The hydrocarbon addition can then be varied at will to suit the demands of the steel charge for carbon. Typical reactions are discussed in preceding paragraphs.

Pack Carburizing. In contrast with gas carburizing, where the flow of gas is continuous, carbon dioxide, the gaseous product of the interface reaction between carburizing compound and steel, is changed in the container itself to the carburizing component, carbon monoxide. The rate at which carbon dioxide may be re-formed is one of the controlling factors of this process. Although the choice of carbonate energizers may alter the rate at which carbon

may be supplied at the interface, the flexibility of pack carburizing is small compared with that of gas carburizing.

Liquid Carburizing. Fused salts depend on cyanides for the supply of carbon; the common form of addition is sodium cyanide, NaCN. Barium chloride forms a percentage of the bath content. The postulated reactions at the interface are concerned with sodium cyanate, NaCNO, and barium cyanide $Ba(CN)_2$, both of which are formed from sodium cyanide by interaction with the oxygen of the air and with barium chloride, respectively. The decomposition products include $NaCO_3$, NaCl and $BaCN_2$. In addition to carbon, nitrogen is supplied to the steel surface, although the percentage of nitrogen added is low at temperatures above 1550 F.

Carbonitriding. Ammonia is added to carburizing gases for carbonitriding. The decomposition of ammonia is written:

$$NH_3 = \tfrac{1}{2}N_2 + 3/2H_2;$$

and the interface reaction for nitrogen supply, such as

$$NH_3 = (N) + 3/2H_2$$

where (N) represents nitrogen dissolved in iron, must occur before this decomposition. There is considerable evidence that a reaction between NH_3 and the carburizing gas components may evolve HCN, which is much more stable than ammonia at high temperatures. Only a small percentage of the nitrogen furnished by ammonia finds its way to the steel surface, and the nitrogen concentrations in the case are very low, although metallurgically effective.

General Comments. The investigation of Wells and Mehl[4] on the diffusion rates of carbon in austenite is of interest in connection with the mechanism described above. This investigation demonstrates that, in steel, factors such as the common alloying elements (in small quantities) and grain size have no perceptible influence on diffusion coefficients. The method by which these facts were established has the advantage of being independent of artificial mediums of supply.

The confirmation of these findings by carburizing experiments requires only that the conditions of supply be sufficient. That the mechanism of the flow of carbon in steel is one of solid diffusion seems incontestable. The formulation may thus be made without simultaneously considering mediums of supply.

Undoubtedly the ideal conditions for mediums of supply should permit no reactions at the interface except those directly concerned with the supply of carbon. Perhaps many of the anomalies reported in technical publications have resulted from factors of supply that are incapable of exact analysis.

A study of combustion reactions will demonstrate the complexity of intermediate and chain-forming components that are possible before stable products are formed. Similar possibilities exist when oxidizing elements (carbon dioxide and water vapor, for example) react at the interface with carbon-rich components. The exact role of such side reactions needs further investigation.

The phenomenon of surface concentrations in excess of saturated solubilities is reported too often to be disregarded. Various explanations have been reviewed recently.[7]

The numerous and varied investigations of R. W. Schlumph on carburizing practice, and the previous edition of this article by him, have contributed much to the present paper.

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Selection of Carburizing Steel, Case Depth and Heat Treatment

By Gordon T. Williams*

A GREAT variety of types of steel may be used for the production of case carburized parts requiring a hard, wear-resistant or fatigue-resistant surface, supported by a tougher, more ductile core.

The following two basic factors must be considered first when selecting a steel for use in the carburizing process: (*a*) the quenching medium to be used for hardening after carburizing, as demanded by sections, shape, and distortion limits; (*b*) the type and degree of stresses to which the finished part will be subjected. Other considerations, such as availability, shop performance, and equipment, may further influence the choice. Since these are also the factors that will determine the heat treatment to be used, obviously steel and treatment must be considered simultaneously.

Quenching Medium. The quenching medium best adapted to a carburized part is ordinarily rather easily determined. Water or aqueous solutions are preferred because of the low first cost, the high rate of cooling, and the ease of cleaning parts subsequently. Such coolants are used wherever simple shapes or massive sections permit. When sections are thin, so that cracking or warping is probable, and when accurate contours must be preserved, as in gears, a medium that provides a slower cooling rate (usually oil) must be used. From such considerations, a decision can be made concerning the hardenability required and permitted in the steel.

The quenching medium must be one that will produce the desired hardness of the carburized surface, and also, in many instances, the required hardness and strength of the core at some depth below the surface. The critical cooling velocity of the steel is, of course, the controlling factor here. If maximum surface hardness is the only requirement, low-carbon steel with no alloying elements or with only small amounts of alloying elements, should be selected, to be quenched in water or, better, in an aqueous solution.* However, if too much distortion would result from so drastic a quench, or if the steel is likely to crack, then oil should be used, and a suitable alloy steel should be selected on the basis of necessary hardenability, so that the lower cooling velocity provided by oil will still be greater than the critical rate for the steel. Martempering (that is, quenching the steel in a salt bath maintained at a temperature above M_s, and then cooling the metal in air) is frequently advantageous in reducing distortion.

Stress Considerations. The type and magnitude of stresses to which the finished part will be subjected, indicate the mechanical properties demanded in the core, as well as the preferred metallographic character of the case and the depth of case. Static compressive loads normal to the surface require only sufficient depth of case and hardness of core to prevent the case from deforming when stressed. A case too shallow or core too weak will result in surface deformation under the load. This type of failure is often called "brinelling" because of similarity to the effect of Brinell testing of a hardened case. Abrasion of the case hardened surface will usually be resisted best by

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Prepared for the Subcommittee on Carburizing

* See the article "Quenching Mediums", page 615.

a case of maximum hardness, with low content of austenite to resist flowing under the load, and with sufficient depth to give reasonable life in wear. However, wear is of several types, and there are many exceptions to the above statement. The case selected should be of the type that will best resist the specific kind of abrasion encountered. For instance, for sliding (abrasive) loads, highest mineralogical (or indentation) hardness is preferred; for impact-wear loads, when some metal flow can be tolerated, a partially austenitic case is acceptable.

When bending stresses are to be encountered, the factors of core hardness and case depth are so closely related that they must be considered simultaneously, as the following discussion shows. Since stress in a beam is proportional to distance from the neutral axis, maximum resistance to stress is required at the surface. Higher resistance is readily provided by the presence of a hard, more fatigue-resistant case. In the absence of residual stresses, the effect of the case would be geometrically predictable, and it would be necessary only that sufficient case depth or core hardness be present so that the stress resistance at all points from neutral axis to surface would be greater than the proportionate stress. However, it has been shown[1] that the situation is more complicated because the hardened case is in compression resulting from its greater tendency to expand during the hardening transformation and from the resistance of the core to this

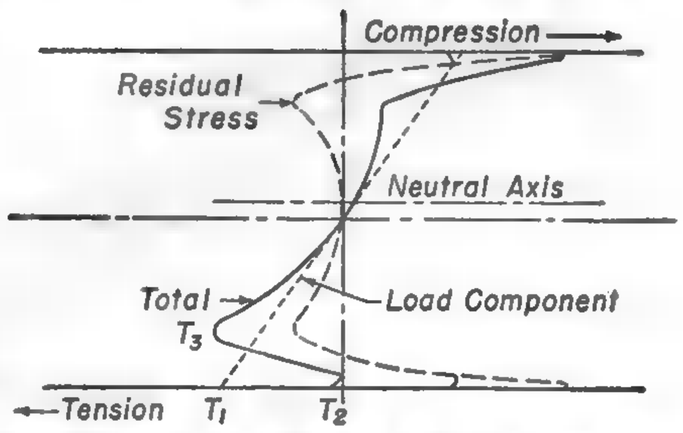

Fig. 1 Stress diagram for a loaded prestressed beam with conditions as in a case hardened piece (Almen[1])

expansion; also because the surface, even if ideally finished, carries a higher increment of stress than the simple-beam diagram would indicate, merely because it is a surface. Thus the actual situation will probably be about as shown in Fig. 1, according to Almen.[1] The residual stress (with no applied load) is shown by the broken line; a compressive stress exists in the surface, with a balancing tensile stress immediately under the case. The distribution of an imposed static load is shown by the dotted line; the solid line indicates the total stress, including the increment in surface load mentioned above. It should be noted that the surface effect also displaces the neutral axis toward the compression side, resulting in a higher tensile load effect at T_2 and T_3. Since fatigue failures are believed to occur only as a result of tensile stresses, particular attention should be given to the high stress at T_2 at the inside of the case, where the strength decreases and the residual stress is changing sharply. An increase of case depth may not be advantageous,[2] because it may result in further enlargement of the subsurface tensile stress and in added displacement of the apparent neutral axis. The foregoing considerations apply to stress conditions in bending, which may be responsible for tension failures at the surface, such as may occur at the root of a gear tooth. For compressive loading at the surface (as in antifriction bearings or at the pitch line of gear teeth) a subsurface tensile component will cause failure by pitting if necessary resistance to this tensile load is not provided.

At equal hardness, the composition of the case has a minor effect on the strength; that is, alloying elements in the steel do not necessarily improve the strength of the case. It must be remembered that the surface, being very hard, is highly sensitive to notch effects and may be harmed severely by tool marks, sharp corners, or harsh grinding.[3]

Since the combination of case depth and core strength must be such that the service stress does not exceed the resistance at any given point, and increased case depth may not improve the over-all resistance, serious attention should be given to the strength characteristics of the core of the finished piece. Raising the core strength may be much more effective than increasing case depth, to protect against fatigue failures from compressive loading. On the other hand, increasing the core hardness and strength reduces the compressive stress that will be developed in the case and may, therefore, be detrimental to fatigue life in bending. Because mixed structures, resulting from incomplete hardening, have undesirable properties, the core should be fully hardened for the most severe services.

When such considerations apply, the steel to be used must be selected with care. Carbon content alone will not permit the development of high core properties—or even of uniform properties—except with high rates of quenching, as in thin sections drastically cooled. When a slower (oil) quench must be used, because of the need to avoid warpage, and when the cooling rate will be slow at best, because a section is large, a steel of sufficient hardenability must be selected. Since the percentage of alloying elements is reflected in the cost of the steel, and the more highly alloyed steels are ordinarily more difficult to process, both in machining and in heat treating operations, there is a continuing trend toward the use of moderately alloyed steels, with carbon content higher than the former range of 0.08 to 0.25%. For example, gears and other automotive parts are being made currently to withstand high stresses, by use of moderately alloyed steels with carbon content as great as 0.40%; often the case depth can be reduced in such parts.

However, when sections are large or vary widely, a steel of high hardenability may be demanded, a fairly large alloy content will be necessary to ensure full hardening of the core, and it will be necessary to restrict the maximum carbon content of the steel in order to avoid excessively high hardness of the core. This problem is important when uncarburized surfaces must be machined after hardening.

Selection of Steel

Plain Carbon Steels. In this class are the steels that contain only carbon (in addition to the usual percentages of such elements as silicon and manganese) or such small amounts of alloying elements that the critical cooling velocity of the carburized case is normally reached only by quenching in aqueous mediums. Carbon contents greater than 0.25% are used infrequently in standard practice because of the brittleness of such steels in the fully quenched core. Ordinarily the maximum core strength with adequate toughness is about 100,000 psi. Heat treatment is simple and easily controlled.

Moderately Alloyed Steels. Steels that contain from 1 to 2% total alloying elements (such as nickel, chromium, manganese, and molybdenum, in proper combination, in addition to carbon) usually have sufficient hardenability for maximum hardness to be attained by oil quenching, and desired core properties up to a tensile strength of 200,000 psi are obtainable with suitable toughness by proper selection of steel composition. Carbon content up to 0.40% may be specified to increase the core strength further; the alloying elements provide the required toughness and hardenability. The differences among the various types of alloy steels in this classification are difficult to demonstrate, being easily overshadowed by differences in processing technique and individual preferences.[4] The "triple-alloy" or NE steels, developed to meet an emergency shortage of alloying elements and to take full advantage of the residual alloy content, have been widely and successfully applied, particularly when selected on the basis of hardenability. Simple and accurate heat treating procedures have been established for these steels.

Highly Alloyed Steels. In some instances the sections and service requirements are such that a total of alloying elements of more than 2% must be used to give the desired properties in the core. The added elements are the same as above, but carbon content is held to 0.25% max, because of the high hardenability of these steels. Extreme core toughness and strength may be developed. With this class

of steels the core hardness may easily become excessive in thin sections or on uncarburized surfaces, unless the maximum carbon content is severely restricted. The cost of steel and of processing, limits the use of these highly alloyed steels. Probability of austenite retention in the hardened case necessitates special, sometimes elaborate, heat treating cycles.

Grain Size and Abnormality. Grain growth of a steel at the carburizing temperature has a marked effect on mechanical properties and distortion after subsequent hardening. Steels of grain size 5 or finer, when tested in accordance with ASTM E 19, Method (*a*) (the McQuaid-Ehn test), are almost invariably preferred and usually demanded. In a limited number of applications, the greater hardenability of the coarser-grained steels warrants the use of such steels in spite of increased distortion and reduced toughness. Abnormality often accompanies fine grain in the test for grain size. Although the cooling velocity for full hardening must be greater for an abnormal than for a normal steel of a given composition, the change in critical rate is marked only in plain carbon steels, for which a quenching solution of NaCl or NaOH is often required, in order to avoid soft spots. Therefore, "normal" steel is sometimes specified in the plain carbon types where, after water quenching, freedom from soft spots is required. A moderate increase in manganese content (for example, SAE 1022 instead of 1020) will reduce the probability of abnormality and will help to decrease the effect of it by providing improved hardenability. Specifications concerning normality are rarely used in the alloy steels. Abnormality, implying rapid spheroidization of carbides, may be definitely advantageous in avoiding residual networks of carbide after certain treatments, such as *A* and *B* of Fig. 2.

Selection of Case Depth

Case Depth. For ordinary engineering application, choice may be made from several combinations of case depth and steel composition. In accordance with the stress diagram (Fig. 1) an increase in core strength, accomplished by increasing alloy content or carbon content or both, permits a reduction in the depth of case required to resist bending stresses. Likewise, if compressive loading is to be resisted, an increase in core hardness will aid in giving a non-deforming case, as will increased case depth. For resistance

Table I. Typical Automotive Carburizing Applications and Requirements[a]

Depth of Case, inch	Typical Parts Made from Low-Carbon Steel	Surface Condition When Treated	Requirements	Typical Parts Made from Medium-Carbon Steel	Requirements
Less than 0.020	Push-rod balls Push-rod sockets Speedometer gears Shackle bolts Shifter forks Tie-rod ball studs Tie-rod ball-stud sockets	Finished before treatment except for possible polishing operation	High degree of wear resistance Clean surface after treatment	Transmission gears Transmission main shafts and synchronizer sleeves (Surface generally finished before treatment)	Maintain or increase carbon content of the surface for higher resistance to wear and to fatigue Resistance to high occasional or shock loading Clean surface after treatment
	Water-pump shafts	When nitrided, 0.0003 to 0.001 in. per side removed for maximum wear resistance			
0.020 to 0.040	Pitman-arm ball studs Intermediate steering-arm ball studs	Finished before treatment except for possible polishing operation	High degree of wear resistance Sufficient strength to withstand service loads Clean surface after treatment	Transmission gears Ring gears Drive pinions (Surface finished before treatment except for lapping operation)	Increase carbon content at surface for greater wear resistance, load carrying ability and fatigue resistance. Clean surface after treatment
	Steering-arm bushings Valve rocker arms Valve rocker-arm shafts Gear-shifter shafts Brake and clutch-pedal shafts Water-pump shafts	Generally semifinished before treatment and finish ground after treatment	Enough case to permit finish grinding and maintain high hardness for necessary wear resistance		
0.040 to 0.060	Ring gears Drive pinions Transmission gears Side gears Side pinions	Finished before treatment except for lapping operation	High wear resistance to resist sliding, rolling or friction of abrasive nature. Resistance to heavy crushing. Resistance to high alternate bending stresses.		
	Piston pins Steering-knuckle pins[a] Side-pinion axles[a] Reverse idler-gear shafts[a] Counter-gear shafts[a]	Semifinished before treatment Finish ground after treatment	Operated frequently in bronze bushings High wear resistance Resistance to relatively high unit loads that cause brinelling. Resistance to fairly high alternate bending stresses. King pins also require resistance to high instantaneous or shock loads		
	Roller bearings		Resistance to heavy rolling action		
More than 0.060	Camshafts[b]	Semifinished before treatment	High wear resistance. Resistance to shock. Resistance to relatively high unit loads with a rapid sliding action.		

For more severe service, as in trucks and busses, the depth of case for corresponding parts may be somewhat deeper and the general tendency is to change to a steel that permits better mechanical properties, especially in the core.

(a) More case than is actually necessary to satisfy service requirements is put on parts of such length as these in order to avoid the necessity for extremely accurate straightening before grinding.

(b) Carburize deeper than is necessary to satisfy service requirements in order to compensate for inaccuracies in machining that are caused by the length of these parts, and by distortion from heat treatment, and to ensure sufficient case for necessary hardness and wear resistance after grinding.

to abrasion only, service life will usually be proportional to case depth alone. Obviously, therefore, a wide range of case depths may be employed on any given part; consideration of over-all properties and manufacturing economy will determine the steel and case depth.

As shown by the time-penetration formula, the rate of increase in case depth decreases with the time at temperature. Since this means a continuously increasing cost per hour, specifications for case depth are held to a minimum so that the time required will not be excessive.

Increased case beyond the normal depth is expensive to attain, and should be specified only when demanded by service requirements. Heavy-duty gears, for example, are often made with case depth of 0.060 to 0.090 in. and parts that require long service under highly abrasive conditions may have cases as deep as ⅛ in. If much of the case is to be removed by grinding, obviously allowance must be made in carburizing. Removal of case by grinding

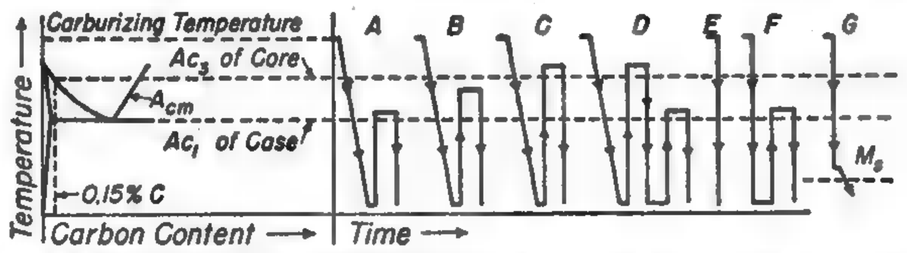

Fig. 2 Diagrammatic representation of various hardening treatments for carburized steels and summary of the properties of case and core; adequate hardenability is assumed.

Treatment	Case	Core
A (Best adapted to fine-grained steels)	Refined; excess carbide not dissolved.	Unrefined; soft and machinable.
B (Best adapted to fine-grained steels)	Slightly coarsened; some solution of excess carbide.	Partially refined; stronger than *A;* erratic.
C (Best adapted to fine-grained steels)	Somewhat coarsened; solution of excess carbide favored; austenite retention promoted in highly alloyed steels.	Refined; maximum core strength and hardness. Better combination of strength and ductility than *B.*
D (Best treatment for coarse-grained steels)	Refined; solution of excess carbide favored; austenite retention minimized.	Refined; soft and machinable; maximum toughness and resistance to impact.
E (Adapted to fine-grained steels only)	Unrefined with excess carbide dissolved; austenite retained; distortion minimized; fileproof when carbon content is high.	Fully hardened
F (Adapted to fine-grained steels only)	Refined; solution of excess carbide favored; austenite retention minimized.	Low hardness; high toughness.
G (Interrupted quench; martempering)	Unrefined with excess carbide dissolved; austenite retained; distortion minimized; filehard when carbon content is high.	Fully hardened.

should be held to a minimum, because of the high cost both of producing the case and of grinding it off; the serious danger of damaging the case by grinding-burns or grinding-cracks; and the fact that the outermost part of the case has the best resistance to wear. Grinding also reduces compressive stresses in the case, both by removal of the stressed layer and by thermal stress relief incidental to localized heating.

In connection with the selection of case depth, the maximum carbon content and thus the maximum actual hardness at the surface are relatively independent of case depth, as shown in the article on "Mechanism of Carburization", page 678. However, if the hardness test to be applied involves a heavy load with considerable penetration into the piece, a relatively deep case may be necessary to give a satisfactory result in the hardness test. For example, a high Rockwell C reading can be obtained only in cases that have a hard layer deeper than 0.025 in., yet a case only 0.005 in. deep may exhibit file hardness as great as that of the deeper cases. The readings obtained also depend on the support given to the case by the core. Allowance should be made for these factors in selecting test methods for use with lighter cases.

Table I, from Boegehold and Tobin,[3] summarizes typical applications and requirements.

Type of Case. For two reasons it may be desirable to avoid a hypereutectoid layer. First, if the pieee is cooled slowly from carburizing, proeutectoid cementite will be precipitated at the grain boundaries, usually forming a network. This will be redissolved during subsequent austenitizing, but slowly, especially if the carbides are complex, and only if heated above the required A_{cm} temperature. Residual grain-boundary cementite in the finished piece is a frequent cause for failure from brittleness, and is a common cause for checking or cracking during grinding. Second, even though direct quenching is employed and the separation of proeutectoid cementite is inhibited, the hypereutectoid carbon content will increase the amount of retained austenite. For most applications a martensitic case free from austenite is preferable. Consequently, if the steel is highly alloyed and thus susceptible to the retention of austenite, the carbon content of the case should be held to the lowest amount compatible with full hardness, usually eutectoid content. Limitation of maximum carbon content to less than 1.0% is very difficult in pack carburizing, and gaseous mediums are favored when a lower-carbon case is desired or required.

In certain applications, the presence of cementite in the case is a desirable aid in wear resistance. For such applications it is important that the carbon content be high while the excess carbides are preferably in spheroidal form.

Selection of Heat Treatment

A carburized piece must be regarded as a duplex material, that is, a high-carbon surface, and a low-carbon core, with a gradual transition from one to the other. Two critical temperatures are thus involved in hardening, and the excess carbide of the case may or may not be dissolved at the hardening temperature selected.

Figure 2 illustrates the requirements and summarizes the usual methods by which carburized work is heat treated.[5] Table II shows transformation temperatures and preferred treatments for the usual carburizing steels.

Annealing. The annealing temperature and method of cooling should be selected to provide the required machinability and necessary grain refinement. When machining operations are severe, and when best dimensional accuracy is required, the steel may be stress relieved between rough and finish machining.

Carburizing. The type and depth of case must be carefully controlled.[3,6] The temperature employed will usually be 1650 to 1700 F, to give a fair rate of penetration without increasing furnace costs unduly. When steels of higher carbon content are used (for example, 0.40% C) and a shallow case is desired, carburizing is often done at 1550 to 1600 F to give better control of case depth. Uniform temperatures must be provided in order to produce uniform carburizing and hardening, and to control distortion.

Cooling from Carburizing. Since steel is carburized above the transformation temperatures of case and core, obviously both case and core will harden if the piece is cooled from the carburizing operation at a rate faster than the critical cooling rate. Before the advent of steels controlled to have a fine grain size at carburizing temperatures, such "direct quenching" was useful only for parts of simple shape and section because of the danger of cracking and distortion. Coarse-grained steels, when directly quenched, often show objectionable brittleness, and a more complicated hardening treatment must be used. With fine-grained alloy steels and suitable equipment, it is usually preferable to quench directly in oil, since with this treatment distortion is lower and more regular than when parts are cooled slowly and then reheated for hardening. In handling pieces from the higher (carburizing) temperature and in the quantities delivered discontinuously from carburizing furnaces, more difficulty is involved than in reheating for hardening; consequently, the reheat-

Table II. Heat Treatments for Carburized Steels

SAE No.[a]	Alloy Content	Approximate Transformation Temperatures: Case Ac_1 deg Fahr	Approximate Transformation Temperatures: Core Ac_3[b] deg Fahr	Preferred Treatments (*See* Fig. 2)	Quenching Medium	Retention of Austenite
1015	None (0.4% Mn)	1355	1585	A, D, F	Water or 3% NaOH sol	Very slight
1019	None (0.85% Mn)	1350	1550	A, D, F	Water or 3% NaOH sol	Very slight
1117	1½% Mn	1345	1520	A, D, F	Water or 3% NaOH sol	Slight
1320	1¾% Mn	1325	1500	E, C	Oil	Slight
3115	1¼% Ni, ½% Cr	1355	1500	E, C	Oil	Moderate
3310	3½% Ni, 1½% Cr	1330	1435	C, D, F	Oil	Strong[c]
4119	½% Cr, ¼% Mo	1395	1500	E, C	Oil	Moderate
4320	1¾% Ni, ½% Cr ¼% Mo	1350	1475	C, E	Oil	Strong[c]
4615	1¾% Ni, ¼% Mo	1335	1485	E, C	Oil	Moderate
4815	3½% Ni, ¼% Mo	1300	1440	C, E	Oil	Strong[c]
8620 } 8720 }	½% Ni, ½% Cr ¼% Mo	1350	1540	E, C	Oil	Moderate

(a) All steels preferably of grain size 5 or finer. (b) Ac_3 of core will decrease as carbon content is increased.
(c) Spheroidization of excess carbide by subcritical treatment before hardening may be used to decrease the amount of austenite retained.

ing procedure is sometimes preferred. A further handicap to the full use of direct quenching is the greater amount of retained austenite in the hardened case. The more highly alloyed steels can rarely be used in the direct-quenched condition for this reason, and many of the moderately alloyed steels retain so much austenite that the treatment is not acceptable, especially when finished parts will be subject to rolling under load (such as spiral or hypoid gears). Retention of austenite and distortion may both be decreased in direct quenching, by retarded cooling to a temperature close to Ar_1 before quenching. This may be accomplished by transferring the work pieces to a furnace held at a temperature just above Ar_1 and stabilizing the temperature of the steel at this level before quenching. Quenching from the carburizing temperature may be followed by reheating the steel above the Ac_1 temperature of the case to provide maximum refinement of the case, with a minimum amount of retained austenite. Direct quenching will give the highest attainable strength and hardness of the core with less than maximum toughness. The case will be file hard, but with more highly alloyed steels, may have a low indentation hardness because of the retention of austenite. This treatment will minimize the amount of grain-boundary cementite.

When machining operations must be performed on carburized surfaces after carburizing, the steel must be either slowly cooled or annealed. With steels of high hardenability, and with certain types of equipment, the available slow rate of cooling may still produce enough hardening so that subsequent softening is necessary. An intermediate cooling rate may be necessary in order to avoid the separation of carbide in network form. Decarburization may occur during slow cooling without suitable precautions.

Steel to be water quenched subsequently, may be either slowly cooled from the carburizing operation, or oil quenched to give some refinement to the core without danger of cracking or severe distortion.

Separate Hardening Treatments. As indicated in Fig. 2, various hardening treatments may be applied when steel is reheated after cooling from carburizing, depending on whether the case only or both case and core are to be hardened. For the more highly alloyed steels, the method is preferable that most nearly approaches direct quenching; that is, a single reheating to a temperature 25 to 50 F above the upper transformation point of the core (and thus, of course, also above the transformation range of the case). In this way, maximum core strength may be attained with good toughness, and nearly all the excess carbide in the case may be dissolved. Thus retention of austenite is probable in the more highly alloyed steels, although less than would result from direct quenching. Distortion will be higher than after direct quenching, but may be held within acceptable limits. This treatment, like direct quenching, is rarely applied to plain carbon steels.

Steels may be reheated to a temperature just above the transformation range of the case, either after slow cooling or after quenching from carburizing. If the steel is reheated after slow cooling, the core will be soft but only moderately tough because of the omission of any refining treatment; the case will be hard, but may be brittle because of undissolved carbide; distortion will be low because the core has not been quenched. However, if the work has been quenched directly from the carburizing temperature, a high degree of refinement will result from this combination of treatments. The core will be fully refined, having high toughness and low hardness; and the case will be fully hardened, with good toughness resulting from the absence of cementite as network; however, distortion will be considerable. Slow cooling from the carburizing temperature, then reheating and quenching from above the transformation temperature of the core, and finally quenching again from above the transformation range of the case, will give similar results but with maximum possible refinement, coupled with a high degree of distortion. Control of steels for grain-growth characteristics, together with the demand for high-strength cores and a realization of the futility of high toughness of core and high impact values, has made this treatment less used.

The steel may simply be reheated to a temperature well above the transformation range of the case, but below that of the core. With such hardening, the core is partially refined and the case is improved slightly because of partial solution of excess cementite. This is not recommended for critical applications.

For some applications, interrupted quenching treatments, such as martempering, may be useful in reducing distortion. Martempering consists of quenching the steel in a salt bath that is maintained at a temperature higher than the M_s point of the steel (500 to 700 F is the usual bath temperature) and then cooling in air. Since the cooling velocity provided by the salt bath is relatively low, a steel of relatively high hardenability is required, if case and core are to harden fully, but distortion will be low in comparison with that resulting from normal quenching.

Cold treatment, preceded and followed by tempering, may be useful for elimination of austenite and is frequently the only way to obtain high hardness readings from cases of high alloy content, particularly if the carbon content of the case is hypereutectoid.

Tempering. Residual stresses from quenching will be relieved somewhat, and resistance to cracking during grinding operations will be improved by reheating the hardened piece to the highest temperature (usually 275 to 350 F) that will not reduce appreciably the hardness and wear resistance of the case. The tempering treatment is frequently omitted. Some stress relief is obtained by any washing operation conducted at or near the temperature of boiling water.

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Measurement of Case Depth

BY R. B. SCHENCK*

THE following discussion of case depth measurement is intended to apply to cases produced by carburizing, cyaniding, nitriding, carbonitriding, induction hardening and flame hardening. Case depth is usually determined either by direct measurement, by chemical analysis or by measurements of hardness. Other methods have been used but are not important enough to warrant discussion here.

Direct Measurement. This method, in its various modifications, is the one most commonly used. It can be applied to any type of case in the hardened state, and also, with certain limitations, to unhardened cases where a difference in composition distinguishes the case from the core.

Regardless of the process by which they are produced, all cases are characterized by a transition zone in which the case blends into the core. This blending of case and core may be so gradual that no sharp line of demarcation can be observed. The usual practice is to measure from the outer edge of the case to the line where the case ends, estimating as accurately as possible when the "end point" is indistinct.

The accuracy of measurement, as determined by the distinctness of this "end point", is influenced by a number of factors, such as composition of core, composition of case, previous heat treatment and method of preparing the sample. Differences in quenching temperature and the degree of hardening may influence the apparent case depth appreciably. A possible source of error is the angle at which the specimen is sectioned. It is essential that the measurement be along a line normal to the outer surface of the case.

The several methods employing direct measurement are:

Scale Measurement of Rough Fracture. This method is approximate only and should be standardized by scale measurements of a highly polished cross section by means of a high-power microscope. Carbon steel test plugs, water-quenched and properly standardized with the high-power microscope, are often helpful in checking cases in alloy steels that are difficult to measure.

This method applies only to cases in the hardened state and is usually limited to carburized cases. The measurement can be made either with the unaided eye and a suitably graduated steel scale (preferably in hundredths of an inch), or with a low-power microscope (× 10 to 15) containing a suitable scale. A Brinell microscope answers the purpose well. The fractured surface may be either untouched, etched or blued before measurement. Untouched fractures can be measured with fair accuracy when the core hardness is sufficiently low to provide good contrast between case and core. Hard cores usually require coloring by either etching or bluing. Etching is used extensively and produces good results; cold nital is the usual reagent. Bluing offers an effective method for producing the required contrast. Any means of heating may be employed that will develop the necessary temper colors.

Scale Measurement of Rough-Polished Cross Section. Of the various methods involving direct measurement, this is the one most extensively used; it is considered more accurate and dependable than measurement of rough fracture. As mentioned above, standardization with the microscope and the use of carbon steel test plugs are recommended for increased accuracy.

Although approximate results can frequently be obtained in measurement of unhardened cases, the use of this method is generally confined to cases in the hardened state. The required contrast may be developed by etching, bluing or shot blasting. Etching is the usual method.

Scale Measurement of Highly Polished Cross Section, Using High-Power Microscope. Both hardened and unhardened cases can be measured by this method with a high degree of accuracy. This is essentially a laboratory method and requires trained personnel. Magnifications of × 100, made by using an eyepiece equipped with a scale graduated in thousandths of an inch, are suitable for a wide variety of work. Either cold nital or cold picral is the usual etching reagent. This method provides greater accuracy than measurement either of rough fracture or of rough-polished cross section, especially where it is desired to measure the individual zones, or where it is difficult to develop the necessary contrasts.

Chemical Analysis. Successive layers are machined from the surface and subjected to chemical analysis in this method, which can be applied only where the case is machinable and different in composition from the core, as in work that has been slowly cooled or quenched and tempered after carburizing. This is strictly a laboratory method, slow and costly. The chief value of it is in research work and in control of case composition.

Hardness Measurements. This method applies only to cases in the hardened state. The sample may be either taper-ground, step-ground or sectioned in a plane normal to the surface. A series of hardness measurements (a traverse) is then made across the section by means of a suitable indentation test. This is primarily a laboratory method and requires the utmost precision if dependable results are to be expected. The accuracy decreases as the case depth decreases. The preparation of the taper-ground and the step-ground specimens is more exacting, but the readings can be more accurately spaced than with the samples sectioned normal to the surface. On the other hand, the readings from the taper-ground and step-ground samples are subject to error because of the effect of the softer underlying metal. In spite of the difficulties just mentioned, the various modifications of this method are coming into more extended use. The main application in the past has been in research work. Recently the use of hardness measurements has been extended to production control. Large quantities of nitrided work have been produced under specifications calling for minimum hardnesses at the surface and at a given depth. Both taper-grinding and step-grinding have been used for this purpose.

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Prepared for the Subcommittee on Carburizing.

Pack Carburizing

BY H. W. MCQUAID*

WHEN solid carburizers are used, carbon is formed on the surface of steel by the decomposition of carbon monoxide into carbon and carbon dioxide. The carbon dioxide that is formed reacts immediately with the incandescent carbon in the compound to produce fresh carbon monoxide. This process is repeated as long as there is enough carbon present to react with the excess of carbon dioxide. The decomposition of carbon monoxide occurs at the surface of the steel, which must be at such a temperature that the carbon formed will dissolve in the steel.

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Prepared for the Subcommittee on Carburizing.

Carburizing Compounds. The usual commercial carburizing compound contains a mixture of approximately 20% alkali or other metal carbonates bound to a hardwood charcoal by oil, tar or molasses. This carbonate energizer is generally in the form of barium carbonate with occasionally a small percentage of sodium and calcium carbonates. Approximately 20% of coke is usually added as a diluent. The presence of the coke increases the rate of transfer of heat through the compound and hence is valuable in obtaining uniform temperatures.

Because of the loss of the carbonate energizer, the powdering of the compound and the burning in service, new

compound must be added before the carburizer is used again. It is necessary to have approximately 8% of the carbonate energizer present in the mixed compound. A percentage greater than this has little effect on the rate of carburization, whereas a decrease in the amount of energizer to less than 8% retards the carburizing action and decreases the maximum carbon content of the surface. The addition of new compound will vary according to the care used in handling, the amount of direct quenching that is done, and the type of binder used in the compound. If care is taken in the selection of boxes and the handling of the compound, it is possible in most plants to utilize at least five parts of old compound with one part of new, and some plants are operating with even smaller additions of new compound. In many plants, however, the conditions are such that more new compound is required and it is not unusual for plants to make an addition of one part of new compound to three parts of used compound.

Several carburizing compounds available do not consist essentially of charcoal coated with a carbonate energizer. Carburizing compounds have been made from various combinations of organic materials, such as charred leather, burned bone, raw bone, or bone with charcoal. When applied properly, these compounds will give satisfactory results. However, they are relatively expensive and if no energizer is used, the carburizing action is slow. Large quantities of bone-black compound containing a comparatively low percentage of energizer have been used for applications where low-carbon cases are desirable. Large quantities of a carburizing compound have also been used, consisting of very dense charcoal impregnated with a water-soluble energizer; these compounds will usually give satisfactory results. Some compounds on the market vary greatly from the standard by substitution of a special type of coke for charcoal. Other compounds that have been developed do not use a carbonate type of energizer.

Special compounds have been developed to resist burning when in contact with air at carburizing temperatures. These compounds usually have a binder in which the energizer is mixed before coating and the material is preheated to incandescence during manufacture. Compounds of this type are important in operations where work is quenched directly from the carburizing box.

Selection of Carburizing Compound. In the selection of a carburizing compound, many factors should be considered. The handling equipment is important as well as the quenching methods. When the work pieces are cooled in a well-designed box where the compound is not subject to exposure to air while at red heat, it is not necessary to give much consideration to the burning characteristics. Where there is much quenching from the box, the rate of burning is an important economic factor and should be considered in selecting a compound.

Since the amount of new compound to be used is determined by the amount of energizer retained in the used compound, the method of incorporating the energizer is important. The cost of a compound should be based on the number of pounds of steel that can be satisfactorily carburized per pound of compound.

The coated compound is at a disadvantage when compared with the impregnated compound, except where handling and cooling conditions are exceptionally favorable. However, if no attempt is made to take advantage of a more stable compound by increasing the ratio of used compound to new, then the more expensive compound is of little advantage.

Packing. The packing of pieces in a compound is a dusty and disagreeable operation. For this reason the grouping of boxes, work pieces and compound should be carefully planned so that the compound will require a minimum of handling. The work pieces should come to the packer, if possible, already stacked and sorted, preferably on open trays or in pans.

A layer of compound is first put into the empty box. This layer should be approximately 1 in. deep, although with lighter work pieces the depth can be reduced to ½ in. The amount of compound that is used should be kept to a minimum, which depends on the design of the box and the type of piece. If the boxes are warped badly, more compound must be placed on the top to prevent exposure of the steel by burning away of the compound. Ordinarily with alloy boxes much less compound is required than is commonly used. The compound is an excellent heat insulator; the metal is a very good conductor. Therefore, if the amount of compound is increased to even a little more than the minimum necessary to support the work material, an immediate and important increase in heating time will result. An increase of ½ in. in the compound between the work pieces and the wall of the box is equivalent to increasing the wall thickness of the box by many inches.

It is the usual practice to remove the dust and fine particles by screening, and between rough handling and the screening a large percentage of energizer and charcoal is wasted. The ordinary coated charcoal compound is extremely friable and must be handled with great care. If due attention is given to this problem the amount of compound used can be greatly reduced. Some of the conveyers, storage arrangements, and cleaning devices destroy so much carburizing compound that they become a liability rather than an asset.

Boxes for Carburizing. Heat-resistant alloy boxes have become quite standard, but there are still many applications where rolled steel or cast steel boxes have an advantage. The heat-resistant boxes are usually made from a nickel-chromium alloy. The heat-resistant alloy can be obtained either as sheet or as a casting. Each type has its advocates. The cast form is generally the less expensive, especially where boxes are of a nonsymmetrical design. It is possible to obtain the cast boxes with a wall thickness that compares favorably with that of rolled sheets; consequently there has been a general tendency toward reduction in thickness of the walls of cast carburizing containers. The sheet alloy boxes, ordinarily used for cylindrical shapes, prove quite successful in this application, provided the welding is properly done. Poor welding has caused a large percentage of the failures that have occurred in the use of sheet alloy boxes.

Before a decision that heat-resistant alloys are to be employed for carburizing boxes, the services expected from the containers should be thoroughly investigated. For boxes that are used infrequently, especially where the type of work piece to be carburized is large and nonsymmetrical in section, cast steel or welded steel plate often proves more economical than the much more costly alloy boxes. As a rule, however, where boxes are frequently used and the shape and size of the pieces do not require excessively large boxes, the best heat-resistant alloy will prove economical.

The design of the box* and the method of packing will influence the results of carburizing.

Whenever possible, pieces should be packed with their longest dimension vertical. This requirement is important for shafts and stem pinions. Vertical packing permits vertical quenching with the least tendency of the tongs to distort the hot steel.

Uniform heating is important, and therefore a cylindrical box is to be preferred to rectangular boxes, in which the corners heat at a different rate from the sides, and where the pieces in the corners come to temperature before pieces in the center. Center tubes should be used wherever possible. These can be designed as integral with the box or as separate parts, depending on whether or not they must be removed to facilitate handling the work pieces.

Temperatures for Carburizing and Depth of Case. For steels of the fine-grained type, a carburizing temperature between 1675 and 1700 F will be satisfactory. However, many carburizing furnaces operate at 1725 F or even 1750 F with good results; these are usually continuous furnaces with carefully controlled cycles.

To reduce the concentration of carbon on the surface of some steels, especially the higher-nickel alloy steels, lower carburizing temperatures are employed (1625 to 1650 F). The same temperature is used in some plants to reduce warpage to a minimum. For pieces that have a small section where the case depth must be controlled to a maximum of a few thousandths of an inch still lower carburizing temperatures are employed, and in some applications 1550 F is used with a bone-base compound low in energizer.

* R. W. Rousch and A. C. Dames, A Study of Commercial Carburizing Containers, Trans ASM 26, 646 (1938)

Even with the best of furnaces and practice at 1700 F, it is difficult to obtain a case depth that has a total variation of less than 0.010 in. from maximum to minimum in a given furnace load. Pack carburizing has disadvantages if a case less than 0.025 in. deep is to be produced, unless boxes are properly designed and pieces are efficiently packed to minimize variation in temperature. With the standard practice of today, case depths of less than 0.025 in. should not be specified for pack carburizing.

It is difficult to control the maximum carbon content in the case of a pack carburized part. In pack carburizing, the rate of evolution of carburizing gas is fixed and is virtually always in excess of the amount required to supply the necessary carbon for ■ saturated surface, so in this process it is customary to obtain ■ saturated outside surface layer. If the energizer is deliberately controlled to reduce the carburizing effect (and ordinarily none but a bone compound can be controlled easily), it is possible to obtain cases of lower carbon content than the maximum that would be obtained under ordinary conditions at the carburizing temperature. The total carbon content in excess of the eutectoid composition will be greater as the carburizing temperature increases, because the solubility of carbon in austenite increases with increasing temperature.

Furnaces for Pack Carburizing. The fundamental requirement of pack carburizing is the control of variables that affect the temperature of the steel. The first problem is to secure a furnace that can be controlled within plus or minus 10 F, heating uniformly throughout within 20 F.

Many of the so-called "standard" box-type furnaces on the market, especially those built for oil fuel, are unsuitable for carburizing because of the great variation in temperature from one point to another. This type of furnace is likely to have a low temperature near the door and a high temperature at the back. Compensation is often arranged by placing in the back of the furnace the pieces requiring a deep case, and placing in the front the pieces requiring a lighter case.

Where the volume of production will permit, a pusher type of continuous furnace is desirable. The economic justification for this type of furnace is closely related to the design of the boxes and to the depth of case required. Where case depth is not too great and where boxes are designed to reduce the heating time to ■ minimum, the continuous pusher type of furnace has many applications. With careful attention to box design, the depth of case can be held to reasonably close limits, even though the pieces differ greatly in size. Careful attention is required in order to approach uniformity of steel temperature at approximately 1500 F, at which temperature the carburizing rate is low. When a minimum of compound is used, the over-all carburizing time can be reduced and a wide range of commercial pieces can be carburized to a depth of 0.040 to 0.050 in. in 4 hr at 1700 F.

Pusher furnaces are designed to have the exit end of the furnace at the carburizing temperature to facilitate quenching from the carburizing furnace and also to permit air cooling of the box, which is sometimes desirable. At one time counterflow furnaces were employed, designed to utilize the high heat content of the finished pieces in preheating the cold steel moving in the opposite direction. These furnaces were considered desirable because of the great economy of fuel, especially when electrically heated. It was found, however, that the very slow cooling of the heated pieces—especially at temperatures higher than 1000 F—was detrimental to good case hardening, because of decarburization. A continuous pusher furnace should allow approximately 50% more production than a batch-type furnace that has the same clear hearth area of 16 sq ft.

The continuous furnace will produce more uniformly carburized pieces, with lower cost of fuel and container. The actual cost depends on the design of the container and the heating characteristics of the continuous furnace.

Rotary retorts like those used for gas carburizing are sometimes used with compound. This operation is most satisfactory for small pieces, because they are continually agitated during the slow rotation of the horizontal retort. With large quantities of small pieces, the movement insures good contact with the compound, which acts not only to furnish carbon but also to cushion and protect the steel. The ease of loading and unloading facilitates the carburizing of small parts when the rotary retort is used.

Gas Carburizing

By J. A. Dow*

IN GAS CARBURIZING, the carbon of the furnace atmosphere is in the form of gaseous hydrocarbon compounds or carbon monoxide. In order to transfer the carbon to the steel, the gaseous compounds must react with the steel on the surface or in the immediate subsurface of the work.

The chemical reactions involved can be exemplified by the following equations:

$$CH_4 \rightleftarrows (C) + 2H_2 \quad (1)$$

$$C_2H_6 \rightleftarrows (C) + XCH_4 + YH_2 \quad (2)$$

$$C_3H_8 \rightleftarrows (C) + XC_2H_6 + YCH_4 + ZH_2 \quad (3)$$

$$2CO \rightleftarrows (C) + CO_2 \quad (4)$$

$$CO + H_2 \rightleftarrows (C) + H_2O \quad (5)$$

where (C) is carbon dissolved in austenite.

For an understanding of the part that each of the above reactions plays in gas carburizing, the reactions must be studied not only with regard to the weight of carbon available per unit volume of the reactants, but also with regard to the concentration of reactant that must be maintained in the gas surrounding the steel, if carbon is to be supplied to the steel at the desired rate.

A measure of the weight of carbon available per unit volume of reactant, is indicated by a study of the equilibriums of the five reactions at carburizing temperatures. The equilibrium data required for this work have been obtained largely by experiment, and by the use of the principles of thermodynamics expounded by Lewis and Randall.[1] The results of a study of reactions (1) and (4), based on equilibrium constants, appear on page 678 of this Handbook. The figures on the available carbon in CO and CH_4 are based on the assumption that reactions (1) and (4) proceed until they are in equilibrium with the austenite of the surface of the steel. However, hundreds of analyses of the atmosphere surrounding the work pieces in commercial furnaces for gas carburizing show that the concentration of CH_4 in an atmosphere must be many times the concentration that would be in equilibrium with saturated austenite, in order to carburize at a commercially acceptable rate and to produce the desired surface carbon content. Laboratory experiments* that were made with gas mixtures treated for the removal of hydrocarbons heavier than CH_4, further substantiate this. In none of these experiments was a saturated austenite case produced in four hours or less at 1700 F by a gas mixture free from decarburizing agents, and containing as high as 250 times the concentration of CH_4 for equilibrium with saturated austenite. Carbon contents closely approaching saturation were, however, formed in a 16-hr test.

In contrast with the experimental data above, experience indicates that reactions (4) and (5) are very rapid; that a carbon monoxide atmosphere quickly brings the surface

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of the steel to a carbon content almost in equilibrium with the atmosphere, or will itself change rapidly in composition until the gas mixture and the steel surface come close to meeting equilibrium requirements.

It may therefore be concluded that the rate of the reaction involved must also be considered before the amount of carbon available for carburizing in a reactant gas can be calculated with assurance; and that the degree of advancement that the reactions can attain, as shown by their equilibrium constants, is no indication of their relative reaction rates.

The rate at which carbon diffuses into steel, and the factors governing this rate, are discussed in this Handbook on page 678, and in greater detail elsewhere.[2] It should be noted that this rate is a variable, much faster in the early part of a carburizing cycle than in the later stages; and since the rate at which carbon is supplied to the steel by the reactions indicated above, must be related to this varying rate of diffusion, the subject of gas carburizing must be primarily a study of the rates of the reactions involved.

Factors Influencing Gas Carburizing. In the absence of more definite data, the following observations or comparisons will be of value toward an understanding of the reactions listed above. Such an understanding is necessary for intelligent control of gas carburizing.

1 Effect of Time. When a constant surface carbon content is maintained, the demand of the steel for carbon varies inversely as the square root of the elapsed time of the cycle (*see* page 679 of this Handbook). It follows from this and the discussion above, that when carburizing with CH_4 it is necessary to reduce the concentration of the CH_4, as the cycle progresses, leaving just enough to satisfy the demand of the steel for carbon, if the most desirable operating conditions are to be attained. In practice, when carburizing to saturated cases, the atmosphere is usually too weak to produce a saturated austenite surface the first few minutes at operating temperature, and is more concentrated than necessary in the later stages.

2 Source of Carbon. In all commercial atmospheres used today for gas carburizing, two or more hydrocarbons react with the steel, supplying it with carbon. Although the source of carbon may be a pure propane, other hydrocarbons, principally methane, will be formed in the initial pyrolysis of the propane and can themselves add carbon to the steel; and all natural gases contain appreciable percentages of hydrocarbons heavier than methane.

3 Hydrocarbons. The hydrocarbons encountered in gas carburizing atmospheres can be classified in three groups, in terms of their relative rate of breakdown when exposed to surfaces at carburizing temperatures.

Group I methane
Group II ethane and propane
Group III oil vapors

The gases in groups II and III apparently break down, at carburizing temperatures, from 30 to 300 times as fast as CH_4, when present in equal concentrations.[3]

4 Hydrogen Concentration. An atmosphere containing just enough methane to be in equilibrium with saturated austenite, will quickly carburize an infinitely thin piece of steel (in which diffusion of carbon from the surface does not take place) to a carbon content closely approaching saturation. From the definition of the equilibrium constant of reaction (1), namely, $K = (CH_4)/(H_2)^2$, the concentration of methane in such an atmosphere may vary over a wide range and is proportional to the square of the hydrogen content of the atmosphere.

To illustrate, an atmosphere containing 0.05% CH_4 and 19.95% H_2 would be in equilibrium with saturated austenite at 1700 F (*see* curve, page 680 of this Handbook), whereas in an atmosphere with only 2% H_2 this same methane content would be almost 100 times the concentration for equilibrium with saturated austenite. In spite of equal methane concentrations, the latter atmosphere has the necessary potential to supply carbon many times as fast as the first atmosphere, to a steel part being carburized and whose surface composition approaches saturated austenite.

It may be for this reason that the major part of the carbon of hydrocarbons supplied to a furnace seems to enter the steel if the hydrogen content of the furnace atmosphere is low; whereas by comparison between the compositions of input and effluent gases, less than 30% of the calculated available carbon is generally usable in atmospheres containing 40 to 50% H_2. The remainder leaves the furnace as undecomposed hydrocarbon. This undecomposed hydrocarbon serves as a reservoir of carbon that may be drawn on if the furnace load is increased, with a lesser sacrifice in the surface carbon content of the case produced than if the effluent gas were very low in hydrocarbon—a condition that has been reported with low-hydrogen atmospheres.

5 Methane Content. Measurements of the methane content of a furnace atmosphere can readily be made by conventional methods of gas analysis and are generally used along with measurements of case depth to control the operation of continuous furnaces. From the above discussion (1) the demand of steel for carbon as a function of the length of the carburizing cycle, (2) the ethane and propane content of the gas supply, and (3) the hydrogen content of the furnace atmosphere, all affect the methane concentration required to produce a result. Other factors, such as rapidity of circulation of the atmosphere, the amount of free space in the furnace load, sulfur content of the atmosphere, probably also affect the required methane concentration. For this reason, comparisons of the methane concentration required in two different furnaces cannot by themselves mean much, but in any single furnace if certain conditions outlined below under Furnace Operation are met, methane determinations are quite satisfactory as an indication of the carburizing activity of the atmosphere.

Analyses of gas samples from a continuous furnace usually show some variation in the methane content in different parts of the furnace; but by extreme means only, if at all, can the methane content be made to vary enough to maintain the same surface carbon content on parts in the various zones as the parts progress through the furnace. In contrast, the hydrocarbons of Group II, with a lower diffusion rate and a much higher rate of breakdown, should be more readily usable to vary the carburizing activity of the atmosphere throughout a furnace so as to satisfy the demand of the steel for carbon.

In any given furnace, the methane content of the atmosphere required to produce a certain desired surface carbon content of case, less than saturation, seems to vary approximately as the square of the fractional degree of saturation of the desired case. For this reason the operation of a continuous furnace to produce cases of less than saturated carbon content and within commercial tolerances, is not too difficult and the operation is not particularly sensitive to minor variations in loading.

6 Overactive Atmospheres. Carburizing atmospheres may be considerably more active than is required to maintain a saturated case and still not deposit soot in detrimental quantities on the surface of parts that are being carburized. However, these overactive atmospheres can carburize to carbon contents, at the surface, that are well above saturation values, a phenomenon particularly noticeable with certain steels. Naturally, these highly active atmospheres permit considerable variation in concentration throughout a furnace, with no noticeable effect on the uniformity of the case, and are particularly good in penetrating blind holes and crevices.

7 Effect of Carbon Monoxide. In contrast with methane pyrolysis, the reactions represented by equations (4) and (5) above have very high rates, and will quickly carburize or decarburize a part, or the system will adjust itself by change in reactant concentration until the atmosphere and the surface layer of the part closely approach equilibrium conditions. In fact, if reactions (4) and (5) are on the decarburizing side, they determine the effect of an atmosphere, even though it has a high methane content.

8 Sampling for Analysis of the Gas. Obtaining representative samples of the atmosphere surrounding parts that are being treated is quite easy for the determination of compounds that react slowly—methane, for example—but can be almost impossible for quickly reacting substances such as carbon dioxide and water vapor. The amount of these quickly reacting gases contained in the atmosphere at the surface of the steel may be quite differ-

ent from the amount in any open spot where a sample can be taken. Rapid circulation of the furnace atmosphere will reduce the amount of error in sampling.

9 Sulfur. Sulfur compounds in the furnace atmosphere, in some manner greatly reduce the carburizing activity of the hydrocarbons. Even extremely high concentrations of hydrocarbon may produce cases of 0.6 to 0.8% C max with sulfur present in any quantity, and the depth of hardenable case produced in a given time is reduced along with the reduction in surface carbon content. Less soot is deposited in the furnace than would be expected. Traces of sulfur are not apparently injurious but sufficient data are not available to set a top safe limit.

The sulfur is apparently present, in the furnace itself, almost entirely as organic compounds probably in equilibrium with small percentages of H_2S. Lead acetate checks for H_2S have not proved a very satisfactory indication of the total sulfur content of the gas.

Sulfur can also be the cause of early failure of the alloy fixtures used for handling the work in the furnace.

Diluting Gases. Diluting gases serve three purposes in all gas carburizing: first, to avoid an excessively concentrated atmosphere adjacent to the gas inlets; second, to provide some slight movement of gas in the furnace; third and most important, to make it possible to feed gas to the furnace in sufficient volume to maintain a positive pressure at all points, while at the same time avoiding the necessity of adding too much hydrocarbon. In all continuous furnaces sufficient gas to flush the furnace vestibules adequately is mandatory, and is usually more than sufficient to maintain positive furnace pressure.

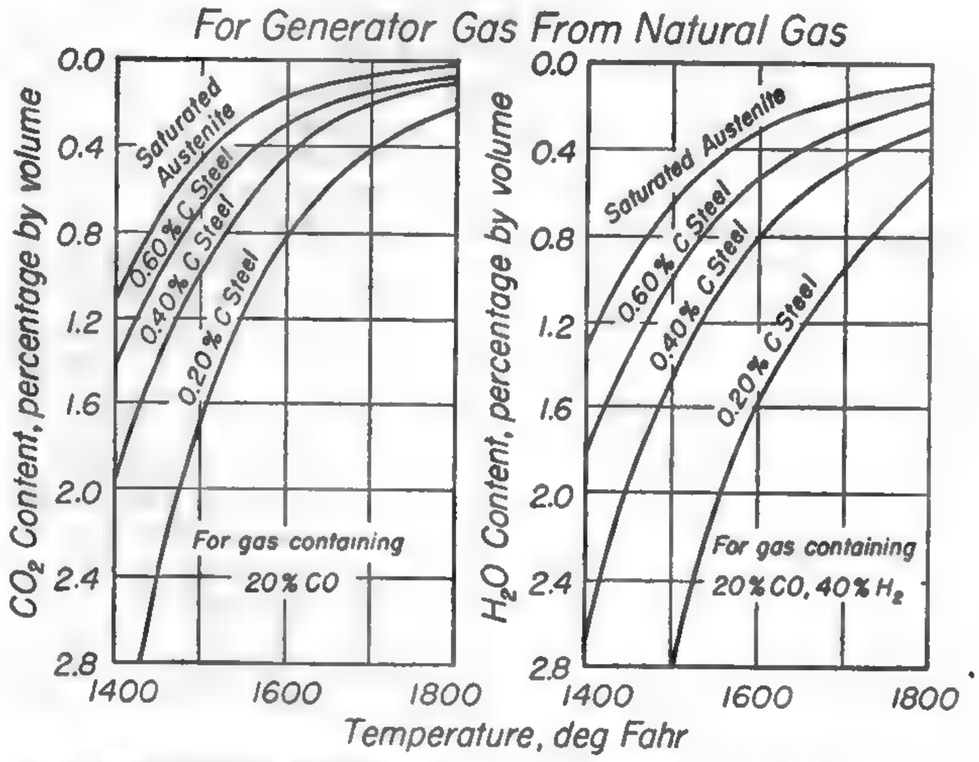

Fig. 1 Equilibrium curves for generator gas from natural gas

A good diluting gas must be neutral or only slightly carburizing in its action with high-carbon steel at the temperature of carburizing.

Decarburizing Diluents. The diluting gases first used in gas carburizing were air or slight variations from the gases now used for bright annealing low-carbon steel. All of them were actively decarburizing and required an excessive hydrocarbon addition to accelerate the intergaseous reactions by which the decarburizing agents were eliminated. This excessive hydrocarbon addition, in turn, caused soot to be deposited on the parts being treated. However, any reduction in hydrocarbon to avoid the deposition of soot often resulted in nonuniform carburizing, since the decarburizing agents were permitted to persist too long. No furnace should be operated with a diluting gas of this type.

Charcoal Gas. The first nondecarburizing diluting gas employed commercially was charcoal gas[4] made by passing air, or products of partial or complete combustion of a fuel gas, through a retort containing charcoal maintained at 1700 F or above. Here, by reaction with the charcoal, the gas mixture loses its decarburizing tendency and becomes mildly carburizing in its action.

Catalytic Gas Generators. The charcoal gas generator has now been replaced largely by one that produces an equivalent and very similar product, through the use of a catalyst, to accelerate the reactions shown below. An accurately controlled mixture of air and natural gas, or air and propane, first burns above the catalyst to form considerable carbon dioxide and water vapor, leaving an excess of hydrocarbon unchanged. This hydrocarbon then reacts on the heated catalyst with the carbon dioxide and water vapor, by the chemical equations below:

$$CH_4 + CO_2 \rightarrow 2CO + 2H_2$$
$$CH_4 + H_2O \rightarrow CO + 3H_2$$

In a well-designed unit little or no hydrocarbon in excess of that required by these reactions need be used, and the reactions proceed to the right to virtual completion.

This type of gas generator, first described by J. R. Gier,[5] has several advantages over the charcoal unit—chiefly the lower cost of maintenance, since there is no charcoal or ash to handle.

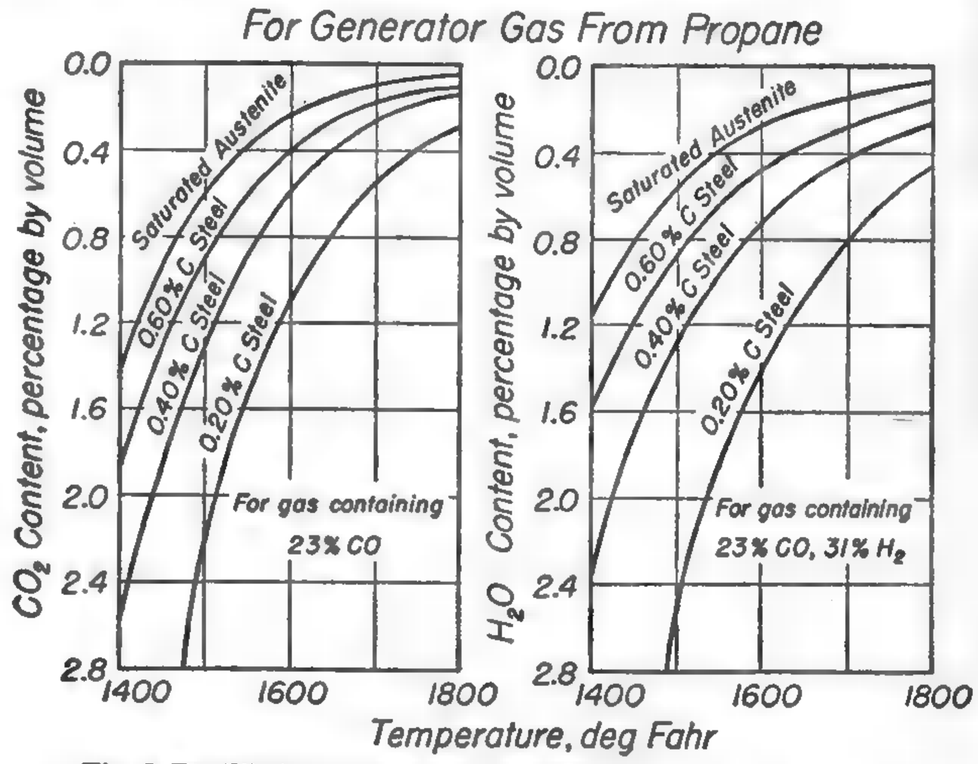

Fig. 2 Equilibrium curves for generator gas from propane

The following observations may be of value in the successful operation of one of these units:

1 For best results, the ratio of gas to air must be held within plus or minus 1% of the desired ratio. Any excess of gas causes formation of soot on the catalyst and this should be avoided as far as possible.
2 The activity of the catalyst decreases as soot accumulates on it.
3 The activity of a nickel catalyst is destroyed by gases containing sulfur.
4 Finely divided nickel deposited on a carrier is more active than an apparently equivalent surface of fused nickel or reduced nickel scale.
5 Finely divided nickel is much less active if overheated, a condition very difficult to avoid when burning out the generator, if any great amount of soot is allowed to accumulate.

The catalytic gas generator is also used widely for clean hardening, and since the requirements of a gas for clean hardening are closely related to those of a diluting gas for carburizing, the curves in Fig. 1 and 2 will be of value for both. These curves show at a glance the composition of gases prepared catalytically from natural gas and from propane, in equilibrium with any steel, at any normal operating temperature. For example, if it is desired to harden 0.40% C steel bolts at 1550 F, avoiding both carburizing and decarburizing, the composition of an atmosphere prepared from natural gas is obtained from Fig. 1. The 1550 F line intersects the 0.40% C curve at a point opposite 0.7% CO_2 on the ordinate of the curves for CO_2, and 1.1% water vapor (dew point, plus 48 F) on the water vapor curves.

Such an atmosphere can be made and controlled by varying the amount of air that is added to a constant volume of generator gas of the catalytic type. The addition of air should be regulated to keep the composition of the furnace atmosphere constant at these values.

Restoration of Carbon Content. In a like manner, decarburized parts may be returned to their original content

of surface carbon within commercial limits, by varying an addition of hydrocarbon or air (depending on the degree of decarburization) to a generator gas of the catalytic type, to maintain the CO_2 and H_2O contents of the furnace atmosphere at the values dictated by the original carbon content of the steel, and by the operating temperature. Figures 1 and 2 are useful here also. The time required at temperature to meet most commercial requirements is the time required to produce a case equal in depth to the total depth of any apparent decarburization. For uniformity of product, as well as for ease in obtaining representative samples of gas, circulating fans are advisable in this type of work and are mandatory for such parts as bolts loaded several layers deep.

Other Diluents. Diluting gases constitute a large percentage of the products of initial pyrolysis of certain liquid hydrocarbons that contain oxygen, and some dilution is brought about in this way in furnace atmospheres prepared from oil.[6] In general, the degree of dilution obtainable is less than is desirable, particularly in furnaces that have been used for some time, since all furnaces are likely to develop small leaks with use.

Coke-oven gas with several times its volume of spent carburizing gas drawn from the furnace chamber has been used successfully as a diluting medium for propane and for natural gas. A similar treatment of the water-gas type of manufactured gas has not proved successful.

Furnace Operation. Many of the requirements for successful control of a gas carburizing furnace can be deduced from the previous discussion and can be listed as follows:

1 Volume of Gas. Gas must be fed to the furnace in sufficient volume to flush any furnace vestibules adequately and to maintain a positive pressure at all points in the carburizing chamber. A furnace can be considered a low but very effective chimney. Infiltration of air tends to occur at the bottom of the chamber or around fan shafts where there is usually a low-pressure area resulting from the action of the fan.

This requirement normally dictates the use of a diluting gas that must be of proper and constant composition. Good practice calls for generous quantities, preferably constant in volume.

2 Regulation of the Hydrocarbon Addition. Carburization is controlled by regulating the hydrocarbon addition.

In the operation of batch furnaces, this addition should be reduced periodically (usually once or twice) as the carburizing cycle proceeds, more or less in accordance with the demand of the steel for carbon. The hydrocarbon addition is normally somewhat greater than that required for producing and maintaining a surface layer of saturated austenite. If cases lower in carbon are desired, a carburizing period can be followed by a diffusion period; that is, a period during which diluting gas only is fed to the furnace, allowing some of the carbon at the surface of the steel to diffuse inward. A reduction in the carbon content of the surface and an increase in depth take place.[7]

A recent article by Harris[8] presents a method of calculating the length of carburizing and diffusion periods to produce various gradients of carbon content.

In continuous furnaces the hydrocarbon addition is varied to maintain a constant methane content in the furnace atmosphere, but if the methane content is to be an adequate measure of the carburizing activity in a given furnace, the following must be held constant:

(*a*) Composition of the hydrocarbon supply.
(*b*) Composition and volume of the diluting gas. With a varying methane content in the diluting gas, the methane content of the furnace atmosphere cannot be a measure of its ethane or propane content and has been reported as a cause for poor control of the carburizing. (*See* Methane Content, page 689.)
(*c*) Proportioning the hydrocarbon supply to the various inlets.
(*d*) Adequate furnace pressure and flushing of the vestibule. Any infiltration of air can seriously upset the carburizing balance.
(*e*) Any uncontrolled addition of hydrocarbon (for instance, quenching oil fumes) must be avoided.

To produce cases with the surface carbon content below saturation in a continuous furnace, it is necessary merely to reduce the hydrocarbon content of the furnace atmosphere by reducing the volume of the hydrocarbon added. Unless proper precautions are taken, however, this may give an atmosphere too weak in hydrocarbon in the first carburizing zones, causing the formation of very low-carbon cases in the first few hours of the cycle. Then as the parts progress through the furnace, the surface carbon content and the case depth both increase, resulting in a much shallower depth of hardenable case than would otherwise be obtained in a given time. This phenomenon is most noticeable when the carburizing time is short—for example, less than four hours. From previous discussion, to avoid this it is necessary to have several times as great a concentration of hydrocarbon during approximately the first half hour of carburizing as in the last zone. (*See* observation 5 above.)

It is worth mentioning here that the method of carbon control described for recovering carbon at 1500 to 1550 F cannot be used successfully at 1700 F. Reference to the curves of Fig. 1 and 2 shows that methods of analyzing gas for carbon dioxide and water vapor are not accurate enough for control. But even if more accurate methods of analysis are developed, the speed of the reactions between these gases and hydrocarbons at 1700 F is too great for representative samples to be obtained.

3 Furnace Conditioning. A varying degree of furnace conditioning must either be prevented or compensated for. Most furnace alloys can be carburized and decarburized almost as extensively as steel, and the depth to which the alloy is carburized can affect considerably the rate of demand for carbon. Since the furnace alloy usually has a large surface area, considerably more hydrocarbon must be fed to a new furnace, or to an old one that has been left open at temperature for any long period, than to one that has been thoroughly conditioned. The furnace brickwork may also contribute to this phenomenon.

It is good practice to keep batch furnaces closed tightly whenever they are not in use, and to allow them to cool if the idle period is to be an hour or more. To test for the furnace condition, determinations of dew point or CO_2 can be made on the effluent gas from an empty furnace at temperature, while diluting gas only, or diluting gas with about 10% of the normal addition of hydrocarbon is being fed to the furnace. At 1700 F, the CO_2 content should not exceed 0.2% and the dew point should not exceed plus 10 F, if catalytic generator gas is the diluting medium.

Continuous furnaces require periodic burn-outs, which should be as rapid as the accompanying increase in furnace temperature will permit. The furnace should then be closed immediately and kept closed until it is to be prepared for operation. During this holding period, residual carbon in the furnace serves to recarburize the alloy partially. In preparation for carburizing, generator gas plus approximately 20% of the normal hydrocarbon addition should be fed to the furnace, until the dew point of the furnace atmosphere drops to plus 5 F or lower. Operation can then be started and the hydrocarbon addition can be increased to obtain the desired methane content in the furnace atmosphere. The volume of hydrocarbon addition required to maintain a desired hydrocarbon concentration usually decreases gradually for 48 hours or more, and then becomes fairly constant for a long period.

It is general practice to burn out continuous furnaces during week ends if required. On other week ends, the emptying of the furnace of stock may be avoided in many instances by shutting off the hydrocarbon addition and cutting the furnace control temperature to approximately 1350 F. Often this treatment reduces the carburizing rate to such an extent that the parts are not carburized beyond acceptance.

Comments. No attempt has been made to describe the many types of gas carburizing furnaces now being produced. The reader is referred to the furnace manufacturers.

The following additional observations may be of interest:

1 The life of cast heat-resistant alloy in carburizing atmospheres is apparently governed more by the soundness of the casting than by any other factor.

2 Rolled alloy is normally not subject to serious gas attack but may carburize. Rolled alloy is serviceable much longer than cast alloy, provided the structure is not subject to failure in welds.

3 The rate at which gas will attack furnace alloy is a

function of the penetrating power of the gas. (*See* observation 6 above.)

4 Oil fumes can be very objectionable in a continuous furnace because they contain sulfur; furthermore they tend to overcarburize protruding surfaces and to disturb the hydrocarbon balance otherwise.

5 It should be recognized that the gas carburizing process is still in a state where developments are coming in rapid succession, accelerated by the demand of metallurgists for cases that have the carbon content of the surface controlled within definite limits. Better methods of case control will probably be developed. Better instrumentation should play a large part in the progress of gas carburizing.

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Liquid Carburizing

By Robert J. Peters*

LIQUID CARBURIZING is a method of case hardening or carburizing steel or iron in a molten salt bath that contains the chemicals required to produce a case comparable with one resulting from pack or gas carburizing. Carburizing in liquid baths provides a convenient method of case hardening, with low distortion and with considerable flexibility and uniformity of control of the case.

Liquid carburizing may be distinguished from cyaniding by the character and composition of the case. The cyanide case is high in nitrogen and low in carbon. The reverse is true of liquid carburized cases. The rate of penetration of carbon in liquid carburizing is faster than that in cyaniding, at a given temperature. Cyanide cases are seldom applied more than 0.010 in. deep, but carburizing baths permit cases as deep as 0.250 in. For very thin cases, light-case carburizing baths may also be used instead of straight cyanide.

Chemistry of Liquid Carburizing. The carburizing action depends primarily on the sodium cyanide, activated or catalyzed by the presence of alkaline earth salts—usually barium, calcium or strontium salts. The formation of sodium cyanate is greatly reduced and less nitrogen and more carbon are liberated. The basic reaction may be represented by the equation:*

$$Ba(CN)_2 + 3\,Fe \rightarrow Fe_3C + BaCN_2$$

Barium cyanide + Iron → Iron carbide + Barium cyanamide

The carbon liberated by the shift from barium cyanide to barium cyanamide, is absorbed by the steel and the small amount of nitrogen available is absorbed, producing a beneficial effect on the file hardness of the surface.

Table I. Compositions of Liquid Carburizing Baths[a]

Salt	Composition, percentage — Light-Case Bath	Deep-Case Bath
Sodium cyanide	17 to 23	7½ to 12
Barium chloride	15 to 40	45 to 55
Other alkaline earths	0 to 3½	2 to 10
Potassium chloride	.....	5½ to 20
Sodium chloride	20 to 30	0 to 15
Sodium carbonate	30 max	30 max
Sodium cyanate	1 max	0.30 max

(a) R. S. Komarnitsky, Metal Progress, 50, 665 (Oct 1946)

For general use, the most economical operating range of liquid carburizing baths is 1550 to 1750 F. Higher temperatures may be used, providing faster penetration, but at increased material cost and deterioration of equipment.

Light-case baths, operating from 1550 to 1650 F and having an average cyanide content of 20%, produce cases as deep as 0.030 in. Deep-case baths average 10% cyanide and operate at temperatures of 1650 F and higher.

Composition of Bath. Compositions of light-case and deep-case baths are given in Table I.

* Chief Metallurgist, Warner Gear Division, Borg-Warner Corporation, Muncie, Ind. Prepared for the Subcommittee on Carburizing

* Barium cyanide is formed by reaction between sodium cyanide and barium chloride in the bath.

Although most of the carburizing baths use sodium cyanide as the active element, a proprietary bath utilizing calcium cyanide has been employed successfully, particularly for case depths up to 0.035 in. The calcium cyanide content of such a bath is approximately 0.5%. The most serious disadvantage of the calcium cyanide type of bath is the necessity for using approximately 70% of calcium chloride, a highly hygroscopic salt, which makes necessary special precautions to avoid rusting of the finished work.

Temperature and Duration of Carburizing. Carburizing baths operating at less than 1650 F produce case characteristics similar to those that result from cyanide, as the temperature approaches 1500 F. Nitrogen content increases and the carbon content decreases. At 1650 F and higher, the carbon content and metallographic characteristics of the case are similar to those from gas or pack carburizing.

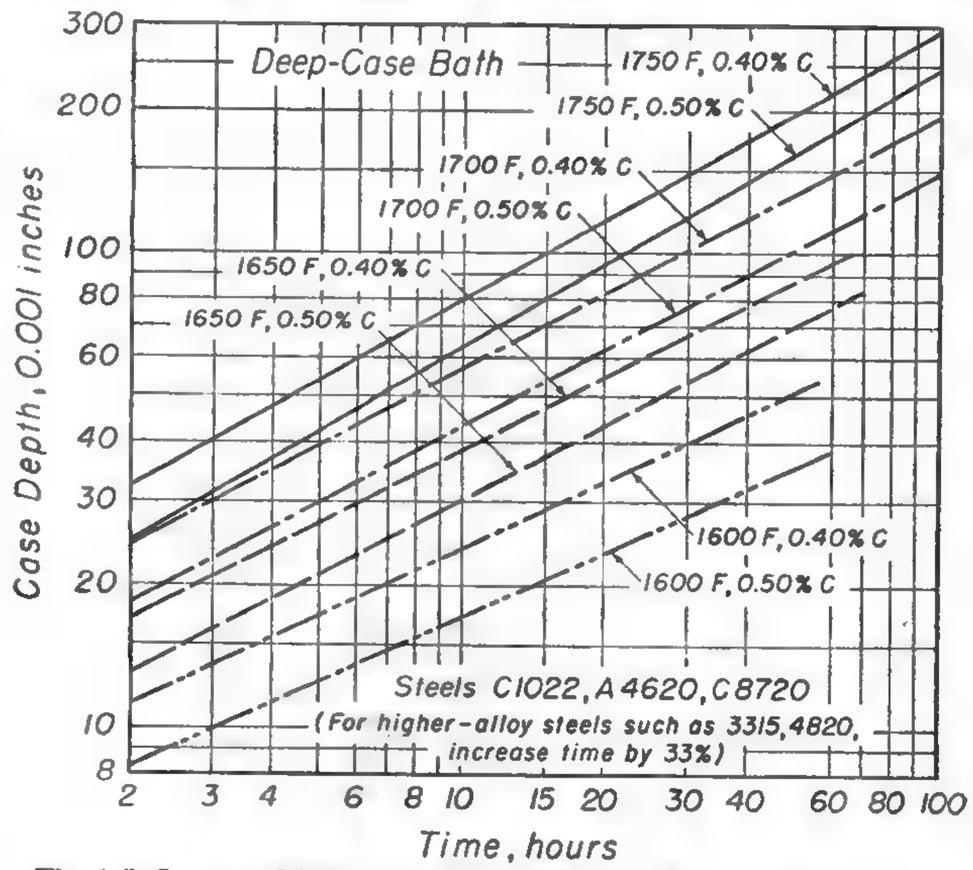

Fig. 1 Influence of time and temperature on the case depth of steels C1022, A4620 and C8720, carburized in deep-case bath (R. S. Komarnitsky, Metal Progress, 50, 665, Oct 1946)

Time-penetration values for various steels processed in light-case and heavy-case baths, are shown in Fig. 1 and 2.

Process. The mechanism of carburization in the salt bath is quite similar to that in other carburizing mediums. Sodium cyanide or barium cyanide supplies carbon and in the process some nitrogen is liberated. The article on "Mechanism of Carburization" in this Handbook (page 678) discusses the technical data and describes diffusion phenomena characteristic of all standard carburizing mediums, including those used in liquid carburizing.

Two types of mixtures are available for carburizing baths: one type contains all the ingredients in the proper balance to maintain continuous action; the other requires the mixture of a neutral base and activated cyanide.

Periodic addition of catalytic material keeps the bath in operating condition. The single bath is more expensive to maintain since drag-out replacement is usually insufficient to maintain the proper composition. Frequent ladling is therefore necessary to allow for make-up additions. The baths may be adequately controlled by analysis for cyanide and frequent checking of case depth.

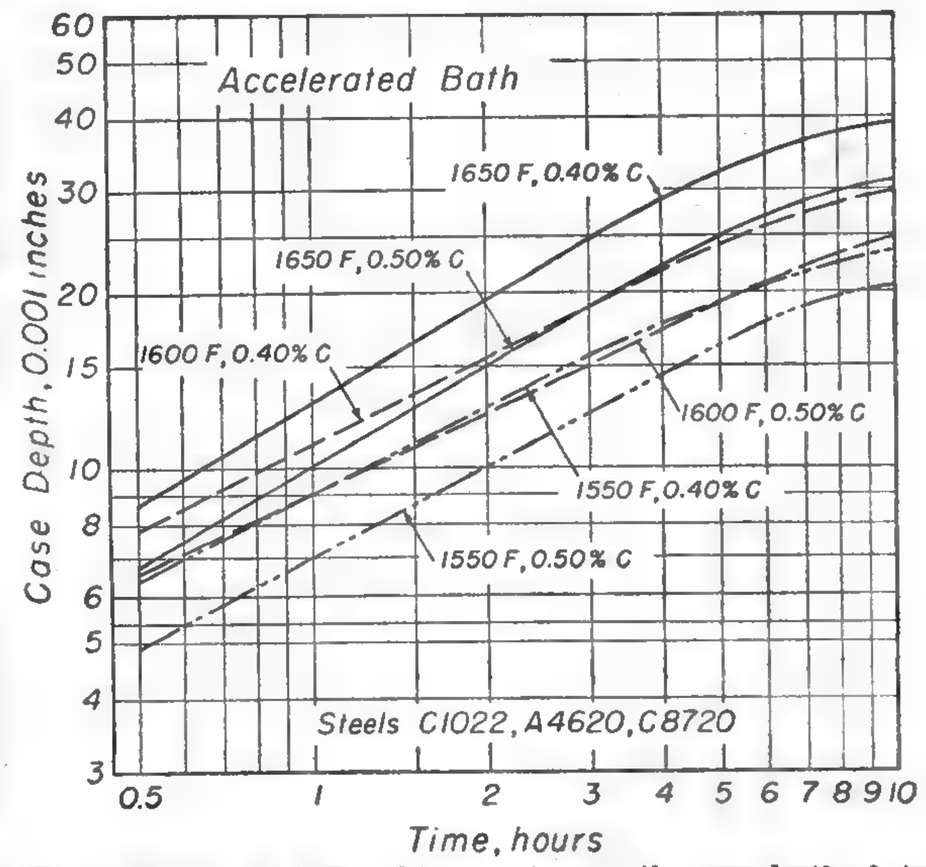

Fig. 2 Influence of time and temperature on the case depth of steels C1022, A4620 and C8720, carburized in accelerated (light-case) bath (R. S. Komarnitsky, Metal Progress, 50, 665, Oct 1946)

Liquid carburizing baths should have a "cover". This cover is ordinarily incorporated into the salts but may be produced or maintained by the addition of low-silica graphite to the molten bath.

Precautions. The precautions necessary for handling liquid carburizing salts are the same as for any cyanide mixture. Work material must be clean and dry and the bath must be enclosed and well ventilated. The raw material and baths contain cyanide but, when handled properly, this chemical should not present a serious hazard to health or safety.

Parts treated with accelerated salts and quenched in oil, may be cleaned in spray washers with clear water. Cleaning compounds often render deposits very hard to remove. Any white deposit remaining on a work piece may be removed by immersion in 2% hydrochloric acid, followed by a dip into an alkaline solution of 2 or 3 oz of soda ash per gallon.

Equipment. Two general types of equipment are available for external and internal heating. Baths operating at temperatures lower than 1650 F may be heated externally with gas, oil or electricity. Above 1650 F, internal electrode heating is almost imperative.

Cast steel pots give excellent results when properly installed and cared for. Heat-resisting alloy pots give proportionately greater service for low-temperature baths. High-temperature baths require alloy cast or welded plate containers. Ceramic containers with built-in electrodes are successful for liquid carburizing baths.

Specially designed pots and furnaces may also be adapted to operations in continuous sequence. Heat treating in liquid carburizing baths may be almost completely mechanized with consequent improvement in economy, uniform treatment of work in process and adaptability to continuous production.

Selective Carburizing

By L. A. Lanning* and R. W. Woodward*

SELECTIVE carburization is used when certain portions of the surface are to remain soft after hardening, in order to permit machining, polishing and straightening, to increase toughness and to control distortion.

Selective carburization may be obtained in many ways, but only the principal methods will be considered here. In practice, it is more difficult to obtain selective carburizing with gas carburizing than with pack carburizing.

Excess Stock at the Surface Portion Desired Soft. Excess stock is left at portions desired soft. After the carburizing operation, the piece is cooled slowly. The excess stock is then machined off to below the case so that the piece will have a soft surface area after the hardening treatment. For certain types of tool work or where few pieces are to be treated, this is an excellent method. Where threads or sharp corners are to be left soft, this method is perhaps the most reliable.

Sand Packing. The work is packed in sand so that only the desired portions are exposed to the carburizing compound. The line between the hard and soft portions will not be sharp, since the gas from the compound penetrates the sand to a slight depth. This method cannot be used with compounds that have a high shrinkage, because the sand will be displaced, causing hard spots at the protected points. The sand should be fairly fine, and reasonably free from dirt. It must also be thoroughly dried before packing; otherwise caking will occur, exposing surfaces that should be protected. It is an advantage to have the sand at the bottom of the carburizing container and to subject the container to as little jarring as possible after the pieces have been placed in it.

Covering Parts Desired Soft with Cement. For preventing carburization of tapped holes and bores of gears, a satisfactory method is to plug these parts with a cement made of finely sifted fire clay mixed with sodium silicate (water glass). The proportions (approximately 2 parts fire clay, 1 part sodium silicate, and 1/10 part water) should be regulated to secure a cement that will not crack or shrink excessively during heating and firing. The addition of sand to the cement will sometimes help to prevent shrinkage. After carburization the cement may be knocked out of the holes. Although this cement will form glass, it is possible to apply it carefully to external surfaces; but it is less satisfactory than other covering materials. Prepared cements are available.

Such parts as bushings, sleeves and piston pins are often strung on close-fitting steel rods, a practice that minimizes the case in the bore.

Covering Parts Desired Hard with a Carbonaceous Cement. Selective carburization is obtained by covering the portions to be carburized with a carbonaceous paste or cement, which acts as the carburizing compound. After the work pieces have reached the proper temperature, the portions covered with the paste are carburized and the other portions are unaffected. With this method, the case will not be sharp, but will gradually slope to the portion of the work desired soft.

Protection with Copper Forms. Copper, in the form of tubing, bars, cups, sleeves and disks, is used to prevent carburization of tapped holes, piston pins and ends of shafts. The copper form is placed on or in the work with a clearance of not more than 1/64 in. This method is not completely efficient but substantially decreases both the depth and the carbon content of the case.

Solutions or Pastes. Solutions or pastes are now available that are quite effective in preventing the carburization of surfaces to which they are applied.

Electrodeposited Copper. Electrolytic methods of copper plating are the most widely used where production warrants the expense of installation and operation. Copper plating is effective with most carburizing compounds, although with certain compounds copper does not prevent carbon from penetrating. Besides there is considerable

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difficulty in depositing the copper plate in recesses. Two methods may be employed when using copper plate:

Plating the Entire Piece. The entire piece is plated and then the copper is removed by machining or grinding from the portion which is to be hardened.

Selective Plating. By the use of suitable protective paints, copper plating can be applied so that the areas where hardness is desired remain free from copper. In the usual method a baking japan or suitable lacquer is painted on the area to be hardened and is then baked or dried. Then the plating may be performed in the usual manner, but no plate will form on the *covered* surfaces. In the carburizing operation the japan or lacquer burns off, permitting the carburizing gases to penetrate the areas that are desired hard. Masking may also be done with rubber or with wax stop-off.

The copper-plating operation is standard. The chief requirement is to produce a fine-grained, continuous plate. For compositions of plating baths, see page 718.

Precautions. Certain precautions must be observed for successful plating and selective carburizing.

1 The parts must be thoroughly cleaned before painting, and the japan or lacquer must adhere tightly.
2 Before the plating operation, the work must be chemically clean. Usually the pieces are first dipped into a metal cleaning solution, and are then washed in water, dipped into weak hydrochloric acid, washed in water, dipped into a cyanide solution and again washed. This procedure may seem elaborate, but it is necessary if complete protection is to be assured.
3 Care must also be taken to insure that the bath is of the proper concentration to give a solid continuous plate.
4 The thickness of copper plate necessary for protection depends on a number of factors, such as the plating method used, the duration of carburizing and the carburizing temperatures. However, for satisfactory protection in most carburizing work, a minimum plate of 0.0003 in. should be maintained.
5 Copper plating should not be subjected to oxidizing conditions before or during the carburizing operation, because the protection afforded by the plating will be destroyed.

The above methods for selective carburizing are successful under certain conditions, but their use depends largely on plant conditions and the type of work.

Cyaniding

By H. B. Northrup*

A HARD, superficial wearing surface or case can be obtained rapidly and satisfactorily on low-carbon steels by means of the cyaniding or case-hardening process. Steels treated by this method absorb both carbon and nitrogen from the molten salts; then when quenched in water or a suitable oil, they develop appreciable hardness in the case.

Because of greater efficiency and lower cost, sodium cyanide is now widely used instead of the more expensive potassium cyanide. For case hardening, sodium cyanide is used in either of two ways: (1) as a powdered mixture into which the red hot steel is dipped or which is applied to the heated surface of the steel; or (2) as a molten bath in which the steel to be treated is immersed long enough for the reactions to take place.

Caution. Cyanides are violent poisons if allowed to come in contact with scratches or wounds—for example, on the hands; they are fatally poisonous if taken internally. Also fatally poisonous fumes are evolved when cyanides are brought into contact with acids.

Properties of Sodium Cyanide. In the case hardening of steel, sodium cyanide is used in four different strengths or grades. Each of these grades, because of its chemical composition, has individual properties as shown in Table I.

Molten sodium cyanide is decomposed quite rapidly when heated above 1580 F in an open pot. The heavy white fumes that arise from the bath are not especially dangerous, although they are decidedly obnoxious because they irritate the mucous membrane in the nasal passage and thereby induce violent sneezing. When these fumes are disseminated in the air, they become almost entirely sodium carbonate, neither dangerous nor particularly detrimental to health or property, but annoying. The escape of the fumes can be prevented by the installation of equipment for gathering and washing fumes. The equipment includes a suction fan, which draws the fumes from the pots and passes them through a large washing drum and water spray (mist) before they are vented into the outside air. The washers and the spray dissolve the sodium carbonate fume and precipitate any solids carried by the ventilating apparatus.

The chemistry of the decomposition of the bath involves the oxidation of the sodium cyanide to sodium cyanate by the application of heat and exposure to oxygen in the air as follows:

$$2NaCN + O_2 = 2NaCNO$$

It is probable that, in order to carburize steel, the sodium cyanate (NaCNO) in the bath must exceed a definite minimum concentration and must be kept uniform by means of regular additions of sodium cyanide. Baths high in cyanide but free from cyanate have no carburizing action. Fortunately this condition is very rare, since the formation of cyanate is automatic, according to the reaction above. Continued heating of sodium cyanate in air forms sodium carbonate, carbon dioxide and nitrogen, as follows:

$$4NaCNO + 3O_2 = 2Na_2CO_3 + 2CO_2 + 2N_2$$

Sodium cyanide is a strong reducing agent in the molten state, readily reducing the oxides of most metals. It is deliquescent and gradually decomposes if left in an open container, because of the action of moisture and carbon dioxide. Sodium cyanide is soluble in water and the solubility of the anhydrous salt is almost independent of the temperature.

Uses of Sodium Cyanide. *96 to 98% Sodium Cyanide.* In the heat treatment of steel, powdered sodium cyanide (96 to 98% NaCN) is sprinkled on red hot steel, for case hardening; as a "sweetener" to replenish the cyanide content of depleted baths for case carburizing; as a bath material for carburizing directly with cyanide; and in admixture with potassium cyanide for nitriding steel by immersion in a bath.

75% Sodium Cyanide. This mixture is sometimes used as a bath for direct carburizing with cyanide, but because of the volatility of the cyanogen (CN) radical, the use of 75% NaCN in heavy production work is not recommended. More frequently 75% NaCN is used as a replenishing material to raise the cyanide content of depleted baths or to maintain concentrations by regular additions.

45% Sodium Cyanide. This mixture is recommended as a suitable bath for the general case carburizing of low-

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Table I. Properties of Sodium Cyanide

Grade	Percentage: Sodium Cyanide, NaCN	Percentage: Sodium Carbonate, Na_2CO_3	Percentage: Sodium Chloride, NaCl	Melting Point, deg Fahr	Specific Gravity at 77 F	Specific Gravity at 1580 F	Appearance
96 to 98[a]	97	2.3	trace	1040	1.50	1.10	White crystalline solid
75	75.3	3.5	22.2	1094	1.60	1.25	White fused solid
45	45.3	37.0	17.7	1058	1.80	1.40	White fused solid
30	30.0	40.0	30.0	1157	2.09	1.54	White fused solid

(a) This grade contains 0.50% sodium cyanate (NaCNO) and 0.20% sodium hydroxide (NaOH). The content of sodium sulfide (Na_2S) nil.

Table II. Case Depths and Carbon Concentrations[a]

SAE Steel No.	Temp, deg Fahr	Time at Temperature, hr	Case Depth, in.	Carbon, %
1020	1550	1	0.010	0.62
2315	1550	1	0.012	0.59
3115	1550	1	0.010	0.63
1020	1550	3	0.018	0.74
2315	1550	3	0.018	0.69
3115	1550	3	0.020	0.69
1020	1600	1	0.010	0.50
2315	1600	1	0.010	0.47
3115	1600	1	0.010	0.38
1020	1600	3	0.015	0.65
2315	1600	3	0.016	0.66
3115	1600	3	0.018	0.60

(a) Specimens 1 in. in diam by 6 in. long.

carbon and alloy steels. It is very fluid at the operating temperature. The addition of "inerts" (sodium chloride and sodium carbonate) to sodium cyanide tends to retard the decomposition of the sodium cyanide without being detrimental to the case carburizing properties. When this mixture is used continuously in production work, the strength of cyanide will need to be maintained nearly constant by addition of the 96 to 98% or the 75% NaCN.

30% Sodium Cyanide. When the case carburization of low-carbon and alloy steels is to be maintained under conditions of heavy production, 30% NaCN is preferable to any of the preceding mixtures. It has the lowest first cost and, because of the content of inert material, the decomposition of the sodium cyanide of the bath is greatly retarded without detriment to the case carburizing properties.

It is necessary to keep the strength of the bath constant by addition of either the 96 to 98% or the 75% NaCN. The 96 to 98% NaCN is preferable because of the absence of inerts in material of that concentration. The bath is already loaded with sufficient inerts to "fix" the concentrated material, which should be added in proper amounts at regular intervals. If the cyanogen content of the bath is too low, the bath tends to decarburize and cause scaling of the work material. "Drag-out" of the bath material is replenished by the 30% NaCN as needed.

The Cyanide Bath. Baths of sodium cyanide are employed as a heating or reheating medium in connection with the hardening of steels, or to prevent surface decarburization, thus producing work with a clean surface; and to act as a liquid medium for case carburizing, affording a quick, efficient and economical means of obtaining a hard superficial wearing surface. Baths to accomplish the first purpose are discussed on page 283. To accomplish the second purpose (that is, to act as a liquid medium for case carburizing) a bath regulated to maintain a uniform 30% NaCN concentration has been found to meet all the requirements.

When low-carbon and alloy steels are to be cyanided to produce a good wearing surface, the surface must usually be backed up by a fine-grained, tough core. This requires an operating temperature of approximately 1600 F in the bath. Case depths and carbon concentrations for three steels are given in Table II. These results show the inefficiency of cyanide as a medium for obtaining deep penetration of carbon. They also show that even after a 1-hr immersion, the carbon concentration is insufficient to account for the extreme hardness obtained from quenching cyanided steels. Usually immersions range from 30 min to 1 hr and produce case depths and carbon concentrations corresponding to those given in the table. Lowering the temperature will correspondingly and proportionately lower the results given in the table.

Since the results obtained in the practice of cyaniding steel are directly proportional to the four variables—time, temperature, mass, and cyanide concentration of the bath —the data in Tables III, IV and V, all derived from the heat treatment of SAE 1020 steel, show clearly the results of accepted practice involving these variables.

Within the range of time used in commercial cyaniding practice, almost the same depth of case is produced in steels of different compositions. The nickel and nickel-chromium steels give a nicer carbon gradient from case to core than do the carbon steels, but at the same time exhibit a lower concentration of carbon in the case.

The hardening properties imparted to the steel by the added carbon are not entirely responsible for the file hardness obtained after cyanided steel has been quenched in water. One of the decomposition products of a sodium cyanide bath is nascent nitrogen, and evidently some of this nitrogen combines with the iron of the steel, forming the extremely hard and brittle iron nitride.

Cases obtained by the cyanide process are hard and resist wear, although they do not contain the high concentration of carbon possible with solid carburizing compounds.

Generally, the steels that are case carburized by packing in solid carburizing material, or that are subjected to a carburizing gas, can also be carburized by cyaniding. They are usually treated by the liquid bath method because of some particular advantage of the process, such as speed of production, the economies of the process, or the peculiar quality of hardness desired in the resultant case.

Ordinarily, cyaniding should be carried out at a temperature just higher than the upper transformation point of the core, and the steel should be quenched directly from the cyaniding temperature. At this temperature the case, which does not approach a tool steel composition and which has not been held for a sufficient length of time to cause brittleness from excessive grain growth, will quench to the desired hardness, and the core will be thoroughly refined and tough.

Control of Temperature. Liquid carburizing and nitriding operations are usually performed under standardized conditions; namely, a standard weight of pot, a standard weight of salt per pot, a standard weight of steel treated for a standard length of time at a predetermined temperature, for any given set of physical requirements. Under these conditions, the "time to come to temperature" and the "time at temperature" can be standardized by controlling the temperature of the heating chamber.

"Nitriding" in a Molten Salt Bath. Molten cyanide salts have been widely adopted as an agent for increasing the surface hardness of high speed steel tools by building up the nitrogen content of the case. (*See* page 283.)

Quenching of Cyanided Steels. Whether to quench in oil or water depends on the requirements of the service for which the cyanided steels are intended and on the chemical composition of the steel. When water is used, it should be as free as possible from dissolved gases, which have a tendency to produce soft spots; so for straight hardness quenching, water should not be agitated by means of air. For maximum hardness and to minimize warpage, the water should be moving, except where long or thin cyanided parts are to be quenched, and normally it should be as cold as possible.

For oil quenching, a mineral oil should be used. The blended mineral-animal hydrocarbon oils should never be used for quenching cyanided steel, because the fatty matter of the animal oil will saponify with the decomposition product of the cyanide bath (alkali), causing the formation of a hard soap. This soap will retard the quenching speed of the oil and may also clog the drains.

Hardness of Cyanided Steels. The usual requirement for the hardness of cyanided steel for shop production is "file hard". This value of hardness is subject to many

Table III. Effect of Temperature and Duration of Heating on Depth of Case in SAE 1020 Steel

Temperature, deg Fahr	Immersion Time, min	Case Depth, in.	Immersion Time, min	Case Depth, in.	Immersion Time, min	Case Depth, in.
1300	15	0.00025	30	0.00050	45	0.00100
1400	15	0.00135	30	0.00250	45	0.00375
1500	15	0.00175	30	0.00400	45	0.00500
1600	15	0.00320	30	0.00480	45	0.00600

Table IV. Effect of Mass on Depth of Case in SAE 1020 Steel Cyanided at 1500 F

Diameter of Specimen, in.	Case Depth, in. 15-Min Immersion	30-Min Immersion
0.25	0.0045	0.0058
0.50	0.0035	0.0042
0.75	0.0030	0.0040
1.00	0.0027	0.0040
2.00	0.0025	0.0040
3.00	0.0023	0.0040

Table V. Influence of Sodium Cyanide Concentration on Case Depth in SAE 1020 Steel

NaCN in Bath, %	Case Depth, in.	NaCN in Bath, %	Case Depth, in.
1-in. diam bars, cyanided 30 min at 1500 F			
94.3	0.0060	20.8	0.0055
76.0	0.0070	15.1	0.0050
50.8	0.0060	10.8	0.0040
43.0	0.0060	5.2	0.0020
30.2	0.0060		

ramifications, but it is still the criterion for testing hardness in the shop. The Rockwell C impression and the scleroscope are also used for testing cyanided surfaces.

The depth of the cyanided zone is determined best by means of the microscope. The cyanided case is composed of two fields distinct in character—a martensitic outer zone and a troostitic inner zone of lower carbon content. The case depth is usually determined by measuring the distance from the outer edge of the specimen to the center of the second zone.

In steels that are cyanided and that do not contain more than 0.65% C in the case, the hardness cannot be attributed to the carbon content alone. Since one of the decomposition products of the cyanide bath is nitrogen, iron nitride, an extremely hard and brittle product, is formed. At the lower cyaniding temperatures (about 1425 F) a considerable amount of iron nitride is observed in the form of nitride needles and patches. When the temperatures are approximately 1550 F, few of the nitrides are observed, but it is generally accepted that this iron nitride in indistinguishable form produces the hardness otherwise unattainable from the additions of carbon.

Although the absorption of nitrogen affects the hardness of the case, by the formation of iron nitrides, the core is not affected. Steel of the proper grade, which has been cyanided above the transformation range of the core and quenched into water, will snap readily when subjected to stress. When the case is removed by grinding, the core is found to possess ductility. The apparent brittleness may result largely from a notch effect in the core after a crack has been formed in the hard case.

Cyanide Containers. Many types and compositions of cyanide containers have been used to hold the molten salts. Most of them are cylindrical with hemispherical bottoms; if the containers are rectangular, the corners are well rounded. They are constructed of gray cast iron, cast steel, pressed steel and cast nickel-chromium alloy, with the cost and the life both increasing in about the same order. This subject is discussed more fully in an article entitled "Salt Baths", on page 283 of this Handbook.

Carbonitriding (Gas Cyaniding)

By J. A. Dow*

CARBONITRIDING, known also as "gas cyaniding", "dry cyaniding", and "ni-carbing", is a process for case hardening a steel part in a gas carburizing atmosphere that contains ammonia gas in controlled percentages. Both carbon and nitrogen are added to the steel; the nitrogen serves chiefly to reduce the critical cooling rate of the case. The carbon content of the surface of the case is controlled as described in the article entitled "Gas Carburizing", on page 688. The nitrogen content of the surface is controlled by maintaining the desired ammonia content in the furnace atmosphere, through varying the amount of the ammonia additions.

When the work pieces are to be quenched, the ammonia content of the atmosphere need not exceed 1%, except for special surface requirements, and may be as low as 0.1%. For work that is to be cooled in an air blast, the ammonia content in the furnace atmosphere is usually between 1 and 5%. When the case is to be formed at 1300 to 1400 F and the steel is to be cooled slowly, the atmosphere may contain as much as 15% ammonia.

The nitrogen and carbon contents of a steel part after carbonitriding at a given temperature, decrease from the surface to the core, and since both nitrogen and carbon contents have a pronounced effect on the critical cooling rate, the depth of case must always be considered in terms of the depth of effective or hard case. Carbonitriding is no different in this respect from other methods for producing carbon-nitrogen cases—for instance, cyaniding.

Carbonitriding is normally carried on above the Ac_1 temperature of the steel and the process is practicable up to 1700 F. The depth to which carbon and nitrogen penetrate the metal, varies with temperature and time. The rate of penetration of carbon is apparently quite close to that obtained in carburizing (*see* page 678).

By far the widest application for carbonitriding is as a low-cost substitute for cyaniding. The operating costs may be as low as one-fourth the cost of cyaniding in modern electrically heated baths. Since both the carbon and nitrogen contents of the case can be controlled, the rate of cooling attained in an oil quench is as rapid as is ever required for file hardness of the surface. As in other methods of heat treatment, oil quenching has a marked advantage over water quenching, where distortion is concerned. The martempering form of quenching after carbonitriding, has reduced distortion still further on certain parts, and seems likely to become increasingly popular in the future.

Very small additions of ammonia to a gas carburizing atmosphere are sufficient to impart, to any of the standard carbon or low-alloy steels, sufficient hardenability for the attainment of maximum surface hardness with an oil quench. Frequently the immediate subsurface portion of the case is largely austenitic when the concentrations of ammonia used are high enough to give full hardening in oil to the low-carbon hypoeutectoid portion of the case. But in contrast with the low wear resistance that might normally be expected, such cases have been reported to wear many times longer than the best carburized or cyanided cases previously produced. After careful metallographic preparation, microscopic examination usually reveals a very thin layer of some constituent other than austenite or martensite on the immediate surface of a carbonitrided specimen, and the surface is file hard.

From the standpoint of operating cost, any method of carbonitriding without quenching should not be considered until the methods that involve quenching have been proved unsatisfactory because of excessive distortion. To reduce the critical cooling rate of a carbonitrided case sufficiently for it to have satisfactory hardness after quenching in an air blast, the ammonia addition must be increased so greatly that the operating cost is often doubled and in some instances trebled. However, these relatively high costs may be lower than the cost of liquid cyaniding. The file-hard surface constituent mentioned above has been formed successfully with gas quenching on a production basis. The formation of this constituent on the surface seems to depend as much on the carburizing activity of the gas as on the ammonia content; and when this constituent is formed either with oil or gas quenching, it will be file hard after subsequent tempering at 800 F. The

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Prepared for the Subcommittee on Carburizing

factors that govern the depth and hardness of this layer are not fully known. Depths of several thousandths of an inch have been attained and, when properly treated, such cases are extremely hard to the file, yet do not spall. The constitution of this layer is still unknown. It should not be confused with a similar-looking but apparently quite different layer formed with higher concentrations of ammonia at temperatures usually below 1450 F.

Cases formed by this high-ammonia, low-temperature treatment can vary markedly, not only in hardness but also in tendency to spall, and should be specified with care, from the standpoint of cost and of consistent quality.

The Ford Motor Company laboratories have done creditable work on the complicated problem of determining the constitution and variations in structure that appear in cases formed in high concentrations of ammonia (10 to 20%) at approximately 1400 F. This research, based mainly on X-ray diffraction, using the powder technique, indicates that in a case with a tendency to spall, a body-centered cubic structure is predominant, and that this constituent is probably a solid solution of nitrogen in ferrite. These investigators have observed that cases not inclined to spall usually contain both close-packed hexagonal and face-centered cubic constituents and show higher penetration hardness if the hexagonal structure predominates.* It is not certain that the hexagonal and the face-centered cubic constituents are present in cases formed above 1450 F and cooled in an air blast.

There is a need for research concerning the constitution and physical properties of these outer layers and the conditions under which they are formed. Carbonitriding is still in the experimental stage, although 40 or 50 continuous furnaces, with outputs ranging from 500 to 2000 lb per hr, are in daily use, and an increasing number of batch furnaces are employed for such processing.

*D. M. McCutcheon, private communication

Nitriding

By V. O. Homerberg*

THE NITRIDING PROCESS consists in subjecting machined and heat treated steel to the action of a nitrogenous medium—commonly ammonia gas—under certain conditions to be described later, whereby high surface hardness is imparted to the steel without necessitating any further treatment.

Nitriding can be accomplished with a minimum of distortion, because of the low temperature at which the parts are case hardened and because no quenching is required after exposure to the ammonia gas. Great wear resistance, retention of hardness at elevated temperature, increased endurance limit and resistance to certain types of corrosion are other properties imparted to steel by nitriding.

The particular alloy steels that are used for nitriding are known as nitralloy. They contain aluminum as one of the alloying elements. Compositions of the most commonly used nitriding steels are listed in Table I.

Table I. Compositions of Nitriding Steels
(All these steels contain 0.85 to 1.20% Al)

Steel	Composition, percentage C	Cr	Mo
Nitralloy 125 (Type H)	0.20 - 0.30	0.90 - 1.40	0.15 - 0.25
Nitralloy 135 (Type G)	0.30 - 0.40	0.90 - 1.40	0.15 - 0.25
Nitralloy 135 modified (Aircraft Specification)	0.38 - 0.45	1.40 - 1.80	0.30 - 0.45
Nitralloy N (3½% Ni)	0.20 - 0.27	1.00 - 1.30	0.20 - 0.30
Nitralloy 230 (Alamo)	0.25 - 0.35	.....	0.60 - 1.00
Nitralloy EZ (0.15 to 0.25% Se) (Type G with Se)	0.30 - 0.40	1.00 - 1.50	0.15 - 0.25

Note All these steels contain 0.20 to 0.40% Si and 0.40 to 0.70% Mn, except Nitralloy EZ, which contains 0.50 to 1.10 Mn.

Condition of Steel for Nitriding. Nitrided parts neither warp nor distort to any appreciable extent provided the residual stresses resulting from the machining and heat treating are removed before nitriding. Nitralloy should possess a sorbitic structure before nitriding. The steel is generally purchased in the heat treated condition. This is desirable whenever the articles are to be machined directly from bar stock. It is not necessary to use heat treated stock when forgings are to be made, since they must be heat treated after forging in order to refine the grain structure and to make them machinable.

Enough of the heat treated stock must be removed to eliminate all traces of decarburization; otherwise the case produced during nitriding will be very brittle at the surface and will tend to spall. Before nitriding, the steel should be reheated to a sufficiently high temperature (generally 1100 to 1300 F depending on the core hardness desired) to remove stresses that are produced during the rough machining. This reheating is generally done before the final machining or grinding operation.

A forging temperature of 1950 to 2200 F is commonly used. Quenching in a suitable medium, followed by tempering at 1100 to 1300 F, is common practice for producing a sorbitic structure suitable for machining and nitriding. Small sections up to 1 in. in diam or thickness are quenched in oil, while large sections are generally quenched in water from 1700 to 1750 F. In general, a Brinell hardness number of approximately 225 to 250 produces satisfactory machining properties.

For annealed forgings, the steel should be rough machined, then heat treated so as to have a sorbitic structure, after which the final machining or grinding is performed. Enough stock should be left for this final operation to ensure the complete removal of the decarburized layer that is produced during the heat treating operation.

Typical procedures to be followed for annealed, heat treated and forged nitralloy 135 and nitralloy 135 modified, are given below:

Procedure 1

Nitralloy 135 and 135 modified, in the annealed condition

1 Rough machine the annealed material. Leave at least $\frac{1}{32}$ to $\frac{1}{16}$ in. on a side for final machining after heat treating. The annealing can be performed by heating to 1700 F, and then cooling slowly. The material can also be softened by subjecting hot rolled bars to a subcritical anneal at 1250 to 1300 F.

2 Heat to between 1700 and 1750 F. Quench in oil or water, preferably water when sections exceed 1 in. in thickness or diameter. The recommended times at temperature for various sections, if heated slowly

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Table II. Average Mechanical Properties of Heat Treated Nitralloy 125(H) and Nitralloy 135(G) (a)

Steel	Tempering Temperature, deg Fahr	Yield Point, psi	Ultimate Strength, psi	Percentage Elongation in 2 in.	Percentage Reduction of Area	Brinell Hardness Number	Izod Impact, ft-lb
Nitralloy 125	1100	117,000	132,000	18.0	61.0	280	62
	1200	103,000	122,000	21.0	67.0	255	70
	1300	85,000	102,000	26.0	70.0	225	85
Nitralloy 135	1100	137,500	155,000	15.0	52.0	310	52
	1200	120,000	138,000	20.0	58.0	280	65
	1300	103,000	121,000	23.0	62.0	230	80

(a) The test specimens were quenched in oil from 1750 F and then tempered at the temperature indicated.

Table III. Mechanical Properties of Heat Treated Nitralloy 135 Modified[a]

Tempering Temperature, deg Fahr	Yield Point, psi	Ultimate Strength, psi	Yield Ratio	Percentage Elongation in 2 in.	Percentage Reduction of Area	Rockwell C Hardness Number	Brinell Hardness Number
1000	181,500	206,000	0.89	13.2	45.8	44.6	415
1100	165,000	181,000	0.91	15.5	54.3	41.0	368
1200	141,000	158,750	0.89	17.5	55.8	36.0	320
1300	125,000	145,000	0.86	20.5	64.5	32.0	285

(a) Composition: 0.39% C, 0.27% Si, 0.62% Mn, 1.63% Cr, 1.44% Al, 0.41% Mo
Tension-test specimens were quenched in oil after ½ hr at 1700 F, and then were tempered 1 hr at the temperatures indicated.

Table IV. Average Mechanical Properties of Heat Treated Nitralloy EZ[a]

Quenching Temperature, deg Fahr	Tempering Temperature, deg Fahr	Proportional Limit, psi	Tensile Strength, psi	Percentage Elongation in 2 in.	Percentage Reduction of Area	Brinell Hardness Number	Rockwell Hardness Number
As hot rolled		30,000	121,000	18.0	33.0	229	B 98
1700 in oil	1100	67,500	139,000	16.0	43.6	293	C 30
1700 in oil	1200	90,000	125,500	17.0	44.6	255	C 24
1800 in oil	1100	72,500	141,500	14.0	40.6	293	C 31
1800 in oil	1200	90,000	127,500	18.0	46.2	262	C 23
Annealed at 1400 F		42,500	93,125	26.0	52.7	179	B 90

(a) Allegheny-Ludlum Steel Corporation

to the quenching temperature, are approximately as follows:

1 in. or less	½ hr
1 in. to 2 in. inclusive	1 hr
2 in. to 3 in. inclusive	1½ hr
3 in. to 4 in. inclusive	2 hr

3 Temper at 1100 to 1300 F, depending on the desired core hardness. Hold at temperature for 1 hr or more, depending on size of section. At least 1 hr per in. of thickness is recommended.
4 Finish machine or grind.
5 Nitride.

Procedure 2

Parts machined from heat treated bar stock

1 Rough machine. Leave about ⅛ in. on a side for finish machining or grinding. In many instances only a few thousandths of an inch may be necessary.
2 Stress relieve by reheating to between 1100 and 1200 F. Hold at temperature for 1 hr or more, depending on size of section. Ample time for stress relieving should be allowed whenever this operation is necessary; this is especially important when freedom from distortion during nitriding is desired.
3 Finish machine or grind.
4 Nitride.

Procedure 3

Parts machined from forgings

Anneal forgings by heating to 1700 F. Then after slow cooling, follow the operations given in *Procedure 1*.

Alternate Treatment

1 Normalize the forgings by heating to 1800 F, and cooling in still air.
2 Heat to between 1700 and 1750 F, and quench in oil or water, preferably water, when the sections exceed 1 in. in thickness or diameter.
3 Temper at 1100 to 1300 F, depending on the desired core hardness.
4 Rough machine.
5 Finish machine.
6 Nitride.

Mechanical Properties. The mechanical properties of several nitralloy compositions are given in Tables II, III and IV. Standard specimens (0.505-in. diam and 2-in. gage length) were used for the tension tests.

Effect of Size on Mechanical Properties. The mechanical properties will vary with the size of section. Tables V and VI present the results of tests in which the specimens were taken longitudinally, as nearly as possible halfway between the center and the edge of the piece.

Judgment is required in using the tables given above. The mechanical properties will vary not only with the compositions of different heats of steel but also with the size of section. The properties given in Tables II, III and IV were obtained with sections not exceeding 1 in. in diam. Frequently specifications give minimum values.

Nitralloy 135 modified is widely used by the aircraft industry. U. S. Army Specification 57–107–28A requires the minimum mechanical properties given in Table VII. This specification states that the mechanical properties given in Table VII shall be met after quenching in oil or water from 1725 to 1750 F, and then tempering at a temperature not lower than 1100 F for 5 hr. Sizes up to 2 in. are quenched in oil; sections greater than this may be quenched in water.

The quenching temperature used in establishing the values given in Table VII was 1725 F, and the tempering temperature 1200 F. The 3-in. and 5-in. bars were water quenched. The test specimens were taken from the heat treated bars midway between center and edge.

Nickel Nitriding Steels. Nickel in nitralloy strengthens and toughens the case with a moderate decrease in case hardness; it also strengthens and hardens the core and thereby provides better support for the case. In steels that contain appreciable proportions of aluminum, nickel causes dispersion hardening, by means of which articles may acquire higher core strength and elastic properties during nitriding.

A typical example of the properties of nitralloy N is shown in Table VIII. The steel was quenched in oil from 1650 F and was then tempered at 1200 F.

Before nitriding, lower hardness can be obtained by tempering at a temperature higher than 1200 F, in order to promote machinability without affecting the final hardness of the core. The steel should not be tempered below 1100 F; otherwise precipitation hardening will take place, thereby rendering the steel difficult to machine. The precipitation hardening should occur only during nitriding.

Nitriding of Steels with High Core Hardness. Special steels must be used for applications that require a high

Table V. Effect of Size on Mechanical Properties of Nitralloy 125[a]

Tempering Temperature, deg Fahr	Tempering Time, hours	Size of Round Section, in.	Yield Point, psi	Tensile Strength, psi	Percentage Elongation in 2 in.	Percentage Reduction of Area	Brinell Hardness Number
1000	4	4	102,300	117,900	19.5	54.7	277
1100	4	4	93,900	110,000	19.5	58.5	228
1200	4	4	82,800	103,900	20.0	61.0	217
1000	3	3	103,900	119,800	18.0	54.7	269
1100	3	3	96,800	114,800	18.0	57.3	255
1200	3	3	83,500	104,300	21.0	61.0	223
1000	2	2	124,900	141,900	14.5	49.2	302
1100	2	2	104,900	121,300	18.0	59.8	262
1200	2	2	94,900	112,000	19.0	63.6	228
1000	1	1	130,900	146,300	14.0	53.3	332
1100	1	1	112,300	126,800	15.5	58.5	293
1200	1	1	104,900	122,300	18.0	64.8	255

(a) Composition: 0.26% C, 0.50% Mn, 0.13% Si, 1.04% Cr, 0.21% Mo, 0.95% Al. Bars were quenched in water from 1725 F.

Table VI. Effect of Size on Mechanical Properties of Nitralloy 135[a]

Tempering Temperature, deg Fahr	Tempering Time, hours	Size of Round Section, in.	Yield Point, psi	Tensile Strength, psi	Percentage Elongation in 2 in.	Percentage Reduction of Area	Brinell Hardness Number
1000	4	4	134,800	155,900	13.0	40.8	340
1100	4	4	113,300	132,800	16.5	47.8	302
1200	4	4	100,500	124,900	18.0	51.9	269
1000	3	3	140,500	158,800	13.0	40.4	340
1100	3	3	120,500	140,000	15.5	47.8	293
1200	3	3	104,900	126,900	17.5	56.0	255
1000	2	2	149,800	171,300	12.5	40.4	340
1100	2	2	137,900	158,300	15.5	50.6	302
1200	2	2	135,000	154,900	15.5	49.2	269
1000	1	1	164,800	182,300	12.5	44.4	351
1100	1	1	138,900	156,000	15.0	51.9	302
1200	1	1	120,900	139,300	20.0	58.5	269

(a) Composition: 0.35% C, 0.60% Mn, 0.22% Si, 1.30% Cr, 0.25% Mo, 0.94% Al. Bars were quenched in water from 1725 F.

Table VII. Minimum Mechanical Properties Specified for Nitralloy 135 Modified

Size of Section	Tensile Strength psi, min	Yield Strength psi, min	Percentage Elongation in 2 in. min	Percentage Reduction of Area, min	Brinell Hardness Number	Extension under Load, in. in 2 in.[a]
Up to and including 1½ in.	135,000	100,000	16	50	280 to 340	0.011
1½ to 3 in.	125,000	90,000	15	40	280 to 340 (on surface) 269 to 321 (on test specimen)	0.011
3 to 5 in.	110,000	85,000	15	40	269 to 321 (on surface) 240 to 300 (on test specimen)	0.010

(a) In high-carbon steels, alloy steels and cold worked steels, yielding is so gradual that there is no sharp break, hence no definite yield point. It is customary to adopt an arbitrary amount of permanent strain that is considered admissible for general purposes. This is the strain value given in column 7, and the stress at which this occurs is the yield strength given in column 3.

core hardness to support the nitride case. The compositions and nitriding data for a number of steels of this type are given in Tables IX and X. These steels were heat treated in accordance with the recommendations of the manufacturers. The data for nitralloy N are included, since this steel has a high core hardness after nitriding. Nitralloy N and steel B are the ones most commonly used when high core hardness is required.

Nitriding of Stainless Steels. Considerable attention has been given to the nitriding of stainless steels, especially steels of the austenitic type. An austenitic steel (0.45% C, 14% Ni, 14% Cr, 2.5% W and 0.30% Mo) is used widely and advantageously for exhaust valves in aircraft engines, because the stems of the valves can be nitrided.

Since the protective oxide film present on the surface of the stainless steels, inhibits nitriding, this film should be removed by pickling or should be reduced by active hydrogen or other suitable agent before nitriding.

A somewhat prevalent belief is that stainless steels can be nitrided to produce a hard surface without any loss of resistance to corrosion. This is not true, since the resistance to corrosion depends on the existence of a suitable amount of chromium in solid solution. During nitriding, the chromium at the surface is precipitated as submicroscopic particles of chromium nitride; consequently the material has considerably less resistance to corrosion.

Nitriding of SAE and Similar Steels. Chromium-molybdenum-nickel and other medium-carbon steels that do not contain aluminum are being nitrided extensively. Although, after nitriding, such steels have a hardness considerably lower than that of steels containing aluminum, nevertheless these SAE steels exhibit improved resistance to wear, increased endurance limit and nonseizing properties superior to those of the same steels when not nitrided.

The Nitriding Process. Nitriding, as carried on commercially, consists in subjecting the heat treated articles to the action of ammonia gas at temperatures ranging from 930 to 1200 F. The most commonly used temperature is between 930 and 1000 F.

Nitriding Equipment. Although special furnaces for nitriding are now being built, the essential requirement is that the furnace must maintain a uniform temperature within the nitriding container.

Table VIII. Mechanical Properties of Core, Nitralloy N[a]

Property	Before Nitriding	After Nitriding
Yield strength, psi	114,600	180,000
Tensile strength, psi	132,400	190,250
Elongation, % in 2 in.	22	15
Reduction of area, %	59.4	43.4
Brinell hardness number	277	415

(a) Quenched in oil from 1650 F; then tempered at 1200 F

Nitriding furnaces may be of the batch, semicontinuous or continuous type. The first two types are in general use.

Ammonia Gas. The tank of ammonia must be placed in such a position that the bent tube inside the tank has its open end in the gaseous atmosphere and does not dip into the liquid ammonia. The use of a suitable needle valve ensures the control of a steady and even flow of gas. Although anhydrous ammonia is a commercial product, final traces of water can be removed by passing the gas through a tower that contains lime. The inlet and outlet tubes are made of nickel or inconel, and the articles in the container are supported preferably on screens made of nickel or nickel alloy. The gas mixture from the container passes through a wash bottle to indicate the back pressure (which should be about 1 to 2 in.) as well as the rate of flow of the gas, and finally passes into the atmosphere or is washed into a drain by means of a suitable baffle.

Ammonia gas decomposes to a certain extent into nitrogen and hydrogen, according to the following reaction: $2NH_3 = 2N + 3H_2$. Nitrogen, which is very active at the moment of the decomposition of the gas, combines to a certain extent with the alloying elements in the steel to form nitrides. These nitrides, in a fine state of dispersion in the case, impart extreme hardness to the surface of the steel, a hardness that gradually decreases inwardly until it corresponds to that of the core.

The gas mixture leaving the furnace consists of hydrogen, nitrogen and undissociated ammonia. The ammonia gas has high solubility in water, whereas the hydrogen and the nitrogen are insoluble, a circumstance that is used advantageously in the determination of the extent of the ammonia dissociation during nitriding.

Floe studied the depth-hardness characteristics and microstructures after varying the dissociation from 15 to 85%. He found that an appreciable saving in ammonia and an improvement in the surface of the case could be accomplished by keeping the dissociation at 30% for several hours and then permitting it to increase to 75% while the flow of ammonia was kept constant. The increase in dissociation is caused by catalytic action of the nitride case.

Containers for Nitriding. The question of suitable container materials and the methods of sealing have received considerable attention. Unfortunately, low-carbon steel absorbs nitrogen and the inside surface of the container becomes embrittled. Besides embrittling the container, the nitrided surface is also believed to have a harmful influence in catalyzing the decomposition of the ammonia in contact with it and thereby preventing the proper nitriding of the articles. The atomic nitrogen in immediate contact with the steel parts is responsible for the nitriding.

Enameled low-carbon steel containers have been used successfully, since the enamel coating presents an inert surface. Such a coating

Table IX. Compositions of Steels for Which Properties are Listed in Table X

Steel	Composition, percentage									
	C	Mn	Ni	Co	Cr	Mo	W	V	Si	Al
A	0.53	0.34	...	...	3.65	0.51	...	0.74	...	...
B	1.50	...	...	...	12.11	0.94	...	0.94	...	...
C	1.33	0.28	0.55	3.08	13.31	0.81	...	...	...	...
D	0.77	0.24	...	...	3.83	8.63	1.35	1.01	...	...
E	1.20 to 1.30	...	...	...	1.00 to 1.25	...	4.75 to 5.25	0.15 to 0.25	...	...
F	1.04	...	...	...	1.25	1.33	0.51	0.25	...	...
G	0.37	0.34	0.23	...	4.92	1.32	...	0.44	1.06	...
Nitralloy N	0.25	0.55	3.54	...	1.11	0.30	...	...	...	1.30

Table X

Nitriding Data for Steels Having High Core Hardness

(*See* Table IX for the compositions of these steels.)

Steel	Nitriding Temperature, deg Fahr	Nitriding Time, hr	Vickers Hardness, (10-kg load)	Depth of Case, inches	Core Hardness, Rockwell C
A	975	72	975	0.018	47
B	1000	48	1150	0.012	59
C	1000	72	970	0.012	50
D	1000	72	1400	0.015	63
E	1000	48	925	0.008	56
F	1000	48	975	0.018	47
G	900	48	1100	0.014	43
Nitralloy N	975	35	1064	0.016	44

however, has a number of objectionable characteristics. It is easily chipped and may spall at the nitriding temperature because of the pressure of the gases within the steel. The articles to be nitrided must be carefully handled so that the enamel will not be chipped or cracked.

High-chromium and high-nickel alloy containers are being used successfully. Two of them have the following approximate compositions: 80% Ni, 14% Cr, 6% Fe (inconel); and 25% Cr, 20% Ni, remainder iron. Welded containers made from these two materials—especially the former—are giving excellent service.

Depth-Hardness Data. Typical depth-hardness curves for several nitralloy compositions after nitriding are shown in Fig. 1. The effect of the tempering temperature on the depth-hardness of nitralloy 135 modified is shown in Fig. 2.

The hardness testing machines most commonly used for testing the hardness of nitrided steels, are the Rockwell superficial hardness tester (15-kg or 30-kg load) and the Vickers hardness tester (usually 10-kg load). The regular Rockwell tester using the A scale, is also being employed.

Growth During Nitriding. Articles increase slightly in size during nitriding. This growth depends mainly on the temperature and the duration of nitriding, although the structure of the steel is also a factor. In parts larger than 1 in. in section or diameter, a sorbitic structure with no free ferrite is difficult to procure. As a result, the larger the section, the greater is likely to be the growth. Absence of decarburization is of vital importance since the nitriding of a decarburized surface produces not only excessive growth but also a brittle case. The amount of growth is constant under identical conditions, so after it has once been determined for a given material or article, growth can be allowed for in the final machining or grinding, or it can be removed by lapping or careful grinding of the nitrided part. An increase in diameter of 0.002 in. in a specimen that has a case depth of 0.030 in., is representative.

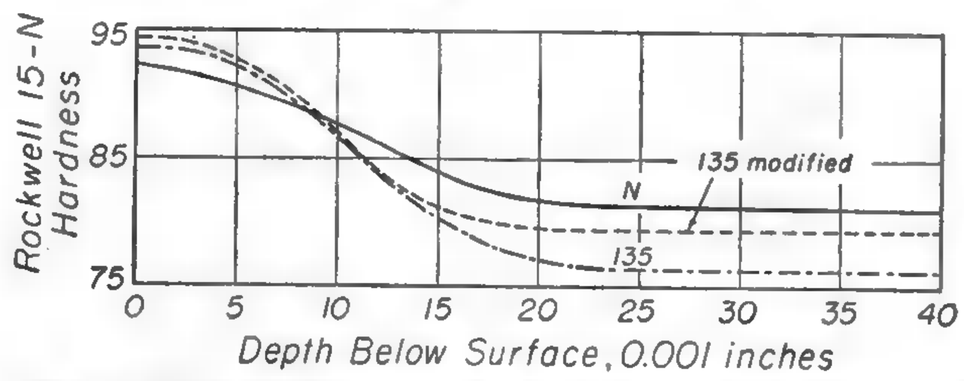

Fig. 1 Depth-hardness of nitrided nitralloy 135, 135 modified and N. Nitralloys 135 and 135 modified were quenched in oil from 1725 F, and tempered at 1250 F. Nitralloy N was quenched in oil from 1650 F, and tempered at 1200 F. All three steels were nitrided at 975 F for 48 hours. Compositions were as follow:

Nitralloy	Composition, percentage						
	C	Mn	Si	Cr	Mo	Al	Ni
135	0.35	0.56	0.36	1.18	0.20	1.07	....
135 modified	0.41	0.58	0.28	1.73	0.36	1.10	....
N	0.27	0.67	....	1.24	0.25	0.92	3.60

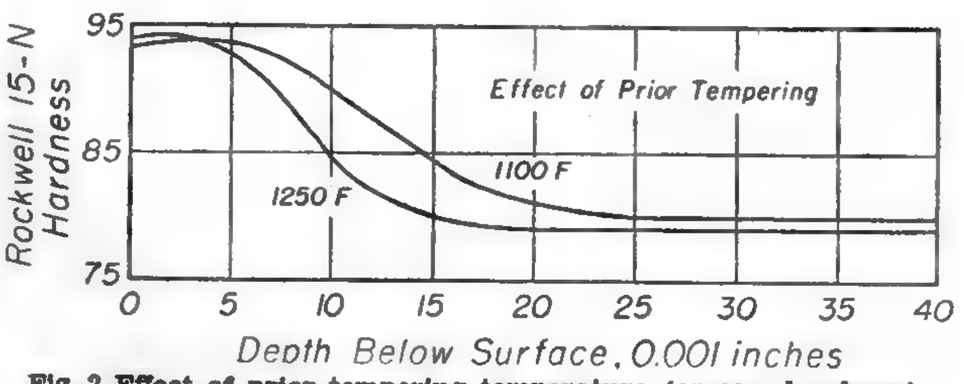

Fig. 2 Effect of prior tempering temperature (or core hardness) on the depth-hardness characteristics of nitralloy 135 modified. Samples were nitrided at 975 F for 48 hours.

Protection Against Nitriding. Tin plating is an excellent means for providing protection. A plating of 0.0003 in. will protect the parts and will not run. Bronze and copper plating are also being used successfully. A protective

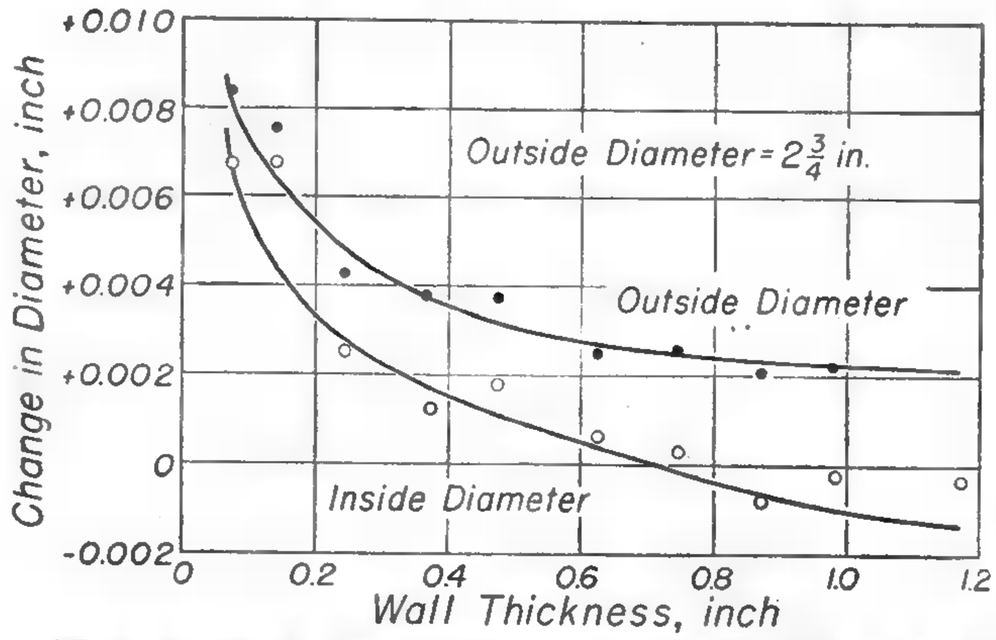

Fig. 3 Growth in rings or cylinders of nitralloy 135, caused by nitriding. Steel nitrided at 975 F for 72 hours. (Hubbard and Robinson)

Table XI. Coefficient of Linear Expansion of Nitralloy

Nitralloy 135 Modified, Not Nitrided		Nitralloy 135, Nitrided	
Temp, deg Cent	cm per deg Cent	Temp, deg Cent	cm per deg Cent
0 to 100	0.00001184	0 to 100	0.00001214
0 to 200	0.00001188	0 to 200	0.00001218
0 to 300	0.00001192	0 to 300	0.00001222
0 to 400	0.00001196	0 to 400	0.00001226
0 to 500	0.0000120	0 to 500	0.0000123

For mild steel (0.25% C) the coefficient of linear expansion from 0 to 200 C is 0.0000115 cm per deg Cent.

paint known as Sel-Nite gives satisfactory results. Care should be taken to permit the paint to dry before the parts are placed in the furnace.

Distortion. Many parts can be nitrided without appreciable distortion. Such parts are of uniform section and have been treated so that no machining stresses are present. The stresses produced by rough machining are removed by reheating the parts between 1100 and 1200 F before final machining or grinding. The time at temperature varies with the articles. Usually a period of 1 to 4 hr at temperature is sufficient. Slight distortion may occur in other sections because of unequal growth. The nitriding of a water-pump spindle with a long keyway on one side, can be cited as an example. Such a part tends to bow during nitriding, with the keyway at the top of the arc. This can be explained by the fact that a greater area adjacent to the keyway is exposed to the nitriding gas than on the opposite side and in consequence greater growth takes place, with attendant distortion. If the keyway has been protected against nitriding, the nitriding treatment tends to bow the part slightly in the opposite direction, because no growth takes place on the protected portion. Parts of this kind are generally straightened hot after nitriding.

Slightly distorted parts can be straightened either cold or hot, but hot straightening is preferred. Straightening, especially when it is done cold, should be performed with caution, in order not to crack the case. Fatigue failures may result from any cracks at vital points in parts that must resist alternations of stress or a repeated stress. The presence of such cracks will also result in failure to withstand corrosion. Since no softening of the case takes place when a part is heated at 1200 F for a short time, it is entirely safe to heat to this temperature for straightening. A typical procedure is to heat the part to 1200 F and then to straighten it in a press, using a copper shoe for distributing the load. The complete removal of residual stresses before nitriding and the proper placing of the parts in the nitriding container, will greatly lessen the possibility of warping or distortion.

Surface Defects. If the decarburized surface is not removed before nitriding, the case will spall very readily. This condition may be caused by improper centering during the machining, so that an insufficient amount of material is removed from some points. When parts are coated with rolling or forging scale, $\frac{1}{32}$ to $\frac{1}{16}$ in. of material must be removed in order to eliminate the decarburized layer.

Softening. Occasionally it is desirable to soften the case of nitrided parts in order to make changes in design. This softening can be accomplished by heating the nitrided parts in a fused bath consisting of a mixture of 50% each of sodium and potassium chlorides at a temperature of 1500 F, thus causing the nitrides to decompose. Softening the case by annealing at 1800 F has also been recommended and will render the material machinable, but renitriding will not restore the original hardness.

Neither method will produce entirely satisfactory results. For ensuring satisfactory results, the softened layer should be completely removed before renitriding. Such a procedure prohibits a softening process for finished articles.

Retention of Hardness of Nitride Case. One of the valuable characteristics of nitrided nitralloy is retention of hardness at elevated temperatures. The material can be heated for long periods of time at 1000 F and for short periods at 1200 F, without producing any softening of the case. The case of nitrided nitralloy is just as hard when tested at 750 F as at room temperature. This retention of hardness makes the material of great value for many applications, especially where lubrication may be faulty.

Coefficient of Expansion. Data concerning the thermal expansion of nitralloy 135 and 135 modified, are shown in Table XI. The Firth-Brown Research Laboratory reports the coefficient of expansion of the case (as distinct from the core) to be as follows:

Temperature, deg Cent	Coef Exp per deg Cent	Temperature, deg Cent	Coef Exp per deg Cent
20 to 100	0.0000107	20 to 400	0.0000123
20 to 200	0.0000113	20 to 500	0.0000129
20 to 300	0.0000118		

Endurance Properties of Nitrided Nitralloy. Since nitrided nitralloy is frequently used in applications where it is subject to a repeated stress, the effect of nitriding on the endurance properties is of considerable importance. A number of investigations give results that are in agreement and show that the effect of nitriding is to increase the endurance range as determined by reversed bending. Fatigue failures do not begin at the surface but at the junction of the case and the core, indicating that the endurance of nitrided parts is controlled to a considerable extent by the characteristics of the core.

Surface features that lead to stress concentrations, such as notches, threads and scratches, have a much slighter effect in nitrided material than in unnitrided material.

The results of rotating-beam fatigue tests performed by a number of investigators are summarized in Table XII.

Table XII. Results of Rotating-Beam Fatigue Tests

	Investigator								
			Hengstenberg and Mailander						
Composition	Mochel	Inglis and Lake	FP15	FP13	FP13A	FPK13	FPE23	FK345	Sutton
Carbon	0.35	0.26	0.30	0.52	0.52	0.32	0.42	0.15	0.44
Chromium	1.67	1.58	1.43	1.74	1.74	1.24	1.68	0.85	1.71
Aluminum	0.91	0.87	1.12	1.28	1.28	0.93	1.33	...	1.33
Silicon	0.22	...	0.43	0.14	0.14	0.22	0.19	0.25	0.13
Manganese	0.54	...	0.41	0.27	0.27	0.72	0.38	0.40	0.34
Nickel	0.20	...	...	...	...	...	2.65	...	trace
Molybdenum	0.20	0.33	...	...	...	0.34	...	0.41	.....
Heat Treatment	(1751 F) OQ955 C T590 C (1094 F)	...	(1688 F) OQ920 C T650 C (1202 F)	(1652 F) OQ900 C T650 C (1202 F)	(1616 F) OQ880 C T670 C (1238 F)	(1544 F) WQ840 C T660 C (1220 F)	(1598 F) OQ870 C T660 C (1220 F)	(1706 F) OQ930 C T650 C (1202 F)	.....
Tempering treatment after machining, 3 hr at	(1004 F) 540 C	(1022 F) 550 C							
	Fatigue Strength (rotating-beam test), psi								
Heat treated bar material	76,200	.....	60,500	71,700	66,100	69,440	78,400	61,600	.....
Heat treated and given same thermal treatment as in nitriding	.....	73,900	58,210	73,900	.....	.....	.....	66,100	.....
Heat treated and nitrided	84,000 (a)	.....	78,400 (b)	96,300 (b)	84,000 (b)	89,600 (b)	96,300 (b)	96,300 (b)	86,000 (c) (d)
Heat treated and nitrided, core material	.....	.....	.....	.....	.....	.....	.....	.....	71,400 (d)

(a) Nitrided 90 hr at 510 C (950 F)
(b) Nitrided 48 hr at 500 C (932 F)
(c) Nitrided 90 hr at 500 C (932 F)
(d) Rotating cantilever beam

OQ = oil quench; WQ = water quench

The summary by Sutton gives values in tons per square inch. These have been converted into pounds per square inch by multiplying by 2240.

Table XIII. Results of Rotating-Beam Fatigue Tests on a Typical Nitralloy Steel
(Composition of the steel: 0.34% C, 0.49% Mn, 1.4% Cr, 1.23% Al, 0.38% Mo)

Condition	Tensile Strength, psi	Fatigue Strength, psi — Polished Smooth	Fatigue Strength, psi — Sharply Notched[a]	Fatigue Strength, psi — Fillet[b] r = 0.04 in.
Not nitrided	138,900	73,900	40,300 to 41,400	45,900 to 47,000
Nitrided for 60 hr	.....	87,400 to 88,500	87,400 to 88,500[c]	87,400 to 88,500

(a) 0.004 in. deep, as sharp as possible; notched before nitriding
(b) At the joint of test length (0.30-in. diam) to ends (0.48-in. diam). Samples finish machined before nitriding
(c) Specimens did not break at notch.

In fatigue tests conducted by Sutton, an examination of the fractures of Wohler test specimens indicated that the cracks originated at a point near the junction of the case and the core, but within the core material. His results indicate that, in a nitrided specimen, fatigue fracture occurs when the stress exceeds the fatigue limit of the core, at a point near the junction of the case and the core. Therefore the permissible loads on nitrided specimens are ordinarily limited by the fatigue properties of the core. Since fatigue cracks in nitrided parts do not begin at the surface, small surface defects are not so important as in hard steels of other types.

In a rotating-beam type of fatigue test, a nitrided specimen that had been notched to a depth of 0.004 in. by grinding, remained unbroken after being subjected to a test at a stress range of ±71,700 psi, but failed at ±88,500 psi at an undamaged place, since the origin of the fracture was in the core. A turned notch 0.004 in. deep that was cut before nitriding, had no effect on the fatigue strength, but the same notch on a specimen that had not been nitrided, reduced the fatigue strength by 45%.

For results of fatigue tests, see Table XIII.

V-notches in the case do not reduce the fatigue limit, provided the notches are cut before nitriding.

Nitrided steels may be expected to retain their high endurance value at temperatures as high as 800 to 1000 F, because the hardness and strength values of the case are not affected greatly by these temperatures.

Bittel* tested heat treated nitralloy 135 modified, in a Rayflex fatigue-testing machine in which the specimen is vibrated at a controlled amplitude in the natural frequency of the sample.

The Brinell hardness number of the steel was 269. The specimens, 18 in. long and ½ in. in diam, were ground, polished and nitrided at 975 F for 40 hr.

A series of tests was made first on the heat treated material. In order to determine the effects of notches on the endurance limit, a circumferential groove was machined 0.010 in. deep, with radius 0.005 in. and an included angle of 50 deg, in the center of one set of specimens. A V-notch 0.010 in. deep, with radius 0.005 in. and an included angle of 60 deg, was machined in a second set of specimens. The endurance limit was determined for each set of nitralloy specimens before nitriding and after nitriding. Table XIV gives the results of the investigation.

Wear Resistance of Nitrided Nitralloy. Since the nitride case loses none of its hardness when tested at temperature, until heated above 750 F, it possesses marked advantages over case hardened and other hardened steels, which soften when heated to this temperature. Nitrided nitralloy is therefore less susceptible to galling and scoring than these steels. A number of industrial applications involve the use of nitrided nitralloy parts against other nitrided nitralloy parts, under conditions where faulty lubrication may be experienced and consequently a marked increase in temperature.

* F. J. Bittel, The Effect of Notches on the Fatigue Strength of Nitralloy, Thesis M.I.T., 1940

Table XIV. Endurance Limit of Nitralloy, Unnitrided and Nitrided

Condition	Endurance Limit, psi
Unnitrided without notch	45,000
Nitrided without notch	90,000
Unnitrided with half-circle notch	25,000
Nitrided with half-circle notch	87,000
Unnitrided with V-notch	24,000
Nitrided with V-notch	80,000

Leaded and graphite bronzes are generally used as bushings to run against nitrided nitralloy. A bronze containing 80% Cu, 10% Sn and 10% Pb is suitable for the purpose.

Nitrided nitralloy is used widely for cylinder barrels of high-power aircraft engines; the excellent resistance of nitralloy to wear, along with its other characteristics, makes it a satisfactory material for this purpose.

Creep Tests on Nitrided Nitralloy. Nitrided nitralloy has been tested by Malcolm under a load of 10,180 psi. After 4000 hr the extension amounted to 0.002 in. per in. with no further extension during 5000 hr more at 1000 F.

Resistance to Corrosion of Nitrided Nitralloy. Although the resistance to corrosion of nitrided nitralloy has been studied by a number of investigators to show that this material strongly resists the action of alkalies, atmosphere, crude oil, tap water, still salt water and combustion products of natural gas, it must be understood that nitrided steels do not resist corrosion as effectively as stainless steels. The outermost part of the case exhibits maximum resistance to corrosion and for that reason the parts should be left as nearly as possible in the condition in which they come from the nitriding furnace. The removal of part of the case will greatly decrease the resistance to corrosion. Nitrided nitralloy will not withstand the corrosive action of mineral acids.

Welding of Nitralloy. Nitralloy can be welded successfully by the atomic hydrogen process and by flash welding. A welding rod made of nitralloy should be used in the atomic hydrogen process. After nitriding, no appreciable difference is evident between the hardness at the weld and the hardness away from it.

Determination of Ductility of Case of Nitrided Nitralloy. The character of the impression produced by the various hardness-testing machines is indicative of the ductility of the case. If the impression is free from spalled edges, the nitride case is more ductile than one in which the edges are not well defined. The ductility of the nitride case can be determined qualitatively with the Brinell machine, by observing the load necessary to crack the case.

After experiments with a number of different methods, it has been found that the torsion test gives more significant results for ductility than other mechanical tests.

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METALLIC COATINGS

Prepared under the chairmanship of

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National Bureau of Standards

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Aluminum Impregnation

By B. J. Sayles*

CALORIZING is a trade name for a process of alloying the surface of carbon or alloy steel with aluminum by diffusion. The depth of penetration varies from 0.005 to 0.040 in., but on thin articles is usually 0.025 to 0.030 in. The surface layer of iron-aluminum alloy usually contains approximately 25% Al.

Methods. The old-style powder method was in general commercial use until 1935. The articles were packed in a powder compound, of which the active ingredient was powdered aluminum, together with a small proportion of ammonium chloride, and were then sealed gastight in heated revolving retorts in which a neutral atmosphere was maintained. Duration of treatment was usually 4 to 6 hr at 1550 to 1700 F. The resulting aluminum-iron surface alloy, about 60% Al, was 0.001 to 0.006 in. deep.

The surface alloy layer gave excellent resistance to heat and to corrosion by sulfurous gases, but was brittle and inclined to spall whenever the article was subjected to mechanical abuse, for instance by a rotary tube cleaner.

Modern Powder Calorizing.[1] Since 1935 both the foregoing method and a new method have been used for securing an initial aluminum-iron alloy layer. After removal from the retort, the work material is subsequently heat treated for periods of 12 to 48 hr at temperatures from 1500 to 1800 F, to cause further penetration of the aluminum by diffusion to depths ranging from 0.025 to 0.040 in. Since no compound is in contact with the work during the heat treatment, the aluminum content of the surface is decreased. The usual content of 25% Al or less is ample to ensure good resistance to heat and corrosion. Because of the lower aluminum content, the surface alloy layer exhibits toughness and ductility not obtainable by the older process.

Pack Calorizing. This method consists in packing the work material, along with the powdered aluminum compound, in stationary boxes that are then sealed tight and heated. The process requires from 6 to 24 hr at temperatures ranging from 1500 to 1800 F. Since the process is a combination of aluminizing and diffusion heat treatment, no further treatment is needed after the metal has been removed from the container. Pack calorizing is recommended especially for articles of light gage or irregular shape that might be damaged by processing in a rotating retort.

Dip Calorizing. In this method the article is coated by dipping in molten aluminum in a manner analogous to hot dip galvanizing. (For details, see page 704.) The coating consists principally of aluminum with only a thin layer of bonding alloy. The *Fink Process,* characterized by treatment in a hydrogen atmosphere just before the immersion in molten aluminum, is readily adaptable to the treatment of wire or strip, which can be passed continuously through a hydrogen tunnel.

Martin Process. The surface layer of aluminum-iron alloy is formed, in this process, by treating the metal in aluminum chloride vapor at a high temperature. It is reported that the surface alloy thus obtained is shallow compared with the coating produced by the other processes.

Metal Spraying. See page 720 for information concerning the spraying of molten aluminum.

Resistance to Oxidation. Calorized steel is highly resistant to oxidation and to corrosion by flue gas at high temperature. This can be attributed to the formation of a surface film of aluminum oxide, which is self-replacing as long as any appreciable amount of aluminum remains at the surface. Calorized parts remain serviceable for years at temperatures not exceeding 1400 F. Such parts, however, are often used at temperatures up to 1700 F for purposes where the usual life of the part (for example, a heat treating pot) is long enough to justify the higher cost as compared with that of carbon steel. Table I gives the relative resistance to oxidation of some steels before and after calorizing.

Resistance to Corrosion by Sulfurous Gases. One type of resistance to corrosion that is important commercially, is immunity to the attack of various kinds of sulfurous gases—H_2S, SO_2, SO_3—found in furnace flue gases at fairly high temperature. Calorized articles may be used in furnaces that employ fuels high in sulfur. Calorized steel has been accepted widely in oil refineries and in heat exchangers for contact sulfuric acid converters. Calorized steel is rapidly attacked, however, by aqueous solutions

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Table I. Resistance to Oxidation, Increase in Weight

Nominal Composition of Steel	Increase in weight, mg per sq cm — 1000 hr at 1100 F — Not Calorized	1000 hr at 1100 F — Calorized	1000 hr at 1200 F — Not Calorized	1000 hr at 1200 F — Calorized
0.08 to 0.20% C, 18% Cr, 8% Ni	...	...	1.1	0.6
0.08 to 0.18% C, 0.30 to 0.60% Mn, 5% Cr, 1% W	...	...	17.5	1.0
0.08 to 0.18% C, 0.30 to 0.60% Mn, 5% Cr, 0.50% Mo	16.6	...	36.6	0.8
0.08 to 0.18% C, 0.30 to 0.60% Mn, 5% Cr	...	...	39.5	0.6
0.08 to 0.18% C, 0.30 to 0.60% Mn, 1% Mo	35.3	...	83.6	1.0
0.08 to 0.18% C, 0.30 to 0.60% Mn, 1.50% Mo	35.4	1.3	...	...
0.08 to 0.18% C, 0.30 to 0.60% Mn, 2.00% Cr, 0.50% Mo	21.4	...	...	...
0.08 to 0.18% C, 0.30 to 0.60% Mn, 1.25% Cr, 0.50% Mo	19.9	1.5	...	...
0.08 to 0.18% C, 0.30 to 0.60% Mn, 1.75% Cr, 0.50% Mo	37.2	...	...	...
0.08 to 0.18% C, 0.30 to 0.60% Mn, 0.50% Si max	41.0	4.3	...	...

of mineral acids and, hence, is not suitable at the low-temperature end of the furnace ducts, where condensation of water vapor in the flue gases is favorable to the formation of sulfurous acid.

Calorizing improves the resistance of steel to corrosion in hydrogen sulfide, as is indicated in Table II. The test was conducted in a muffle type of furnace with hydrogen sulfide flowing continuously at atmospheric pressure.

Table II. Resistance to Corrosion in Hydrogen Sulfide

Increase in weight (mg per sq cm) during 24 hr at 1200 F

Nominal Composition of Steel	Not Calorized	Calorized
0.08 – 0.18% C, 18% Cr, 8% Ni	36.5	0.1
0.08 – 0.18% C, 0.30 – 0.60% Mn, 5% Cr, 1% W	175.6	0.5
0.08 – 0.18% C, 0.30 – 0.60% Mn, 5% Cr, 0.50% Mo	172.8	1.3
0.08 – 0.18% C, 0.30 – 0.60% Mn, 5% Cr	183.4	0.5
0.08 – 0.18% C, 0.30 – 0.60% Mn, 0.50% Mo	109.0	0.3
0.08 – 0.18% C, 0.30 – 0.60% Mn, 2% Cr, 0.50% Mo	124.3	0.5
0.08 – 0.18% C, 2.50% Cr, 0.50% Mo	90.5	0.1
0.08 – 0.18% C, 0.30 – 0.60% Mn, 1.25% Cr, 0.50% Mo	101.3	0.7
0.08 – 0.18% C, 0.30 – 0.60% Mn, 0.50% Si max	173.5	0.6

Creep Strength at High Temperature. Calorized coatings, by protecting the base metal from reduction in cross section through oxidation, extend the useful, working range at high temperature of many low-priced steels that have low resistance to oxidation. As an example, a killed carbon steel containing 0.08 to 0.18% C, 0.30 to 0.60% Mn and 0.50% Si, required, before aluminum impregnation, 1400 psi stress to produce 1% creep in 10,000 hr at 1100 F. Calorizing this steel increased the stress to 2050 psi, under the same condition of test.

Ductility. The aluminum-iron surface alloy is hard, but is sufficiently tough to exhibit about 5% elongation before the development of surface cracks. This enables the surface alloy to bend with the steel when hot, and the product is not subject to cracks under stresses within commercial limits.

Fabrication. Except with thin coatings low in aluminum content, like coatings employed on automobile exhaust pipes, cold fabrication of aluminum impregnated steel is not practicable. Usually, bending and forming must be performed at a bright red heat, but unless the bending radii are liberal, cracking may occur. Calorized steel will withstand about 5% elongation before surface fissures appear.

Uses. Calorized metal is used for pots for salt, cyanide, and lead, preferably operating at a bath temperature not higher than 1550 F; bolts for use at temperatures up to 1400 F; tubes for air heaters, radiant steam superheaters, oil and gas polymerizers; furnace parts to be used at temperatures up to 1400 F; glass lehrs and furnaces for heating nonferrous alloys.

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Hot Dipped Aluminum Coatings on Steel

By B. P. Finkbone*

ALUMINIZING is a relatively new method of applying a nonferrous protective coating to a metal, usually iron or steel, by hot dipping. After being suitably prepared, the iron or steel is passed through a bath of molten aluminum alloy, and the coating is allowed to solidify on the surface. This coating can be applied to sheets, strip and wire.

Aluminum owes its corrosion resistance to the existence of a self-renewing film of surface oxide that forms in air. The aluminum coating provides the resistance to corrosion and to heat, the heat reflectivity, and the attractive appearance of aluminum; the base metal gives the strength and other mechanical properties of iron or steel. Under many conditions the aluminum coating, like zinc, affords galvanic or electrolytic protection on bare spots, by sacrificing itself as the anode to reduce corrosive attack of the exposed steel base metal, the cathode.

Base Metals. Aluminum coating is applied commercially to mild steel, copper steel and low-alloy high-strength steel. When sheet steel is needed for superior drawing qualities and more uniform workability, drawing quality may be specified.

Table I lists some mechanical properties of steel that has been coated with aluminum by hot dipping.

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Weight of Coating. The weight of an aluminum coating on sheet or strip usually is approximately 0.50 oz per sq ft. The coating thickness is approximately 0.001 in. per side or 0.002 in. over-all on sheet and strip. This is approximately equivalent in thickness to a 1.30-oz coating of zinc. The difference in coating weights results from the different specific gravities of the two metals.

Table I. Mechanical Properties of Aluminized Steel

Property	Low-Carbon Steel Base	High-Strength Steel Base
Yield point, psi	40,000	50,000 to 60,000
Tensile strength, psi	50,000	65,000 to 80,000
Elongation, % in ▮ in	10 to 25	12 to 20
Rockwell B hardness	75 max	70 to 85 max

Fabrication. Aluminized steel can be fabricated by all the conventional processes, including punching, shearing, and forming on a press brake, and can be drawn moderately or stamped if the article to be drawn or stamped is designed with large radii to relieve friction, strain and sharp corners. Such drawing should be done on a slow-action press.

Aluminized steel can be joined by any one of several methods: double seaming, arc welding, seam or spot welding, oxyacetylene welding, or brazing. Certain precautions

are necessary, similar to those employed in joining aluminum. During the welding operation excessive oxidation of the coating must be prevented; and in spot and seam welding, it is desirable to remove the film of aluminum oxide from the surface before welding. The material can be soldered after the edges to be joined have been suitably prepared.

Heat Resistance. Up to about 900 F, the aluminum coating gives complete protection to the steel beneath it without discoloration. Above 900 F the coating reacts with the steel base to form an aluminum-iron alloy that is tightly adherent and highly refractory. Tests have shown that this aluminum-iron alloy completely protects the steel base from oxidation and scaling during short exposures to temperatures as high as 1750 F.

Heat Reflectivity. Aluminized steel will serve as an efficient and stable reflector of heat and light. The superior heat-reflecting quality is preserved by the resistance of the aluminum coating to oxidation and discoloration by heat.

Superior heat-resisting and heat-reflecting characteristics make aluminum-coated sheets desirable for such uses as oven linings, heat deflectors and heating element retainers. Parts fabricated of aluminum-coated steel serve equally well in units heated by electricity, gas, oil or solid fuels.[2]

Resistance to Atmospheric Corrosion. Aluminum-coated steel is comparatively new and corrosion tests have not continued long enough so far to supply complete data concerning the resistance of the material to atmospheric corrosion.

However, tests based on four years of exposure in a mild industrial atmosphere, have shown aluminum coatings to lose approximately one-tenth as much weight as galvanized coatings under the same conditions. Exposures for two years in a marine atmosphere have shown that aluminum coatings lose approximately one-fifth as much weight as galvanized coatings. Although aluminum coatings in the outdoor atmosphere do not offer the same galvanic protection as zinc coatings at sheared edges, the rusting of edges has not been serious in the aluminum-coated samples in the above tests.

Possible Uses. Aluminized steel fills a recognized need for a relatively low-priced, heat-resistant sheet metal. In circulating heaters of advanced design, the drums or inner jackets are being made of this material in order to resist the destructive effects of high temperature.

Aluminized steel has also been used successfully in the aircraft industry, to replace less easily obtainable material in firewalls and accessories.[3]

Aluminized steel mufflers and tail pipes for gasoline engines have shown a noteworthy increase in serviceability beyond that of similar parts made of such materials as hot rolled, cold rolled and terne-coated sheets. Service of this kind demands a combination of resistance to corrosion and heat.

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Chromium Impregnation

By F. C. Kelley*

CHROMIUM impregnation or "chromizing" consists in packing the metal to be treated in a mixture of powdered alumina and chromium. Alumina is used to prevent the sintering of the powdered chromium into a solid mass. The amount of each material used may be varied, but a satisfactory mixture consists of 45% dry alumina and 55% chromium by weight. The work material is usually packed in a tube or container of iron and then heated to between 2375 and 2550 F in hydrogen for 3 to 4 hr. The duration of treatment may be varied according to the penetration and concentration of chromium desired.

Atmosphere. A protective atmosphere like hydrogen, free from oxygen and water vapor, is absolutely necessary to prevent oxidation of the chromium. The particles of chromium in contact with the metal to be treated, must be kept clean to permit diffusion. The hydrogen should be pure enough to reduce chromic oxide, for this will preserve the chromium powder in the metallic state and prevent loss by oxidation. The hydrogen may be passed directly into the iron container that holds the charge. The container should be provided with a vent to allow circulation of the pure hydrogen. The atmosphere of the furnace may be commercial hydrogen with enough water and oxygen removed to protect the molybdenum winding from oxidation.

Furnace. The temperatures in this process require a furnace capable of maintaining a high temperature through a long period. An electric furnace is used that is provided with a molybdenum or tungsten winding as the heating unit; a satisfactory type of unit consists of an alundum tube wound with molybdenum wire. The tube is placed in a suitable furnace casing and surrounded with alumina powder, which acts as insulating material. The furnace casing should be tight to prevent the loss of hydrogen and the infiltration of air.

Material. The metal best suited for chromizing is low-carbon steel that contains 0.10 to 0.20% C. Steels of higher carbon content may be used if the surface is first decarburized, as by heating in hydrogen. Materials to be chromized should have a clean surface so that diffusion can take place freely. Machined parts should be free from oil, grease or soap.

Structure of Coating. The layer of chromized material on the surface of iron treated by this process, consists of large columnar grains. This structure is typical of many coatings formed on iron by diffusion processes. Elements such as aluminum, silicon, molybdenum and tin, form coatings of similar structure when diffusing into iron.

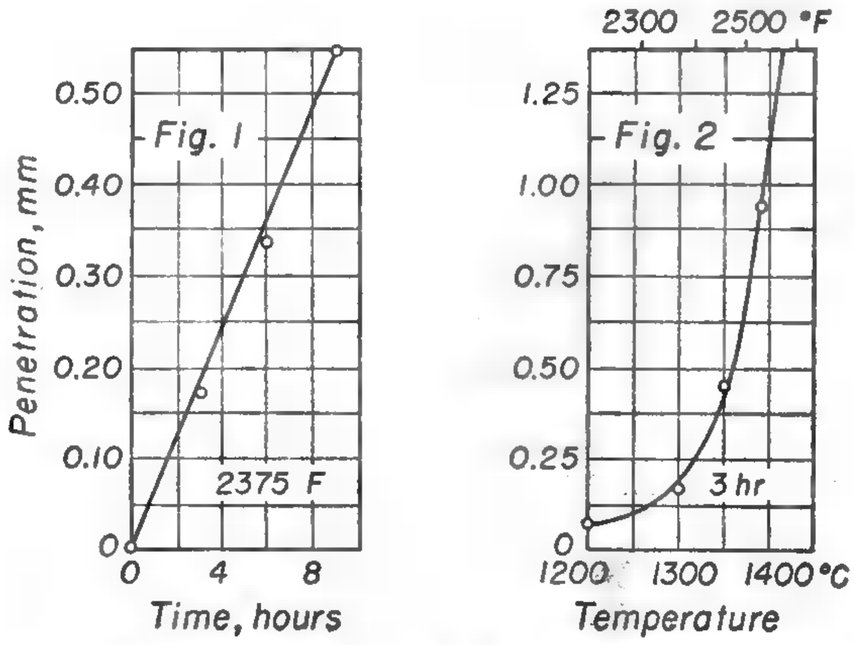

Fig. 1 Curve showing the change in penetration of chromium with the time, at 2375 F

Fig. 2 Effect of temperature on the penetration of chromium during a 3-hr period

Diffusion Rates. The penetration of the chromium with respect to time and temperature is shown by Fig. 1 and 2.

Resistance to Corrosion. Chromized iron has high resistance to corrosion in salt spray, steam and regular atmospheric conditions, and will withstand 10% nitric acid for long periods of time without discoloring the solution.

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The chromium content of the diffused layer varies between 10 and 20%, depending on the time and temperature of heating.

Other Methods. G. Becker, K. Daeves, and F. Steinberg have utilized a reaction between gaseous chromous chloride and iron at 1000 C to produce a chromium-rich solid solution that is highly resistant to corrosion.

A mixture of H_2 and HCl is passed over chromium or ferrochromium, heated to 900 C or above, and the resulting $CrCl_2$ is passed over the material to be treated. When the gas ($CrCl_2$) comes in contact with the iron, an exchange of a chromium atom for an iron atom takes place, and the resulting $FeCl_3$ sublimes and is carried off by the hydrogen. The "valve" on this reaction, regulating the rate at which the chromium is deposited, is the rate of diffusion of iron through chromium. At 900 C this rate is slow and the diffused layer is thin.

Becker, Daeves and Steinberg have also used a ceramic material impregnated with $CrCl_2$, for packing around the article to be chromized. This method ensures uniform impregnation.

It is necessary to use low-carbon material (0.1% C or lower) to secure satisfactory coatings. The mass of the metal to be treated is most important, because the larger the mass, the greater the amount of available carbon. Elements such as titanium, columbium and molybdenum have been used in the steels to "fix" the carbon and to improve the resistance of the coatings to corrosion.

Coatings about 0.0005 in. thick are obtainable at 900 C after 3 hr. Thicker coatings are obtainable by increasing the temperature. The thin coatings obtained have been reported to contain as much as 35% Cr at the surface.

W. M. Mitchell secured a United States patent on a process for coating the surface of a steel ingot with a chromium-iron alloy. The surface of a mold is coated with chromium; sodium silicate is used as a binder. Hot metal, when poured into the mold, alloys with the coating and produces a chromium-iron alloy on the surface. The ingot can then be rolled into sheets with a high-chromium alloy on the surfaces. Castings with a high-chromium alloy on the surfaces can be made in the same way.

A British patent was granted to M. Fiedler for a process of coating a metal with a chromium-rich alloy. This process consists in electroplating chromium on the surface of steel and then heating the plated article by passing it through a high-frequency field. As a result, alloying occurs between the base metal and the chromium plate. By this process, iron pipe can be plated with chromium on the outside and then passed continuously through a high-frequency coil until heated to about 2200 F so that alloying takes place between the chromium plate and the iron.

Folliet and Sainderichin were granted a United States patent on a cementation mixture for treating ferrous articles. The components are an oxide of chromium, 2 to 10% of a chloride of chromium, and a quantity of finely divided aluminum. The aluminum content depends on the amount of oxygen in the metallic oxide used. The articles to be coated, together with the mixture in which they are packed, are heated in a closed vessel to between 1825 and 2375 F. The action of the aluminum and the chloride results in an alloy between the liberated chromium and the iron. The depth of penetration depends on the percentage of metal oxides and the time at the working temperature.

Application. Chromizing has been used to protect turbine buckets against corrosion and erosion. Containers used for copper brazing tungsten contacts have been chromized so that the copper would not braze the contacts to the container. The hydrogen atmosphere used for copper brazing usually contains enough water vapor and oxygen to oxidize the chromium on the surface, thus preventing the copper from wetting it.

Any steel parts that must withstand atmospheric corrosion or the attack of nitric acid, can be chromized to give satisfactory resistance. The chromized surface layer is virtually free from carbon, and no attack occurs as a result of carbide precipitation.

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Lead Coatings on Steel

By J. L. Bray*

LEAD has excellent resistance to atmospheric corrosion as compared with iron or zinc, because of its less negative electrode potential as well as the formation of a relatively continuous and adherent protective film over the surface. Lead deforms easily under applied force, and the low temperature of recrystallization permits lead to conform to movements in a steel base with a minimum of disruption. The melting point of lead is relatively low, and consequently few operational difficulties are encountered in hot dipping. At temperatures slightly above the melting point (621 F) lead is quite fluid, easily handled, and its vapor pressure is very low. Lead always costs much less than tin and usually somewhat less than zinc. (In 1939 lead sold at 5.05 cents per lb, zinc at 5.51, and tin at 50.3.) The losses of lead from oxidation and drossing, are less than the corresponding losses of zinc; less time is consumed in cleaning the bath, and the life of the equipment is lengthened considerably by reason of the lower operating temperature and the lower solubility of iron in lead. Lead-coated sheets solder easily and rapidly, consuming less solder than uncoated sheets. The lead also serves as an effective lubricant in forming, stamping and spinning.

Operating against these advantages are some very serious disadvantages. (1) Lead does not form intermetallic compounds or solid solutions with iron and consequently, when pure lead is used as a coating medium, the bond is entirely mechanical with all the shortcomings of that type of bond. For this reason pure lead is seldom used for hot dipped coatings and is generally alloyed with other elements to form a bond with the steel. (2) Great care in manufacturing is necessary to minimize pinholes, which form readily when the molten coating solidifies and which become areas for accelerated corrosion. (3) Lead is relatively soft and its resistance to wear and abrasion is low. (4) Although lead is resistant to atmospheric corrosion, it readily forms an unsightly initial coating of oxide or sulfate, particularly when the lead contains impurities. It is noteworthy too that lead coatings may not provide as good protection in rural atmospheres, probably because of the absence of constituents that form sulfate. (5) The metal is commonly regarded as cathodic to iron, although the potential difference is not great, and corrosion will occur at the expense of the iron.

Lead Spraying. A metal surface may be coated with "atomized" lead or a lead alloy by means of a special spray gun. For details, see the article on "Sprayed Metal Coatings", page 720 in this Handbook.

Hot Dipping with Pure Lead. This requires very care-

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ful preparation of the steel base, the use of a closely controlled and relatively pure flux, and close regulation of dipping temperature and duration of immersion. Oil or grease may be removed by the conventional solvents or detergents. Then the steel is pickled (at 160 F) in a bath containing 6 to 12% sulfuric acid. The iron content of the bath should not exceed 5%. After pickling, the steel articles are treated for 10 to 15 min in a bath of 5 to 10% hydrochloric acid (at 120 to 150 F) containing an inhibitor (5% Fe max). The articles are then immersed in a solution of 1 part of zinc-ammonium chloride in six parts of water (8% Fe max). It is essential that the articles remain wet with this solution until they are dipped into the bath of molten lead.

The bath of commercially pure lead is maintained at a temperature of 690 to 710 F, and should be covered with a layer of molten flux, the preparation and composition of which are extremely important. The flux bath prepared from zinc-ammonium chloride should be about ⅛ in. deep. When operating best this bath has a dark color and gives off almost no fumes. Aside from additions to replace losses, the principal precaution is to ensure complete solution of the crystals and to confine flux additions to the entrance end of the bath.

Immersion in the flux bath for 10 to 20 sec is sufficient, but a much longer immersion, depending on the mass of the article, is required in the lead bath. When the coated article is withdrawn from the bath, the excess metal and flux are removed by shaking or centrifuging. Then the article is quenched in water, and in some instances, tumbled in sawdust to improve the appearance. Sheet metal workers often rub linseed oil and lampblack on freshly exposed lead installations to develop a more sightly appearance. A coating of pure lead may "crawl". This is particularly important in pipe linings where a correlation must be established between diameter of the pipe and thickness of the lining, because of the effect of increased arc.

The weight of the coating thus produced may be varied from 0.16 to 1.4 oz per sq ft. The thickness may be controlled by variations in the temperature of the bath, the length of immersion and the amount of shaking or centrifuging. This method should probably be used only with articles subject to a minimum of distortion, because the bond is altogether mechanical and might not serve in many applications of wire or sheet.

Low-Tin Alloy Coatings. Tin, as a constituent of the bath, is used as a binding agent with considerable success. The most satisfactory alloy has been one that contains not more than 2.5% Sn, nor more than 2% Sb, with the remainder lead. Antimony serves to harden the alloy and to reduce the amount of white corrosion product formed during weathering. One company uses an alloy containing 0.25 to 0.50% Ag also, and maintains that such an alloy has better bonding properties. Sheets to be coated are first pickled in sulfuric acid, with or without an inhibitor, are washed well to remove acid and iron salts, and then are stored under water in a storage bosh. The sheets pass from this tank through a pair of "squeegee" rolls into a preflux tank, then through an anhydrous flux on top of the molten alloy bath, and finally into an alloy-coating machine similar to that employed in the conventional process for galvanizing sheet. After the sheets have passed down through a flux box into the alloy bath (held at a temperature of 630 to 650 F) they come out through a set of stripping rolls that serve to regulate the thickness of the coating. At present this thickness may be controlled between 0.4 and 1.1 oz per sq ft. (The nomenclature is the same as for galvanized sheets; that is, a 1.0-oz coating means 0.5 oz on each side of the sheet.) Still lighter coatings may be produced by "oil wiping" (passing the sheet through oil held at a temperature of about 600 F). When an asbestos or charcoal wipe is applied to wire, coatings as heavy as 1.25 oz per sq ft may be produced.

Another alloy that may be used for coating—especially on sheet and wire—contains about 0.55% Zn. Molten lead can hold only a small percentage of zinc in solution—approximately 2% or less, depending on the temperature. If the zinc content is too low, the adherence of the coating to the steel base will be imperfect, and if too high, the sheet may have a rough surface. Apparently the bond is a chemical one between the needles of zinc in the alloy and the steel sheet, through the medium of an intermetallic compound similar to that produced in galvanizing. One method uses a sheet with a very light coat of zinc as a base. Such a "tight" sheet may be passed down through a conventional flux in a galvanizing unit and coated with a layer of the alloy described above. Theoretically, this type of sheet has the superior corrosion resistance of lead, but is also reinforced by the zinc that remains underneath. However, after a prolonged exposure in a marine atmosphere, the lead coating may blister.

High-Tin Alloy Coatings. These are described in the article "Tinning of Steel", page 709 in this Handbook.

Applications of Dipped Coatings. Sheet and wire (a large tonnage is used as "terne" coating) coated with lead, can compete actively with galvanized articles wherever atmospheric corrosion alone is concerned, although such articles are ordinarily painted. If wear or abrasion is involved, lead is too soft to give satisfactory service. Many fabricated articles—for example, pole-line hardware—lend themselves to hand dipping, by reason of shape or use. Bolts, washers, nuts, plates, hooks and other fixtures used in industry, can be coated effectively, as well as gasoline tanks, barrels, cans, farm equipment, military equipment, air ducts and electrical hardware. Other ferrous alloys can be coated with lead after suitable preparation; for example, cast-iron objects, after they have been given a decarburizing treatment before fluxing and dipping.

Incidentally it has been found that paints adhere better to lead-coated sheets than to most metallic coatings and these sheets are more easily painted. Such articles as gutters, spandrels, flashing, and corrugated siding must frequently be decorated with color. Any of the standard lead pigments are suitable as priming coats for lead-coated sheets.

Lead Plating. The ductility of electrodeposited lead is greater than that of hot dipped coatings because of greater purity. However, lead is frequently deposited in the form of a loosely adherent, sometimes spongy metal, and is likely to contain pinholes. Lead cannot be deposited with the brilliant lustrous surface of nickel, cadmium or tin. More than ordinary care must be used in preparing the steel base for plating; if the steel surface is not clean, any attempt to plate it will result in failure. Lead is soft and easily worn; consequently, the common limits of coating thickness are rather high—0.003 to 0.005 in. Slight porosity may be overcome by light mechanical working of the coating.

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Silicon Impregnation

By Harry K. Ihrig*

THE IMPREGNATION of iron and steel with silicon (siliconizing) to form a case that contains about 14% Si, greatly increases the resistance of the steel to corrosion, heat and wear.

Metals Treated. Wrought or cast low-carbon steel, low in sulfur, is best suited for impregnation with silicon. High-carbon low-sulfur steels can be treated satisfactorily, but impregnation is slower. For example, SAE 1045 steel requires about twice as long as low-carbon steel, for production of a specific depth of case. The silicon case on high-sulfur free-machining steels may be penetrated under corrosive conditions, with subsequent cracking and spalling of the case, resulting from attack on the underlying core.

White and malleable irons can be treated, but because of the high sulfur content, the resulting cases are ordinarily less satisfactory than those obtained on low-sulfur steel. Gray iron, because of high sulfur content and because of the tendency to "grow" at treating temperatures, does not usually form a satisfactory case.

Generally, alloy irons and steels, particularly those containing chromium, do not respond to treatment so well as do plain low-carbon steels.

Preparation of Metals to be Treated. The decarburized layer often found on forgings need not be removed. Sand embedded in castings must be removed by pickling or sand blasting. Though light mill scale is harmless, heavy annealing scale should be removed. Because the temperature for the treatment is above the transformation temperature range for irons and steels, it is advisable that all residual stress be removed before the impregnation process; otherwise, the stress will be relieved during the process and distortion may result.

Process. Essentially, the process consists in subjecting iron or steel to the action of silicon carbide and chlorine at a temperature of 1700 to 1850 F. Instead of silicon carbide, ferrosilicon or mixtures of ferrosilicon and silicon carbide may be used. Either a rotary or pot type of furnace is satisfactory. The chlorine is added after the parts have reached the desired temperature. Ordinary carburizing equipment is used with only slight modifications, and no inert or reducing gas is necessary during the silicon impregnation.

The exact nature of the reaction is not fully known. At temperatures up to 1850 F, it appears essential that the carbide be in contact with the article to be treated. It is probable that chlorine liberates nascent silicon from the silicon carbide, and this diffuses immediately into the metal under treatment.

The case may be of any desired depth from 0.005 to 0.100 in. A case from 0.025 to 0.030 in. deep is usually produced on low-carbon steel in two hours. Ordinary chlorine gas of about 99% purity is used. The amount of chlorine needed depends on the size of the charge to be treated and the thickness of the case desired. The amount is determined experimentally for a specific job and then held constant for the particular charge.

Structure and Composition of the Silicon Case. Iron can hold approximately 15% Si in solid solution.[4] In a determination of the composition of the case, analyses were made of successive surface slices (0.01 in.) of the case on a low-carbon steel (0.12% C, 0.14% Si, 0.52% Mn, 0.026% S). The results showed the silicon content of the outer portion of the case (approximately two-thirds or 0.040 in.) to be substantially constant (14.02 to 13.54%, avg 13.85%) and to decrease within the remaining portion (approximately one-third or 0.020 in.) to 5.4%. The uniformity in silicon content of the outer part of the case makes it possible to grind such a case to a considerable depth without damaging it. The outer silicon-rich portion consists of a single microstructural constituent—a solid solution. The second (carbon-bearing) constituent first appears with the marked decrease in silicon content. A structural peculiarity is the higher concentration of the carbon-bearing constituent immediately below the higher-silicon layer, which suggests forced migration of carbon ahead of the silicon that is diffusing inwardly.

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Mechanical Properties. Siliconized articles show a case hardness of Rockwell B 80 to 85. Although not file hard, such parts cannot be machined or cut with a hacksaw by ordinary means.

Standard tension-test pieces cut from the same bar of SAE 1015 steel showed the following results before and after impregnation with silicon:

Property	Untreated	Treated
Elastic limit, psi	37,750	37,900
Ultimate strength, psi	60,550	51,400
Elongation in 2 in., %	38.5	19.5
Case cracked at psi	.....	41,600

The case did not crack until the steel had been stressed beyond the elastic limit. After the case had cracked, the cross section was reduced and thus the tensile strength was lowered. Although the ductility of the case is not so high as that of the core, treated tubes are ductile enough to withstand being rolled into headers. The case will not spall off under vigorous hammering. However, sharp corners should be rounded off to provide support by the core for all portions of the case.

Impregnation with silicon destroys the effect of all previous heat treatment. The case cannot be changed by any known heat treatment, but the core of a siliconized steel may be heat treated to obtain any properties possible with the type of base metal used.

Resistance to Corrosion. Articles impregnated with silicon are resistant to nitric, sulfuric, and hydrochloric acids, with decreasing resistance in the order named.

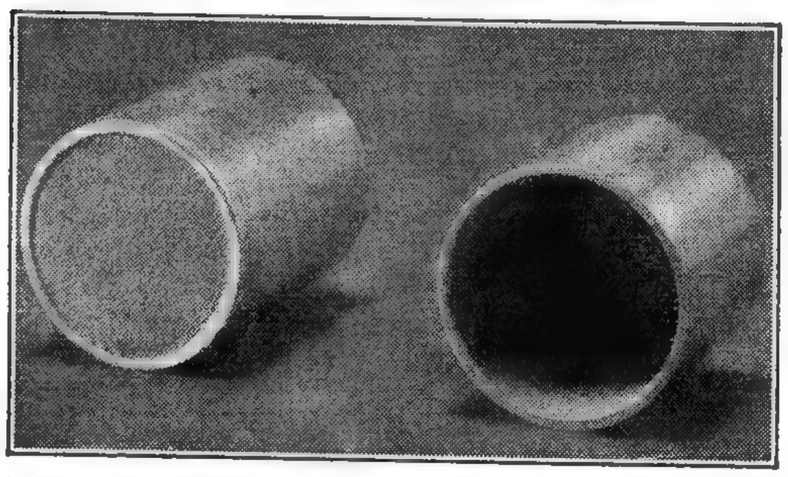

Fig. 1 Bar with silicon case, cut in half, one surface (*left*) lightly etched and the other (*right*) boiled in dilute nitric acid, leaving only the corrosion-resistant shell

Figure 1 shows two portions of a treated bar, one of which was boiled in dilute nitric acid to dissolve the core; only the case was left. The other half was etched lightly to show the case.

In 10% boiling sulfuric acid, a ½ by 2-in. siliconized round showed the following losses in weight in successive 24-hr periods:

Period	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Loss, %	3.1	0.5	0.3	0.4	0.4	0.2	0.7	0.7	0.7	0.3

Characteristic of high-silicon alloys, the attack in the first 24 hr was relatively high, but after that it decreased greatly. A companion specimen of carbon steel under the same conditions was entirely dissolved in about 18 hr, and one of 18-8 Cr-Ni stainless steel in 24 to 30 hr.

Articles that have silicon cases are not recommended for use in boiling mineral acids, because after the case has been perforated the core is rapidly attacked.

Resistance to Heat. The silicon case is resistant to scaling up to 1800 F. At this temperature excessive grain growth occurs in the steel core and the case may crack, but temperatures of 1200 to 1600 F permit long life.

Resistance to Wear. Under conditions of frictional wear, such as those to which shafts and cylinder liners are subjected, the siliconized case has stood up well and the surface is virtually nongalling. Parts that have silicon cases wear well against each other. Where conditions of corrosion and wear exist together, the silicon case is especially effective.

If, after finish grinding, a part that has been treated with silicon is heated to 250 to 300 F in a heavy oil, some of this oil is absorbed, and thus the treated part functions as a self-lubricating bearing. This property of absorbing oil is especially effective where outside lubrication is impossible. Amsler wear tests have shown a fivefold improvement in resistance to wear of an oil-treated, siliconized part, as compared with a plain siliconized companion specimen.

The reason for the oil absorption is not certain; a plausible explanation is that the case contains graphitic spots or voids left by graphite, which retain the oil.

The silicon case is not recommended for high-velocity abrasion, such as exists in sandblasting.

Distortion. A slight expansion that has not been adequately explained, occurs during the treatment of steel parts. This varies with the type of alloy being treated. Parts actually lose in weight during treatment because the heavier iron has been replaced by the lighter silicon. The following table illustrates the changes in dimensions and weight before and after treating an SAE 1020 steel bar, 1 in. in diam.

Property	Before Treatment	After Treatment
Weight, grams	602	571.4
Diameter, inches	1.000	1.003
Length, inches	5.985	5.989

Because parts are not quenched after the silicon impregnation, only slight distortion occurs. Where the type of part permits, it may be straightened cold a few thousandths of an inch, or considerably more if heated to a temperature of about 1200 F.

Applications. The following are some of the applications in which siliconized parts made from ferrous metals have given satisfactory service when subjected to corrosion, heat, or wear: automotive water-pump shafts, rocker arms, cylinder liners, and valve guides; valves, fittings and similar parts for the chemical, paper, and oil industries. Also forgings, steel and malleable iron castings, thermocouple tubes, nails, screws, bolts, and tubing are siliconized where corrosion, heat, or wear are problems.

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Tinning of Steel

By Robert J. Nekervis* and Bruce W. Gonser*

THE IMPORTANCE of the tin plate industry in the United States is indicated by the 1945 production of 2,836,339 tons. Hot dipped tin plate accounted for 70% of this total and electrotin plate for 30%. Containers and closures use about 95% of the tin and short terne plate consumed in this country. Packers cans (and closures) and general line cans are the two large divisions in container manufacture.

The steel base for these containers is usually furnished in six temper classifications; the stiffness increases from Temper 1 to Temper 6 (T1 to T6). Tin plates that have the characteristics of T1 and T2 are used in deeply drawn containers. Plates of T3 and T4 are commonly used for ends and bodies of cans for processed food. The T5 plate is used where higher resistance to buckling or paneling is required. T6 is used for the ends of cans that are subject to exceptionally high internal pressures. The carbon, manganese, and sulfur contents of the steel base will usually be within the following ranges, depending on the temper: 0.04 to 0.11% C, 0.25 to 0.53% Mn, 0.03 to 0.05% S max. Apparently these compositions have no critical influence on the resistance to corrosion of cans for processed food, whereas the influence of phosphorus, silicon, and the heavy residual metals affects the resistance to some products. The composition of the steel base is controlled to obtain the proper balance of strength and resistance to corrosion for individual applications. Necessary stiffness is obtained by the control of both the extension of the sheet (temper rolling) and the metalloid content of the steel. The low-metalloid steel used for many corrosive foods is known as Type L. This steel is produced in the lower tempers; the stiffness is controlled by the amount of extension received during temper rolling. The higher tempers (that is, the stiffer base plates) are known as Type MC plates, and the stiffness is obtained largely through control of the metalloid content. This type is suitable for mildly corrosive and noncorrosive food products.

Other classifications, such as nonaging aluminum-killed steels, are produced, but are for special uses and are too numerous to include here. In the United States, all the thin sheets for tin plate and terne plate are cold reduced; the last hot pack mill for the production of tin plate was closed in August 1943.

Details concerning the cold reduction of sheet to the thickness used for tin plate may be found on page 352. The thickness, or gage, of tin plate is measured in terms of pounds per base box, a unit peculiar to the tin industry. A base box corresponds to an area of sheet of 31,360 sq in. (217.78 sq ft) of any gage, and is applied to tin plate weighing from 55 to 275 lb per base box. For conversion to the approximate thickness in inches, the basis weight is multiplied by 1.1 and divided by 10,000. For example:

$$107 \text{ lb per base box} = \frac{107 \times 1.1}{10{,}000} = 0.0118 \text{ in.}$$

The amount of the tin coating on tin plate is expressed also in pounds per base box. Amounts of most terne coatings are expressed in pounds per double base box, which is equal to twice the area of the standard base box for tin plate. However, for light terne plate that is made with the same equipment as tin plate and used instead of tin plate for containers, the amount of coating is ordinarily expressed in pounds per single base box.

The Manufacture of Hot Dipped Tin Plate and Terne Plate. After the temper pass, in one operation on a shear line, the coils are uncoiled, trimmed, sheared to size, leveled or flattened, and sorted into piles of sheet that are within gage limits and free from pinholes. The sheets are then "white pickled" in three successive tanks, the first two of which contain 3 to 6% sulfuric acid at about 160 F. The final tank is for rinsing. After being rinsed, the plates are stored in boshes that contain slightly acidulated water.

Hot Dip Tinning. With the exception of a small amount of plate coated more heavily than is usual, steel sheet is tinned in automatic machines. These machines feed the base plate through a flux of zinc chloride into a tin bath and up through a compartment containing palm oil, where excess tin is removed. Auxiliary equipment carries the sheet through suitable cleaning attachments, where part

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or almost all of the adhering palm oil is removed and the plate is polished. The steel sheets are conveyed through the tin and palm-oil compartments by means of pairs of steel rolls, one pair in the tin compartment and three pairs in the palm-oil compartment, one above another, to squeeze off the excess of molten tin. The rolls in the palm-oil compartment have fixed scrapers of asbestos or soapstone, which aid in removing tin and tin-iron "scruff" that adhere to the rolls after contact with the tin plate. The rolls in the palm-oil bath are held against the sheets by slight spring pressure. The pot and rolls of the tinning machine are designed so that two or three sheets can be tinned, side by side, at the same time. The tin bath, containing 5 to 7 tons of first-quality tin, is usually heated near the entrance end by immersed gas-heaters.

Palm oil acts as a flux to aid in obtaining good distribution of tin, and serves as a cooling and protective medium so that the emerging tin will freeze quickly without oxidizing. The temperature of the palm oil at the top of the bath is kept as low as possible by recirculation; this temperature is preferably 460 to 470 F. At higher temperatures, the palm oil polymerizes readily, which may cause yellow streaks in the tin plate. In a typical individual circulating system, each pot holds about 475 gal of oil with an additional 125 gal in a water-jacketed reservoir, which is replenished daily. When the Saybolt viscosity of the oil reaches 100 to 108 at 210 F, the reservoir is drained and refilled with new oil. This cycle takes about two weeks. For starting a tin pot, some used oil is always mixed with the new oil, so that the Saybolt viscosity is at least 80 at 210 F. Sumatra palm oil is generally considered to be the best for use in tinning, because it is of more nearly uniform quality and contains a maximum of 5 or 6% fatty acid, compared with perhaps double this amount in African palm oil.

Steel sheets are passed through the tin pot at the rate of 25 to 30 fpm. The temperature of the bath may vary from about 575 to 650 F at the entrance end of the bath, according to the tinning speed, and may be 100 F lower near the palm-oil compartment. Some tin is lost in dross and in concentrations of tin along the edges, particularly at the bottom or "list" edge of each sheet; hence the yield, as calculated from the tin on the finished sheets near the center, is only 85 to 90% of the tin consumed. Thus, an average coating of 1.10 lb per base box of tin, as measured by the consumer, may mean a calculated coating or "tin yield" of 1.25 lb, based on the tin consumed in the mill.

Palm oil is removed from a finished plate by the use of an alkaline cleaner, by absorption in a dry material, such as bran, or by a combination of the two. Dry flannel rolls may be used for final cleaning. When the plate is to be lithographed or enameled, it is desirable that virtually all the oil be removed; for other uses, a residual film of oil may be desirable to preserve the finish or to act as a lubricant during stamping operations.

Grading of Tin Plate. After being coated, every sheet of tin plate is inspected and is either classified as "unassorted" (meaning that one lot contains both "primes" and "seconds") or is separated into four grades as follows:

"Primes" are tin plates that are free from defects readily observed by the unaided eye.

"Seconds" is the designation given to tin plate that has imperfections in moderate degree or extent, which may be classed in three general groups—imperfections in the coating, imperfections in the base material, or other manufacturing defects.

"Menders" are plates having a defect that may be eliminated by passing the plate through the tinning unit a second time.

"Waste sheets" are sheets that have prohibitive defects, for example, seams and buckled plates. Such plates are detinned and the base plate is returned to the steel plant as scrap.

The proportion of prime sheets varies from time to time, but usually is approximately 85% of the total, with seconds and menders about 15% and about 2% waste.

Terms Indicating Thickness of Coatings. Sheets that have the standard thicknesses of coating are known as "cokes", and those with heavier coatings are "charcoals" (Table I).

Because the supply of tin in the United States was seriously curtailed during World War II, the WPB imposed a maximum tin yield of 1.25 lb per base box on hot dipped plate lighter than 112 lb per base box in thickness.

The production of charcoal plates, a very small percentage of the total tin plate, usually requires special equipment. Sometimes heavy coatings are produced by first tinning the sheets in a tin pot used for dipping coke plates, then dipping them in a second pot at a relatively low temperature, and finally dipping them in palm oil. In other instances, an entirely separate unit is used. Charcoal plates may carry as heavy a coating as 14 lb per base box, but for most uses, the coating is from 2 to 7 lb per base box.

Table I. Weights of Coating on Hot Dipped Tin Plate

Class		Minimum Average Weight of Coating, lb per base box (Fed. Spec. U. S. 1936)
Standard Coke Plate		Not specified
Best Coke Plate		1.19
Kanner's Special		1.40
Charcoal	1A	1.80
	2A	2.30
	3A	2.80
	4A	3.50
	5A	4.20
Premier		4.90

Testing Tin Plate. Since virtually all hot dipped tin plate is used in making cans, or closures for cans and bottles, the resistance to corrosion is an important property, and is frequently tested at the tin mill as well as by the fabricator. Actual records of performance provide the most reliable information. Accelerated tests are made by holding the packed container at an elevated temperature. In an even more accelerated test that has been used rather widely, the time is measured for a definite amount of hydrogen to be evolved when the tin plate is immersed in warm dilute hydrochloric acid, under standardized conditions.

Terne Plate. The sheet steel for terne plate is prepared in the same way as for making tin plate. Likewise, much of the thinly coated terne plate ("manufacturing ternes") is made in the same way and with the same machinery. The only difference is that a terne metal bath consists of an alloy of tin and lead, and the temperature of the bath and oil is somewhat higher. Spent palm oil from the tin pots is commonly used for draining. Hydrogenated fish oils also are used to some extent. Ternes so made contain only 15 to 25% Sn, and the coating thickness for most applications—for instance, for lubricating-oil cans—is only about 0.00005 in. The WPB (M43, March 8, 1945) defined terne plate made with tin-mill equipment as "short ternes", and limited the pot yield to 1.30 lb per base box.

Common "roofing tin" is heavily coated, hand-dipped terne plate, which is usually designated as "short terne" to differentiate it from the "long terne" or larger sheets. The composition of the base plate is usually selected with some regard for resistance to atmospheric corrosion, and is frequently machine-coated with the terne mixture as part of the preparation for hand dipping. For roofing, a 25% Sn–75% Pb bath is commonly used. Sheets are dipped singly in one or two terne baths, then into palm oil. The coatings are designated in terms of pounds per double base box. The range of coatings varies from 12 to 40 lb on this basis. The size of the spangle or mottle gives some indication of the thickness of coating. The size of mottle decreases with an increase in coating thickness if the conditions of manufacture are similar. However, the size of mottle may be varied by changing the rate of cooling.

Long ternes, machine-coated sheets that are comparatively large, are usually made in galvanizing shops rather than tin mills, and are similar to galvanized sheets in size. As with thinly coated terne plate, the base metal is passed through a zinc chloride or zinc-ammonium chloride flux, through a terne metal bath, and through a palm oil finishing compartment, by machine. The coating obtained is normally 8 lb or less per double base box. The WPB

(M43, March 8, 1945) defined long ternes as terne coated in sheet-mill coating machines, and restricted the pot yield to 4 lb per base box and the tin content to 10% max. Hot dipped terne coatings have been applied continuously to coils of 24-gage and 26-gage sheet commercially.

Terne metal is more expensive than zinc, but much cheaper than tin. The advantage of terne lies in the fact that it has certain of the properties of tin at a much lower cost. Under alternating exposure to air, terne metal will remain bright where zinc will form oxides and carbonates. Therefore, terne plate is used for gasoline tanks, where any products of oxidation might clog the fuel line. The surface of terne plate is soft and has a greasy feel. The metal will not flake off, is very ductile, and is much used for deep drawing operations where a corrosion-resistant material is desired. A further advantage lies in the fact that it can be painted without weathering, which makes it a useful roofing material.

Tinning of Wire and Narrow Strip. Wire and narrow strip are hot tinned continuously. The excess of tin is removed by running the wire or strip through a wiping fixture, which is packed with asbestos, or through charcoal or, for wire, through a tungsten carbide die. This gives a thin coating, usually less than 0.00005 in. thick or amounting to about 0.025 to 0.035 oz per sq ft of single surface. (Strip of this weight would be doubled to give weight per square foot of material, or the equivalent of 0.6 to 0.9 lb per base box of tin plate.) For heavier coatings, other means of wiping have been suggested and used to a limited extent; for example, steam jets, compressed air, and a strong countercurrent flow of palm oil.

Preparation consists essentially of cleaning or pickling and passing the wire or strip through a zinc chloride flux before it enters the pure tin bath. Since no palm oil is used, the surface of the tin bath should be covered with charcoal to avoid oxidation. Strip wider than 6 in. is seldom tinned continuously in this way.

Tinning of Fabricated Articles. Before tinning, fabricated articles are degreased by vapor cleaning or other suitable methods. This operation is followed by pickling, as in hot dilute sulfuric acid; by temporary storage in dilute hydrochloric acid, as in making tin plate; and finally by fluxing and tinning.

Zinc chloride, or zinc chloride containing a small amount of ammonium chloride, is a positive flux widely used in tinning fabricated articles. Molten tallow is sometimes used for fluxing. Usually the products to be tinned are first immersed in a preliminary tinning bath and then immersed in a second tinning pot to secure a better coating. In this way much of the iron-tin dross remains in the first pot, and the second pot can be maintained with a purer tin bath. To ensure complete coverage, the articles may be brushed or wiped while the tin coating is still fluid and then redipped momentarily to leave a free, smooth surface. As a final operation, the articles are either withdrawn through a palm-oil or molten-tallow division of the final tinning pot, or are dipped in a separate bath of such material to permit drainage of the tin coating. The amount of tin adhering depends largely on the temperature of this finishing bath and on the time permitted for drainage, but the coating is always heavy in comparison with that on standard coke tin plate. As a final step, the edge or bottom portion of the article, to which excess tin has drained, is usually dipped into a hot tin bath to remove the heavy tin concentration. Cloth, bran or sawdust may be used for the final polishing and removal of grease.

Tinning of Cast Iron. Cast-iron parts are not readily tinned, because of the graphite in the iron and the difficulty in pickling to give a clean surface. Where possible, it is best to use sandblasting or other mechanical means to remove the casting skin effectively. This treatment is followed by pickling in warm sulfuric acid (5 or 6%) containing an inhibitor, storage in dilute hydrochloric acid, fluxing in zinc chloride containing up to 35% ammonium chloride, and tinning in the general manner described for fabricated articles. Frequently, pickling in cold 5% hydrofluoric acid is necessary in order to remove residual sand. Surface decarburization does not always help to make the casting more easily tinned, but it is advantageous to have an intermediate layer of pure iron, copper, or nickel, which may be plated on electrolytically or by replacement.

A marked departure from the traditional procedure in preparation for tinning, is the immersion of castings in a salt bath immediately after sandblasting.

Electrotin Plating. Two advantages of electrotin plating —the possibility of tinning in continuous lengths and of regulating the coating to any desired thickness—led to large-scale experiments before 1942. The need for strict economy in the use of tin during the three years thereafter, resulted in the construction of 28 electrolytic tinning lines in the United States. These have been used largely to give coatings of 0.25 to 0.75 lb per base box, or thinner than it is possible to obtain by hot dipping.

Plating Baths. The types of electrolytes used in tin plating are of two broad classes—those using an acid electrolyte and those using an alkaline electrolyte. Satisfactory tin plate can be made from either type. Each has certain advantages, and the choice of bath is governed by plant considerations and administrative aspects, such as patent rights.

The alkaline baths consist essentially of either sodium stannate and caustic soda, or potassium stannate and potassium hydroxide electrolytes. Buffer salts (acetates) and agents to oxidize traces of stannites, may also be added. The current density of the sodium stannate baths is approximately 20 to 30 amp per sq ft; the temperature is 180 to 190 F. Anode and cathode current efficiencies range from 60 to 80%.

Greatly increased plating (cathode) current densities are possible (up to about 200 amp per sq ft) if potassium stannate and hydroxide are substituted for the sodium salts. However, higher anode current densities are not possible in present practice without greatly reduced current efficiency. The anode current density thus limits the use of this process.

The acid bath consists essentially of stannous sulfate and an aromatic sulfonic acid with addition agents. The bath depends on the use of colloidal addition agents for successful operation.

Possible current densities with various types of baths vary from 10 to 400 amp per sq ft. The temperature of the bath ranges from 70 to 100 F. Cathode and anode current efficiencies are nearly 100%.

Halogen electrotin plating solutions are being used by two major producers of tin plate. The principal constituents of the solutions are tin chlorides and fluorides with an organic addition agent. The tin content may be varied from 15 to 40 g per liter, depending on current density and the speed of the strip. The total organic addition agent is about 2 g per liter. The bath is operated at a pH of 2.7 with an optimum temperature of 150 F. Current density in actual operation is 185 amp per sq ft. With various compositions of the solution, a range of current densities from 50 to 500 amp per sq ft is possible. Cathode and anode efficiencies are reported to be 97 and 100%, respectively.

Basic Design of Lines for Electrolytic Tinning. In typical practice, the sheet is received directly from the temper mills in coils. These coils are tinned in one of three basic types of lines: the vertical tank line for use at constant plating speed; the vertical tank line for use at variable plating speed; and the horizontal tank line for use at variable plating speed.

In the sequence of operations on these lines, the strip is uncoiled and the ends are welded together, either at lower line speeds or with provisions for feeding strip to the plating tank at an unchanged rate, by means of a looping device. The strip is usually free from grease so an electrocleaning step may be omitted. Pickling follows, either in a regular acid pickle or in an electrolytic pickle; then the strip is scrubbed or washed and passed into the plating tank. The strip may be passed through the line either in a vertical serpentine manner or horizontally. If passed horizontally, the two sides of the strip are plated separately. Most plants filter the electrolyte continuously. After leaving the plating tank, the strip is washed, dried, and flow-brightened, that is, the electrodeposited tin coating ■ momentarily melted and is then quenched im-

mediately. Fusion is accomplished in many ways—by induction heating, resistance heating, between radiant tubes or banks of ceramic radiant heat burners, or by melting in heated oil. All such methods can be used at high speeds.

Sometimes the brightened strip is passed through a chromate solution, where it is treated chemically to provide an invisible oxide film. Then after the strip has been rinsed in water and dried, a thin film of oil is imparted to the surfaces by one of several methods—branner oiling, emulsion oiling, spraying, or vapor condensation. From this point, the strip is sheared in tandem with the electroplating line or as a separate operation, if the speed of the plating line exceeds 600 fpm, the maximum shearing speed. Plating line speeds vary from about 500 to 1000 fpm. The higher-speed lines have been operated as rapidly as 1350 fpm.

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Zinc Coatings

By W. M. Peirce*

ZINC COATING, or "galvanizing" as it is commonly termed, is a very old method of protecting iron and steel against corrosion. It is applied to a greater tonnage of steel products than any other method of metallic coating and provides the most economical protection for products of the type to which it is properly applicable. The major established applications of zinc coating on steel products include roofing and siding sheets, wire and wire products for all outdoor exposure, articles fabricated from sheet steel such as range boilers, pails, cans and tanks, hardware for outdoor use, pipe and conduit, and exposed structural steel. Nails are galvanized not only to extend the life of the nail but also to prevent rotting of the wood, which occurs around rusted nails. In short, wherever steel is exposed to atmospheric corrosion, zinc coating is a standard and effective method of protection.

The usefulness of zinc coatings depends, first, on the relatively slow rate of corrosion of zinc as compared with that of iron, and the much less objectionable appearance of the white, nonstaining corrosion products of zinc as compared with iron rust; and, second, on the electrolytic protection afforded to iron by zinc. This electrolytic protection prevents iron from corroding at minor discontinuities in the zinc coating, such as sheared edges of sheets, cut ends of wire, or abrasions in the surface. This electrolytic or "sacrificial" protection extends away from the zinc coating over exposed iron surfaces for a sufficient distance to protect the steel at cut edges, scratches and other discontinuities in the coating. The distance varies with the properties of the film of moisture as an electrolyte, and is a maximum under such conditions as the presence of salt water.

Zinc coatings have the longest life under conditions of rural exposure where the air is free from sulfur gases and other industrial fumes. They give satisfactory service in salt air, also. They are more rapidly attacked in highly acid industrial atmospheres, but nevertheless are widely used in such atmospheres because no more effective and economical method of protection has yet been found. Frequently the combination of a zinc coating and an acid-resisting paint or other organic coating is most effective. The zinc forms a more durable base for the organic coating and prevents rapid failure by undercutting corrosion when the organic coating is penetrated.

When zinc coatings are to be painted for decoration or protection, it is desirable to use a suitable primer, such as a zinc dust primer that ages without serious loss in adherence. The adherence of ordinary paints is improved by weathering of the zinc surface or by chemical etching. The best adherence is obtained by the use of phosphate-treated galvanized sheets to which even ordinary paint adheres well.

Zinc coatings are occasionally subject to an abnormal type of corrosion that results in bulky white corrosion products. Such corrosion originates from contact with water without free access of air. Galvanized sheets should be stacked on edge rather than flat, to prevent rain or condensed moisture from being held between them, which can cause this type of corrosion. Zinc-coated material to be used where "sweating" or other exposure to stagnant water may occur, can be protected by a chromate surface treatment that has been developed for this purpose.

Since zinc has an appreciable rate of corrosion under the conditions of exposure where zinc coatings are used, and since the coatings that can be applied readily are measured in thousandths of an inch or less, it is obvious that the life of the coating will not be indefinite but will be determined by the thickness of the coating. Many comprehensive researches have shown that all other factors—such as the method of applying the zinc coating, the purity of the zinc, and the extent to which it is alloyed with the iron—are minor in determining life, as compared with the thickness of the coating.

Occasionally, zinc coatings on steel are specified in terms of thickness in thousandths of an inch, or in terms of the weight of coating expressed as a percentage of the weight of the steel base. As a rule, however, zinc coatings are measured in ounces per square foot of surface for most products except sheet. The weight of coating on sheet is stated in ounces per square foot of sheet. Since the sheet is coated on both sides, this weight is twice the average weight of coating per square foot of surface. The terms "Regular", "Tight Coat", and "Extra Tight Coat", as used in the trade, refer to relative freedom from visible flaking of the coating when bent. Since this "tightness" of the coating to the base is ordinarily achieved by reducing the weight of coating, the terms have come to connote varying weights of coating. The "Extra Tight Coat" corresponds to the thinnest coating. Weights of coating for many classes of galvanized products have been specified by the ASTM and are given in Tables I and II. The ASTM specifications should be consulted for a description of the methods of measuring properly the thickness of coating (which varies in uniformity according to the method of application).

It should be noted that an unusual system of terminology is used in the wire specification; Class 1 or Class A is the lowest grade material and Class 3 or Class C is the best in every instance.

Tables I and II do not represent the maximum weight of coating desirable for every application nor the maximum obtainable.

Zinc coatings are applied commercially by four methods. The oldest and most widely used is hot dipping. In this process the steel is first pickled in sulfuric or hydrochloric acid to remove all scale, then washed to remove iron salts and finely divided iron. To be completely effective, this washing must be combined with scrubbing.

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Any iron salt or finely divided iron that is left on the surface, forms dross in the galvanizing pot. The steel is next "fluxed" in weak hydrochloric acid or in a strong zinc chloride solution, partially dried and introduced into a bath of molten zinc. Fluxes — usually ammonium zinc chloride mixtures — and various mechanical devices are used to keep the surface of the zinc bath clean at the points of entry and exit. These vary, of course, with the type of material being handled. Sheets are fed by driven rolls immersed in the bath, and come out between partially submerged grooved rolls. Wire is pulled through guides and emerges through sand, charcoal or a wad of asbestos held mechanically in contact with it. These exit rolls and "wipes" smooth the surface and remove some of the zinc. Products other than sheet and wire are handled semi-mechanically or by hand and may be shaken, jarred, rotated or centrifuged (as, for example, nails and small parts), to distribute the coating evenly and remove excess zinc. In all cases the work pieces must be handled properly until the coating has frozen, in order to avoid marking and to secure as even a distribution as possible. The appearance may be controlled by the use of cooling air, by the application of SO_2 or ammonium chloride to the still molten coating, and by local chilling to start crystallization and control spangle pattern.

Table I. Nominal Weights of Coating for Sheet According to ASTM Specification A 93–46

(Weight of coating on two sides expressed in ounces per square foot of sheet)

Ordered Coating Weights and Minimum Coating Limits	Minimum Coating — By Sheet Test	By Diagonal Triple-Spot Test	By Single-Spot Test	Practicable Limits of Galvanized Sheet, gage
2.75	2.50	2.35	2.00	No. 8 to 24
2.50	2.25	2.10	1.80	No. 8 to 26
2.25	2.00	1.85	1.60	No. 8 to 28
2.00	1.75	1.65	1.40	No. 11 to 28
1.75	1.50	1.40	1.20	No. 14 to 28
1.50	1.25	1.15	1.00	No. 16 to 30
1.25	1.00	0.90	0.80	No. 18 to 30

Variations of every step described above have been proposed and many are in use. For example, cleaning may be accomplished by oxidation and reduction of the surface. Fluxes can be eliminated if the material, with the surface free from oxide, is introduced through an inert or reducing atmosphere. The character of the alloy layers (*see* below) and of the coating may be varied by varying the composition of the steel surface—for instance, through control of silicon, carburizing, and phosphorizing—or by the addition of alloying elements to the zinc bath. Tin and aluminum, discussed later, are frequently used in this way.

The zinc bath for hot dipping is contained in a melting pot of suitable dimensions, fabricated from mild steel plates and heated, usually from the sides, by a uniform and carefully controlled source of heat, such as gas or electricity. If the temperature of the zinc is kept below 490 C and local overheating of the pot is avoided, the rate of solution of the iron pot in the zinc is very slow. The rolls and other machinery for handling the sheets or other materials through the bath, are also made of iron or steel.

In recent years an important development in sheet galvanizing has been made possible by the advent of the continuous sheet mill. Many of the problems of sheet galvanizing are connected with the entrance of a new sheet into the bath. The ends of single sheets must be trimmed after galvanizing, to remove irregularities and imperfections. The feeding of a continuous coil to the galvanizing pot overcomes operating problems and eliminates scrap losses from trimming. Methods of cleaning, annealing and after-treatment that are impractical with single short sheets, become practical and are used commercially with continuous sheet. Thus all steps of the hot galvanizing process for sheet are undergoing an important evolution (1947).

At this point, attention may be directed to the increasing production of flat wire and narrow strip in the field intermediate between wire and continuous sheet.

Table II. Minimum Weights of Coating for Wire According to ASTM Specifications

(Weight of coating in ounces per square foot of surface)

Telephone and Telegraph Wire (A 111–43) and Tie Wire (A 112–33)

0.109 in. diam and greater... 0.8 0.083 in. diam 0.7

Railroad Right-of-Way and Farm Field Fencing (A 116–39)

Size of Steel Wire, Gage	Diameter, inch	Class 1	Class 2	Class 3
7	0.177	0.40	0.60	0.80
9	0.148	0.40	0.60	0.80
10	0.135	0.30	0.50	0.80
11	0.120	0.30	0.50	0.80
12	0.105	0.30	0.50	0.80
12½	0.099	0.30	0.50	0.80

Barbed Wire (A 121–39)

Size	Diameter, inch	Class 1	Class 2	Class 3
12	0.105	0.30	0.50	0.80
12½	0.099	0.30	0.50	0.80
14	0.080	0.25	0.45	0.65

Chain Link Galvanized After Weaving (A 117–38)

0.120 to 0.192 in. diam..... 1.2

Wire Strand

Galvanized Common (A 122–41)	Diameter, in.	Class A—Extra or Double Galvanized (A 122-41)	Class B (A 218-41)	Class C (A 218-41)
Strand				
0.041-0.072 in. 0.15	0.041-0.052	0.40	0.80	1.20
0.080-0.125 in. 0.30	0.062-0.072	0.50	1.00	1.50
0.143-0.207 in. 0.40	0.080	0.60	1.20	1.80
	0.093-0.100	0.70	1.40	2.10
	0.104-0.113	0.80	1.60	2.40
	0.120-0.125	0.85	1.70	2.55
	0.143-0.179	0.90	1.80	2.70
	0.188-0.207	1.00	2.00	3.00

In the hot dip method the zinc alloys with the iron, forming one or sometimes two layers of definite iron-zinc alloys between the steel base and the outer layer of substantially pure zinc. The character and thickness of these alloys depend on many factors in the process: the temperature of the zinc bath, the duration of immersion, the composition of the steel and the condition of the surface. The adherence of the coating when bent is affected by the alloy layers; a thin, even layer of alloy is most desirable. During the last ten years more attention has been given to the influence of the steel base itself, and there is no doubt that important improvements in final quality have been made in some cases by attention to the type and quality of steel and the proper adaptation of the several steps in the hot galvanizing process to the type of steel used.

Hot dip coatings that consist entirely of iron-zinc alloys, are produced on sheet and wire either by very tight "wiping" of the steel (*see below*) or by subsequent heat treatment, which causes all of the zinc to alloy with the iron. Such coatings, when bent, crack in an infinite number of fine cracks with some dusting of the coating. The resulting appearance of the bend is more desirable than the flaking that sometimes occurs when ordinary heavy coatings are bent; but unless the flaking is very severe, the life remains proportional to the thickness of the original coating, regardless of flaking or bending, because of the electrolytic nature of the protection.

The purity of the zinc used in hot galvanizing, has an effect on the bending properties of the coatings. Of the common impurities found in zinc, cadium alone seems to be important. Its presence affects the bending properties of the coatings adversely by embrittling the outer layer of zinc. Aside from this, the grade of zinc used has no known effect on the properties of the coating. Because of the greater ease of obtaining heavy coatings with good bending properties when high-purity zinc is selected, this grade has been used for many years in producing high-quality galvanized wire, where the coating must be heavy and must not flake when bent as, for

example, in splicing. Attempts to use high-purity zinc for sheet galvanizing have not met with great success in operations with single short sheets, primarily because the flux on a zinc bath that is free from lead and cadmium lacks the fluidity of a flux on a bath containing a few tenths per cent of cadmium and from a few tenths to one per cent of lead (the amount found in the commercial grades commonly used). This lack of fluidity accentuates the operating difficulties and results in defects originating with the entrance of a new sheet into the bath. The advent of continuous sheet galvanizing has opened up the possibility of using high-purity zinc for sheet with the same success as on wire.

Tin, to the extent of 1 or 2%, is frequently added in the galvanizing of sheet and hardware, to control the spangle—that is, the crystalline appearance of the surface. To improve the brightness of the finish, aluminum also is added in very small fractions of a per cent, in the "hand dip" galvanizing of material other than sheet and wire. Aluminum has another very important effect when added in amounts of about two tenths per cent or higher. In such concentrations, it largely inhibits the formation of alloy layer, and thus improves the bending properties. In the ordinary sheet or galvanizing processes where chloride fluxes must be maintained, the presence of aluminum in such amounts ruins the flux. In a continuous sheet or wire, however, the steel can be cleaned and introduced into the zinc bath through an inert or reducing atmosphere instead of through flux. This makes it possible to take advantage of the desirable effects of aluminum.

The thickness of the coating applied by hot dipping depends on the duration of immersion (which controls the thickness of alloy), the speed of withdrawal from the bath (which controls the amount of zinc adhering), the temperature of the bath (which affects both), and the amount of zinc removed by wiping, jarring, or centrifuging. On sheets, the depth of metal above the line of contact of the exit rolls is an important factor.

The electrogalvanizing method of zinc coating is simply a zinc electroplating process. Modern practice makes possible the production of coatings of virtually any desired weight for outdoor or other severe service, and of bright thin coatings where appearance is the primary consideration.

In the deposition of both thick and thin coatings, as in other electroplating operations, cleaning of the surface is of major importance, and a considerable part of modern development in the art—particularly in the field of rapid deposition—relates to cleaning. Parts supplied for bright zinc plating normally carry only a film of grease and drawing lubricant, which is removed by cathodic treatment in an alkaline solution. Flat and round steel wire and continuous sheet, furnished for rapid plating at high current density, may carry a film of rust, which, when removed by suitable acid treatment, leaves a film of undissolved or redeposited material that must be removed before plating. An alternative method, involving electrolytic treatment in molten caustic soda, has been used commercially.

Rapid electrodeposition is obtained by the use of current densities as high as 1000 amp per sq ft in conjunction with very pure electrolytes.

The replenishment of the zinc in this process is accomplished by one of two means. In one process, zinc ore is leached with sulfuric acid to abstract the zinc. The resulting solution is too impure for electrolysis at high current density and requires removal of the impurities before use. Insoluble anodes (usually of a lead alloy) are employed in the electrolysis. In the less highly acid solutions zinc is supplied directly in the form of anodes of high-purity zinc, which are readily available. Each method has its own advantages but relatively few data are available concerning comparative costs.

Solutions for applying bright lustrous deposits are of the alkaline cyanide type, containing various organic and inorganic ingredients to promote brightness. In one process brightness and high luster are obtained solely by maintaining the electrolyte in a state of very high purity. In all processes the zinc content is supplied by means of zinc anodes. In the industry the consensus is that zinc of high purity is required for best results.

Electrogalvanized coatings consist of a single layer of zinc with no layer of alloy. As a result, these coatings are very adherent when bent, regardless of thickness, unless the preliminary cleaning was not thorough. Electrogalvanizing offers the advantage, important in many cases, of requiring no heating of the steel. Also it is claimed that greater uniformity of coating can be obtained. This is probably true of wire, but on sheet some edge effect may occur, and on irregularly shaped material the difficulties of securing uniformity increase as with any plating process. The appearance of electrogalvanized coatings is considered preferable in some applications. The practical range of coating thickness obtainable by electrogalvanizing is greater than by hot dipping, but little information is available concerning relative costs of comparable weights of coating applied by the two methods.

An important new field in the application of galvanized steel has been opened by the advent both of electrogalvanized steel wire, strip and sheet, and of the same products coated by improved hot dipping methods to yield heavy adherent coatings. Many articles that could be given adequate protective coatings of zinc only by relatively expensive methods of galvanizing after fabrication, can now be fabricated from heavily coated stock. Weaving of such wire and deep drawing of heavily coated sheet are now commercially practical.

Sherardizing, described on page 715, a third method of coating zinc, produces coatings consisting entirely of iron-zinc alloy, uniformly distributed.

Spray coating, described on page 720, should be mentioned here since it affords a means of zinc coating parts too large for treatment by any of the other methods. Like electrogalvanizing, spray coating involves no heating of the steel.

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Zinc Impregnation

By F. C. Kelley*

THE PROCESS of zinc impregnation dates from an English patent obtained in 1901 by Sherard Cowper-Coles and is called "sherardizing" to honor the inventor.

Apparatus. In order to minimize oxidation of the zinc, this process should be carried out in tightly sealed drums, which are rotated in gas-heated or oil-heated furnaces to produce a uniform coating of high density. Electrically heated drums that have properly insulated double walls are also used. The electrical heating units are placed between the walls of the drum, which is supplied with several coarse wire-screen containers so that the work pieces in any container may be removed at any time. The drums are not completely filled with powder. This allows the parts under treatment to rub against one another and the powder to change its position, ensuring close contact with the charge.

The Zinc Powder. The zinc dust should be as free as possible from impurities, especially lead. However, small amounts of silica or iron oxide do not seem to be deleterious. Periodic chemical analyses are necessary, and on the basis of the results, the metallic zinc content is maintained between 80 and 92%; the remainder is zinc oxide and impurities. A common method used for determining the amount of metallic zinc in the powder, depends on displacing hydrogen from sulfuric acid.

Table I. Results of Typical Analyses of Dust Used in Zinc Impregnation

Metal or Compound	Percentage in New Dust	Percentage in Used Dust
SiO_2	Trace	0.43
Cu	0.01	Nil
Pb	0.99	0.81
Fe	0.39	1.16
Cd	Nil	Nil
Zn	97.98	84.50
ZnO	0.46	12.12
Total Zn	98.34	94.57

Results of typical analyses of new and used dust are listed in Table I.

Before the metal to be coated has been charged, new powder is heated alone in the drums for a sufficient time to oxidize somewhat, so that the zinc content comes within the specified range. Used powder is analyzed frequently and some new powder is added when necessary, to keep the zinc content above 80%. The iron and iron oxide must be removed from the mixture periodically by magnetic separation in order to maintain the uniform quality of the coating. The particle size varies in zinc powder of the composition given above; results of screen analysis are shown in Table II. Some of this zinc dust has a particle size as small as 1/40,000 to 1/50,000 in.

Table II. Particle Size of Zinc Powder

Screen	Percentage Zinc
On 100-mesh	3.65
On 150-mesh	1.05
On 200-mesh	3.55
On 350-mesh	6.25
Through 350-mesh	84.50

Powder that has a zinc content of 90% gives a coating of specific gravity 6.75 when a temperature of 660 to 700 F is used. The powdered alloy $FeZn_{10}$ has been used to a limited extent, but the temperature must be higher than that for powdered zinc.

In the early process, sand was added to the powder to prevent caking at the higher temperatures, and a small amount of carbon was added to limit the oxidation of the zinc.

Temperature. The wide range of temperatures originally used, caused widely varying results. Today the process is usually carried out within the temperature range from 660 to 700 F, which gives a satisfactory product. Lower temperatures result in a thinner coating, while higher temperatures produce a coating that has a greater iron content and somewhat lower resistance to atmospheric exposure. The duration of treatment varies from 3 to 12 hr, according to the desired thickness of coating.

If the operating temperature is much above 660 to 700 F, the coating will be coarsely crystalline; if the temperature is much below that range, the coating will be relatively soft and porous. For the best coating, the charge should be heated as rapidly as possible to between 660 and 700 F. When electrically heated drums are being used, rapid heating can be obtained by the use of parallel series connections to the heater units.

The Coating. The coating is ordinarily gray, but when cleaned by brushing or rubbing, the color is nearly that of pure zinc.

Usually only one structural layer is observed on the surface of the iron, but after the zinc-impregnated iron has been heated to higher temperatures, a second layer is sometimes found. Opinions differ concerning the composition of the single-phase layer; some assert that it is $FeZn_7$, and others, $FeZn_{10}$. McCulloch found that after iron foil had been heated in zinc dust for 45 days at 779 F, the alloy formed contained about 6% Fe. He obtained about the same result on a similar piece of iron foil heated for two days at 689 F. Accordingly, he concluded that the limit of the iron-zinc solid solution is 6% Fe, instead of the higher percentage usually shown in the phase diagram. McCulloch gave 8 to 10% as the average iron content of good sherardized coatings.

When the second layer appears it is much richer in iron, and Rawdon has suggested that it might be $FeZn_3$.

All sherardized coatings are fissured with minute cracks, which probably result from the large differences in expansion between the coating and the iron base.

The thickness of the coating produced in 3 hr at 660 to 700 F is about 0.0025 in.

The Cementation Process. Some have stated that in the cementation process, the coating is deposited directly from the vapor phase; others believe that the coating is formed on contact between the metal and the zinc powder.

Several years ago Kelley investigated the possibility of improving the process by carrying out the operation in a vacuum of 1-mm pressure. It was found that there was little if any difference in the thickness or character of the coating if the charge was revolved, as compared with samples produced in the usual way. This would seem to indicate that the coating is formed largely through contact of the powder with the iron. The vapor pressure of zinc is probably high enough to give a slight coating, but not high enough to produce the thickness obtained in the usual process. The results of Trood, who obtained a much heavier coating in vacuum in a shorter length of time, have not been confirmed. The fact that particles of iron oxide and silica are sometimes found embedded in the coating supports the theory that the coating is formed by contact.

The Weathering of Sherardized Coatings. All sherardized coatings are anodic toward the iron with which they are in contact; however, they are less anodic than pure zinc. Burgess found that the potential of the alloyed coating with respect to iron was 0.20 to 0.25 v as compared with 0.50 v for zinc. This accounts for the protective value of the zinc coatings.

Coatings with low iron content gradually darken during weathering and finally become almost black, but those with higher iron content become reddish because of the oxidation of the iron. The red color is deceptive and does not necessarily mean that the iron underneath has been attacked. In general, however, coatings high in iron do

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not resist the action of the atmosphere so well as those with lower iron content. The coatings high in iron will rust almost immediately in salt spray, while those low in iron will stand up well. Coatings that contain 15 to 20% Fe, break down rapidly when exposed to the action of the atmosphere, while those with 8 to 10% Fe or less stand up well. The life of a good sherardized coating depends also on the thickness. According to the 1936 report of ASTM Committee A 5, sherardized, hot dipped, and plated zinc coatings of the same thickness have about the same service life in similar environments.

Uses. A sherardized coating is very nearly uniform in thickness and so can be used on threaded parts like bolts and nuts. The threads are not filled up as they are by hot dip galvanizing. Allowance can be made for the coating when the threads are cut and, after sherardizing, rethreading or tapping is not necessary.

The principal application of sherardizing is for small steel parts, such as bolts, nuts and washers, or for castings that must resist the action of the atmosphere. Iron wire has also been coated, but the heavy coatings are brittle and may flake when the wire is bent sharply. However, processes have been perfected for producing on steel sheet and wire, a coating similar to a sherardized coating, in that it consists substantially of iron-zinc alloy. The process, known under various trade names, consists in heat treating a zinc coating produced by conventional hot dip galvanizing and thus converting it into iron-zinc alloy. Superior merit is claimed for this material, especially for ovens and other articles to be used at elevated temperature; wire so treated is used under atmospheric conditions.

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Electroplated Metal Coatings

By William Blum*

IN THIS SECTION concerning the selection, application and testing of plated coatings, factors are summarized that are likely to be of interest to metallurgists and engineers who are not engaged directly in plating operations. Persons actually engaged in plating will require much more detailed information, which can be found in the textbooks and journal articles referred to.

Since almost all the metals applied by electroplating are nonferrous, these plating processes might be classified under nonferrous metallurgy. Although plating is applied extensively to copper, brass, nickel brass, zinc, zinc-base die castings, and aluminum, actually the largest part of commercial plating is applied to iron and steel; consequently the important commercial plating processes will be summarized in this section, with appropriate references to their applications to either ferrous or nonferrous metals.

The Selection of Electroplated Coatings. The choice of a coating—plated or not—for a specific purpose, depends on the advantages and limitations of that coating. "Electroplating" has been defined as the electrodeposition of an adherent coating upon an electrode for the purpose of securing a surface with properties or dimensions different from those of the base metal. Among the specific reasons for applying plated coatings are the following:

1 To produce and retain ■ desired appearance, for example, color and luster. This requirement usually also involves resistance to tarnish. In general (unless lacquer is applied subsequently) this aim can be accomplished by plating with the noble metals, such as platinum and gold; or with less noble but passive metals, such as nickel and chromium. Silver resists oxidation but is readily tarnished by sulfur compounds; copper is tarnished both by oxygen and sulfur.

2 To protect the base metal against corrosion. Because uncoated iron usually rusts during exposure to the atmosphere, it is customary to apply some protective coating. Plated coatings may protect iron in either of two ways.

(a) The coating may be less resistant to initial corrosion than iron. Therefore it may protect small exposed areas of iron by electrolytic action, in which process the coating is anodic (that is, it dissolves) and the base metal is cathodic (that is, it is protected against corrosion). The two anodic metals that are applied commercially are zinc and cadmium. Coatings of both these metals furnish prolonged protection to steel in mild or marine atmospheres, but are attacked rather rapidly in industrial locations where sulfur compounds are present. When exposed to industrial atmospheres, zinc coatings last longer than cadmium coatings of the same thickness.[1] Both zinc and cadmium coatings afford protection approximately proportional to the thickness. Electroplated zinc furnishes about the same protection as zinc coatings of the same thickness that are produced by hot dipping or sherardizing.[2] One objection to zinc coatings is that under marine or tropical conditions, bulky white corrosion products are formed. Various chromate treatments are used to retard this corrosion of the zinc.

(b) The coating may be more resistant to initial attack than the steel. This is true of copper, nickel, tin, lead, chromium, silver, gold and nearly all electrodeposited metals except zinc and cadmium. Such coatings furnish complete protection to the base metal only if they are impervious. If any pores exist, corrosion of the steel beneath them is usually accelerated. The most practicable method of decreasing the porosity and increasing the protective value, is to increase the thickness of the coating.[3]

Of these more resistant metals, nickel is most commonly used to protect steel against corrosion. A preliminary coating of copper is frequently applied, partly because the copper may be more cheaply polished than the underlying steel or the superposed nickel. The customary thin, ornamental layer of chromium increases the resistance to tarnish, but adds little to the protection against corrosion. Tin and silver coatings are used largely because of their resistance to foods and beverages. Lead is generally applied for resistance to sulfuric acid, but under many conditions furnishes good protection against corrosion of steel.

All plated metals applied commercially to zinc or aluminum are more noble than these base metals, and must therefore be thick enough to be nearly impervious in order to furnish good protection against corrosion. As a first approximation, about the same thickness of nickel or of copper plus nickel is required on zinc as on steel. On less corrosive base metals, such as copper and brass, thinner coatings of nickel are usually adequate.

The electrochemical series of equilibrium potentials is an approximate guide to the ability of a metal coating to protect other metals against corrosion, but in practice there are many exceptions. Although the accepted standard potential of cadmium is less negative (more noble) than that of iron, a cadmium coating protects iron that is exposed through small pores. On the other hand, under equilibrium conditions, chromium is more negative (less noble) than iron, but because chromium becomes passive in the air, it accelerates the corrosion of exposed iron.

3 To protect a base metal against some specified chemical reaction. The most extensive use of this type of coating is in copper plating to prevent certain parts of steel articles from absorbing carbon during case hardening. Experience indicates that the thickness of copper coating determines the protection afforded for any given period and temperature of carburizing.[4] It is probable that the increased thickness is more effective as a result of reducing the porosity.

A similar application, usually confined to laboratory

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practice, is the use of silver coatings to protect steel against oxidation during heat treatment. Chromium is helpful but apparently not equal to silver for this purpose.

Nickel-plated steel is used in alkaline storage batteries and oxygen-hydrogen cells because nickel resists alkaline solutions. Nickel and chromium coatings are used in the manufacture of films and plastics because these metals resist most organic compounds. Heavy silver coatings are used under thin layers of lead and indium on airplane bearings. Such coatings are very resistant to corrosion by the lubricants.

4 To protect the base metal against wear caused by either abrasion or erosion. ("Erosion" is used here in the same sense as "surrosion", that is, the combined result of corrosion and abrasion.) Resistance to abrasion requires that the coating shall be harder and tougher than the base metal. Protection against erosion involves also ability to resist chemical attack by the surrounding medium. Chromium more nearly meets these requirements than any other single plated metal and is used extensively for resistance to wear on gages, dies, molds, printing plates, and certain cutting tools.

5 To increase the dimensions. This process, known as "building up", may be applied to parts accidentally made undersize, or to worn parts. To serve this purpose, coatings must be at least as hard as the metal to which they are applied. The three metals commonly used are iron, nickel and chromium. Iron has the advantage of cheapness (significant in large-scale operations) and ability to be case hardened subsequently. Nickel is the most easily applied, and the hardness can be controlled over fairly wide limits. Chromium is most commonly used when greater resistance to wear is desired than can be secured with the base metal alone. In practice, the two difficulties that have limited the use of the building-up process (especially in the United States, with high-priced labor) are the selection and application of suitable "stop-offs" to prevent deposition on areas not to be built up, and the care needed to secure consistently the high degree of adhesion usually required.

The Specification and Testing of Plated Coatings. The principal properties of coatings that determine their value and may therefore serve as a basis for specifications are (1) thickness, either average or minimum, (2) porosity, (3) adherence, (4) hardness, (5) luster and reflecting power, (6) protection against corrosion.

1 Thickness. The *average thickness* is estimated by stripping (dissolving) the coating from a known or measured area, and determining the amount of removed metal by loss in weight or by chemical analysis of the resultant solution. The average thickness was formerly the basis of most plating specifications, but now it is being replaced by requirements for a certain minimum thickness on significant surfaces.

The *minimum thickness* or the thickness of coating at any point, may be measured by the following methods: (*a*) microscopic examination of a suitable cross section;[5] (*b*) the "chord" method,[6] in which the coating is cut through with a grinding wheel of known radius; (*c*) methods depending on rate of chemical reaction, such as the Preece test for zinc coatings,[7] the "spot" test with concentrated HCl for chromium coatings,[8] the "dropping test" for zinc and cadmium deposits,[1] and the "jet" test for nickel coatings;[9] (*d*) nondestructive magnetic methods that depend either on the attraction of a magnet to the coating[10] (for example, to nickel on a nonmagnetic base metal) or on the reduction in attraction of the magnet by the presence of a nonmagnetic coating[11] such as copper, zinc or chromium on a magnetic base metal such as iron or steel. Of these methods the microscopic is the most reliable (except for very thin coatings) and is usually the basis of umpire tests.

The minimum thickness obtained on a given article depends on the average thickness and can be controlled by the time and current density used. The minimum thickness depends also on the distribution of coating, which varies according to the throwing power of the solution, as well as the shape of the article and the position of it with respect to anodes and racks.

2 Porosity. Small pores have little significance in zinc and cadmium coatings that are more than 0.0002 in. thick. Porosity in coatings of more noble metal on steel may be detected and estimated approximately, by some form of ferroxyl test such as the ferroxyl paper,[12] and by the boiling water test,[13] but the results are not sufficiently accurate to be used in specifications. With the noble coatings, the salt spray test is principally a measure of porosity.

3 Adherence. Poor adherence can be detected by deforming the specimen—for example, by bending, twisting, hammering, extruding, or stretching. These methods do not yield quantitative results. The methods of Ollard[14] and Jacquet[15] for measuring adhesion require special specimens and are not applicable to finished products. An excellent review of methods for measuring adherence was published recently by A. L. Ferguson and L. F. Stephan.[19]

4 Hardness. Most of the customary methods of measuring hardness (*see* page 93) are directly applicable to plated coatings only when the coatings are much thicker than those used commercially, because with thin coatings the results are influenced by the base metal. The results from thick coatings do not necessarily represent the properties of the thinner coatings usually applied in commercial plating. Measurements show that for each plated metal it is possible to vary and control the hardness over a fairly wide range by altering the conditions of deposition. For example, electrodeposited nickel and iron vary from about 150 to 400 Bhn, and chromium varies from about 500 to 900 Bhn. No simple correlation has been found between the results of each hardness test and the behavior in service.[16] Where wear is caused principally by abrasion —for instance, on intaglio printing plates—the scratch hardness is at least approximately proportional to the wear resistance.

5 Luster and Reflecting Power. Egeberg and Promisel[17] express the brightness of a plane surface as the ratio of the specular reflection (in which the angle of reflection is equal to the angle of incidence, 45 deg in their tests) to the diffuse reflection (that is, the reflection at all other angles). This method is applicable only to plane specimens but may be useful in research, especially on deposits from "bright plating" solutions.

6 Protection Furnished Against Corrosion. Continuous exposure in typical atmospheres[1, 3] yields results that are closely related to the life in similar service, but such tests require months or years. Accelerated corrosion tests are useful for comparing the behavior of similar coatings under conditions corresponding to those in the test.[1, 12] For example, the salt spray test yields results that may be similar to those in marine but not in industrial locations.

Typical Specifications. Tentative specifications adopted by the American Electroplaters' Society and the American Society for Testing Materials[18] are summarized in Table I.

Important Factors in Electroplating. The quality, including appearance, adhesion, porosity and protective value of electroplated coatings, depends on numerous factors, such as:

Base Metal. It is not possible to apply high-quality coatings to poor-quality metals. The composition of the base metal should be known and controlled. The structure of the base metal may affect the reactions in cleaning and pickling processes and the structure of the coating. The *condition of the surface,* including the degree and nature of the polishing processes, and the presence of pores, cracks, or inclusions, may have a direct bearing on the character and porosity of the coatings. However, with "clean" cold rolled steel, marked differences in the method or the extent of polishing have little effect on the protective value of subsequently plated coatings.[20]

Preparation for Plating. It is necessary to have the base metal surface chemically clean in order to secure good adhesion of deposits. The preparation usually involves "cleaning", that is, removal of grease and foreign particles; and "pickling" (for steel) or "dipping" (for nonferrous metals) to remove oxides or other compounds, including adsorbed alkali, and in some instances to etch the surface.

Electrodeposition. The principal variables that are subject to control in the plating process are listed on the next page.

1 *The composition of the bath,* including the concentrations of major constituents and of objectionable impurities, is of primary importance. In general, it is necessary to keep the major constituents constant only within plus or minus 5% of the amounts present; analytical methods that are accurate to plus or minus 2% are usually adequate. The permissible content of each impurity must be determined by experience under the conditions employed. The acidity or pH should be controlled in all except very strongly acid or alkaline solutions.

2 *The temperature of the bath* should be kept within specified limits, which are narrower for chromium than for other plating baths.

3 *The average current density* must be kept within desired limits for the sake of uniformity in thickness and quality of coatings.

4 *Agitation* permits an increase in the current density in many baths. Some agitation is secured by the movement of oscillating rods or continuous conveyers, but stronger agitation is sometimes obtained by using air, or rotating the electrodes.

5 *Filtration,* either continuous or intermittent, is often used to keep the solution free from suspended matter. Filtration is especially desirable if agitation is used or if very thick deposits are applied.

6 *The anodes* should ordinarily be of such composition and structure as to maintain the metal concentration and the pH; that is, the anode efficiency should be nearly the same as the cathode efficiency. In chromium plating and a few other operations where insoluble anodes are used, the metal content is maintained by replenishment.

Table I. Summary of ASTM Tentative Specifications for Electroplated Metal Coatings

	DS	FS	KS	QS
Nickel and Chromium Coatings on Steel				
Type				
Minimum thickness on significant surfaces, in.				
Copper plus nickel	0.0020	0.00125	0.00075	0.0004
Final nickel	0.0010	0.0006	0.0004	0.0002
Chromium (if required), in.	0.00001	0.00001	0.00001	0.00001
Salt spray, continuous exposure, hr.	96	72	48	16
Zinc Coatings on Steel				
Type		GS	LS	RS
Minimum thickness on significant surfaces, in.		0.001	0.0005	0.00015
Cadmium Coatings on Steel				
Type		NS	OS	TS
Minimum thickness on significant surfaces, in.		0.0005	0.0003	0.00015
Nickel and Chromium Coatings on Copper and Copper Alloys				
Type		FC	KC	QC
Minimum thickness on significant surfaces, in.				
Nickel		0.0005	0.0003	0.0001
Chromium (if required)		0.00001	0.00001	0.00001
Nickel and Chromium Coatings on Zinc and Zinc Alloys				
Type		FZ	KZ	QZ
Minimum thickness on significant surfaces, in.				
Copper plus nickel		0.00125	0.00075	0.0005
Copper (if present)		0.0004	0.0003	0.0002
Final nickel		0.0005	0.0003	0.0003
Chromium (if required)		0.00001	0.00001	0.00001
Salt spray, continuous exposure, hr		48	32	16

Equipment. *Electrical.* Most commercial plating is conducted with motor-generator sets, usually with potentials from 6 to 12 volts, and with current outputs depending on the area of work to be plated and the current density. In recent years many large rectifiers have been used for plating, principally of three types—copper oxide, copper sulfide and selenium.

Tanks. Wooden tanks are used principally for rinse tanks. Steel tanks are used for alkaline cleaning baths and for cyanide plating baths. Steel tanks lined with rubber or plastics, are used for acid pickles, acid copper baths, and nickel baths. Lead-lined steel or wood tanks are satisfactory for sulfuric acid solutions, acid copper, and chromium baths. Tanks lined with acidproof brick are used for pickling and chromium plating. Acidproof stoneware is used for dips containing nitric acid and for small plating baths. Enamel-lined tanks are suitable for small baths.

Typical Plating Baths and Conditions. The following concentrations and conditions are typical, but changes may be required in order to meet specific needs.

1 Copper Plating

Acid bath, used in electrotyping, and for intermediate layers of copper, or for copper on brass.

	oz per gal
Copper sulfate, $CuSO_4.5H_2O$	33
Sulfuric acid, H_2SO_4	8

Temperature, 75 to 120 F
Current density, 20 to 40 amp per sq ft

Additions of organic matter are made to produce smoother or harder deposits.

Cyanide bath, used for plating copper directly on steel, as well as on brass or zinc.

	oz per gal
Copper (cuprous) cyanide, CuCN	3
Sodium cyanide, NaCN	4.5
Sodium carbonate, Na_2CO_3	2
(Free sodium cyanide), NaCN	1

Temperature, 95 to 120 F
Current density, 3 to 15 amp per sq ft

Rochelle salt – cyanide bath, used especially for plating copper on zinc die castings.

	oz per gal
Copper cyanide, CuCN	6
Total sodium cyanide, NaCN	7.5
Free cyanide, NaCN	0.75
Rochelle salt, $NaKC_4H_4O_6.5H_2O$	6
Sodium carbonate, Na_2CO_3	4

Temperature, 130 F
Current density, 20 to 30 amp per sq ft

2 Nickel Plating

Plating on steel or brass at low current density.

	oz per gal
Nickel sulfate, $NiSO_4.7H_2O$	16
Ammonium chloride, NH_4Cl	2
Boric acid, H_3BO_3	2

pH, 5.3
Temperature, 70 to 90 F
Current density, 10 to 20 amp per sq ft

Plating on steel or brass and over copper on zinc, at high current densities.

	oz per gal
Nickel sulfate, $NiSO_4.7H_2O$	30 to 40
Nickel chloride, $NiCl_2.6H_2O$	6
Boric acid, H_3BO_3	4

pH – high pH, 5.0 to 5.2
– low pH, 2.0 to 2.5
Temperature, 100 to 150 F
Current density, 25 to 50 amp per sq ft

Many organic materials are added to produce "bright nickel" deposits now used extensively.

Plating directly on zinc die-castings.

"High-Sulfate Bath"

	oz per gal
Nickel sulfate, $NiSO_4.7H_2O$	10
Sodium sulfate, Na_2SO_4	15
Ammonium chloride, NH_4Cl	2
Boric acid, H_3BO_3	2

pH, 5.5
Temperature, 70 to 80 F
Current density, 20 to 30 amp per sq ft

3 Chromium Plating

	oz per gal
Chromic acid, CrO_3	30 to 50
Sulfuric acid, H_2SO_4	0.3 to 0.5

(The sulfuric acid, or an equivalent amount of any soluble sulfate, should be in such concentration that the ratio CrO_3/SO_4 is about 100
Temperature, 100 to 160 F
Current density, 60 to 500 amp per sq ft

The temperature and current density should be related so as to give a cathode efficiency of about 12% for bright deposits and 16% for hard deposits. In general, the current density must be increased as the temperature is raised and must be slightly higher for hard deposits than for ornamental coatings. For example, at 113 F, current densities from 100 to 150 amp per sq ft yield bright deposits, while current densities from 150 to 200 amp per sq ft yield slightly dull but harder coatings.

4 Zinc Plating

Acid Bath

	oz per gal
Zinc sulfate, $ZnSO_4.7H_2O$	50
Aluminum chloride, $AlCl_3.6H_2O$	3
Sodium sulfate, Na_2SO_4	10

pH, 3 to 4
(Organic agents are frequently added to produce brighter deposits.)
Temperature, 70 to 95 F
Current density, 20 to 50 amp per sq ft

Cyanide Bath

	oz per gal
Zinc cyanide, $Zn(CN)_2$	8
Sodium cyanide, NaCN	3
Sodium hydroxide, NaOH	7

(Various agents, both organic and inorganic, are often added to produce brighter deposits.)
Temperature, 70 to 95 F
Current density, 10 to 30 amp per sq ft

5 Cadmium Plating

	oz per gal
Cadmium oxide, CdO	6
Sodium cyanide, NaCN	16

(With organic and inorganic addition agents as brighteners.)
Temperature, 70 to 95 F
Current density, 10 to 30 amp per sq ft

6 Tin Plating

	oz per gal
Sodium stannate, Na_2SnO_3	12
Sodium hydroxide, NaOH	1
Sodium acetate, $NaC_2H_3O_2$	2
Hydrogen peroxide, H_2O_2 (25 vol)	0.3

Temperature, 130 to 160 F
Current density, 20 to 60 amp per sq ft

7 Lead Plating

	oz per gal
Basic lead carbonate, $Pb(OH)_2.2PbCO_3$	20
Hydrofluoric acid, HF (50%)	32
Boric acid, H_3BO_3	14
Glue	0.03

Temperature, 70 to 95 F
Current density, 10 to 20 amp per sq ft

8 Iron Plating

	oz per gal
Ferrous chloride, $FeCl_2.4H_2O$	40
Calcium chloride, $CaCl_2$	45

Temperature, 190 F
Current density, 50 amp per sq ft

9 Brass Plating

	oz per gal
Copper cyanide, CuCN	3.6
Zinc cyanide, $Zn(CN)_2$	1.2
Sodium cyanide, NaCN	7.4
Sodium carbonate, Na_2CO_3	4.0

Temperature, 90 to 120 F
Current density, 2 to 5 amp per sq ft

Specialized Applications of Electroplating. The applications of electroplated coatings are too numerous and varied to itemize. Nevertheless certain special applications warrant discussion because they involve unusual types of coatings or equipment.

Plating of Strip Metal or Wire. These processes differ from conventional plating methods by being continuous rather than intermittent. One of the largest developments of wire plating is the bethanizing process, in which steel wire is plated with zinc.[21] The procedure differs from other zinc plating in that insoluble anodes are used and the electrolyte is prepared by dissolving zinc ore or dross in sulfuric acid and purifying the resultant solution very carefully. Special methods are employed for cleaning the wire, including cathodic treatment in a bath of molten caustic soda. The wire passes successively and continuously through the cleaning, pickling and plating baths. Because of the rapid movement of the wire, and the high acidity of the bath, it is possible to use very high current densities; for example, more than 1000 amp per sq ft. Largely because of their high purity, these zinc coatings are very ductile.

Similar equipment is used for continuous plating of wire with tin, copper or other metals. However, soluble anodes are generally used with these metals.

During World War II, scarcity of tin led to the extensive production of "electrolytic tin plate",[22,23] because thinner coatings can be applied by plating than by the hot dipping method commonly used. The latter method usually produces coatings with from 1.5 to 2 lb Sn per base box, corresponding to a thickness of 0.00009 to 0.00012 in. Sn. Much of the electrolytic tin plate carries a coating of only 0.5 lb Sn per base box, or 0.00003 in., although thicker coatings also can be applied by plating. Electrotinning is discussed in the article on page 709.

Hard Chromium Plating. The extreme hardness, low coefficient of friction, and resistance to wear and chemical attack of electrodeposited chromium have led to its extensive application to dies, gages and tools. This process is commonly referred to as "hard chromium plating" or "industrial chromium plating" to distinguish it from ornamental plating. The hard chromium coatings are relatively thick, usually from 0.0003 to 0.010 in., and are applied directly to the base metal, generally steel, in contrast with the decorative coatings, which are from 0.00001 to 0.00005 in. thick, and are almost always applied over a coating of nickel. The baths and conditions of deposition are not essentially different, though slightly higher current densities are generally used for the industrial coatings. In both applications the chromium usually has a hardness of 850 to 950 Bhn.

Because of the more severe mechanical conditions of service, it is important to achieve the best possible adherence of the chromium. A typical cycle involves the following steps in plating steel with hard chromium:

1 Removal of grease by an organic solvent
2 Electrolytic cleaning in an alkaline solution, first as cathode, then as anode
3 Anodic etching in chromic acid or sulfuric acid
4 Stopping-off areas not to be plated
5 Racking, if necessary, with auxiliary anodes so as to produce a nearly uniform current density on the parts to be plated
6 Plating for the required period
7 (Especially on high carbon steels) heating at about 200 C (392 F) to expel hydrogen
8 Grinding or lapping, if necessary, to produce the desired dimensions.

More details of these operations are described in a Recommended Practice of the ASTM.[25]

Porous Chromium.[26,27] A special process of hard chromium plating (the Van der Horst process) has been developed in recent years for use on cylinders and piston rings of aircraft and Diesel engines. The chromium deposit is made porous in order to retain oil and thereby aid lubrication and resist wear. In general, chromium is applied to the surface of the cylinder under conditions that yield hard deposits. The exact conditions are chosen that will lead to the desired type of porosity. The porosity is usually produced in a supplemental process by etching the chromium surface anodically in a chromic acid solution. In this process the chromium is not dissolved off uniformly, but in such a way as to reveal and enlarge the fine cracks that are present in the chromium as deposited. The result is the formation of a network of fine channels in the chromium surface, in which oil is subsequently held. The distribution of these channels, and the size of the "plateaus" between them, are used to define and specify this channel type of porosity. When the plateaus are very small, the etched surface has the "pin-point" type of porosity.

After the surface has been etched, it is usually honed down to the desired dimensions.

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Sprayed Metal Coatings

By R. A. Ehrhardt* and A. Mendizza*

SPRAYED metal coatings are produced by use of an air blast to spray heated metal particles against the object to be coated. The impingement of the metal particles on a surface causes them to flatten and interlock, forming a continuous though somewhat porous coating. The chief advantages of metal spraying are the much greater rate at which the coatings are formed, in comparison with other methods of metal coating, and the portability of the equipment, which permits the coating of objects too large to be treated by other methods.

The process is particularly suitable for coating large structures, such as storage tanks, towers, dock gates, tank cars, turbines and bridges. It is also especially useful for applying thick coatings to limited areas, as in the rebuilding of worn parts such as bearings, shafts, pistons and cylinders, and in the reclamation of undersize parts in general. This process has also been applied, to a limited extent, in coating nonmetallic materials—wood, plastics and the like—for a variety of uses, frequently ornamental.

Sprayed metallic coatings are porous because of the method by which they are formed. For some purposes the pores must be filled, but for most purposes the greater thickness of the coatings makes this unnecessary. In some uses, particularly for bearings, porosity is advantageous, since it permits retention of a lubricant.

The density of the sprayed metal is less than that of the cast metal, as indicated in Table I.

Table I. Density of Cast and Sprayed Metal

	Density in Cast Form	Density of Sprayed Metal
Aluminum	2.70	2.31
Zinc	7.14	6.32
Tin	7.31	6.82
Copper	8.92	7.51
Lead	11.34	9.77
Brass	8.30	7.32
Bronze	8.76	7.77

The density of the coatings may be increased by working or by heat treatment.

The particles that form the sprayed coatings contain oxide and are slightly work hardened, a circumstance resulting in higher hardness than in cast metal. The scratch hardness of sprayed metal compares with that of cast metal as shown in Table II.

The adhesion of sprayed metal coatings to the base metal is generally much less than that obtained by other methods of application. In the absence of alloying or chemical action between the coating and the base material, it is essential that the surface of the base material be clean and roughened. The best results are obtained on freshly sandblasted surfaces that have sufficient roughness to anchor the deposit. For this purpose, hard sharp sand is essential. Preheating the surface sometimes improves the adherence. Babbitt gives excellent bonds when sprayed on tin-plated surfaces that have been heated to just below the melting point of tin. Etching the surface usually results in a less satisfactory bond than sandblasting, but etching after sandblasting improves the bond.

Table II. Scratch Hardness of Cast and Sprayed Metal

	Width of Scratch in Millimeters	
	Cast	Sprayed
Tin	0.08	0.056
Aluminum	0.06	0.044
Zinc	0.05	0.032
Copper	0.05	0.029
Brass	0.05	0.032
Bronze	0.023	0.025

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Resistance to Corrosion. Sprayed metallic coatings are often used where protection against corrosion is an important factor. Although sprayed coatings are generally considerably thicker than coatings produced in other ways, inherent porosity limits the application of sprayed coatings to specific uses.[16]

In general, metallic coatings may be either electronegative or electropositive toward the base metal. Zinc, aluminum and cadmium are of the electronegative type and protect more noble metals by sacrificing themselves. For this reason, it is not necessary that such coatings be completely free from pores. On the other hand, electropositive metals, such as nickel, stainless steel, copper, tin or lead, must be relatively free from pores when used over metals such as iron or steel, since otherwise the underlying metal would dissolve anodically through the imperfections and pores in the coating.

When zinc, cadmium and aluminum are sprayed on ferrous metals, the thickness of the coating ordinarily ranges from 0.004 to 0.012 in., depending on the severity of exposure. Sprayed zinc and cadmium coatings, as thin as 0.0012 in., afford considerable protection to steel or iron in sea water. In order to enhance the protective value of porous coatings, it is sometimes advantageous to impregnate the pores with a good phenolic resin varnish. Silicates have also been used as impregnants for certain specific applications.

Metals sprayed in neutral atmospheres, such as nitrogen, are generally denser, more adherent and ordinarily more resistant to corrosion than those produced by the use of compressed air. Because of the absence of oxygen, coatings produced in inert atmospheres are free from oxide and are therefore more uniform electrochemically; whereas coatings produced by the compressed-air method are composed of myriads of oxide-coated metal particles, which, under proper conditions, constitute as many galvanic cells. Under such conditions, the metal will tend to corrode anodically, because it is more electronegative than the oxide. Coatings of aluminum, chromium steels and stainless steels, when sprayed in neutral atmospheres, have been successful in preventing corrosion by hydrogen sulfide gas.[12]

Soft coatings, such as lead, may be strengthened mechanically by rolling. This method has proved advantageous in preventing corrosion by sulfuric acid. Rolled lead coatings 0.002 in. thick will protect baser metals against 70% H_2SO_4 at temperatures as high as 80 C. Slightly thicker coatings are used for more dilute acid.[16] Slip areas of riveted joints have been sprayed with light metals to replace linseed oil and red lead.[24] This process, although more effective, has the disadvantage of being considerably more expensive. Metal spraying has been

used to some extent on spring steel parts in order to avoid hydrogen embrittlement, generally associated with processes for depositing metal electrolytically.[18] Aluminum, high-carbon and low-carbon steels, lead, monel, red brass and stainless steels have been employed successfully for the prevention of corrosion in the oil industry. Aluminum coatings on steel have remained unimpaired in cracking units after 4½ years, as compared with previous losses of 0.036 in. of metal per year.[22] Aluminum is also used for protecting iron and steel parts that are to be exposed to high temperatures—grate fingers, stacks and certain superstructures of boats. Coatings from 0.006 to 0.010 in. thick are used on these parts.

Reclamation of Undersized and Worn Parts. Metal spraying is frequently used for reclaiming worn or undersized parts. Since the sprayed metal is harder than the original metal and retains oil better, the reclaimed parts are usually superior to the original surfaces in performance. In this application, adhesion is extremely important and the surfaces to be coated are usually rough turned on a lathe or are rough threaded to improve the bond. The parts are then sprayed oversize, turned and ground to size. For special purposes the new coating can be selected to provide greater resistance to wear and to corrosion than is afforded by the base material. Metal spraying is also used for hard surfacing light metal members where a combination of light weight and resistance to wear is desired.

Sprayed metal coatings have been used for providing shields and the grounding of electrical equipment such as vacuum tubes, and for producing metal-to-glass seals in hermetically sealed meters and the like. To facilitate bonding, the glass is preheated before the metal is sprayed.

Hard Surfacing. Certain alloys, for example nickel-base alloys that contain chromium and boron, may be sprayed onto a surface desired to be hard, and the coating may subsequently be melted and alloyed with the base metal by torch, furnace or induction heating, in order to provide a hard, wear-resisting surface. Coatings as thick as 0.060 to 0.075 in. have been sprayed economically. When a greater thickness is needed, welding is usually preferable as a method of hard facing.

Methods of Application. Two methods of producing sprayed metal coatings are in general use—the wire gun method sometimes referred to as "Schoop Spraying", and the powder method. Because of the availability of metals in wire form, the wire gun method is the more commonly used. The metal, in the form of wire, is fed into an oxyhydrogen or oxyacetylene flame by means of an air-driven turbine of variable speed. The wire is fed into the flame at a speed just sufficient to permit melting, and the molten metal is then atomized and projected by an air blast surrounding the flame. If the metal melts too soon, it is oxidized excessively; if it does not melt soon enough, it is projected in lumps of various sizes. Formerly, most of this spraying was done with a hand gun weighing a few pounds, but recently a larger gun, designed for mounting on the tool post of a machine, has come into more general use. The machine-mounted guns are capable of handling wires as large as $\frac{3}{16}$ in. in diam and can be controlled more accurately than the hand guns, which are limited in design by the weight factor. Any metal that can be made in wire form and melted in the flame, can be sprayed.

In the powder method, the metal is supplied in the form of a fine powder that is carried into the flame by suction produced in the nozzle of the gun. This method, particularly suitable for metals that cannot be produced readily in wire form, can also be used for spraying nonmetallic materials, such as plastics and rubberlike substances, as well as mixtures of metal powders and mixtures of metal and nonmetal powders. Because of the added cost of producing metals in powdered form, powder is not ordinarily used where the wire gun is satisfactory. However, the application of powder is very economical of material, because the flow of metal can be stopped promptly by breaking the suction between the pistol and the container—an action that requires merely removing the thumb from an orifice on the head of the pistol.

Health Hazards.[25] In the spraying of metal coatings, some material misses the mark or bounces off and is entrained in the air as fine metal particles, usually with a superficial coating of oxide. Obviously this is one of the easiest ways to suspend finely divided metals in air, where they may be inhaled easily by anyone present. Therefore, if the metals used for coating are toxic, the operator of the spray gun and his helper should be protected by respirators that have been approved by the Bureau of Mines for this special work. If there is any question concerning the efficiency of the respirator for this particular job, it would be better to rely on air-supplied masks.

For information on health risks involved in spraying any particular metal, the reader may refer to the article on page 755 in this Handbook.

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Facing or Surfacing by Welding

By C. W. Obert*

FACING or hard surfacing is a process of welding onto a wearing part, a layer, edge, or point of a metal that is resistant to abrasion or corrosion. Hard facing has proved to be an easy and economical means of keeping equipment in good operating condition. There are also soft surfacing operations—for example, the application of a bronze bearing metal.

Hard Facing. Hard facing was applied originally to metal-working dies, oil-well drilling tools, and certain types of excavating equipment. Numerous other applications have been found and hard facing is now an important factor in the welding industry.

The principal cost-reducing features of hard facing are (1) longer life of equipment, (2) fewer replacements with resultant saving in labor charges and lost production time, (3) utilization of low-price base metal for wearing or corroding parts, (4) salvaging of worn parts, (5) savings in power consumption and (6) general increase in operating efficiency.

No single grade of hard facing material is suitable for all applications. To secure hardness, toughness, resistance to shock, resistance to corrosion, and other desired qualities, alloys of widely different compositions have been developed. These may be classified in groups, as follows. Although the resistance to wear of the materials in the various groups increases, in general, from one group to the next (those of Group 1 being lowest in wear resistance) this is not invariably true. The conditions of wear may reverse the order.

Group 1. Alloy Steels That Contain Less Than 20% of Alloying Elements. Alloying elements used are mainly chromium, tungsten, manganese, silicon and carbon. Although not so hard as higher-priced hard facing metals, alloy steels of this group possess greater toughness and resistance to shock. They have much greater resistance to wear than low-carbon steels and some compare favorably with Hadfield's high-manganese steel in this respect. Certain low-priced alloys, such as low-alloy cast iron, might be listed, but they are not used widely.

Group 2. Ferrous Alloys That Contain More Than 20% of Alloying Elements. Chromium, tungsten, manganese, silicon, carbon, and sometimes cobalt, nickel and other elements are used in these alloys, which are higher in price than those of Group 1. However, high hardness and greater resistance to abrasion ensure longer service for alloys of Group 2. As a rule they are not so tough or resistant to shock as alloys of Group 1, but are particularly well adapted for use as the final wear-resisting surface, after the worn part has been built up with high-strength welding rod.

Group 3. Nonferrous Alloys. Cobalt-chromium-tungsten alloys are available in several grades, all highly resistant to wear and corrosion. Differences in strength and toughness make them suitable for a wide range of applications. Many of them retain their original hardness virtually unimpaired at elevated temperatures.

A newer development is the use of nickel-base alloys (Hastelloys) for the facing of parts subjected to severe chemical corrosion. This type of alloy is gaining increased favor in the chemical and process industries, because it combines outstanding resistance to corrosion with excellent mechanical properties; some grades are comparable with high-strength steels in tensile properties. Some grades will also take a high polish and retain it even when subjected to severe atmospheric and chemical corrosion.

Group 4. So-Called "Diamond Substitutes". These are the hardest and most wear-resistant of all hard facing materials. Some are almost pure tungsten carbide; others contain 90 to 95% tungsten carbide with the remainder cobalt, nickel, iron or similar elements. Some materials contain boron compounds or tantalum carbide. The alloying elements are added to impart toughness and impact strength to the tungsten carbides; the hardness, however, is slightly reduced as a result.

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The diamond substitutes, furnished in the form of small castings, are embedded in the cutting and wearing surfaces of oil-well drilling bits and similar tools. Tungsten carbide inserts are not melted or damaged to any appreciable extent in the usual method of application by the oxyacetylene process. The process of applying tungsten carbide shapes to wearing surfaces is known as "hard setting". After hard setting, the entire wearing surface usually is hard faced, which produces a composite material that has excellent resistance to abrasion with maximum cutting qualities at edges.

Group 5. Crushed Tungsten Carbides of Various Screen Sizes. These are furnished packed in steel tubes, fused to steel strips, or bonded with steel as a composite rod. Both tubes and strips come in short lengths, which are applied like ordinary welding rods. Grains of crushed tungsten carbide are also supplied loose for application with a Haystellite powder dispenser.

Selection of Hard Facing Alloys. The selection of the proper hard facing material for a specific application depends on the factors that cause the deterioration of the wearing part: sliding or rolling friction, shock and impact, heat, and corrosion. Other factors, such as smoothness of the deposit desired, or (in handling sand, rock and gravel) the ability to serve as an efficient digging tool, also influence the choice. When two materials are equally suited, the material of longer life expectancy, although more expensive, will more than justify the greater first cost.

Table I will serve as an approximate guide in the selection of a suitable material.

Hard Facing Procedure. Although hard facing materials can be applied by any standard fusion-welding method, certain factors govern the choice of method for any specific applications: (1) base material to be faced, (2) hard facing material selected, (3) size, shape and thickness of base material and deposited facing material, (4) initial cost of equipment and facing material, (5) smoothness of deposits, (6) over-all cost and (7) quality and appearance of deposits.

Table I. Relative Merits of Hard Facing Materials with Respect to Characteristics of Deposits

(The numbers refer to the five groups listed)

Characteristics of Deposit	Group Number in Order of Preference				
Hardness at atmospheric temperature	4	5	2	3	1
Hardness at elevated temperature	4	5	3	2	1
Resistance to impact	1	2	3	5	4
Resistance to corrosion	3	2	1	4	5
Smoothness of deposit	3	1	2	5	4
Ability to take high finish	3	2	1	4	5
Ability to penetrate (earth-boring or penetrating tools)	4	5	3	2	1
Thinness of deposited layer welding	5	3	2	1	4

Gas Welding. Use of the oxyacetylene blowpipe allows close control of the operation, produces a smooth deposit, ensures easy elimination of particles of scale and foreign matter, and easy forming of edges and corners. Ease of forming is particularly important if grinding of the hard face to close tolerances is required. Other advantages are low loss of expensive alloys by vaporization or spattering, close control of the oxidizing or reducing character of the atmosphere surrounding the molten metal, and more accurate control over the penetration of hard facing alloy into the base metal. This is especially important in the application of certain hard facing materials, some of which should be puddled in, while others are flowed onto the base material by "sweating".

Metal-Arc Welding. The alloy electrode that furnishes the hard facing material is usually coated with flux. The purpose of the coating is to stabilize the arc, to control the melting rate of the electrode, to protect the molten metal from atmospheric contamination and, in some instances, to add alloying elements to the deposit.

Although the process is not so flexible as gas welding, the resultant deposits are of good quality.

Experience has shown that usually, if the area is large, the most efficient method of deposition is to use a weaving-bead type of deposit rather than a straight bead. This requires deposition of a bead ¾ to 2 in. wide. A deposit of uniform thickness with a smooth and regular surface can be obtained readily. Narrow beads are useful for corners, edges and points.

Beading is sometimes used for large areas. For this the beads should be staggered over the entire area and then tied together. This gives an even distribution of heat, minimizes cooling stresses, and usually makes preheating unnecessary, except on round, curved, concave or convex surfaces. The normal thickness of deposit ranges from ⅛ to $\frac{5}{32}$ in., but can be varied in either direction.

The metal-arc welding process is particularly suitable for use on thick base metals where thin, smooth deposits are not required. Another advantage is that only a small amount of distortion is produced in hard facing large steel castings and similar heavy parts because the heat from the arc is localized.

Atomic Hydrogen Arc-Welding. In this process the source of heat is an a-c arc between two tungsten electrodes in a stream of hydrogen. The surrounding envelope of hydrogen protects the electrodes and the base material from oxidation. The arc is defined by a thin brilliant line that forms a loop, under the influence of its own magnetic field and the flowing gas. High-quality deposits are obtained, plus all of the other advantages of the gas process. In addition, a higher rate of deposition may be obtained. The higher initial cost is often offset by the speed and superior results obtained.

Base Materials for Hard Facing. *Medium-Carbon and Low-Carbon Steels.* Carbon steels containing up to 0.50% C can be hard faced with excellent results in nearly all instances. Steels that contain 0.40 to 0.50% C are not only satisfactory for welding, but also possess sufficient strength to withstand severe conditions of service.

High-Carbon Steels. Steels that contain more than 0.50% C can be hard faced if reasonable precautions are taken to prevent cracking. Before hard surfacing, preheating is often desirable and heat treatment, both before and after hard facing, is usually necessary to reduce hardness and brittleness in the base metal.

Low-Alloy Steels. Hard facing alloys can be applied to these steels in much the same manner as to plain carbon steels. Initially, the steel should be in the annealed condition. In a few instances, depending on the composition of the base, heat treatment is required after welding.

High Speed Steels. Hard facing of high speed steels is not generally recommended. Shrinkage cracks and strain checks in many instances render the hard faced piece valueless, regardless of heat treatment.

Stainless Steels. Stainless steels, including the high-chromium steel and the 18-8 Cr-Ni steel, can be hard faced readily if proper preheating and cooling procedures are followed. However, knowledge of the physical properties of the specific type of stainless steel is necessary in order to avoid difficulty from excessive strains, brittleness, or decreased resistance to corrosion.

Manganese Steel (9½ to 14% Mn). These steels can be surfaced by means of a rod that gives an austenitic, work hardening deposit. The electric-arc welding process should always be used, with care to avoid overheating.

Gray Cast Iron. Cast iron can be hard faced, but the method of application differs somewhat from that for steel because of the lower melting point of the cast iron and the surface condition of the iron. Local overheating of the iron must be avoided.

White Cast Iron. Small parts made of white or chilled iron can be hard faced; for larger parts heat treatment is sometimes necessary, taking into consideration the design and location of chills, since preheating may soften some of the chilled areas.

Alloy Cast Irons. The same procedure can be used as for gray cast iron.

Preparation of Metal to be Surfaced. Loose scale, dirt, rust, or other foreign substances should be removed from the area to be hard faced, preferably by grinding or machining. When a file or wire brush is used for cleaning, care should be taken that any scale or other remaining foreign material be floated out during the melting.

When the hard facing material is to be applied in a groove, corner or recess, it is desirable to have all corners well rounded. If only a small area is to be hard faced, a suitable shallow recess or indentation may be prepared for receiving the hard facing metal.

Preheating. In the preheating of parts to be faced, the same general rules should be observed that are applicable to welding. Parts should always be preheated when otherwise the hard facing operation would cause warping or checking, or when time and money can be saved. Steels containing more than 0.40% C should usually be preheated. The optimum temperature for preheating is usually between 700 and 1200 F but may vary with size and composition of the part. For certain classes of electric-arc welding preheating between 350 and 450 F is desirable.

Hard facing of hardened steel is generally unsatisfactory. If a tough grade of hard facing rod must be used and rehardening of the base material is necessary after the hard facing process, oil quenching is recommended; water quenching is seldom used.

Fluxes. In the gas and atomic hydrogen welding processes, fluxes are essential only in special instances. Sometimes a flux may help if a second hard facing layer is necessary, or if removal of scale and oxide from the base metal is desirable. This is especially true with cast iron. The principal advantage of a flux is that, by floating on the molten puddle of deposited material, it smoothes the surface, retards the cooling, and protects against oxidation. A denser, harder deposit of superior microstructure is produced if a flux is used. In shielded electric-arc welding, the flux processed on the electrode itself is sufficient.

Thickness of Hard Facing Deposit. The proper thickness of deposit depends on the specific application, but usually ranges from $\frac{1}{16}$ to ¼ in.; the average is approximately ⅛ in. Usually, however, a part that requires a deposit thicker than ¼ in. should be rebuilt, before hard facing, to within $\frac{1}{16}$ to ¼ in. of the finished size. For this purpose an alloy of Group 1 should be used, or material similar to the base metal. The final hard facing deposit is applied thick enough for grinding to finished size.

Hard Facing of Steel. *Group 1. Ferrous. Less Than 20% Alloying Element.* For applying rods of Group 1 to steel, a flame containing a slight excess of acetylene should be used, since a neutral flame may cause boiling. Penetration into the base metal should be less than $\frac{1}{32}$ in., depending on the type of rod used. Some of these materials are work hardening, and light peening is recommended, especially on large areas, to harden the surface and lessen danger of shrinkage cracks.

In gas welding, the hardness of hard facing deposits of Group 1 depends largely on the amount of acetylene in the flame and on the rate of cooling. A small excess of acetylene is usually necessary to prevent boiling of the fused metal. A much greater excess can be used if an exceptionally hard deposit is desired. In general, the greater the excess of acetylene and the slower the cooling rate, the harder the deposit. A quenched deposit is not so hard as slowly cooled metal, but is tougher.

For electric-arc welding, electrodes are available that give a medium-carbon alloy steel facing. In using most of such electrodes the rod should be positive and the work negative. The welding current should be adjusted to give flat beads such as are generally obtained with high currents, and the deposit should be made with a weaving motion. For this class of work, welding should be done in a horizontal position only.

Group 2. Ferrous. 20 to 50% Alloying Elements. Alloys of this group are applied to steel by thorough amalgamation. To assure successful hard facing, the base metal should actually be melted; "sweating" is not sufficient. In gas welding, a neutral or slightly carburizing flame is generally used. Since the significant physical properties of these alloys are virtually unchanged within a range of carbon content from 2 to 4%, penetration of the base metal has no marked detrimental effect on the quality of the deposit.

For electric-arc welding, electrodes are available that will produce a hard steel facing that cannot be machined unless annealed. For most of such electrodes the rod should be positive and the base metal negative. Wide or narrow beads can be used as desired. Each bead should be brushed thoroughly before the next is deposited. In some instances peening of the completed bead will harden the deposit. Quenching in cool water will increase the surface hardness of some alloys. For best results the piece being faced should be in a horizontal position.

Group 3. Nonferrous Alloys. These alloys should be applied with minimum penetration into the steel base. In this manner, dilution with iron from the base is avoided. Thus the hardness at high temperatures and the resistance of the alloys to abrasion and corrosion, are not reduced. For the cobalt-chromium-tungsten alloys, the flame for gas welding must contain an excess of acetylene and should be adjusted so that the outer cone, denoting excess of acetylene, extends double the length of the inner cone. This excess of acetylene will "sweat" the surface of the steel base and allow free spreading of the hard facing metal without any stirring or agitation of the puddle. When Hastelloy facing is selected for resistance to corrosion, a neutral flame is desired to avoid carburization, which reduces such resistance.

A small area of the surface to be hard faced should be brought to a sweating temperature, and the end of the rod should be allowed to melt in the flame and spread evenly over the sweating area. The hard facing material, when applied at the proper temperature, wets the base metal and spreads ahead readily in the flame, while the base metal is brought to the sweating temperature just in front of the puddle. The rod should not be stirred or puddled. The alloy is spread by the welding flame.

It is preferable to deposit the coating to the desired thickness in one operation. A flux is usually unnecessary if the steel base is clean. The alloys in this group can be applied by the metal-arc process with either bare or flux-coated electrodes, preferably coated. Reverse polarity is always used; the rod is positive and the steel base negative.

Group 4. Tungsten Carbide Inserts. Tungsten carbide inserts are now very widely used for hard setting oil-well drilling tools. The size and spacing of the inserts vary with the type of tool. The procedure involves cutting grooves in the steel base metal with either an oxyacetylene cutting blowpipe or a grinding wheel. In setting an insert, the steel in a groove should be melted with an excess-acetylene flame and the insert should be picked up with the heated end of a high-strength steel welding rod and partially submerged in the molten puddle. Finally the insert should be completely covered with steel supplied by the welding rod. This operation is repeated until the desired number of inserts has been set. Maximum resistance to wear is obtained when a final coating of hard facing alloy from Group 5 is deposited over the inserts.

Group 5. Crushed Tungsten Carbide with Steel Binder. Both types of these materials—composite and tube—are applied in much the same manner. The operation should be performed with an oxyacetylene flame that contains a small excess of acetylene. The penetration into the base should not be so deep as in ordinary steel welding, but some stirring with the rod is necessary in order to obtain an even distribution of the deposited metal. These rods are not free-flowing because of the presence of the tungsten carbide particles, which do not melt. The deposit should not be kept molten for too long. The welding tip should be large enough to produce a flame that will supply the required amount of heat at a pressure low enough not to blow the molten metal.

Hard Facing of Cast Iron. *Group 1.* In general, the hard facing of cast iron with the materials of Group 1 is similar to the treatment of steel. However, it is best to heat a small area at a time with the blowpipe and to break the surface crust as it forms, with the end of the rod. A little puddling is usually necessary and a good flux is often helpful. Because of the low melting point of cast iron, considerable care should be taken when working on thin surfaces, edges, and corners.

Group 2. These alloys are applied to cast iron in essentially the same manner as they are applied to steel.

Group 3. In applying these alloys by gas welding, a little less acetylene is used in the flame than for steel. Since alloys of Group 3 do not flow so readily on cast iron, it is advisable to break the surface crust with the end of the rod. A cast-iron welding flux is often helpful. It is usually best to apply an initial thin coating and then go over it again and build it up to the desired thickness. Since these alloys have a higher melting point than cast iron, care must be taken not to melt the base metal too deeply. It will be advisable to back thin sections with wet asbestos or carbon paste.

Groups 4 and 5. Materials of these groups are rarely, if ever, applied to cast iron. When they are, the application is along the same lines as for steel.

Cooling Procedure. Parts hard faced by the oxyacetylene process should preferably be cooled slowly to minimize residual stresses in the deposited metal. Somewhat less care is necessary when the base metal and welding rod are of the same composition. If no further heat treatment is necessary, the hard faced piece may be cooled under the torch, or in dry lime, sand or other packing material. However, if the piece is to be heat treated in order to refine the grain and to improve the strength of the base metal, the hard faced piece should be heated and then quenched in oil (seldom water) or normalized by cooling in air.

Finishing the Hard Faced Deposit. *Groups 1 and 2.* Some shaping of these hard facing materials can be done while they are in a plastic state. If heated with the blowpipe to within about 300 F of the melting point, the deposit can be scraped off in thin layers with an implement, such as an old file, until reduced to the required size and shape. Ordinarily, alloys of Groups 1 and 2 are machined with difficulty. If they cannot be brought down to exact final dimensions by "hot filing", grinding is necessary.

Group 3. Most grades of the nonferrous hard facing materials are not machined readily, but can be finished easily by grinding. The wheel speed should not be less than 2800 nor more than 4800 surface fpm. Grinding checks may result from higher speeds or the use of wheels that are too hard.

Groups 4 and 5. In grinding parts hard faced with these materials, the best results require the use of wheels designed for this particular work.

Bond Between Hard Facing Material and Base Metal. The bond between the hard facing and the base is as strong and sometimes stronger than the hard facing deposit. Naturally, alloys that are puddled into the base metal form a good strong bond. Even the alloys that are merely sweated to the base, form a bond that is stronger than the hard facing metal itself. If properly applied, a hard facing metal does not break away from the base through the bond.

In many instances, surface cracks are not detrimental since they usually extend only through the deposited metal and not into the base. Undesirable surface cracks can sometimes be repaired if the metal adjacent to the crack is heated to a red heat, then melted down into the bottom of the crack and allowed to close in slowly, with a few more drops added from the welding rod. Precautions should be taken to ensure very slow cooling.

Jigs for Hard Facing. Many operations are facilitated by the use of special jigs or fixtures. Some operations are practicable only through the use of such auxiliary appliances. Several typical examples are as follows:

It has been found much easier and faster to hard face undercutter bits for coal mining when they are set up on a jig. Either a "merry-go-round" jig or a moving table is employed to good advantage, as evidenced by a record of 450 bits hard faced by one operator in one hour.

With the aid of a jig, a plowshare can be hard faced and the nose of it shaped in one operation. By the use of another device, the share can be turned completely over and the work adjusted so that the working surface is always level. Rotating jigs or chucks are a great aid in hard facing steam valves, dies, automotive valves and valve seat inserts, and other small parts.

SURFACE TREATMENTS

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The Pickling of Iron and Steel Products

By C. H. McCollam* and D. L. Warrick*

PICKLING is the term applied to the chemical removal of surface oxides from metal by immersion in an acid solution. Wide variations are possible in the type, strength and temperature of the acid solutions used. The procedure depends on the material to be pickled, the character of the scale involved and the surface desired after pickling. The following discussion will deal only with the pickling of ferrous metals.

The pickling of hot rolled, low-carbon steel is typical of the basic principle involved. In this instance the surface oxide to be removed is mill scale, formed at comparatively low temperatures during or after hot rolling. Removal of such scale is one of the simplest of the cleaning problems. The steel is submerged in dilute sulfuric acid until free from scale, and then is removed and rinsed. For purposes of economy and efficiency the acid concentration is held at approximately 10% and the temperature is maintained between 150 and 190 F.

A container is required in which the acid and the material to be pickled can be held for a reasonable time at the desired temperature. To this basic piece of equipment, operating conveniences have been added such as cranes, mechanical agitators and instruments for control of temperature. The pickling tub or tank is subject to changes in construction, which will be discussed further in another part of this article, as will pickling acids, inhibitors, foam-producing agents, and rinses.

Pickling Procedures for Various Ferrous Metal Products. Although pickling appears to be a simple process, modifications are necessary in many instances. Because of the broad influence of sometimes obscure variables in scale formation, and because of the difference in processing practice and equipment encountered even in two plants that make the same product, it is not practicable to reduce pickling procedure to a standard formula. In certain instances, the problem has become so complicated that even the mechanism of scale removal by pickling has become a controversial subject. Therefore, the procedures described in the following paragraphs are merely the methods that have been successful in plants producing the particular material under discussion, rather than formulas that can be followed without modification.

Cleaning, before pickling, is often as important as the operation itself. The iron or steel is frequently covered with grease from previous fabricating processes. This grease is not soluble in acid and renders pickling difficult. Hot alkaline solutions are generally satisfactory for cleaning such material, but their use should always be followed by careful rinsing before the material is placed in the acid. Another cleaning method requires heating the metal to a moderately high temperature for a short time to remove the grease.

When low-carbon steel is pickled for enameling, galvanizing or tinning, special precautions are necessary to ensure a surface that is chemically clean as well as free from scale. In such instances a slightly but definitely etched surface is often considered an advantage, permitting greater adherence of the coating to the metal. In pickling low-carbon steel, inhibitors or foaming agents may be used in the bath, but only with careful selection and proper precaution, because some inhibitors leave a thin but very tightly adherent surface film, which clings persistently to the metal even after careful rinsing.

The trend in recent years toward lower pickling temperatures, about 150 to 160 F, has resulted in economy in steam consumption and in better quality of the finished product. Where time and pickling capacity permit, an acid concentration of 5 or 6% is advisable. However, where comparatively low temperatures are employed, it is customary to compensate for decreased thermal activity by raising the acid concentration to about 10 or 15%.

In the continuous production of sheet or strip steel, provision is usually made for continuous pickling so that fabrication can proceed without interruption. In this continuous system, control of the rate of pickling is accomplished by varying the temperature or the acid content of the bath, or both. Close supervision is necessary if efficiency and economy are to be realized, since the acid content of the bath is constantly changing. Acid concentration and temperature are frequently kept too high for best results in economy or quality, so that the operation may be completed in the time allowed.

In pickling for galvanizing or tinning, many plants use two pickling baths: first a 5 to 10% solution of sulfuric acid in water at 150 to 190 F, and second, a short dip in cold concentrated muriatic acid (18 to 20 Bé) or in a moderately strong solution of muriatic acid at a somewhat elevated temperature. The use of high temperatures with muriatic acid is wasteful because this acid has a strong tendency to evaporate, filling the atmosphere with noxious fumes.

Vigorous mechanical agitation of the bath is always advisable. When the solution is allowed to remain stagnant, gas pockets may form, keeping the acid out of contact with the metal and arresting the pickling action on these localized areas. When the steel is galvanized, these scale-retaining areas remain uncoated. Agitation offers the further advantage of securing uniform acid concentration throughout the bath, assuring a more nearly uniform rate of pickling.

When sheets have been pickled for galvanizing or tinning, as short a time as possible should elapse between

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pickling, rinsing and coating operations. If a delay occurs between rinsing and coating, the material should be stored under water and never allowed to dry. Contact of the moist iron with air will cause rusting. Furthermore, any ferrous salts from the pickling bath that dry on the work, become oxidized and difficult to remove.

When pipe or seamless tubing is to be pickled, particularly pieces of small inside diameter, high acid concentration is advisable, since the acid solution that first enters the tube must often complete the pickling of the inside surface. Lifting the bundle above the bath occasionally, to drain the spent acid out of the tubes, helps to overcome this difficulty. Jets of air or steam that direct a current of pickling solution through the tubes are sometimes a valuable aid. Mechanical rockers may also be used to advantage in removing thick or tight scale.

Heat treated material introduces many special pickling problems. It has been demonstrated that when alloy steels are heated above a certain temperature, which varies with the type of steel, an electrolytic action is set up between the scale and steel during pickling. This action proceeds at the expense of the clean metal and results in serious pitting of the surface. Inhibitors have been found to be of little value in preventing such pitting. Scale formed during normalizing represents the worst condition as far as pickling time and pickle pitting are concerned; scale formed during tempering is the easiest to remove. Best results will usually be secured by using a fresh bath of 5 to 10% sulfuric acid (inhibited) with temperature between 145 and 155 F, and with provision for mechanical agitation.

Scale formed during forging is difficult to remove. Formed at elevated temperature, this scale is likely to be thick, glassy and extremely adherent. Also such scale is likely to be knocked off during handling, leaving small exposed areas of metal. At such places deep pickle pitting is likely to occur. However, when the scale is removed from large areas of metal before pickling, the pitting is much less severe. Pitting is decreased by the mechanical removal of as much of the scale as possible either before or during pickling. Good results have been obtained by pickling in 8 to 15% sulfuric acid, at 150 to 160 F.

Pickling Stainless Steels. Stainless steels present a special pickling problem because scale containing high percentages of chromium oxides is not readily attacked by sulfuric acid alone. A common practice for stainless steels is to employ a mixture of about 10% sulfuric acid with 2 to 10% muriatic acid or a mixture of 10% sulfuric acid with about 10% of common salt. In the latter instance, muriatic acid is generated by reaction between the sulfuric acid and the salt. Muriatic acid alone is sometimes used. For stainless steels, the pickling is followed by a bright dip in 5 to 50% nitric acid by volume. The more dilute solutions of this acid are generally used warm but the higher concentrations should be used cold, because high concentrations of nitric acid are detrimental to many materials used in constructing pickle tubs. Thorough rinsing in hot water is essential for best results. Scrubbing is sometimes done simultaneously.

Equipment. The pickling tank may be constructed of wood, steel, brick, concrete, lead, monel metal or stainless steel. Steel and concrete tanks are generally lined with some acid-resisting material, while wood, brick or alloy tanks are either lined or unlined, depending on the service for which they are intended and on the cost.

Wooden tanks are the cheapest to construct. They are generally made from cypress or long-leaved yellow pine. A lining of asphaltic material is often used between the walls. Tubs may be made of common or acidproof brick, with or without mastic lining material between courses. Rubber linings may be used in tanks of wood or steel. Monel metal and stainless steel offer many advantages but the cost is generally prohibitive. Steel tanks, sheathed in brick and lined with rubber, are satisfactory for most uses.

Storage Tanks for Acid. Muriatic acid can be stored in rubber-lined steel tanks or in tanks lined with wood that has been impregnated with certain waxes. Hydrofluoric acid is generally stored in lead-lined tanks.

Acid lines carrying concentrated sulfuric acid of 58 Bé or higher from the storage tank to the pickle tub, may be of iron pipe with iron fittings. Care should be taken to calk all the joints with a good acid-resisting material. Sections of pipe that are immersed in the pickling bath should be made of lead, copper or bronze. Heavy rubber hose is sometimes employed. Stainless steel lines are satisfactory for use in strong nitric acid.

When copper or bronze is used in connection with equipment for pickling, there is always the possibility of electrolytic deposition of copper on the pickled surface. Ordinarily this is of no consequence, but if the stock is to be carburized without machining after pickling, the copper film will prevent carburization. Also copper stains on full-finished sheets are objectionable. Copper or bronze should not be used in the pickling tub in such instances.

Drainage lines should be made of vitrified tile carefully calked with an acidproof cement to avoid leakage, and should be large enough to provide adequate drainage at all times. A wooden lattice, preferably of cypress, should cover the floors around the pickle tubs.

Agitation. This practice saves time, metal, and acid. Air, steam, or mechanical movement of the tub or charge may be used; each has certain advantages. In some plants the tub is mounted on rockers; in others the charge is supported on chains or saddles of acid-resistant metal, which impart a continuous or intermittent motion to the work. Another system involves the use of a large plunger, which alternately raises and lowers the level of the liquid in the tub. Small articles may be pickled in a tumbling barrel. No definite recommendation can be given, because the means of securing agitation in the tub will depend on the size and kind of material being treated, the equipment available, and the result to be secured. Each installation presents an individual problem.

Adequate Ventilation. This safeguard should be provided for when the pickling room is designed. Good ventilation should be maintained at all times. Ventilating equipment should be of acidproof material.

Pickling Solutions. Sulfuric, muriatic, nitric, and hydrofluoric acids, or mixtures of these, are generally used. Sulfuric acid is the cheapest pickling acid and the one most commonly employed. Muriatic acid is used for special purposes, such as etching before galvanizing or tinning, and sometimes for pickling stainless steel. Nitric acid is used in the pickling of stainless steels and is occasionally employed to oxidize scaled surfaces in order to facilitate pickling. Hydrofluoric acid is sometimes added to the bath to accelerate pickling, and is used occasionally in pickling castings to remove sand.

Concentration of Acid. The action of the pickling solution on the metal is in approximately direct proportion to the acid concentration up to about 25% acid by weight. The concentration used depends on the kind and temperature of acid, the type of material being pickled, and the surface desired. Thus when sulfuric acid is used on mild or pearlitic alloy steels, the maximum concentration is 20 to 25% and the optimum is 8 to 10%. For the pickling of tubes and pipe a high acid content should be maintained because the solution on the inside of the tube does not circulate, and consequently becomes depleted before the scale has been removed if weak acid is used. Muriatic acid solution is maintained between 5 and 50% by volume. The higher concentrations of this acid cause definite etching of the surface. Nitric acid is used in amounts from 5 to 50% by volume. Concentrated solutions of nitric acid have a passivating effect on steel surfaces. The fumes from nitric acid are dangerous and adequate ventilation should be provided.

Testing of Pickling Solutions. This important part of pickling supervision is frequently overlooked. The solution in pickle tanks should be sampled regularly. In the pickling of sheets, the acid strength should be determined after each lift in batch pickling, and every 30 min in continuous pickling. For testing the acid and iron contents of the pickling bath a sample can be titrated with standard solutions. The use of a hydrometer for checking pickling solutions is not recommended, because of varia-

tions in gravity introduced by the ferrous sulfate content. The following procedures can be used for titrating pickling solutions.

Determination of Sulfuric Acid Content. Five milliliters of pickling solution is measured into a 200-ml flask. Then 25 ml of water and 2 drops of methyl orange solution are added. Standard sodium carbonate solution is added until the last drop causes the color of the pickling solution to change from red to yellow. Each 5 ml of the sodium carbonate solution equals 1% of sulfuric acid in the pickling tank. (This simple relation, sufficiently accurate for commercial purposes, is based on the specific gravity of 10% sulfuric acid.)

The standard sodium carbonate solution may be made by dissolving 11.52 g of dried cp sodium carbonate in 1000 ml of distilled water. (This standard solution is slightly stronger than N/5 sodium carbonate solution, which may be substituted without appreciable error in commercial practice.)

Methyl orange solution may be made by adding 1 g of methyl orange powder to 1000 ml of distilled water. This solution should be kept in a dropping bottle.

When the pickling solution is muriatic acid, the determination may be carried out in exactly the same manner as outlined above for sulfuric acid, except that, in the final calculation, each 5 ml of the standard sodium carbonate solution equals 2.07% by volume of 20 Bé muriatic acid, or 2.36% by volume of 18 Bé acid. Each of these values is equivalent to 0.755% by weight of hydrogen chloride (based on the specific gravity of 10% hydrochloric acid solution).

Determination of Iron Content. Five milliliters of pickling solution is placed in a 200-ml flask and diluted with 5 ml of water. Standard potassium permanganate is added from a burette until the last drop turns the pickling solution pink. Each 5 ml of standard permanganate solution equals 1% Fe or 5% $FeSO_4$. The pink color of the end point fades quickly when organic inhibitors are present; therefore, the titration should be carried to completion as rapidly as possible.

The standard potassium permanganate solution can be made by dissolving 6.01 g of cp potassium permanganate in 1000 ml of distilled water. (This standard solution is slightly weaker than N/5 potassium permanganate, which may be substituted without appreciable error in commercial practice.)

Addition of Acid. At all times the acid content should be maintained above the minimum found to be practicable for the material being pickled. For mild carbon steel and most alloy steels requiring a sulfuric acid solution, about 5% acid is a desirable concentration. Acid should be added frequently and in small amounts to keep the bath uniform. When acid is being added, the bath should always be agitated to assure thorough mixing.

If consumption of acid is to be established accurately, many factors must be considered. The acid that is added must be carefully measured, either by metering or by means of a measuring tank. When additions are recorded in terms of so many "minutes of acid" through a pipe, variations generally result from the amount of acid in the tank, the air pressure on the acid line and other factors. Variation in the size and shape of the material being pickled, has considerable influence on consumption of acid.

Changing of Pickle Solutions. It is well known that ferrous sulfate has a damping effect on the efficiency of a pickling bath. The ferrous sulfate content of a bath is five times the iron content; and it has been demonstrated that with 40% ferrous sulfate (8% Fe) the rate of attack of sulfuric acid on steel is reduced 50%. It is common practice to let the ferrous sulfate content reach 25% (5% Fe), then to use the solution until the acid content has been reduced to less than 5%, and dump the tub.

Disposal of Waste Liquor. The practice of dumping waste pickling solutions into sewers and streams has resulted in dangerous pollution of water. Laws in many states require the neutralization of pickling acid before disposal.

In connection with large pickling installations, plants may be installed for recovery of acid and salvage of iron compounds. Such plants are expensive to build and maintain and their application is limited. In smaller pickling plants, it is more economical to kill the spent acid with lime in settling basins.

Pickling Temperatures. Pickling tanks are heated ordinarily by the introduction of live steam through an open or perforated lead pipe. Temperatures can be checked at intervals by an ordinary thermometer, or indicating or recording instruments can be installed for this purpose. Temperature controls are available for installations where temperature variation must be held to a minimum.

The Effect of Temperature. An increase in temperature greatly increases the activity of the pickling bath. Sulfuric acid at 190 F has more than 100 times the solution rate of the same acid at room temperature. Overpickling is likely to occur at high temperatures. The choice of an inhibitor is an important factor in establishing the limiting temperature, since some inhibitors fail rapidly at high pickling temperatures.

Although a temperature of 170 to 190 F is sometimes satisfactory when the time cycle is short, pitting may result if the pickling period is prolonged. With many high-carbon and alloy steels, a pickling temperature of 140 to 150 F has been found satisfactory for efficiency, surface quality, and life of the inhibitor.

Pickling Inhibitors. Pickling inhibitors are agents that may be added to an acid pickling bath to diminish the attack of the acid on the metal areas from which the scale has been removed, without appreciably retarding the rate at which the acid removes scale or rust; and to diminish the severity of hydrogen embrittlement.

Theory and Mechanism of Inhibitors. The actual mechanism of inhibitor action is not well understood. Some investigators believe that inhibitors are negative catalysts that are selective in action, retarding the reaction of acid on metal but not on scale. In practice, no inhibitor continues its original effectiveness unabated throughout the entire pickling cycle. However, inhibitors lose efficiency so slowly that the loss can hardly be attributed to reactions in which the inhibitor plays a major part as reagent. The effect seems analogous to the familiar poisoning of a catalyst.

Various observers have stated that inhibitor action seems to be associated with an increase in the hydrogen overvoltage at the metal (cathode) surface. A protective coating of hydrogen, maintained on the metal surface, helps to protect the metal from direct contact with the acid, thus diminishing the attack.

Another theory is that a thin layer of inhibitor material is adsorbed or plated out on the surface of the metal. Many of the known organic inhibitor solutions are colloidal in nature, a fact that lends support to the possibility of either adsorption or cataphoric migration of inhibitor particles. However, if such a layer exists, it is so extremely thin as to escape detection in many instances.

Nature and Composition of Inhibitors. Widely varied materials have been advocated and used as inhibitors, from cabbage leaves or wheat bran to complex synthetic organic chemicals. In numerous instances raw materials and by-products have been found useful as inhibitors, and many are still being used without the separation or identification of the active ingredient. A comprehensive list of such materials would be difficult to prepare but would include the following: sludge acid from oil refineries, waste animal materials, waste sulfite cellulose liquor, wheat bran or off-grade flour, sulfonation products of such materials as wood tar, coal tar, and asphaltum. These materials, varying widely in their effectiveness and uniformity, have an economic advantage and are not necessarily inferior to synthetic inhibitors.

A wide range of synthetic chemicals has been reported as showing inhibitive properties. Many of these are extremely complex in structure and high in molecular weight. Aldehydes, thioaldehydes, mercaptans and other sulfur-containing organic compounds, as well as organic nitrogen bases and their derivatives, seem to be favorites, particularly those in which the nitrogen is linked within a heterocyclic ring, such as pyridine and quinidine. The cost of synthetic inhibitors often precludes their use for production work. However, some of these compounds are so efficient that extremely small amounts are required.

Foaming Agents. The function of foaming agents is to blanket the surface of the pickling solution with a suds, which traps and holds any fine spray of acid that would otherwise be carried into the atmosphere with the evolved hydrogen gas. The chief advantage of foaming agents lies in their ability to prevent the pollution of the atmosphere by acid fumes.

Confusion still exists in the minds of many, concerning the relation between inhibitors and foaming agents. Actually they represent independent phenomena, although in many preparations they are coexistent. When a sufficient quantity of a good inhibitor is used, the evolution of hydrogen gas is so small that a foaming agent becomes virtually unnecessary.

Methods of Testing Inhibitors. Because of the wide variety of inhibitors and their diversity of behavior, it is important to have some method of testing their efficiency. The ultimate test is their behavior in the pickling bath, but laboratory tests offer a convenient means of comparing the value of inhibitors under carefully controlled conditions.

Laboratory tests for inhibitors are of two general types: (1) tests that measure the loss in weight of metal in inhibited acid, and (2) tests that measure the amount of hydrogen evolved. The latter tests depend on the fact that when metal reacts with a nonoxidizing acid, hydrogen is evolved; but when the acid reacts with metallic oxide, water is formed with no evolution of gas. Hence a theoretically perfect inhibitor should allow removal of the scale with no evolution of hydrogen.

Inhibitors frequently fail in service because of localized overheating at the point where steam is introduced into the bath. Laboratory tests should take this fact into consideration. A satisfactory check may be made by refluxing a sample of the inhibited pickling solution for not less than one hour. Because of the wide difference in the solubilities of high-carbon and low-carbon steels in acid, tests for efficiency of inhibitors should be made on the same grade of steel as will be treated in the pickle tub.

Advantages of Inhibiting the Acid.

1 Reduction in metal loss
2 Saving of pickling acid
3 Prevention or minimizing of scrap losses from overpickling
4 Decrease in blistering and in hydrogen embrittlement

Disadvantages of Inhibiting the Acid.

1 Increased pickling time
2 Possibility of residual surface film, which may interfere with subsequent operations
3 Added cost of inhibitor

Washing and Liming After Pickling. The importance of a clean rinse tub is not always appreciated. Ferrous sulfate gradually accumulates in the rinse water. Traces of ferrous sulfate that remain on the steel after rinsing will oxidize while drying, leaving a film of rust on the surface. Acid also may accumulate in the rinse tub and promote rusting of the steel when exposed to the air.

Even with thorough rinsing in clean tubs, it is difficult to remove the last traces of acid with water alone. When pickled steel must be protected from rust, an alkaline rinse is advisable to remove the last traces of acid. An effective solution may be made of ½% of caustic soda and ¾% of trisodium phosphate ($Na_3PO_4 \cdot 12H_2O$) in hot water. The alkalinity of the bath should be checked frequently and maintained by the addition of caustic soda. Acid titration (methyl orange indicator) is the best means of determining the alkalinity. Five milliliters of the above alkaline solution should require 5 to 10 ml of N/10 sulfuric or hydrochloric acid for neutralization.

A cold dip in milk of lime is also effective for neutralizing traces of acid. This method leaves a coating of lime, which is not easily removed from the surface. If cold drawing operations follow pickling, the lime will serve advantageously as a lubricating agent.

The presence of a white suspension of solid material is not proof that sufficient lime remains in the solution. Calcium sulfate, formed when lime reacts with sulfuric acid, is a white powder only slightly soluble in water, and may easily be confused with lime. Titration of the available alkali with a mineral acid gives a positive index of the lime content of the solution.

Pickling Defects. Pickling is frequently blamed for certain defects that appear during the pickling operation but that have their inception elsewhere. The tendency is to blame all failures on overpickling or to condemn the steel as defective. Certain defects, however, come from neither of these causes, but are the result of earlier operations, such as rolling, heat treating, or forging.

Overpickling. This error causes porosity of the transverse surfaces and a roughening of the whole surface, accompanied by discoloration and decrease in size and weight. Overpickling can be avoided by removing the material from the bath promptly when the pickling has been accomplished. Inhibitors aid in preventing overpickling, but are not a complete guarantee that it will not occur.

Pickle Pitting. This defect may be classified into several different types, according to cause. Three of these types are common enough to justify special consideration.

Electrolytic pitting is by far the most prevalent and troublesome type, particularly on heat treated alloy steels and forgings. It is characterized by a patchwork of pitted areas irregular in shape; the depth is indirectly proportional to the area. Caused by an electrical potential between the scaled areas and the clean steel, electrolytic pitting occurs only where the scale has been removed from small areas before the pickling, or at an early stage in the process. It should be noted that the pitted areas are often longitudinally aligned and that the boundaries are usually rather sharply defined or channeled, probably because maximum potential exists at such locations. When inhibited acid is used, the pitted area is generally uniform in depth, with a channeled boundary; uninhibited acid makes the pitted area irregular in depth.

Although severe pitting is rare, it may be caused by overpickling, particularly in inhibited acid. This serious defect indicates carelessness on the part of the pickler, because such pitting appears only when material is allowed to remain in the bath much longer than is necessary for complete removal of scale.

Pits that have been caused by rolled-in scale or refractories in the rolling process, are intensified during pickling.

Nonmetallic inclusions, segregated carbides, or surface strains are frequently held responsible for pickle pitting. These factors may have some influence but their importance has been overstressed. It is always advisable first to investigate the more frequent causes discussed in the preceding paragraphs.

Blistering. This is a troublesome defect on sheet and strip steel. Of the several theories concerning the origin of blisters, the most reasonable seems to be that gaseous inclusions cause these flaws in the steel by forming gas pockets just beneath the surface during rolling. Hydrogen generated in the pickling operation, penetrates these pockets and lifts the surface, causing a blister. Properly selected inhibitors may minimize blistering, but it is doubtful that they can prevent it entirely.

Hydrogen Embrittlement. This phenomenon gives some trouble when cold working operations follow too soon after pickling. Hydrogen embrittlement seems to result from the penetration of the steel by nascent hydrogen. This type of embrittlement is not permanent and may be eliminated by aging or, more rapidly, by soaking the steel in boiling water. Inhibitors are valuable in minimizing this effect.

Safety. When strong acids and alkali are splashed or spilled, they cause severe burns if not neutralized promptly, and are destructive to clothing. A supply of cold running water should be available at all times for washing. It is important that large amounts of water be used, for when small amounts of water are added to concentrated sulfuric acid, heat is generated, which may add to the severity of the burn. Safety showers are recommended for providing the necessary volume of water in such an emergency.

To remove the last traces of acid from the skin, after thorough rinsing with cold water, sodium bicarbonate or baking soda may be used either dry or mixed with water.

Ammonia may be applied to clothing, but should not come in contact with the skin. In severe injury, consult the medical department for further treatment.

To remove traces of alkali left after washing with cold water, powdered boric acid may be used, or a saturated solution of boric acid in water. A physician should be consulted for further treatment.

Hydrofluoric acid burns are exceedingly severe and painful. Hence, when this acid must be handled, the utmost care should be taken to prevent any contact whatsoever with the skin. Material being pickled in hydrofluoric acid should never be handled without rubber gloves.

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The Electrolytic Pickling of Iron and Steel

By Walter R. Meyer*

ELECTROLYTIC pickling of iron and steel is employed to escape some of the difficulties encountered in still pickling. The removal of rust as Fe_2O_3 is comparatively easy with still pickling methods, but the removal of the black magnetic oxide of iron, Fe_3O_4, which is slowly soluble in sulfuric acid, is difficult without the use of electrolytic methods. Before discussing specific processes, some general problems will be considered, such as the nature of scale and its removal, and hydrogen embrittlement.

The Nature of Fire Scale and Its Removal. The black oxidation product of iron, commonly called "fire scale" or "hammer scale", which forms during the heat treatment of iron or steel, is composed of FeO, Fe_3O_4, and a top layer of Fe_2O_3. The chemical composition of fire scale on hot rolled stock and heat treated parts may vary considerably, but the important point is that the composition of the scale varies from ferrous oxide at the metal interface to magnetic oxide with a thin layer of ferric oxide at the surface. Hering has found that the magnetic oxide is attacked only slightly by sulfuric acid, but that hydrogen, formed either electrolytically or by the attack of acid on the iron, leads to rapid dissolution of the scale. The probable mechanism of removal of fire scale is an acid attack on the ferrous and ferric oxides; partial reduction of the magnetic oxide and the dissolution of the reduction products; the reduction resulting from the electrolytically formed hydrogen, or, in still pickling, by the action of the acid on the iron; and a resultant undermining of the residual scale with some mechanical lifting action provided by the discharged hydrogen.

Advantages of Electrolytic Pickling Over Still Pickling. Electrolytic pickling is usually much more rapid than still pickling because of the greater evolution of hydrogen during electrolytic pickling, which agitates the pickling solution, reduces scale, and tends to pry off scale from the surface of the steel. In acid consumption, however, there is little difference between electrolytic pickling and inhibited acid pickling. Absorption of hydrogen, which may lead to embrittlement, occurs in both electrolytic pickling and still pickling. The effects of absorbed hydrogen can be removed by baking the work material for about one hour at 300 F, or a shorter time at higher temperature.

The Bullard-Dunn Descaling Process. This process is used extensively because it removes scale quickly from heat treated parts, without affecting the base steel. The process can be employed for large parts hung on racks and also for bulk parts contained in special tumbling baskets. The steel is first cleaned of oil and grease electrolytically by making it either anodic or cathodic in special alkaline cleaners. Anodic cleaning is usually preferred because this cleaner is used for stripping tin deposited in the process, and soon becomes contaminated with tin that would plate out if cathodic cleaning were used. The work is then made the cathode in a solution containing 10% by volume of 66 Bé sulfuric acid, at 140 to 150 F. Current densities from 60 to 75 amp per sq ft are recommended. The bath contains about one gram per liter of tin and, when the scale has been removed, the tin is deposited on the clean steel in a uniform coating, which prevents further attack by the acid. Silicon-iron anodes are used and a special surface-active material is added to the acid solution to produce a light foam that minimizes fuming and insures the formation of a smooth continuous coating of tin. Frequently, the tin coating is left on the work to afford some protection against subsequent rusting; however, the coating can be removed quickly by making the work material anodic in the alkaline cleaner that is used for degreasing.

The Madsenell Process. This process employs anodic electropickling to remove carbon smut and absorbed gases, notably hydrogen, from ferrous metal in order to obtain an excellent surface for adhesion of electrodeposits or hot dipped coatings. The work is first cleaned and pickled, either by still or electrolytic methods, and is then transferred to the "degassing" bath. The electrolyte is sulfuric acid of concentration greater than 85% maintained between room temperature and 100 F. The work material is made the anode with the current on when immersed. A 12-v line is usually employed, which provides a current density of 50 amp per sq ft initially, but which drops, within 30 sec to 10 min, to almost zero current with resultant cessation of the gas evolution.

This process removes some of the effects of the pickling of the fire scale rather than being a method designed for the removal of scale. Some possible disadvantages may be the necessity of maintaining a high acid concentration in the bath, the need of direct-current generators or rectifiers, and the maintenance of good electrical contact.

The Hanson-Van Winkle-Munning Electrolytic Bright Dip. This process comprises two steps. First, the work is made the cathode in a warm dilute sulfuric acid bath, 10 to 20% acid, at a current density of from 10 to 150 amp per sq ft for several minutes. The scale is removed effectively but the work may be coated with an "acid black". To remove this smut, the work is rinsed and transferred to a stronger acid bath (40 to 50%) where it is made the anode for 2 to 5 min at a current density of from 100 to 150 amp per sq ft.

High current densities and low temperatures (50 to 90 F) are favorable for the production of a bright surface. If the current density is too low or the temperature too high, the surface will be clean but not bright; however, higher temperatures can be offset, to some extent, by higher current densities. The production of the bright surface may be caused by the formation of persulfuric acid, which is favored by low temperatures and high current densities. The current density referred to is the initial value; polarization sets in rapidly and the current density drops quickly with a cleaning and then a brightening of the work.

The process imparts a silvery surface free from smut and scale with only a small amount of etching and a considerable reduction in embrittlement from the anodic treatment. Good electrical contacts are needed for maintenance of high current density. Also the acid must be cooled for the anodic treatment.

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Coloring Steel

By C. B. F. Young*

STEEL may be colored by heating clean surfaces in contact with various solids, liquids and gases, or by coating the metal with certain solutions and then heating to slightly elevated temperatures. Electrolysis in special solutions will also color steel surfaces without the deposition of a metallic coating.

Coloring of Steel in Molten Salt Baths. Iron and steel that have been polished and cleaned may be colored effectively in molten salt baths; however, the temperatures required are often high enough to decrease the hardness of the metal. Then too, the loss by drag-out may be so great in some types of salt that the metal is too expensive for most purposes.

Both these disadvantages may be avoided by the use of sodium hydroxide baths, since the operating temperatures are moderate (300 to 400 F) and the drag-out is low. Sodium hydroxide baths should be covered so as to exclude all carbon dioxide, which unites with the sodium hydroxide to produce sodium carbonate. If this compound is formed, it can be precipitated by the addition of unslaked lime.

A black color can be produced in a solution of 400 g of sodium hydroxide, 10 g of potassium nitrate and 10 g of sodium nitrate dissolved in 600 ml of water. The solution should be used at 250 to 285 F. The black color appears in 15 to 30 min. Then the object should be rinsed in hot water, dried, and immersed in hot oil.

Color Produced by Temperature. One of the oldest methods of coloring iron and steel consists in heating the material to the desired temperature, and holding it there for a definite period. While steel is being heated gradually through a range of temperatures, each degree of temperature for a given specimen of steel produces a corresponding shade, from straw yellow through brown and purple to dark blue. Each of these colors can be produced by proper control of the temperature.

Below is a table showing at what temperature each of the possible colors is produced. These data are only general; different steels will vary somewhat.

Deg Fahr	Color
400	Faint straw
440	Straw
475	Deep straw
520	Bronze
540	Peacock
590	Full blue
640	Light blue

The colors produced by the above method are ordinarily not uniform, because of the fluctuation of the temperature. If the steel objects are immersed in a molten bath of lead or salt, as described below, the temperature can be controlled much more successfully.

Polished strip steel becomes straw-colored or blue when it has passed through a small lead bath at a suitable temperature and speed. The desired color develops after the steel leaves the bath and comes in contact with the air. The amount of coloring is controlled by passing the strip steel through wet waste located a short distance from where the strip emerges from the lead.

Strip steel is colored satisfactorily also while being passed through a salt bath. The coloring takes place in the bath. Then the adhering salt must be washed off with hot water, and the steel must be dried before it is wound on the reels.

In both methods the strip steel must be thoroughly cleansed and dried before coloring, and must be free from oil and finger marks.

Sand may also be used as the heating medium. The sand may be on a hot plate, or better, in a cylinder that can be rotated slowly and heated by a gas flame underneath. From 5 to 10 min will produce a fine rich blue when the temperature of the sand is approximately 650 F.

The work pieces may also be placed in a sheet metal box with a small amount of sand. The box and contents are agitated back and forth over a fire.

For using either method, experience will be required in order to know exactly when to remove the work material from the fire. The sand is sifted out through a wire sieve and the metal is dipped into oil to set the color.

For tinting steel on a large scale, continuous sand tempering machines are often used. The work material is carried through a perforated drum and heated sand is sifted automatically into the drum. Adjustments of the temperature and rate of feed may be made in such a way that a uniform color is given to a continuous stream of work pieces.

Heat tinting may also be done on a large scale in a rotary retort without the use of sand. The tint is controlled by the operator, who must regulate the temperature accurately and keep close watch of the work material to be certain that it is removed when the desired color is secured.

For continuous simultaneous heat tinting and tempering, machines are procurable with or without sand as part of the process. The sand serves to cushion the work in order to prevent battering that might result from tumbling articles of certain shapes and weights; furthermore, the heated sand ensures complete diffusion of the heat throughout the mass of work and therefore greater uniformity in color.

In all heat tinting, it is important that sufficient time be allowed for oxidation of the steel at the low temperatures used.

Niter Baths. Steel articles that have been polished and properly cleaned, can be given a simple finish by immersion in molten niter. A mixture of half-and-half sodium nitrate and potassium nitrate is melted in a cast-iron or steel melting pot of shape and depth to suit the work. Because rust from any source affects the color of the work, the pot should be cleaned before the saltpeter is put in. The niter is melted, superheated to a temperature of about 900 F, and manganese dioxide is added in the ratio of about 1 part oxide to 50 parts niter, by volume. The manganese gives the molten salt a greenish-black tinge, and causes all suspended matter to settle to the bottom of the pot.

The addition of potassium nitrate increases the cost of the process. Potassium salts are considered necessary when low-temperature operation is desired. Potassium salts may be omitted from the bath, however, with equally good results. Sodium nitrate or Chile saltpeter is an excellent bluing medium, although higher operating temperatures are imperative.

Since bluing by this process forms an iron oxide film on the work pieces, consumption of the manganese dioxide would be expected. One pound of manganese dioxide should be added every 3 hr to a 300-lb batch of saltpeter in order to keep the bath in condition. Although the exact function of the manganese dioxide is still in question, observations indicate that if manganese dioxide is omitted from the pot, the melt does not produce good work. Baths that were found, during analysis, to be charged with iron oxide, gave bad results, whereas no excess iron oxide was found in solution in any bath containing an excess of manganese dioxide. (However, manganese dioxide has been omitted from some baths with satisfactory results.)

In a niter bath a peacock blue or temper blue can be obtained consistently in the following manner: The articles to be blued are first cleaned and polished. The higher the polish, the brighter will be the blue color. A thin coating of oil is then applied and the articles are immersed in the hot niter at 600 to 650 F. The pieces may be suspended individually on wires. Screws, nuts and other small articles may be dipped, enclosed in a wire basket. The parts are held in the niter for a few minutes, after which they are raised to permit observation of the depth of coloring attained. They are then replaced in the molten salt until they acquire the desired color. The time required varies with the temperature and with the size of the pieces, but is never more than 4 or 5 min.

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The oxidation reaction is the same as is obtained when tempering steel to color. If steel objects are left in the niter too long (for example, 10 min) the film produced will not be a temper blue or a gun-metal blue, but a dirty gray. Preliminary cleaning in gasoline or a similar solvent, produces a bad finish, resulting in a mottled dirty surface. The oil carried on the surface of the parts takes fire as soon as they are immersed in the hot niter and, if any moisture is present on the articles, the hot salt will spatter dangerously.

After the right blue has been obtained, the articles are quenched in clean, cold water; then they are immersed in boiling water and finally in hot oil. A dip in hot oil is necessary in treating small screws or other tiny parts, since it removes all moisture, which, if left on the blued article, may form a spot of red oxide rust at the roots of threads or any re-entrant angle. A darker gun-metal blue may be obtained at temperatures around 1000 F.

Care should be taken not to dip articles, after adding manganese dioxide to a niter bath, until the suspended oxide has sunk; otherwise dirty spots will appear on the blued metal. Cast iron, if highly polished, will take on a gun-metal blue corresponding to that given to polished steel, but cast iron requires about 20 min of immersion at 1000 F to accomplish this result.

Charcoal Bluing. The charcoal bluing process consists in placing highly polished work in a bed of hot charcoal approximately 2 ft deep. The lower layers of the fuel are in a state of incandescence, whereas the upper layers have temperatures suitable for the development of oxide colors. After the desired shade of blue has been developed, the work is rubbed vigorously with waste that has been dipped in raw sperm oil.

Oil Blackening. To blacken in oil, the polished steel part is packed with spent carburizing compound in a carburizing box that is properly luted to exclude air. Box and contents are heated to 1200 F, requiring about 1½ hr. At this temperature the box may be drawn, the lid may be opened, and the parts may be riddled free from carburizing compound and quenched at once in oil. A black oxide skin is formed, dull in appearance but uniform in texture.

A comparatively good black color can be obtained quickly by heating the work to a temperature of 1000 to 1200 F and quenching in oil. The appearance of this finish depends on the surface of the work before heating. This finish is inferior to the gun-metal finish, both in color and in lasting qualities.

Small typewriter parts are given a black finish by heating in a rotary retort furnace to about 750 F. After the work has reached the desired temperature, a small quantity (about 1 oz) of linseed oil or fish oil is added to the charge in the retort. The work is revolved from 3 to 10 min longer; then it is taken from the furnace and spread in pans to cool in the air. After cooling, the parts are dipped into an oil that retards rust.*

For oil blackening and tempering simultaneously, articles that have been quenched in oil from the hardening temperature should be placed, while still covered with the quenching oil, in a rotary drum retort (not perforated). Then they should be heated to a temperature between 600 and 650 F and held at temperature long enough to temper properly and to produce the finish desired. The longer the time, the deeper and more durable the black color. The retort and its contents should be allowed to cool to a temperature lower than 500 F. Then the articles may be discharged and tumbled for a short time in granular cork that is slightly oily, to brighten the black color.

Gun-Metal Finish. The gun-metal finish, also known as "carbonia finish", used on a majority of rifles, shotguns, and revolvers, is used too for finishing small parts, such as buttons, screws, pen points, buckles, pins, saw teeth, links for bicycle chains, and parts for typewriters and calculating machines.

Various types of black finish can be secured, depending principally on the finish of the part before the special treatment is given. Cold drawn or highly polished parts will take a glossy black finish. Parts made from ordinary stampings will have a somewhat duller finish, while work that has been sandblasted, before this treatment, will have a black matte-like finish.

Although unable to prevent rust entirely, this finish acts to retard the formation of rust.

For application of the gun-metal or carbonia finish, the work pieces are placed loosely in a retort with a small amount of charred bone and are heated to a temperature between 700 and 800 F. After the articles have been thoroughly oxidized, they are allowed to cool to about 650 F, when a mixture of bone and 1 or 2 tablespoonfuls of carbonia oil are added. Heating is then continued for several hours. When the work pieces come from the retort, they are a dull grayish black. A uniform black finish is secured by dipping the articles in sperm oil or tumbling them in oily cork.

If the suggested temperatures will temper too much, a temperature as low as 500 F can be used, but this lower temperature requires a longer time at temperature to color the articles and the color is not so lasting as the color produced at the higher temperatures.

Gun-metal or carbonia finish may be applied to articles that have first been nitrided. The result is a pleasing finish that resists rusting and retains surface hardness on the articles, since these coloring temperatures do not soften nitrided articles.

Coslettizing, Parkerizing and Barffing. In Coslettizing, the articles, polished and cleaned, are placed in a solution of ferrous phosphate made from iron filings, about 1% of phosphoric acid, and water, boiled together for approximately 2 hr. On steel this treatment produces a strongly adhesive light gray coating of basic iron phosphate. Because of the low temperature used, the mechanical properties of tempered steel articles are not affected. Even fine springs and magnets are unaffected.

The method called "Parkerizing" differs from Coslett's original method by adding an oxidizing agent and catalyzer, usually manganese oxide (MnO), to the 1 to 2% solution of phosphoric acid that contains ferrous phosphate. The coating produced is then a basic ferrous-ferric phosphate. The ideal coating is one that contains 3 parts of ferrous phosphate to 1 part of ferric phosphate. The articles are gray after being coated. After drying they are usually coated with paraffin oil to give them a deep black color. Considerable variation of color is possible by this treatment. When the articles are first placed in the bath, a large quantity of hydrogen gas is liberated. As soon as the evolution of gas ceases, the process is completed.

Barffing renders the metallic surface rather inert by producing a coating consisting of magnetic oxide of iron. This change, reaching to an appreciable depth, gives the surface the same durability as does a gun-metal finish. The articles to be treated are cleaned and placed in an airtight oven that has a connection introducing superheated steam at 60 to 100 psi. When the articles have been heated to a dull red, the steam is introduced. The coating is resistant to heat. These coatings can be dyed and treated with oil or wax to increase their resistance to moisture. The natural appearance before sealing is a light bluish slate color, which darkens when oil or wax coatings are applied. These coatings prevent finger marking.

Browning. There are many processes for browning steel. However, the procedures may be summarized by describing one process, in spite of numerous variations, chiefly in the composition of the browning mixture. Other variations occur in manipulation and in the atmospheric conditions, artificial or natural. The longer browning processes have relatively low temperatures and humidities; the shorter processes have relatively high temperatures and humidities. Conditions for rusting are poor in the longer processes and good in the shorter ones.

Procedures in Browning. The articles are first cleaned thoroughly. One way to accomplish this is to boil them for 15 min in a soda solution. Any grease appearing on the surface of such a solution indicates the need for adding soda ash. Then the parts should be dried on a draining rack. When they have cooled to approximately 120 F, they should next be coated with the browning solution, which should be applied evenly over the surface with a brush or sponge, or as a dip. The articles should be permitted to dry for about 30 min before application of a

* Fuels and Furnaces, page 464, May 1924

Table I. Percentage Compositions of Browning Solutions

	1	2	3	4	5	6	7	8	9	10	11	12	13
Ferrous chloride $FeCl_2$	....	....	....	....	....	....	....	....	....	0.9	....	....	....
Ferric chloride Fe_2Cl_6	3.9	2.8	8.9	2.1	2.8	7.0	....	....	5.3	2.8	3.3	22.2	....
Mercuric chloride $HgCl_2$	1.2	....	....	0.7	....	....	3.3	4.5	....	....	....	....	10.0
Cupric chloride $CuCl_2$	....	....	....	....	....	0.5	1.7	....	....	....	....	....	5.0
Antimony chloride $SbCl_3$	....	....	....	....	....	....	....	....	....	....	....	22.2	....
Bismuth chloride $BiCl_3$	....	....	....	....	....	....	1.7	....	....	....	....	....	5.0
Hydrochloric acid HCl	....	....	....	....	....	7.5	9.9	....	....	....	....	....	30.0
Ferrous sulfate $FeSO_4$	....	1.5	....	....	....	....	....	....	....	....	....	....	....
Cupric sulfate $CuSO_4$	0.6	....	....	0.7	1.5	....	....	....	1.8	....	2.5	....	....
Nitric acid HNO_3	1.8	8.5	....	6.4	8.5	4.3	....	....	2.2	0.5	3.7	....	....
Spirits of niter	6.2	....	....	....	....	....	....	....	....	....	4.1	....	....
Ammonium chloride NH_4Cl	....	....	....	....	....	....	....	4.5	....	....	....	....	....
Alcohol C_2H_5OH	4.0	3.2	40.1	2.4	3.2	78.2	....	....	2.6	1.4	3.7	....	25.0
Gallic acid $C_7H_6O_5$	....	....	....	....	....	....	....	....	....	....	....	11.1	....
Iron filings Fe	....	....	....	....	....	2.5	....	....	....	....	....	....	....
Water H_2O	82.3	84.0	51.0	87.7	84.0	....	83.4	91.0	88.1	94.4	82.7	44.5	25.0
Approximate cost per gal	$0.90	$0.27	$1.45	$0.35	$0.30	$3.38	$0.86	....	....	....	....	....	....

second coat of the solution; thereafter they should dry again for 30 min.

The work pieces are then placed in a warming room or cabinet, and brought to temperature, which may vary from 140 F to as high as 175 F. Dry heat is satisfactory, since its function is merely to heat the articles to such a temperature that when they are placed in the humidor rusting cabinet, dew will not form on the surface, causing spots in the color.

The time in the warming room will naturally vary according to the size of the pieces. From the warming room they should be transferred to the rusting room, which must be at the same temperature as that of the warming room (175 F). Humidity as high as the saturation point is desired, but danger of condensation should be avoided, because pitted and spotted work will result if the dew point is reached. Articles are rusted in approximately 1½ hr for such shapes as bayonets; others take shorter or longer periods, depending on the size and surface.

The rusted metal, now a dirty greenish red, is removed from the humid room to a third cabinet or room, where the conditions are the same as in the first room. This transfer is not absolutely necessary, but the purpose is to set the rust. The rusted metal is allowed to remain in this room for 30 min before being placed in clean, boiling water for 15 min. After this time, the articles are allowed to drain dry, and then are carded on a wire brush or fiber wheel, which removes any loose particles of oxide from the surface, thus completing the first coating.

Three more rustings are applied in much the same manner, after which the browned surfaces are given a coating of thin white slushing oil.

All the rooms should have proper thermometer and thermostatic controls, and the rusting room requires a recording hygrometer. Temperature and moisture should be controlled automatically. The layout of the apparatus should permit a proper flow of work between processes.

For compositions of browning solutions, see Table I.

Electrolytic Coloring. When iron or steel is covered with an electrolytic coat of another metal or alloy, the result is not considered coloring but protecting the base metal. Thus, iron and steel are colored yellow by a deposit of brass; red by a deposit of copper; black by a deposit of black nickel; and white by a deposit of a nickel-cobalt alloy. See pages 718 and 719 for typical compositions of baths and conditions for electrodeposition of metals.

Aside from the deposition of metals and alloys, the deposition of colors by the aid of an electric current is producing good results. Examples are as follows:

Blue on Iron. A good blue can be produced on iron by first depositing on the surface a thin coating of electrolytic copper, using either the sulfate or cyanide bath. The copper-coated steel is then made the cathode in a solution containing 1.25 oz of cupric acetate per gallon and 0.50 oz of gelatin per gallon. A current of 1.5 to 4.0 amp per sq ft should be passed through this solution, using copper as the anode. After depositing the copper from this solution for about 15 to 20 min, the cathode should be washed in water and immersed for 5 min in a 5% cupric acetate solution. Hues of startling intensity are produced one after another, until finally a deep blue develops.

Color Plating. The colors produced by this process have a metallic luster, are free from dyes or pigments and are light-fast. Almost all the colors of the spectrum from violet to red can be produced in a single bath. The colors obtained depend on the thickness of the deposit and this in turn depends on the plating time, which may vary from 1 min to 30 min or more.

The bath is composed of complex organic compounds. The work metal is made cathode while copper is used as the anode. The current density is approximately 0.5 amp per sq ft with about 0.4 volt.

The finish of the base metal determines the appearance after color plating. Thus an article that is highly polished before color plating has a similar polished appearance after color plating. A clear lacquer is applied, after color plating, to increase the resistance of the finish to wear and corrosion.

Molybdate Method. If iron or steel is made the cathode in a bath containing 7 to 14 oz of ammonium molybdate per gallon, with enough ammonium hydroxide to produce a clear solution, and 1 to 10 amp per sq ft is passed through the cell, various colors and hues can be obtained. The colors change several times in a cycle. When a cycle is complete, the colors are reproduced in a somewhat darker shade. If this procedure is allowed to continue, black deposits are finally produced, although most of these deposits have the disadvantage of being brittle. Such a bath, with modifications, can be used for coloring various metals, including aluminum.

Phosphate Coating

By V. M. Darsey*

PHOSPHATING is the chemical treatment of iron, steel, zinc, cadmium, aluminum, and their alloys, by means of a dilute acid phosphate solution saturated with one or more of these metals, so that the metal surface is converted to an insoluble crystalline phosphate coating. The protective coating, integral with the surface of the metal, results from chemical reaction between phosphoric acid and the metal, as contrasted with metallic or paint coatings, which generally do not require chemical combination with the base metal. Reaction of the acid with the metal takes place with the evolution of hydrogen, until the entire metal surface is converted to a uniform phosphate coating. To accelerate the formation of the coating, an oxidizing agent is used,[1] capable of oxidizing hydrogen and thus preventing the formation of a hydrogen film on the metal

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surface during treatment. The characteristics of the coating, such as thickness, crystalline structure, and the extent of the penetration of the coating into the base metal, can be controlled by the following factors: the method of cleaning before treatment, the method of applying the solution, duration of treatment, and modification of the composition of the solution.

The advantage of these factors has been utilized in processes for producing phosphate coatings that are especially suitable for preventing corrosion, and that serve as a base for paint, resist wear, and facilitate the deep drawing of metals.

The method of applying phosphate coatings is usually determined by the size and shape of the article to be coated. Small items, such as nuts, bolts, screws and small stampings, are coated in tumbling barrels by immersion in the phosphating solution; whereas, large fabricated articles, such as automobile bodies and refrigerator cabinets, which are difficult to immerse, are coated by spraying the solution on while they are on conveyers. When steel sheet and strip are to be coated, the metal is usually passed continuously through the phosphating solution or the solution is sprayed onto the steel while rubber rolls or brushes expedite the formation of the coating.[9]

Corrosion-Resisting Phosphate Coating. Phosphate coatings were first used to protect iron and steel from corrosion. The conversion of a metal surface to an insoluble phosphate coating, acts as a physical barrier to exclude moisture from the metal surface. The protective value of such coatings thus depends on continuity and, for this reason, thickness and density of coating are more important than any other factors. Coatings can be produced with a wide range of thickness, depending on the method of cleaning before treatment, adjustment in the concentration of the solution, and duration of treatment. A build-up of 0.00015 to 0.0003 in. of phosphate coating ordinarily results when articles are Parkerized. No electric current is used and formation of the coating depends entirely on contact between the phosphating solution and the metal surface. Because of this fact, uniform coatings can be produced on irregularly shaped articles, in recessed areas and on threaded as well as on flat surfaces.

The affinity of heavy phosphate coatings for oil, wax or color is one of the most valuable characteristics utilized in practice to increase the corrosion resistance of these coatings. Frequently phosphate-coated articles are finished by a dip in nondrying or drying oils that contain corrosion inhibitors, and are then drained or centrifuged to remove the excess.

A recent development is the production of phosphate coatings in color, with more than twice as great resistance to corrosion as coatings without the color treatment. The phosphate-coated articles are immersed in the color bath at boiling temperature for 2 to 6 min, and are then rinsed thoroughly in water. The color results from chemical reaction and is insoluble in water. Because of fading somewhat, as a result of exposure to sunlight, certain colors are not recommended for outdoor use where rigid color fastness is required.

Phosphate Coating as a Base for Paint. In general, the useful life of any paint finish depends on two major factors—the durability of the organic coating itself, and the adherence of the film to the surface on which it is applied. Permanent adhesion is clearly the primary requisite for improving practice in painting most metals. Surface treatment[2, 3] is emphasized in preparing metals for painting; and in most instances, the treatments recommended have as their main objective the formation of a stable and nonreactive coating, combined with the base metal, so as to retard corrosion and also to provide greater adhesion of applied paint films. The primary function of any protective coating of paint is to prevent corrosion of the base metal in the environment in which it is used. To accomplish this purpose best, the method of preparing the metal should reduce the activity of the metal surface, so that underfilm corrosion is prevented at the interface between paint and metal. Wherever the paint film is scratched or abraded the spread of rust is reduced on phosphate-coated steel.

It is common practice to apply various types of air-drying paint and of paint that requires baking, over phosphate-coated steel. Enamel that is baked at a temperature as high as 400 F can be applied successfully to phosphate-coated steel.

Difference Between Metals Cleaned in Phosphoric Acid and Those Coated With Phosphate. Phosphoric acid metal cleaners usually consist of phosphoric acid and a water-soluble, organic grease solvent, with or without a wetting agent. In the preparation of metal with such solutions the purpose[4] is to remove grease and rust in one operation, and to provide a slight etch of the metal to promote the adhesion of paint. For accomplishing this result, the cleaning solution must contain sufficient acid and solvent to remove rust and grease. Of necessity, this concentration is such (15 to 20% H_3PO_4) that the formation of any substantial phosphate coating is prevented. When metal surfaces are to be given a phosphate coating, the articles are first freed of rust and grease by suitable cleaning methods, and are then treated with a balanced dilute acid phosphate solution (0.6 to 1.0% H_3PO_4), so that reaction of the acid with the metal results in the conversion of the surface to a crystalline phosphate coating. Tests made on steel cleaned with phosphoric acid have revealed that the phosphate film remaining from the cleaning operation, averages only 5 to 10 mg per sq ft of surface. In the preparation of steel for painting, treatment with a phosphate coating (Bonderizing) produces from 100 to 400 mg of coating per sq ft of surface, depending on the method of appyling the solution.

Phosphate-Coated Steel for Containers. It is generally recognized that paint coatings applied to phosphate-coated articles are more serviceable than those applied to untreated articles. In 1940 a method[5] was developed for producing on sheet and strip steel at the mill, a phosphate coating that, in addition to inhibiting corrosion and increasing the adhesion of applied paint coatings, will withstand drawing, bending and other mechanical deformations required in the manufacture of caps, crowns and cans. This development has saved tons of tin and has become a recognized method of preparing steel for painting in the container industry. The availability of such phosphate-coated steel, permits painting flat sheet or strip and forming articles from it with the advantage of good paint adhesion and resistance to corrosion.

Phosphated Zinc-Coated Sheet and Strip Steel. Zinc has long been used to protect steel against corrosion. However, it is now used in conjunction with a phosphate coating, to produce sheet and strip steel with superior resistance to corrosion and greater ability to retain paint. The finish consists in the electrodeposition on steel of a uniform coat of zinc, having a minimum thickness of 0.000020 in., and then the phosphate treatment. The deposition of zinc and the phosphate coating is accomplished by passing the steel through a zinc-plating bath, rinsing, and then immediately phosphating. The outer surface of the zinc is converted to an insoluble phosphate coating, but a layer of metallic zinc remains between it and the steel for added resistance to corrosion. This finish makes available corrosion-resisting steel, especially suitable for the fabrication of articles where assurance is needed that the coating will provide an excellent base for applied paint finishes. Success in shipment and storage with freedom from rusting make this steel especially suitable for many uses; thus manufacturers may have the advantages of plating and phosphating without the expense of installing such equipment. Comparison of paint finishes applied over untreated and over phosphate-coated zinc, shows the advantage of surface conversion of the zinc before painting.

Wear-Resisting Phosphate Coating. Various materials and methods are employed to reduce wear on bearing surfaces. There is common agreement that it is essential to maintain an oil film between moving parts, thus preventing metal-to-metal contact, if serious wear is to be avoided. Experience has established phosphating as a widely used method[6] of reducing wear on machine elements. Treatment of properly cleaned iron and steel parts by immersion in the hot phosphating solution for 10 to 15 min, results in the conversion of the metal surface to a nonmetallic oil-absorptive coating, consisting chiefly of

iron and manganese phosphates. The uniformity of the phosphate coating, the penetration of the coating into the metal and the affinity of the coating for oil are considered the most valuable properties in reducing wear. The phosphate coating permits new parts to be broken in rapidly by providing adequate oil on surfaces at such critical times.

A wide variety of parts are phosphate-coated to retard wear, including cylinder liners, pistons, rings, camshafts, valve tappets, gears and many other parts used in machine assemblies.

Phosphate Coating as an Aid in Drawing Steel. The commercial practice of providing a phosphate coating on steel to facilitate drawing,[7] has been common in Europe for several years, and the use of this method is rapidly increasing here.[8] The power employed in deep-drawing operations sets up a great amount of friction between the steel surface and the die. The phosphate coating of steel before drawing, reduces this friction, increases the speed of the drawing operations, reduces the consumption of power and increases the life of tools and dies. When phosphate-coated steel is used in drawing seamless steel tubing, the resulting decrease in friction is so pronounced that greater reduction of tube size per pass is possible. Sometimes the reduction is as great as one third.

Reduction in the number of draws and anneals, in the deep forming of articles, results in economy of operation. Conversion of the steel surface to a nonmetallic phosphate coating permits the distribution and retention of a uniform film of lubricant over the entire surface of the steel. This combination of lubricant and nonmetallic coating prevents welding and scratching of steel in the drawing operations, and greatly decreases rejections.

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Rust-Preventive Compounds

By Howard B. Carpenter*

BEFORE World War II, rust was accepted by many as a necessary evil, partly because of the poor performance of many of the available rust-preventive compounds. Then during the years of war production, many manufacturers were faced for the first time with the necessity of protecting metallic products and equipment against the effects of wide extremes of temperature and humidity, as well as against the corrosive action of sea water. Old methods of packaging were inadequate without an actual rust-preventive film on the surface of the metal itself. In addition, increased precision, involving better finishes and lower tolerances, has necessitated protection for parts in process, and greater decentralization in manufacture has required that assembled units be prevented from rusting during shipment and storage.

For many years, paint and resistant metals, such as tin, lead and zinc, were the principal rust preventives, but the difficulty of removal made such coatings impracticable for finished surfaces, especially for surfaces subject to sliding contact, where rust produces heavy financial losses. Until a few years ago the protection given to such surfaces usually consisted of a so-called "slushing compound" of petrolatum and oil. The protection, however, was not reliable, since uninhibited oil, petrolatum or grease cannot be depended on to prevent rust. As a result of the combined efforts of the Armed Forces, the manufacturers of metals, instruments and machinery, and the compounders of rust preventives, highly effective products have been developed scientifically and their value has been demonstrated under extremely severe conditions. At the same time, industry has come to realize that the use of these inexpensive compounds will minimize one of the greatest sources of economic waste.

The principal function of rust-preventive compounds is to act as a barrier to moisture. Some of them also afford protection against the action of corrosive gases, but this is usually a physical and not a chemical action.

Rust-preventive compounds are *not* rust removers. Furthermore, they are effective only when applied to surfaces that are *thoroughly* clean and dry. This should be emphasized strongly, since the best rust preventives are virtually worthless if applied to a dirty or moist surface. Rust itself is spongy and, if not removed, is likely to retain moisture, thereby promoting corrosion under the film.

Modern rust-preventive compounds are described below, but the comments should be considered of a general nature, since undoubtedly there are exceptions. These compounds are of two general types, which in turn may be subdivided.

Non-Hard-Drying Types. This is the predominant classification, which includes coatings that do not dry to a hard film. In general, these products have a petroleum base and are characterized by ease of removal with petroleum solvents, without adverse effect on the metal surface to which they have been applied. Because of the petroleum content, many of these products will serve as lubricants, if for any reason they are not removed before operation. This group of compounds can be subdivided as follows:

Plastic Type. These are greaselike materials. The heaviest grade usually consists of petrolatum plus rust inhibitors. Other grades, softer and with somewhat lower melting point, are obtained by adding an oil of fairly high viscosity to the petrolatum base. As the consistency of products of this type decreases, the ease of applying and removing them increases, as well as the coverage per gallon; however, the anticipated protection decreases.

These plastic compounds are characterized by moderate resistance to abrasion, a fair amount of self-healing power if film rupture occurs, and the ability to expand and contract with the metal. They also resist displacement that results from contact, under pressure, with the interior surface of a shipping container. Under conditions that involve direct exposure to the elements, the heaviest grade affords the best protection of any in the removable category. Its outer surface hardens slowly when exposed to the atmosphere, but the film underneath retains its original softness and self-healing properties. The plastic type should be used wherever possible, except where the solvent type of products will give adequate protection, as in certain phases of indoor storage.

Fluid Type. These materials consist of petroleum oils of various viscosities, to which rust inhibitors have been added. As a general rule the fluid type of compound is used where the application of the plastic type would be difficult or unsuitable—for example, in oil-lubricated bearings, hydraulic systems, turbines, gear cases and such. However, the fluid type may drain or be removed by wick action, thus giving less permanent protection than that afforded by the plastic type.

Internal-Combustion Engine Type. This modification of the fluid type includes a neutralizer for the acidic products of combustion, plus other additives that make the compound suitable for use as a motor oil, thus ensuring against damage if replacement of oil is neglected when the engine is recommissioned.

Thin-Film Type. Products of this type contain a high

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percentage of a petroleum solvent, which evaporates, leaving a reasonably hard, thin nontransparent film. These materials are usually considered suitable for either outdoor or indoor service, as alternates to the plastic type.

Solvent Type. In general, these products consist of solutions of rust inhibitors in mineral spirits that evaporate, leaving a thin, transparent, but effective rust-preventive film. This film does not dry hard but remains somewhat flexible and tacky over long periods. These solvent products are not suitable for use outdoors, but give excellent indoor protection, particularly on material or parts in process, without interfering with visual inspection or the reading of identifying marks. One special modification of the solvent type of rust-preventive compound is made of materials that give it special protective ability. When this substance is applied to a wet surface, the water is immediately and completely displaced, fingerprint residues are neutralized, and the surface is left coated with an effective rust-preventive film.

Hard-Drying Types. The other general category is the hard-drying group. These compounds, usually of the so-called "lacquer" type, provide a film that is hard yet sufficiently flexible to resist abrasion in shipping and to resist cracking from the expansion and contraction of the metal. The hard-drying types are transparent, hence do not hide defects or the markings meant for identification. The protective film can be machined off, left to wear off, or painted over with pigmented products. The conventional compounds of this class dry to touch in 4 to 6 hr and dry hard in 24 hr. Grades that dry more rapidly are also available.

One special material in the hard-drying group is an aluminum paint with a special vehicle that is highly resistant to the particularly severe action of hot oil, hot water, or a combination of the two. This coating is satisfactory for the protection of the interiors of lubrication systems and sumps, hydraulic gear cases and other surfaces that are subject to the same type of corrosive action.

Another type of inhibited oil should be mentioned to prevent further acceptance of a misunderstanding. Many prime-grade turbine oils contain what is called a "rust inhibitor". This is not a misnomer but refers only to protection from rust resulting from the presence of water with which a lubricant has become contaminated. Such inhibitors are not expected to furnish protection against humid or corrosive atmospheres.

Methods of Test. The development of effective rust preventives has necessitated the development of laboratory methods for the evaluation of performance. Considerable progress has been made, but further improvement is desirable, and a means is needed for predicting service life from laboratory results. The most commonly used test of performance is carried on in a "humidity cabinet", where mild steel panels (usually 2 by 3 in. or 2 by 4 in. and $\frac{1}{16}$ or $\frac{1}{8}$ in. thick) that have been sandblasted or polished, are coated with the material under test and exposed to a temperature of 100 or 120 F and a relative humidity closely approaching 100%. The rust preventives are rated by the number of hours that elapse before rusting occurs. This test indicates the relative protection to be expected from exposure to atmospheric humidity.

In the salt spray test, similar panels are exposed to an atmosphere of atomized sodium chloride solution. The results give a fair indication of the relative protection to be expected from exposure to salt-laden atmospheres, such as those encountered in ocean shipment. Another test, involving immersion in synthetic sea water, gives similar indications.

A water spray test and exposure in a weatherometer indicate relative resistance of rust-preventive compounds to removal by the action of the elements, as well as resistance to the corrosive action of the elements.

The results from these tests are less reproducible than might be desired, but they are informative provided it is realized that they indicate simply an order of magnitude. For example, a product that furnished protection for 225 hr in a humidity cabinet, should not be classed as superior to one that served for 200 hr. A product that protected for 200 hr should be considered better than one that gave 100 hr of protection, but there is no reason to assume that the protection would be twice as long in actual service.

The hard-drying types of rust preventives are usually tested by exposure of panels to the weather, at an angle of 45 deg, facing south, in the same manner as panels are arranged for the testing of pigmented coatings.

Surface Preparation. Rust preventives should be applied only to surfaces that are thoroughly clean and dry, with the single exception of the application to wet surfaces of a solvent type of product with water-displacing properties.

No one general method of cleaning will condition all surfaces suitably for the application of protective coatings. Rust that has already developed may be removed successfully by the use of steel wool, a wire brush, or even sand blasting or shot blasting. A hot alkaline bath followed by thorough rinsing is also suitable. Chlorinated solvents are satisfactory cleansers, although care must be taken to ensure that no chlorine is liberated in a way that will permit a union with water, thus forming corrosive hydrochloric acid. Where the contamination consists of dirt held in place by oil or grease, the use of petroleum solvents is probably the most efficient cleaning method. Mineral spirits, also called "Stoddard Solvent" or "dry cleaners' fluid", is the most generally used petroleum product, having the advantage of a rate of evaporation higher than that of kerosene without increasing the fire hazard, according to the classification of the Underwriters' Laboratories, Inc. The use of kerosene should be avoided because it promotes corrosion. Care should be taken to keep a petroleum solvent from contact with rubber or other materials that would be affected. The use of a clean solvent is essential.

Fingerprints promote active corrosion. Gloves of canvas or synthetic rubber provide the best protection. However, to wear gloves is not always practicable and, although bare hands do not necessarily deposit fingerprints, the chances are great enough to warrant preventive measures. These deposits are not removed by mineral spirits or other cleaning agents that are used commercially. Conventional rust preventives are also ineffective, but the solvent products, to which agents have been added that neutralize fingerprints, have proved very effective over a considerable period of time. The efficacy of some of these special solvent-type products is improved by the addition of 5 to 10% water. Special products of the solvent type that are able to displace water and to neutralize fingerprints, besides preventing rust, have found wide acceptance in industry.

The removal of moisture or a soluble oil emulsion from a surface before the application of a rust preventive, is often less simple than it appears. Compressed air that has been well filtered and dried is suitable for removal of moisture, but the air from regular shop lines is not suitable. Cloths are sometimes used but it is difficult to keep them clean and dry, and objectionable lint may be left on the dried surface. Ovens are also used, but none of these methods is suitable for the removal of emulsions; furthermore, such methods leave the part unprotected during the period between drying and coating with the final rust preventive. Here again a solvent type of rust preventive with water-displacing qualities has evident advantages.

Methods of Application. Although the supplier of a rust-preventive compound is best qualified to specify the detailed procedure for application, the following general comments may be helpful. After the metal article has been cleaned, a suitable rust-preventive compound should be applied as promptly as possible and in such a manner as to provide a uniform and continuous coating to the surfaces to be protected. Dipping is preferred wherever possible, because it ensures complete coverage; however, spraying is effective, as well as application by brush, swab or roller.

In the application of compounds of the plastic type, the piece being dipped should be immersed long enough to increase the surface temperature nearly to the melting point of the compound. Otherwise a poor bond may be expected. For the same reason care should be taken to prevent too rapid chilling when any compound of the plastic type is applied by brush or swab. In general the plastic type of compounds cannot be sprayed, although equipment is available for applying the softer grades by this method.

As an alternate to heating, the plastic type of products may be cut back with mineral spirits that evaporate after application. Heating is preferred, however, since it affords somewhat better protection and does not require time for the evaporation of the solvent.

Whenever possible, rust preventives of the fluid type should be drained, filtered and reused, with the exception of the internal-combustion engine type, in which—to some extent at least—the acid-neutralizer is consumed in service. Therefore, reuse of compounds for preventing rust must be confined to applications that do not require the neutralizing of acids. The manufacturer of the rust-preventive compound is the authority best qualified to recommend suitable types of mediums for filtering. In many products, however, the rust inhibitors are in true solution and will pass unchanged through most of the chemically inert filtering mediums. When liquid rust preventives are drained, the film remaining on the coated surfaces will provide full protection, although it is often wise to attach a prominent tag calling attention to the need for refilling with the normal lubricant before operation.

It is often unnecessary to disassemble machinery such as turbines, gear cases and cylinders, for the application of a rust-preventive oil to the interior surfaces. Fogging by high-pressure spray through openings can be effective, although this method must be used with discretion if complete coverage is to be obtained.

The first step in the preservation of internal-combustion engines is to allow them to cool to ambient temperature. The crankcase is then drained, flushed, and refilled with the minimum quantity of rust-preventive oil necessary for safe operation of the engine. After this, the engine is operated for a short period at idling speed and with no load. The rust preventive is then injected into the cylinders above the pistons by slowly pouring it into the carburetor air-intake of spark-injection engines. In diesel engines the rust preventive is used as fuel during the last few minutes of the run. After the engine has stopped and cooled, the spark plugs or fuel injectors should be removed and the preservative should be fogged into each cylinder, with the pistons down in all instances if possible. Before the plugs or injectors are replaced, the engine should be turned over for a few revolutions to obtain complete distribution.

The thin-film type and the solvent type of products may be applied by dipping, spraying or brushing.

Precautions. Care must be taken—especially in the use of petroleum-base rust preventives—not to apply these compounds to nonmetallic parts made of rubber, cork, paper, leather, fabric or plastics. Where contact cannot be avoided by shielding or other means, the heaviest of the plastic type of compounds should be used. This very viscous type will have the least detrimental effect, and probably almost none, since it contains only a little oil.

Special precaution is imperative when rust-preventive compounds are applied by spray. All petroleum products, when atomized, endanger health if they are taken into the lungs in any appreciable quantity. Therefore it is recommended that adequate local ventilation be provided when a petroleum-base product is applied by spray. Proper precautions, as established by the National Board of Fire Underwriters, must also be observed in connection with any possible fire hazard.

Methods of Removal. The rust-preventive compounds that are not hard drying may be removed with petroleum solvents. Mineral spirits is preferred, although kerosene and white gasoline are also suitable. Rags or waste may be used when soaked in hot water, but this method is likely to be more laborious. Many of the rust-preventive compounds are lubricants and need not be removed from bearings, gears and such, although all sumps, reservoirs and crankcases should be drained and refilled with the lubricant recommended for regular service.

Ordinarily no attempt is made to remove the hard-drying compounds, but should this become necessary, the use of a standard grade of paint-remover is recommended.

Typical Applications. Rust-preventive compounds may be used to great advantage on three classes of articles in the metal and metalworking industries.

The first class is machinery or equipment kept in stand-by storage without disassembly. Any attempt to prescribe in detail for this classification would be impracticable, but the suitable types of products and methods of application can probably be determined from the general descriptions given above.

The second group of applications includes (*a*) tools such as saws, drills, cutter heads, dies, molds and gages; (*b*) spare parts such as mill rolls, mandrels, gears, armatures, antifriction bearings, heavy machine parts and housing screws; and (*c*) finished parts, devices or machinery in temporary storage. For tools, rust preventives of the solvent type are usually preferred—particularly compounds that are able to displace water and neutralize fingerprints. To a limited extent the same recommendation applies to spare parts, although in general the plastic compounds are preferred for this class of service. Finished parts, in storage between fabrication and assembly, or finished devices between assembly and installation, should be protected by a solvent type of product, provided the storage conditions are not too severe. Otherwise a plastic type of product is recommended—or a compound of the fluid type, if circumstances prevent the proper application of the plastic compound.

The third category of applications for rust prevention covers finished products. For sheets, strip metal, bar stock and the like, protected from the weather, a solvent type of product should be used. Preservatives of this class have also given very satisfactory service on continuous strip mills and on steel wire between drawing and stranding in the manufacture of rope. For products that are exposed to the elements during shipping, the use of hard-drying rust-preventive compounds should be seriously considered. This type of material has been used on pipe to a considerable extent and it could probably be used profitably on shapes, plates, bar stock and rod in order to preserve mill finish during shipment and storage, which often involves exposure to the weather for long periods. Such coatings are durable, transparent, reasonably elastic, resistant to water and wear, and ordinarily less expensive than paint. Rough handling and expansion and contraction of the metal have little effect. There are a few exceptions to this recommendation; for example, on bar stock fed to automatic machines, this type of coating might interfere with chucking. In such instances, a plastic product of the heaviest grade would provide adequate protection, although removal with a petroleum solvent would be necessary before machining.

For products such as steel rod for wire drawing, it is entirely possible that pickling could be eliminated, and consequently both labor and materials could be saved if a hard-drying coating were applied at the mill.

Other examples might be cited, but as a rule the selection of a suitable type of compound, represents a compromise between ease of application, the severity of the storage conditions and ease of removal. Naturally cost is also to be considered, but the difference in cost among various grades is small enough to place this factor in a position of secondary importance. The cost of improper protection is too great. Ease of application or removal deserves consideration but should not be permitted to have too great an influence, because usually the products most difficult to apply or remove furnish the best protection.

Emphasis should be placed on the definite economic advantage to be derived from the use of good rust-preventive compounds. Removal of rust is expensive. Where remachining is required, a change in dimension results, often necessitating even more expensive machine work on the companion member. Rusty spare parts have caused the loss of valuable machine hours and have even held up plant operation.

NONFERROUS METALS

Prepared under the direction of the

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OF THE INSTITUTE OF METALS DIVISION,
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AS IN PREVIOUS EDITIONS OF THE METALS HANDBOOK, the Nonferrous Section has been prepared under the direction of the Nonferrous Data Sheet Committee of the Institute of Metals Division, American Institute of Mining and Metallurgical Engineers, through a co-operative arrangement with the American Society for Metals.

After the general plans for this edition were complete, the committee appointed eight chairmen to organize the sections concerning the principal nonferrous metals. In collaboration with these chairmen, many specialists in the nonferrous metals industries have written the articles and compiled the data sheets. Throughout the Nonferrous Section, 217 authors and committee members are named as contributors. Many other metallurgists and engineers have aided directly but anonymously. For instance, more than one-third of the data sheets about specific alloys are credited to the laboratories where the information was assembled, rather than to the numerous individuals who joined in each compilation.

In preparing this edition, the committees and the authors have made two principal changes in the scope and form of the subject matter.

For the first time, discussions of melting, shaping and treating are a prominent part of the Nonferrous Section. Such articles have been given three times as much space as before, and five times as many authors have contributed.

Nearly all the specific data for nonferrous metals and alloys have been presented according to a new, semitabular arrangement. This data sheet form has been used so that the reader can easily find information of the same kind for various alloys by following key numbers, which are the same throughout the Nonferrous Section. This method of presenting the data has also the advantage of being more concise than running text; data for 220 nonferrous alloys are presented on 142 pages.

A few classes of material are described in groups rather than as individual alloys — for example, electrical-contact materials, low-melting alloys, type metals, and silver brazing alloys. Bearing materials are discussed in an article and also, more briefly, in data sheets in the sections that deal with properties of aluminum, copper, lead, and tin alloys.

It has been impossible to include data for all the nonferrous alloys used in industry. In the judgment of the committees, the alloys discussed are the most widely used, or are representative of the important classes of material.

A guide to the use of the data sheets and a list of the key numbers are printed on the inside of the back cover.

TAYLOR LYMAN
Editor, Metals Handbook

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Hot Plastic Working of Nonferrous Metals

BY C. H. MATHEWSON*

HOT WORKING is usually defined as working above the recrystallization temperature, so as to ensure recrystallization and recovery or retention of normal properties in spite of the plastic deformation.

A satisfactory scientific foundation for hot working operations would require complete information concerning: (1) stress-strain curves at temperatures throughout the potential hot working range, and with a rate of application of stress comparable with that desired in the intended hot working operation; (2) from such curves, an evaluation of the energy requirements for economical operation, and of the toughness or ability of the metal to withstand the process (thus, the temperature selected for hot working should be one at which there will be no great increase in the yield strength of the metal during working; that is, the metal should have a flat stress-strain curve and there should be adequate elongation before fracture); (3) the effect of prior structural condition of the alloy and in particular of natural impurities; (4) the requirement of special properties in the metal imposed by the special mechanical characteristics of any given process, such as drawing, extrusion, forging, rolling, swaging. Thus, in drawing, the metal must have strength to support plastic alteration while being pulled through the die; however, in swaging, the metal is supported during deformation and may be worked at its minimum plasticity and strength.

The literature of metal technology contains no systematic or satisfactory accumulation of data on these points, or development of other criteria for judging the hot working quality of metal. The performance of a metal in such operations is usually estimated in an approximate, provisional manner by reference to the softening temperature of the metal after cold work, with an increment allowed for the higher temperature necessary to permit virtually instantaneous softening in a rapid deformational process. Data concerning ordinary static tensile strength and ductility at elevated temperatures are now available[1-7] for many of the ordinary commercial alloys, and are of certain value in indicating proper working temperatures. The details of performance are then settled by trial and error. Similarly, the effect of impurities and the requirements of special processes must be established by a suitable empirical testing procedure. Generally, a high value of reduction of area in the tension test at high temperature, accompanied by moderate tensile strength, is considered to be especially indicative of useful plasticity. For example, in the tests reported by Price,[5] the percentage reduction of area of copper exceeds 90 in the temperature range from 930 to 1830 F, with tensile strength decreasing gradually from about 9000 to about 1200 psi. In Table I, 1550 F is given as the optimum hot rolling temperature for copper to maintain softness, but the metal may be hot rolled satisfactorily at all temperatures between 930 and 1830 F, though with some difficulty at the highest temperatures because of the extremely low strength of copper in this region.

Rather definite statements may be made concerning the adaptability of alloys to the various hot working operations. Much information of this character can be found in the articles on metal technology in this Handbook.

For rapid deformations, as in stamping or forging, useful information may be derived from a drop hammer test in which the decrease in height of a cylindrical sample is plotted against the energy of the blow. Commonly, various approximations are accepted, such as compression for a given blow plotted against temperature, or composition,[8, 9, 10] from which suitable temperatures or compositions may be selected when attention is also directed to the manner in which the specimen stood the plastic alteration; for example, whether cracking occurred at the edges.

When the constitution of an alloy changes with temperature, impact tests on notched bars may show with particular clarity the existence of favorable and unfavorable ranges of toughness. Thus the width of the brittle range in brass in the vicinity of 900 F and the effects of zinc, lead and tin are brought into prominence by the Izod test.[11, 12] There are good indications of this weakness in the ordinary tension test for elongation or reduction of area.[4] However, there is probably no test revealing hot shortness, or far-reaching plasticity and toughness, that can be used as more than a general guide for directing experimentation with the particular equipment in which the given alloy must be deformed.

The empiricism necessary in this work is well stated by Morris.[10] "For instance we wish to extrude a metal *M*. We know that we can extrude another metal *Q* at temperature *T*. We make a drop hammer test of metals *M* and *Q* and find that in order to obtain the same reduction in height as we find in metal *Q* at temperature *T*, we must heat metal *M* to temperature *T'*. *T'* is therefore the temperature at which we first try to extrude the metal *M*, with fair assurance that we shall be able at least to force the metal through the die. Much the same kind of reasoning can be applied to hot rolling. The tendency to crack in extrusion and rolling, however, must be ascertained largely through experience."

Concerning the effect of impurities, embrittlement resulting from segregation of a weak constituent in grain boundaries (for example, lead in alpha brass) and the

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great increase in resistance to deformation generally produced by solid solution even of small amounts of alloying elements (principally responsible for the contrast in properties between commercial and extremely pure metals) have been studied more in relation to cold working than to hot working but have brought certain well recognized limitations into commercial practice. For example, several hundredths of a per cent of lead prevents the commercial hot working of alpha brass, but with Muntz metal (probably because of more favorable distribution attending the structural adjustment of alpha and beta with temperature in the hot working range)[9] lead in considerable quantity does not prevent the majority of hot working processes. Similarly, tin bronzes that contain the $\alpha + \delta$ eutectoid, show marked brittleness in the Izod test and cannot be hot worked successfully, while bronzes that contain tin in solid solution can be hot worked satisfactorily.[11]

Annealing or recrystallization temperatures, as ordinarily determined, do not properly define the softening points of metal while in a process of rapid deformation. The effect of temperature and rate of loading on hardening is particularly marked in this region of temperature, as may be seen from Fig. 1. The solid curves indicate strengthening in single crystals of cadmium under a load applied at the rate of 140 psi per min, and the dotted curves indicate strengthening under a load applied at a rate 100 times greater. Thus it appears that in a region of low temperature where there is virtually no spontaneous recovery towards initial properties, and in a region of high temperature where the recovery is substantially complete during the test, changing the temperature or the

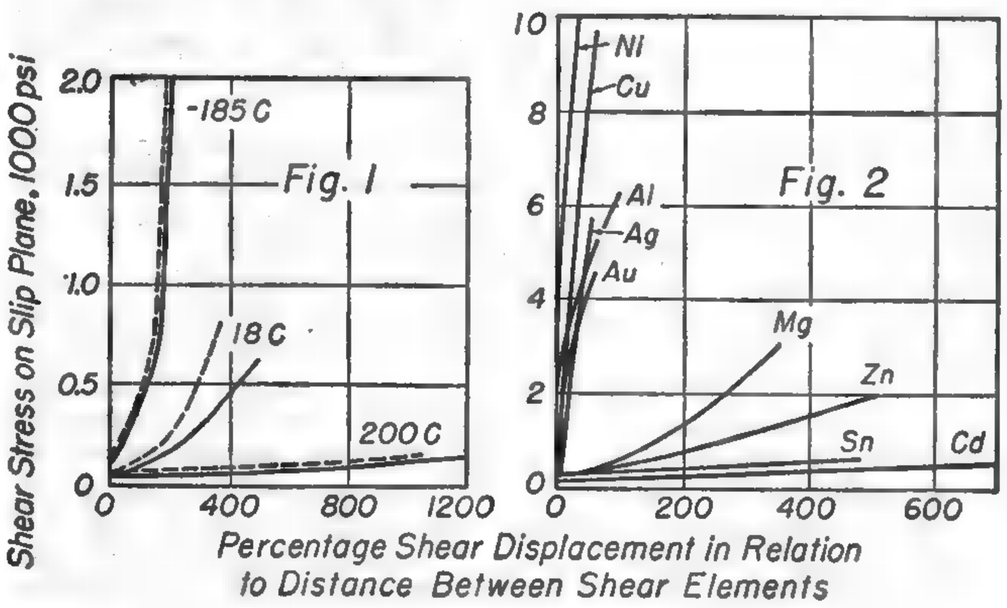

Fig. 1 Shear strengthening of single crystals of cadmium (Schmid and Boas[13])
Fig. 2 Shear strengthening curves of metal crystals (Schmid and Boas[14])

rate of loading has little effect on the strain hardening. In an intermediate region of temperature, which undoubtedly corresponds to the temperature at which ordinary softening and recrystallization begin in severely strain hardened polycrystalline material, much or little recovery may occur, depending on the rate of loading; and the final strain hardening of the metal varies according to these conditions. In the present example, after a shear of 400% at the higher rate, the crystal has a resistance of about 850 psi to further shear, and after the same amount of shear at the slower rate, a resistance of about 425 psi.

Curves of resolved stress versus shearing deformation for loading at room temperature have been obtained for the majority of common metals, as shown in Fig. 2. Since the slope of such curves is governed by the amount of recovery during the test, it appears that the tendency of the metals to recover from the effects of strain hardening during deformation at ordinary temperature, decreases in the following order: (1) cadmium, tin, (2) zinc, (3) magnesium, (4) gold, aluminum, silver, (5) copper, (6) nickel. Recovery in these single crystals does not signify recrystallization, which, however, may be expected to accompany the recovery process at high (hot working) temperatures when, with increasing deformation, crumpling or nonuniform distortion of the crystal becomes too severe to permit a reversion to the unstrained condition without complete reorganization of the grain structure. This condition is attained rapidly in polycrystalline material, which recrystallizes even after a small amount of deformation. Such inequalities of deformation exert only a secondary influence on the amount of strain hardening, and at a temperature of full recovery the occurrence of recrystallization does not appear to add greatly to the softness attainable in the simple recovery process. It is evident that the metals of Fig. 2 exhibit a decreasing tendency to soften or recrystallize after cold work in the order stated; that cadmium and tin would recrystallize at ordinary temperature, zinc and magnesium at not greatly elevated temperatures, and the others at successively higher temperatures. The effective temperature of hot working would also increase in this order but in a commercial operation would have to be determined by trial.

Table I gives temperatures of recrystallization after severe cold deformation, and favorable hot rolling temperatures of the commercially pure nonferrous metals.

Table I. Softening and Hot Rolling Temperatures of Nonferrous Metals

Metal	Effective Softening Temp, deg Fahr, After Severe Cold Deformation[a]	Best Approx Hot Rolling Temperature, deg Fahr (for Softness) [b]
Lead	Approx room temp	Somewhat above room temp
Tin	Approx room temp	Somewhat above room temp
Zinc	200[15]	350
Magnesium	200 +[c]	650[16]
Aluminum	525[17]	950[18]
Copper	700[19]	1550[19]
Nickel	1400 max[21]	2200[20]

(a) Approximate complete softening after one hour
(b) This means in general the highest temperature for satisfactory operation. Special requirements of mechanical properties are met by rolling at lower temperatures.
(c) Private communication from J. D. Hanawalt

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Slush Casting

By G. L. Werley* and G. O. Hiers*

OF ALL the metal casting processes in general commercial use, slush casting is probably the least known. The process has little competition from other methods of fabrication and its field is a restricted one, limited to the production of hollow castings. Also, only zinc-base or lead-base alloys are commonly used for casting by this process. Of the two types, the zinc alloy castings greatly predominate in tonnage.

Slush casting is the name given to that process in which molten metal is poured into a split mold (generally made of bronze) until the mold is filled; then, almost immediately, the mold is inverted and the metal that is still liquid is allowed to run out. The time required for this casting operation is sufficient to freeze a metal shell in the mold, corresponding to the shape of the cavity wall. The thickness of the wall of the casting depends on the time interval between the filling and the inverting of the mold, as well as on the chemical and physical properties of the alloy and the temperature and composition of the mold. However, skilled operators regularly produce good castings with remarkable uniformity in weight.

Zinc Alloys. The zinc alloys used for slush casting are of two classes: the aluminum-zinc type and the aluminum-copper-zinc type. The aluminum-zinc alloy usually has a nominal composition of 5.5% Al with the remainder Special High Grade zinc. Because this alloy is readily slush cast, producing very thin walls, its use is popular from the standpoint of initial cost. However, unless the impurity limits are rigidly controlled, castings made from this alloy are susceptible to subsurface network corrosion and premature failure by warping and cracking. Small variations in the aluminum content are not critical, except that they slightly affect the slushing characteristics of the alloy and consequently prevent the production of thin-walled castings. However, with the eutectic composition of 5.0% Al, it is almost impossible to produce slush castings, since one of the requirements of a slush casting alloy is that it must not have a single solidification point but must have instead an appreciable slushy range between the liquidus and solidus temperatures.

The second class of zinc alloys has a nominal composition of 4.75% Al and 0.25% Cu with the remainder Special High Grade zinc. Alloys of this class produce castings with improved mechanical properties and also with longer service life resulting from the protective effect of the copper addition. Slush casting this type of alloy is more difficult and produces castings with thicker wall sections. Therefore, the initial cost of the castings is generally greater than that for like castings made from the copper-free alloy. It is important to keep the composition of the Zn-Al-Cu alloy under close control since increases in the aluminum content above 4.75% approach the eutectic composition, which is not desired. Decreases in the aluminum content tend to make the alloy too sluggish for slush casting. The copper addition must be sufficient to afford the degree of durability desired but should not exceed an amount that would affect production seriously by causing excessive weight in the castings.

Lead Alloys. The lead alloy used for slush casting is close to the antimony-lead eutectic alloy in composition. Other elements are added to improve both the casting qualities and the grain refinement. A typical composition is 13.0% Sb, 1.0% Sn, 0.5% As, 0.1% Cu, and the remainder lead. The excellent resistance to corrosion of this alloy does not depend on the exact composition of the alloy. However, it is necessary to maintain rigid control of the composition, avoiding impurities which, even in small quantities, impair casting quality.

Finishing. Slush castings can be electroplated or finished with lacquers or baking enamels. However, baking temperatures should not exceed 300 F for the lead alloy nor 375 F for the zinc alloys.

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Secondary Metals

By W. Bonsack* and D. L. Colwell*

THE DISTINCTION between "primary" and "secondary" metals and alloys is usually rather artificial, and therefore not entirely logical. The term "primary" should apply to metals derived directly from ores, and "secondary" to metals and alloys made from scrap and residues. However, there are so many combinations of these types of metals that no line can divide them sharply. Furthermore, in the production of many metals no distinction is made as to the source.

Common nonferrous alloys of copper, lead, tin, nickel, zinc, aluminum and magnesium are regularly produced from scrap and residues, diluted with pure metals when necessary. Many of these metals are called secondary and many are not, according to the principal product of the producers. Other rarer nonferrous metals, such as gold, silver, platinum, mercury and their alloys, are also produced from scrap and residues, but no distinction is made between these and their counterparts produced from ore. The recovery of many ferrous alloys from scrap iron and steel is a necessity, and the whole ferrous industry uses iron and steel scrap as a principal component, yet the term "secondary" is not applied to these metals.

It is possible to separate many nonferrous metals from their alloying constituents and to produce a metal as pure as was originally produced from the ores. Often it is feasible and economical to do so, but frequently also, the costs of such separation would be prohibitive. Copper, for instance, may be separated from zinc, tin, iron and other alloying elements by fire refining and it may be further purified electrolytically so as to produce copper of high purity. In some instances, where the contamination is severe, fire refining is employed and the fire-refined copper is ordinarily used without further electrolytic purification. On the other hand, pure aluminum may be produced from badly contaminated scrap by dissolving the scrap in caustic soda, with chemical elimination of the contaminating alloying elements, and final precipitation of alumina and reduction to pure aluminum. This practice was general in Japan when the supply of bauxite was shut off by the submarine blockade, but such a procedure is decidedly uneconomical. The customary practice in the use of scrap metals is to make use of the base metal and its alloying ingredients by the careful segregation of the scrap and the subsequent production of alloys adjusted to the compositions of the scrap involved. The resulting alloys are commonly termed "secondary".

Because of the difficulty of perfect segregation of scrap, secondary alloys often contain more alloying elements than their primary counterparts. These elements may be harmful, beneficial, or neutral. If harmful, they must be either removed or diluted. When it is feasible, such elements are removed; when removal is impractical, dilution is used as the only means of reduction. In most instances these incidental alloying elements are beneficial and re-

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moval is not necessary. The antimony and tin in lead alloys, the zinc and tin in copper alloys, and the copper and silicon in aluminum alloys, are almost always beneficial in the production of the new alloy. Even when the alloying element is neutral, an ingot of improved characteristics often results from the use of prealloyed scrap, because better alloying is possible and dangers of segregation are lessened with each mixing and remelting. If a certain set of properties is required from a metal and these properties can be obtained only by the alloying of several other metals with the base metal, it is usually immaterial whether the alloying elements are already present in the base metal or whether they have to be added freshly; in fact, it is often helpful to have them already present. If two alloys are identical in composition, the properties of the alloys will be identical, unless their fabrication has introduced other variables.

Secondary metals and alloys have often been considered inferior because of their higher content of oxide. This may be true; however, some secondary metals are superior because of their lower oxide content. The amount of oxide present depends on the treatment the metals have received, and does not depend exclusively on the source of the metal. Many primary metals are refined from oxide ores or concentrates, and many secondary metals have become oxidized excessively during previous use or treatment. This oxide content may or may not be removed in the production of the ingot. Refining, fluxing and cleaning methods used in ingot production should be such that the oxide content is not excessive either in primary or in secondary ingot.

Price differentials between primary and secondary metals fluctuate with supply and demand. When the supply of secondary metal is plentiful and the demand low, the difference becomes substantial, making it more economical to use secondary metals wherever possible. When demand is high, the price difference decreases, and under unusual circumstances a few of the secondary metals have commanded temporarily higher prices. In 1941 pure secondary aluminum brought a higher price than pure primary aluminum, and even the common No. 12 aluminum alloy sold for the same price as pure primary aluminum.

For metals that are not plentiful or for which the price margin between primary and secondary is narrow or nonexistent, the distinction between primary and secondary is lost. There is good justification, therefore, for considering that the distinction between primary and secondary is commercial and not necessarily metallurgical.

In general, the reclamation of metal from scrap and residues varies, depending on the base metal concerned. Following are comments on the principal nonferrous metals commonly used in secondary form.

Aluminum. When aluminum and aluminum alloys are recovered, their compositions are usually the same as they were originally and, wherever possible, they are used again as such. The tremendous expansion of the aluminum-producing industry during the war, coupled with the severe shortage of aluminum while this expansion was being developed, necessitated an urgent program of segregation of alloy scrap in aluminum fabricating plants. Quantities of this scrap were remelted into secondary pig of the wrought alloy composition and were rolled or extruded directly into the wrought forms, either with or without further additions of pure aluminum. Many consumers of such "primary ingot" never recognized the fact that their supplies were actually largely secondary.

Where aluminum scrap has been less carefully segregated or where accidental mixing of alloys has occurred, the scrap is remelted and the composition of alloying metals is adjusted for the production of the kind of ingot used in aluminum castings. Such ingot is commonly used for the production of aluminum castings, either by sand-casting, permanent mold or die-casting processes. During the war certain alloys were developed for the production of castings in order to make best use of the high-grade scrap that accumulated constantly in the aircraft industry. Prominent examples are the die-casting alloys SC2, SC5, SC6 and SC7, and the sand-casting and permanent mold casting alloys SC8, SC42 and SC21 of the American Society for Testing Materials.[3] The careful wartime control of aluminum scrap made this ingot even more desirable than before the war, because alloying elements and impurities could be more carefully regulated.[4]

Aluminum is different from other nonferrous metals in being suited for large destructive uses in which the presence of impurities is not particularly harmful. Aluminum is used in the deoxidation of steel in amounts which, though small for the steel industry, are large for the aluminum industry. It is also used for the production of aluminum salts such as anhydrous aluminum chloride, and for the production of ferro-alloys by the thermit process. The one impurity most troublesome in the fabrication of both wrought and cast aluminum products is iron, and this impurity is entirely neutral when the aluminum containing iron is used in ferrous alloys. All these applications permanently destroy the aluminum for further metallurgical use, and it is by these destructive uses that the badly contaminated grades of scrap are consumed.

Some indication of the increase in quantity of secondary aluminum produced is given in Table I for the years 1942, 1943 and 1944. Particularly noteworthy is the increase in the amount of such aluminum used in wrought products shown in the same table.

Table I. Aluminum Recovered from Scrap and Residues, 1942, 1943 and 1944[5]
(In short tons)

	1942	1943	1944
Secondary aluminum ingot.....	144,694	196,373	214,879
Aluminum in wrought products.....	53,080	121,827	116,582

Copper. Copper is used largely as a conductor for electricity. Its conductivity is very sensitive to small amounts of alloying elements; consequently, secondary copper is seldom used for this purpose. The brass industry also consumes large quantities of copper, and here again, particularly during the war when most brass was cartridge brass, only primary copper was used.

Scrap copper wire and scrap wrought brass are excellent base materials for the production of copper alloy ingot for castings, and most of the cast brass and bronze products used in this country are produced from such so-called "composition ingot". This ingot is made by the blending of the proper grades of brass and bronze scrap so as to secure the required amounts of zinc, tin and lead in the resulting alloy.

In certain instances where copper alloy scrap contains too many alloying elements for the most economical use, the common procedure is to smelt the scrap in a blast furnace, recovering the copper and nickel and burning off the tin, lead, iron and zinc. These alloying elements may or may not be recovered in a baghouse as dust or as oxides. Such fire-refined copper is suitable for use in many brasses and bronzes, and if desired, may be further electrolyzed to produce copper indistinguishable from that electrolyzed from ores.

One of the important measures for conserving copper during the war was the "down-grading" urged by the War Production Board in order to promote the use of secondary alloys. A complete chart was issued showing which alloys it was possible to use as alternates for alloys containing high proportions of primary copper and tin. It was found that many parts normally made from copper-tin alloys of high purity (such as Navy G, 10% Sn) could be produced satisfactorily from other alloys made from ingot with a higher proportion of scrap. The down-grading was from Navy G to Navy M to ounce metal (85-5-5-5) to valve metal (81-3-7-9) to manganese bronze to leaded manganese bronze. Each step used a higher proportion of copper-base alloy recovered from scrap, and not only was copper conserved, but experience indicated that in one instance after another the "lower" alloy was as serviceable as the alloy formerly used and was more economical as well. The criterion of substitution was the minimum permissible copper content compatible with the service requirements of the final product. Secondary copper filled many needs for bronze or brass where it had been believed formerly that virgin material was essential.

The recoverable copper content of copper-base scrap

consumed in 1941 is indicated in Fig. 1.[2] In 1944 the production of primary copper was 1,250,000 tons, and an additional 950,000 tons of copper was recovered in brasses and bronzes and used as such and almost 100,000 tons of pure copper recovered as copper. This proportion is abnormally high because of the huge amount of cartridge brass produced in 1944, but it illustrates the important role played by secondary copper.[1]

Lead. Lead is often considered indestructible, and its recovery from storage batteries, solders, type metals and cable coverings, supplies a large proportion of the lead used in producing more of those same products. The antimony content of such products is also recovered and often the antimonial lead so produced is superior to that made from primary lead and antimony, because alloying is better.

Methods of recovery of the lead from storage batteries, solders, type metals and cable coverings is similar to that used for the recovery of tin. The metals are sorted and melted with proper fluxing and cleaning, and composition is adjusted to meet the requirements. The use of antimonial lead in storage batteries is the largest single application for lead and a considerable part of such antimonial lead is secured from secondary sources.

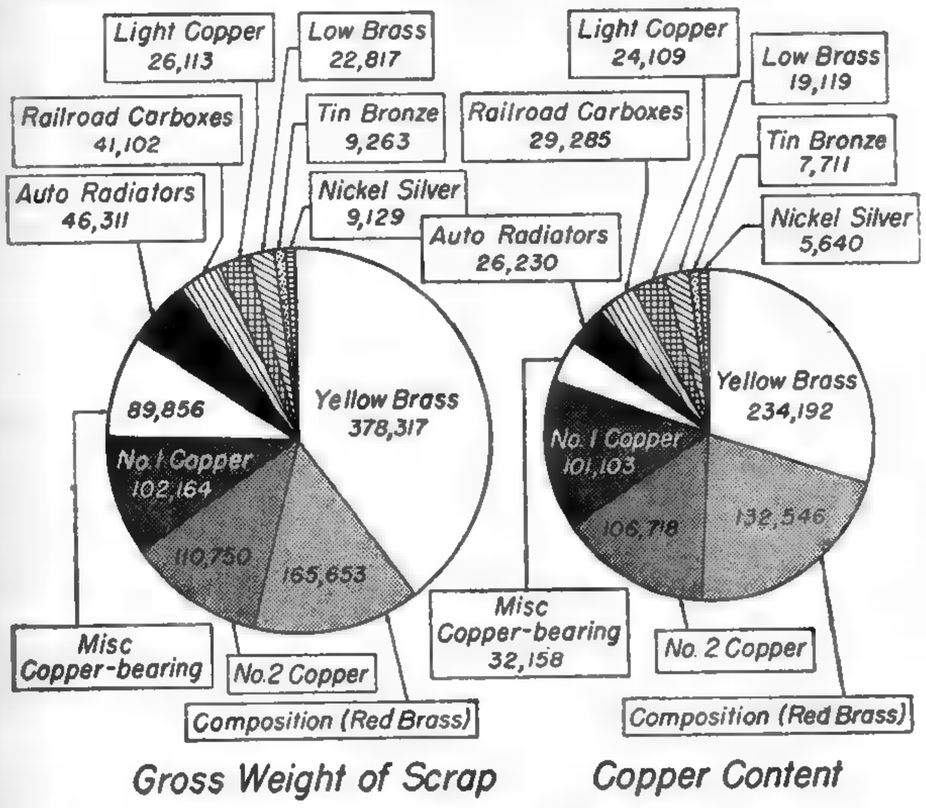

Fig. 1 Recoverable copper content of copper-base scrap consumed in 1941, in tons of 2000 lb (Wright[2])

The lead content recoverable from lead-base scrap in 1941 is illustrated in Fig. 2.[2] During the last ten years secondary lead has been used at the rate of about 300,000 short tons annually.[1] The annual production of primary lead and antimonial lead was only about 450,000 short tons during the same period.

Magnesium. The magnesium industry is comparatively new; consequently the recovery of magnesium scrap has not settled into a definite pattern. More magnesium is used in the cast form than in wrought products, so scrapped magnesium castings may be reclaimed easily for casting alloys. Wrought forms of magnesium may also be reclaimed for casting alloys, but the amounts of wrought scrap available are comparatively insignificant. The reclaiming of magnesium from the more finely divided forms, such as borings, turnings, grindings and drosses, is more difficult than with other nonferrous metals because of the combustibility of such finely divided forms. If the scrap is not too fine it may be used in the production of casting ingot, just as are scrap castings of magnesium. In some instances fine scrap may be used for the addition of small amounts of magnesium to alloys of other metals, as in introducing magnesium into aluminum alloys, or such scrap may be diverted to chemical uses.

The consumption of various forms of scrap magnesium in 1944 was, as follows:[5]

Cast scrap	1,706 short tons
Solid wrought scrap	129 short tons
Borings, grindings, drosses, other	15,179 short tons

It is significant that, of this quantity, 13,370 tons was put into magnesium alloy ingot of various compositions and only 541 tons into chemicals.

Nickel. Nickel used as sheet and in anodes for electroplating can easily be recovered for nickel additions to either ferrous or nonferrous alloys.

Nickel is also a major ingredient of monel metal, nickel silver and certain nickel brasses. From such alloys it is usually recovered with the copper, either by fire refining or by melting and adjusting the composition. The nickel content of such a product is a prime consideration in the production of composition ingot from copper alloys, because nickel is more expensive than any of the common nonferrous metals, with the exception of tin.

Although the world production of nickel for 1944 was 179,000 short tons,[5] only 4321 tons of secondary nickel was recovered in this country in 1944.[5] Of this quantity, the major portion (2994 tons) was in nickel-base and copper-base alloys, and only 410 tons in chemicals.

Tin. Tin is one of the least plentiful of the common nonferrous metals and that used in the United States is almost all imported. Tin is also the highest priced of the common metals, and consequently it has been recovered eagerly and reused wherever possible.

The chief applications for tin are in tin plate, solder, bronze and babbitt, in that order, although this normal relationship was disturbed during World War II. Methods of recovery vary with the product. The detinning of tin plate is not normally economical, although during the war a considerable quantity of pure tin was recovered by this process. The reduction in the quantity of tin used in tin plate made detinning a more and more expensive process per pound of tin recovered, and the practice probably will not continue to a great extent when pure tin becomes available again.

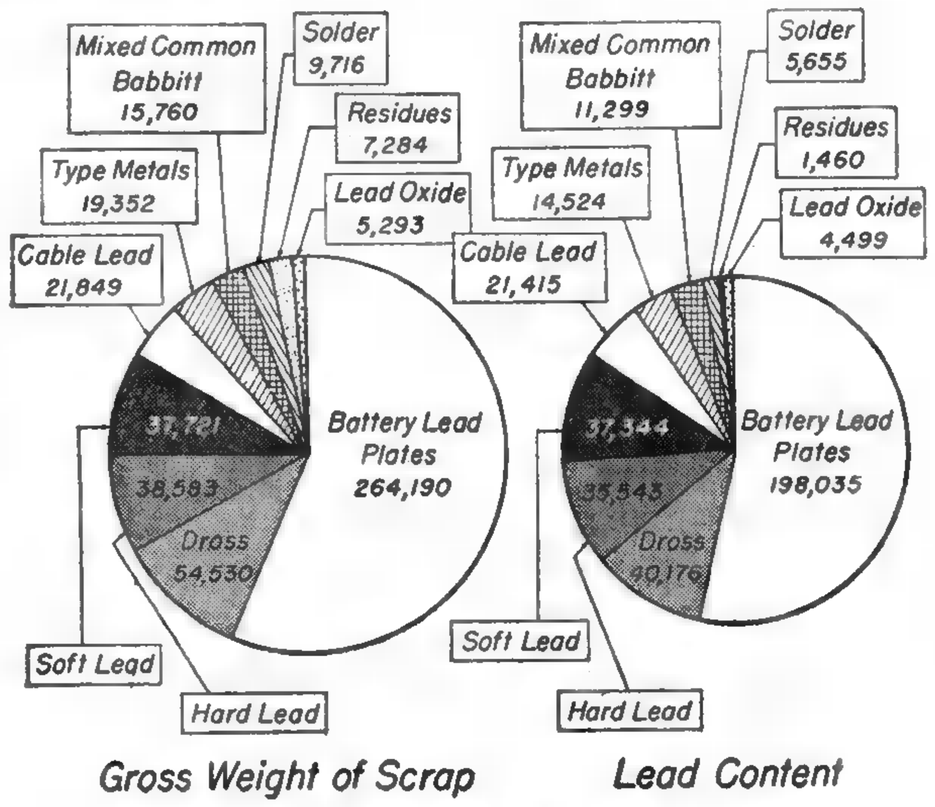

Fig. 2 Recoverable lead content of lead-base scrap consumed in 1941, in tons of 2000 lb (Wright[2])

Solders, babbitt metals and collapsible tubes often contain very high percentages of tin. It is a simple matter to sort these roughly according to tin content, and then to remelt them with proper cleaning and fluxing. The resulting product contains varying quantities of lead and antimony, and is usually free from other metals. It is therefore an excellent base for the production of lead-tin solders or bearing metals that contain lead as well as tin. Collapsible tubes and other pure tin products, such as tin pipe, are an excellent and normal source of tin for solders and bearing metals. During the war there was an extensive drive to collect all such tin-bearing scrap; consequently very little primary tin was used for solders and bearing metals.

Bronzes and many brasses require tin, and quantities of scrap bronzes and brasses are diverted to the production of the necessary tin-bearing copper alloys, because tin is the most expensive common metal normally used in brasses and bronzes. Many of the reclamation processes of these

copper-base alloys are built around the maximum use of the tin content.

The consumption of primary tin in the United States is normally from 40,000 to 100,000 long tons annually. During the war years the tin recovery in this country, as reported by the Bureau of Mines,[1] amounted to about 30,000 long tons annually; in time of peace about half this amount of secondary tin is normally produced.

Zinc. The two largest uses for zinc are in galvanizing and in brassmaking. The zinc used in galvanizing is sacrificially consumed in the protection of the iron and steel, since these are more susceptible to corrosion. Therefore no great amount of zinc is recovered from galvanized ware. The zinc used in brassmaking is normally recovered in the secondary brasses and bronzes, as described under Copper above. The relatively small portion of the domestic production of zinc that is used as pure zinc, appears mainly in the form of sheet. Much of this can be and is recovered from clippings, discarded dry cells and such, and is used in making zinc additions to brasses and bronzes.

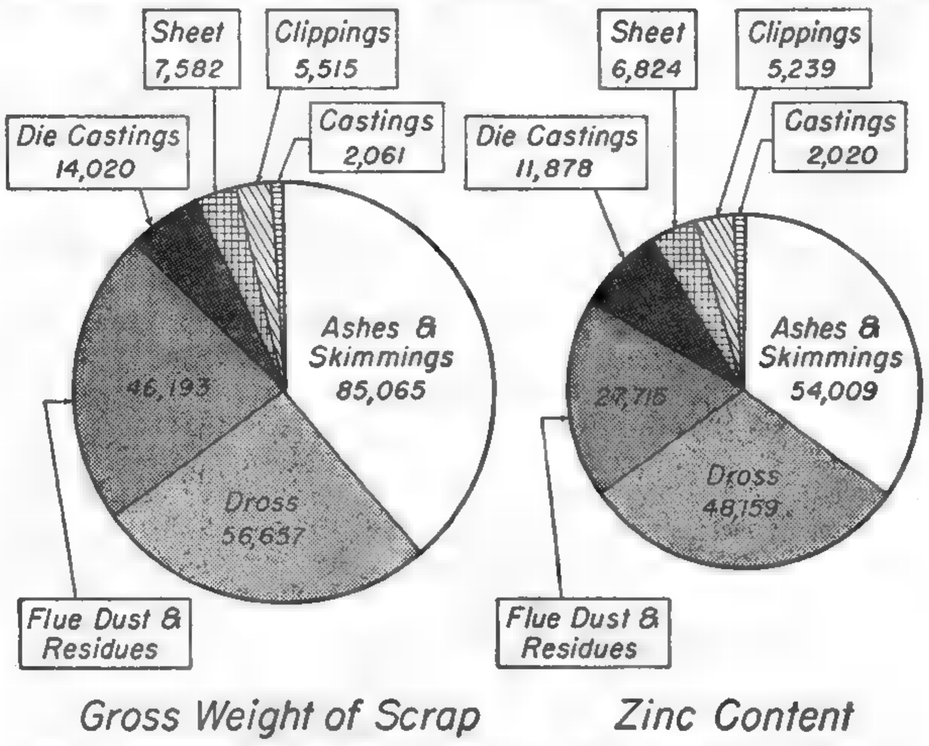

Fig. 3 Recoverable zinc content of zinc-base scrap and residues consumed in 1941, in tons of 2000 lb (Wright[2])

The only zinc-base alloys commonly employed in considerable quantities are those used for die castings and slush castings. Such alloys contain from 90 to 96% Zn with aluminum, magnesium and sometimes copper, and are extremely sensitive to minute amounts of tin and lead when present as impurities. Consequently, only special zinc of high purity is used in their manufacture. Scrap die castings are considered unsuitable for the production of zinc casting alloys of high quality. Instead such scrap is ordinarily used to produce zinc dust or oxide, or to provide the zinc content of other alloys. The zinc that is recovered and used as zinc is principally that redistilled from ashes, drosses, skimmings, baghouse dust and other residues. Although appreciable, the amounts thus recovered do not constitute a large proportion of the domestic consumption of zinc. The recoverable zinc content of zinc-base scrap and residues in 1941 is indicated in Fig. 3.[2]

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Low-Melting Alloys

By Walter C. Smith*

THE TERM "low-melting metal" is sometimes used to describe type metals, lead-tin solders and lead-antimony alloys, but generally the term is applied to alloys that melt at temperatures below 450 F (233 C). The low-melting or fusible alloys are the binary, ternary, quaternary and quinary mixtures of bismuth, lead, tin, cadmium and indium or other metals.

Melting Temperatures. The melting temperatures of the several component metals of the fusible alloys are listed in Table I.

Table I. Melting Temperatures of Component Metals of Fusible Alloys

Metal	Melting Temperature, deg Fahr	Melting Temperature, deg Cent
Lead	621	327
Cadmium	610	321
Bismuth	520	271
Tin	449	232
Indium	313.5	156.4

The eutectic alloys that are produced from these metals and that are of interest as low-melting alloys, are shown in Table II.*

In addition to the eutectic alloys, hundreds of noneutectic alloys have been made and their freezing ranges have been determined. Many noneutectic alloys have been used under conditions where the eutectic alloys are not suitable. All the noneutectic alloys melt over a range of temperature, rather than at constant temperature. The "let go" temperatures vary with the methods of testing, the shape and mass of the alloys, the location in the apparatus, the loading applied to the alloys, the rates of heat input, and other factors. The low-melting alloys are usually rated according to their "yield" temperature, as determined under test conditions established by the Compressed Gas Manufacturers Association, New York, December 17, 1936.

Table II. Compositions and Melting Temperatures of Eutectic Fusible Alloys

Melting Temperature, deg Fahr	Melting Temperature, deg Cent	Composition, percentage Bi	Pb	Sn	Cd	Other
478	248	....	82.50	....	17.50	....
430	221	....	....	96.50	....	3.50 Ag
390	199	....	....	91.00	....	9.00 Zn
362	183	....	38.14	61.86	....	....
350	176	....	....	67.75	32.25	....
291	144	60.00	....	....	40.00	....
288	143	....	30.60	51.20	18.20	....
281	138.5	57.00	....	43.00	....	....
266	130	56.00	....	40.00	....	4.00 Zn
255	124	55.50	44.50	....	....	....
216.5	102.5	53.90	....	25.90	20.20	....
203	95	52.00	32.00	16.00	....	....
196.7	91.5	51.65	40.20	....	8.15	....
174	78.8	57.50	....	17.30	....	25.20 In
158	70.0	50.00	26.70	13.30	10.00	....
136	58.0	49.40	18.00	11.60	....	21.00 In
117	46.7	44.70	22.60	8.30	5.30	19.10 In

Table III includes compositions and both melting and yield temperatures for a few of the noneutectic alloys that are being used currently.

Physical and Mechanical Properties. In general the low-melting alloys that contain less than about 48% Bi shrink

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* In technical and trade publications, the low-melting alloys have been designated by a variety of names. This practice has resulted in many confusing and contradictory statements. For example, a review of the literature will disclose at least eight different alloys designated "Wood's Alloy" and four designated "Anatomical Metal". One alloy of bismuth, lead and tin can be found under three different names. The names of alloys are omitted purposely from the present article, in order to avoid further confusion.

during solidification; those containing 48 to 55% Bi exhibit little change of volume; and those containing more than 55% Bi expand during solidification. Bismuth alloys that contain 33 to 66% Pb, even when moderate amounts of other metals are present, usually exhibit growth after solidification and during aging. Many of the low-melting alloys follow the laws of thermal contraction during cooling from solidification temperature to room temperature. Some show shrinkage for the first few minutes after solidification, and then start growing rapidly; other low-melting alloys shrink during cooling to room temperature

Table III. Compositions, Yield Temperatures and Freezing Ranges of Some Noneutectic Fusible Alloys

Temperature, deg Cent		Composition, percentage				
Yield	Freezing Range	Bi	Pb	Sn	Cd	Others
159	175 to 145.....	12.60	47.50	39.90	....	....
154	163 to 143.....	14.00	43.00	43.00	....	....
145	173 to 130.....	20.00	50.00	30.00	....	....
142	152 to 120.....	21.00	42.00	37.00	....	....
135	139 to 132.....	5.00	32.00	45.00	18.00	....
127	130 to 124.....	56.20	2.00	40.70	0.70	0.40 In
116	227 to 103.....	48.00	28.50	14.50	....	9.00 Sb
111	143 to 95.....	33.33	33.34	33.33	....	....
100	114 to 95.....	59.40	14.80	25.80	....	....
96	104 to 95.....	56.00	22.00	22.00	....	....
89.0	92 to 83.....	52.00	31.70	15.30	1.00	....
72.5	90 to 70.....	42.50	37.70	11.30	8.50	....

and the growth does not begin for 30 min to 3 hr after the alloy has reached room temperature; still others exhibit no shrinkage and grow rapidly while still warm. Approximately 90% of the growth occurs during the first 12 to 24 hr after casting, but some low-melting alloys continue to grow at reduced rates for 500 to 1000 hr after casting. Rapid cooling or quenching of the alloys that exhibit growth, ordinarily increases the rates of growth, but does not affect final growth values. The total growth varies from 0.0001 to as much as 0.007 in. per in. and is governed by the composition of the alloys. The fusible alloys range in hardness from about 5 to as high as 22 Bhn. The tensile strength ranges from 3000 to 13,000 psi and the elongation from 0 to 300%, depending on the composition of the alloy. All the fusible alloys creep at room temperature under relatively light continuous loads.

Uses of Low-Melting Alloys. Before 1930 only a small proportion of the world's bismuth consumption was used in the manufacture of the low-melting alloys. Then the use of these alloys was expanded so rapidly that during World War II the War Production Board had to place them under rigid allocation to insure proper distribution to the essential war industries.

Low-melting alloys are used in:

Ammunition composites
Fire-detection apparatus and alarm systems
Safety plugs for tanks and cylinders for compressed gas
Fusible elements in automatic sprinkler-heads and fire-door release links
Automatic shut-offs for gas and electric water-heating systems
Constant-temperature baths for autoclaves and for tempering
Liquid seals for bright-annealing and nitriding furnaces
Low-melting solders
Forming and stretching dies in aircraft construction
Spotting, erection and checking fixtures for automobile and aircraft construction
Filler for thin-wall tubing and molding that is being bent
Production of accurate patterns
Cores on which copper, iron, nickel and other metals are electroformed
Anchoring dies, punches, machine parts, magnets and ceramic parts
Chucks for holding irregular or delicate parts during machining operations
Coating for wood patterns, core boxes, and the like
Models for engraving machines
Proofcasting of forging dies, plastic molds and other irregular cavities
Selenium rectifiers, as the counterelectrode
Molds for wax models for precision casting
Models in place of wax for large precision castings
For addition of lead and bismuth to aluminum and other metals and alloys to obtain free-cutting materials

Bearing Materials

By the Subcommittee on Bearing Materials*

A BEARING is a machine element designed to transmit loads (or reaction forces) to a shaft rotating relative to the bearing. *Journal bearings* are cylindrical (full cylinders or segments of cylinders) and are used when the shaft load (or reaction force) is essentially perpendicular to the axis of the shaft. *Thrust bearings* are ring-shaped (full rings or segments of rings) and are used when the shaft load is in the direction of the axis of the shaft.

Function, Design and Manufacture of Bearings. When the load has both an axial and a perpendicular component, sometimes *flange bearings* are used. They are, in effect, a combination of journal bearings with one (single-flange) or two (double-flange) thrust bearings.

Characteristic of all plain bearings is the sliding movement of the shaft (or thrust collar) surface with respect to the bearing surface, in contrast with bearings that have rolling contact. In order to reduce the friction that results from this sliding movement the bearings are lubricated with oil or grease. Under best conditions of operation, particularly at high sliding speeds, a continuous layer of lubricant should be maintained between the sliding surfaces. Suitable lubrication, essential for satisfactory bearing operation, can be achieved only through judicious design of the bearing. One factor of great importance in this connection is the *clearance* between the bearing and the shaft. Oil *grooves* are often provided at the bearing surface to help in the uniform distribution of the available oil over the whole bearing surface.

Under ideal conditions of lubrication a continuous oil film would be maintained between the sliding surfaces; consequently the material of the bearing surface would be quite unimportant. However, under actual conditions of bearing operation, some direct contact between shaft and bearing surface is unavoidable. As a result, the "bearing qualities" (*see below*) of the material forming the bearing surface are actually of paramount importance, particularly where sliding speeds are high. Also, the various bearing materials show considerable difference in their ability to maintain a continuous oil film at their surface. The term "oiliness" (of a bearing material) expresses the tendency of the oil to form a tenaciously adhering film at the bearing surface.

A common cause of failure in bearings is the breakdown of the oil film. This results in direct contact between shaft surface and bearing surface, and in greatly increased friction. Under such conditions, the wear of the bearing surface—and often of the shaft surface also—is excessive. The increased friction may finally lead to seizure, or the heat generated may melt the bearing alloy. The most frequent causes of seizure (*see* Antiseizure Characteristics, *below*) include overloading, failure of the oil supply, or a decrease in the oiliness of the bearing material in the course of continued service. The oiliness of the material decreases, for example, in copper-lead bearings, if the conditions of operation cause selective corrosion of the lead, leaving the bearing surface deleaded.

In the large majority of bearings used at present, the bearing material itself is a metal or an alloy. For special applications, such as rolling-mill bearings, nonmetallic bearings are being used successfully. Typical bearing alloys that have excellent *antiseizure characteristics* and can be used at high sliding speeds, are the tin-base and lead-base babbitts and cadmium-base bearing alloys, all relatively soft. To improve their load-carrying capacity, these alloys

*The members of this Subcommittee are O. W. Ellis, *Chairman*, (Ontario Research Foundation), Paul A. Beck (University of Notre Dame) and Arthur F. Underwood (Research Laboratories Division, General Motors Corporation).

must be supported by a bearing shell made of stronger material. Bearing shells are usually made of steel or, in some instances, of bronze.

A good, mechanically strong bond between the bearing alloy and the supporting shell is very important for best performance. Until quite recently, unbonded or poorly bonded babbitt liners were cast thick so that they could be machined to finish with a thickness of ⅛ to ¼ in. or more. It is probable that the practice of using relatively thick linings, well bonded however, will persist where bearings are subjected to substantially steady loads; for example, railroad journal bearings. (*See* Lead-Base Alloys, *below*.) An important recent development is the bearing with well-bonded liner about $\frac{1}{64}$ in. thick. Decreasing the thickness of the soft layer of bearing alloy, results in considerable improvement in the load-carrying capacity. The thinner layer, when well bonded to the steel back, has much less tendency than the unbonded heavy layer to be squashed out under heavy loads. Also, in alternately

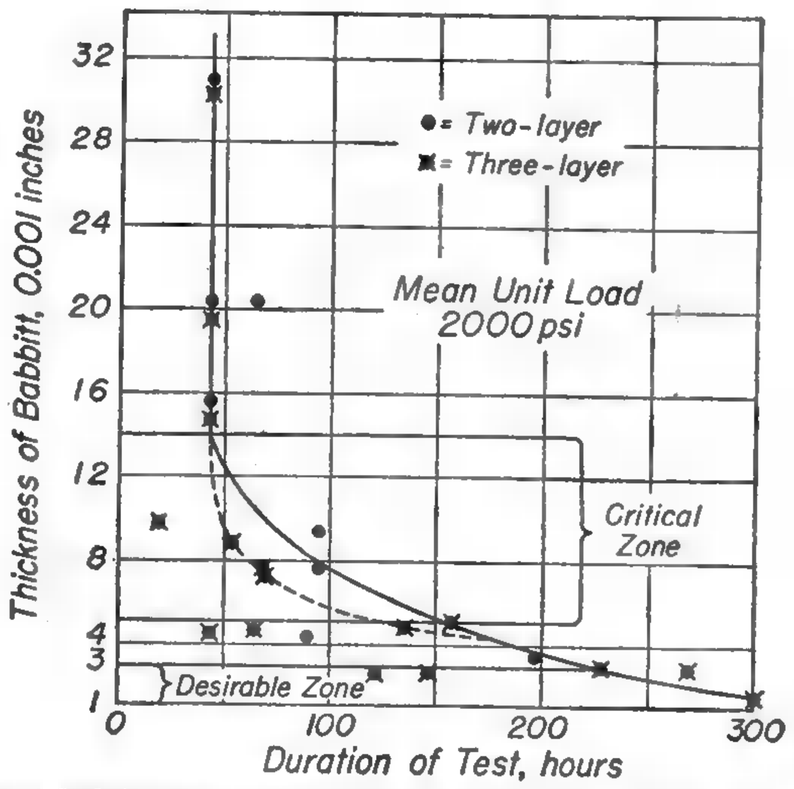

Fig. 1 Relationship between bearing life and babbitt thickness for two-layer and three-layer bearings (Luetkemeyer[7])

loaded applications, the bearing fatigue strength is increased considerably (*see* Fig. 1). A typical thickness of bearing alloy layer in automobile connecting-rod bearings, as now made, is 0.016 in. Thinner layers, down to 0.002 in., are used increasingly with great success. With both types, the bearing alloy is usually bonded to a steel back about 0.040 to 0.120 in. thick (*bimetal bearings*). Recently, electroplated layers about 0.001 in. thick have been introduced and proved to have greatly increased bearing fatigue strength. Such thin layers, however, wear off easily under unfavorable operating conditions. For this reason they are usually not plated directly on the supporting steel back; for safety a stronger intermediate layer of bearing alloy is used. This construction combines the excellent antiseizure characteristics of the babbitt bearings with greatly increased load-carrying capacity.

Formerly all babbitt connecting-rod bearings, as well as most other babbitt bearings, were cast into place as full bearings. This method is still used in many applications, but the large majority of all automotive bearings are manufactured at present in the form of half bearings by the blanking, forming and broaching of continuous bimetal strip. For all strip-type babbitt bearings and most strip-type copper-lead bearings the continuous bimetal strip is produced by casting the bearing alloy on a steel strip. However, a considerable number of automotive bearings are now being manufactured by sintering a purposely porous layer of copper and nickel particles to a continuous steel strip, and then casting a Pb-Sn-Sb alloy on it in such a way as to allow the penetration of the lead alloy into the pores of the sintered layer, and to cause the formation of a lead alloy overlay on top of it. The sintered porous structure, bonded to the steel backing, serves as a bonding medium and a supporting structure for the lead-base bearing alloy.

The resulting strip is then processed further as described above. Still another method recently developed involves the use of bimetal strip made by sintering copper-lead alloy on one or both sides of a steel strip.

Aircraft bearings are made, to a large extent, as full bearings by the casting of the copper-lead alloy or by the electroplating of the silver layer inside a cylindrical steel shell. For casting full bearings, both gravity casting and centrifugal casting methods are in use. Solid bronze bearings, without steel backing, are machined from hollow cylindrical castings or from bronze tubes.

Survey of Bearing Applications. Bearings are used in various types of machinery, under conditions so widely different that the properties required of bearing alloys cover a very broad range. A bearing alloy well suited for a certain application may be entirely useless in another. A good bearing alloy cannot be defined in a general way, but must be determined according to the type of application. The factors to consider in appraising a specific bearing application are rather numerous. Some of the most important are the following:

Type of Load. In the bearings of electric motors with belt drive, the load is essentially steady; that is, it does not change in direction. In applications like railroad-car journal bearings, the resultant force on the bearing changes in direction with the movement of the car, and is affected also by braking and other conditions experienced in operation. However, the changes in direction of the resultant force on these bearings are relatively minor in comparison with those on the connecting-rod bearings of reciprocating internal-combustion engines or the master-rod bearings of radial-type aircraft engines, which are alternately loaded. The load-carrying capacity of alternately loaded bearings is usually determined by the "bearing fatigue strength" of the bearing material used. In steadily loaded bearings this property is of no importance.

Amount of Load. It is important to know what shaft load the bearing is expected to support. High steady loads require relatively hard bearing alloys, such as leaded bronzes. Alternating loads up to approximately 1200 psi are considered low and can be supported by ordinary babbitt bearings but are about the maximum that can be supported. Thin babbitt linings can take loads up to approximately 1400 psi. The limit of alternating load for ordinary copper-lead bearings is about 1600 psi. With three-layer bearings that have a steel back, a 25% Pb copper-lead intermediate layer and a plated lead overlay it is considered allowable to load as high as 3000 psi, with a reasonable life expectancy for automotive and Diesel engine applications, if other conditions are favorable.

The above figures for the alternating loads that can be sustained by various bearing materials are, of course, not to be taken as fixed maximum loads, but only as approximations. The individual bearing applications may have many variables affecting the maximum load that the bearing can sustain. These variables should be taken into consideration when the bearing is designed.

Speed. The sliding speed of the shaft surface against the bearing surface is significant. The bearing alloys best suited for high-speed operation are the babbitts.

Bearing Temperature. Both the strength and the corrosion rate of bearing alloys depend on the temperature. Where the operating temperatures are high, either normally or during emergencies, certain otherwise excellent bearing alloys cannot be used. Sometimes the melting of the bearing alloy limits the operating temperature. For instance, a lead-base bearing alloy that consists of lead plus calcium plus alkaline earth metals, may perform satisfactorily in a railroad-car journal bearing where an alloy of lead plus tin plus antimony, with lower solidus temperature, would melt out as a result of the rise in temperature caused by "waste grab".

Corrosive Conditions. Certain bearing alloys (such as tin-base babbitts) are much more resistant than others to the corrosive action of the acids contained or formed in the lubricating oils during operation. In some applications, where the corrosiveness of the oil cannot be decreased by the use of inhibitors, or otherwise controlled, the different corrosion resistances of the various bearing alloys may be the decisive factor in selection.

Type of Oil Supply. The amount of oil available in the bearing, and the reliability of the oil supply depend to a great extent on what type of lubrication the design requires. For instance, with wick lubrication a bearing alloy of much better "emergency running qualities" is required than with the more reliable forced-feed lubrication.

Dirt Conditions. A railroad-car journal bearing operated in the desert suffers much more wear than otherwise because of the abrasive effect of sand particles that find their way into the bearing. A certain amount of dirt can be embedded by a soft bearing alloy like babbitt and thereby rendered relatively harmless. Conversely, an otherwise desirable bearing alloy with less embeddability may be unsuited for use where dirt is present.

Shaft Hardness. Harder bearing materials require harder shafts. Babbitt bearings may be used with soft steel shafts, but copper-lead bearings will cause excessive wear of the shaft unless the hardness of the surface of the shaft is at least 250 Bhn.

Properties Required of a Bearing Material. A bearing material may have to withstand a variety of imposed conditions. The relative importance of the properties of the bearing will change from one application to another. Thus, severely corrosive conditions will determine the choice of metal in a certain application, whereas requirements of fatigue strength will necessitate a different material for another installation. The following order of discussion does not indicate relative importance.

Resistance to Fatigue. The fatigue life of a bearing material is likely to be the most important characteristic for conditions of alternating load. As in steel parts, fatigue is cumulative and the fatigue failure of a bearing may occur after many millions of cycles of satisfactory operation. However, in contrast with steel, for example, the endurance limit for a bearing metal in a specific application is not so well defined, because so many factors influence this limit. When a bearing is failing by fatigue, the effective area decreases gradually until the remaining surface will not support the load. Then sufficient heat is generated to cause burning out, or seizure.

The fatigue resistance of a bearing metal is properly tested under operating conditions or by a method that reproduces operating conditions. The results of tests made in devices such as rotating-beam test machines, in which specimens are subjected to bending stresses, do not necessarily indicate the probable life of bearings in service. Resistance to bearing fatigue is a property distinctly different from the usual fatigue resistance.

Formerly, fatigue failures were universally blamed on poor bond between the bearing metal and its backing. It is now recognized that fatigue cracks start at the bearing surface and work down almost to the bond surface between bearing alloy and steel back. Then the cracks are propagated parallel to the bond surface, but just above it, leaving a minute layer of bearing material attached to the steel or bronze. As the cracks progress, they separate the metal into "loose tiles" that may be eroded away.

Temperature is of varying importance with different materials. Alloys of the "white metal" class have fatigue life greatly increased as the operating temperature of the bearing is decreased. Under certain conditions of high operating temperature, a babbitt bearing will have twice the fatigue life when the temperature is decreased 20 F. Copper-leads, cadmium alloys, aluminum alloys and, more especially, silver, are much less affected.

Since about 1936, improved production techniques have allowed the use of a decreasing thickness of the bearing metal. This has increased the fatigue limit, especially of white metals. The relative improvement for a tin-base babbitt is as follows:[7] (*See also* Fig. 1.)

Thickness, inch	0.030	0.020	0.010	0.005	0.003
Life, ratio	1	1	1.5	3.2	4.6

Considerable research has been done to improve the fatigue resistance of white metals by the addition of alloying elements. Although additions will develop an increase in such mechanical properties as hardness and compressive strength, they are ordinarily of little value in fatigue. As usual, there is no general rule in this matter; tin, for example, is effective in copper-lead.

Antiseizure Characteristics. This property can be the most important. If journals always ran on an oil film, there would never be metal-to-metal contact with the bearing surface. Then very hard bronze or even steel would be satisfactory. But under starting and stopping conditions, heavy load, high surface speed, or shaft deflection, the oil film may not be uniformly established, so the surface qualities are important. When two metals are rubbed together in contact, heat is generated, thereby raising the temperature of the surface. Ultimately the temperature is high enough to cause intermittent welding of the metals. If the energy available in the journal is sufficient, the junctures are torn apart. The bearing and journal are said to be "scored". If the welding is so severe that the machine is stalled, the term "seizure" is applied. Certain metals stand these extreme conditions better than others, and are said to have superior antifriction quality.

The rating of materials for this quality is based largely on experience, because of the complex sets of operating conditions. However, a general arrangement of popular metals would be, in order of decreasing ability, white metals, copper-lead, leaded bronzes, bronze (Table XIX).

At one time it was thought necessary for a bearing to have two constituents if it was to have the characteristics of good antiseizure quality. Experience now shows that this supposition is not true. Further mention of these observations will be made under Structure.

Bonding Ability. All commercial bearing materials can be well bonded to appropriate backings provided the correct procedure is followed. Details of proper cleaning and "tinning", where required, correct temperature and suitable quenching rate must be adhered to. Such information, in detail, can be obtained in publications that deal with bearings, in handbooks, and from the suppliers of casting babbitts. The casting of materials other than "white metals" usually involves relatively high temperatures and is done in special bearing plants.

Naturally, some metals have higher bond strengths than babbitts, for instance. But "poor bond" is relatively so rare that fatigue is usually the cause of a failure. A badly bonded metal will peel cleanly from its backing or will have an undesirable interlayer that can be detected by metallographic examination.

Compressive Strength. The compressive strength of bearing metals is important when the load (usually unidirectional) is heavy enough to cause extrusion. In white metals compressive strength decreases rapidly with increased temperature. All metals increase effectively in strength as the thickness is decreased; therefore, there has been ■ steady reduction of lining thickness, except where wear is ■ factor.

Unfortunately, there appears to be little correlation between compressive strength and fatigue resistance when considering ■ single class of material. For example, certain additions increase the compressive strength of tin-base babbitt, but do not increase the fatigue resistance.

Deformability. Some authorities include this property with antiseizure characteristics, and there is good reason to do so. "Deformability" is used here to cover two rather special requirements that are closely related.

Many bearing installations support shafts that are flexible with respect to the imposed load, so that the shaft deflects at a considerable angle when going through the bearing. Such a condition causes heavy bearing pressure at the ends of the bearing and leads to rupture of the oil film. This series of events often results in scoring and seizure in the end areas, ultimately causing complete failure. (With bad deflections, a narrow bearing may perform better than a wider one with lower loading in pounds per square inch.) But if the bearing material has the ability to yield sufficiently to take care of the misalignment, then trouble will not develop. In equipment, from punch presses to electric motors and automotive engines, this property can be of prime importance.

A second feature under Deformability is the ability to embed dirt. Here again the operating conditions vary from a totally enclosed refrigeration unit, where no dirt is ever present, to certain tractor applications. Some bearing materials will embed considerable quantities of dirt without seizure, whereas a bearing of another material will fail if

as little as 0.01 oz of sand is introduced. It is true that when the dirt is embedded, wear of the journal is likely to increase, but this is preferable to seizure. The grooving both of bearing and of journal surfaces frequently originates in dirt introduced by the oil. Hardness readings, in general, indicate the embeddability. Obviously dirt should be kept from a bearing, but this is not always possible.

Resistance to Corrosion. The corrosion of a bearing material depends on two factors—a corrosive lubricant and a bearing that is corrodible under the operating conditions. Without both factors, corrosion will not occur.

The corrosive lubricant can result from the addition of other compounds, such as animal or vegetable oils, to petroleum oils. Or, a petroleum oil may oxidize to form acidic products. In either instance, the acids are then available to attack any susceptible bearing metal by a chemical reaction.

Table I. Chemical Compositions of Tin-Base Bearing Alloys (ASTM B 23-46T)

Alloy Grade	Composition, percentage[a]					
	Tin	Antimony	Lead	Copper	Arsenic	Bismuth
1	91	4.5	0.35 max	4.5	0.10 max	0.08 max
2	89	7.5	0.35 max	3.5	0.10 max	0.08 max
3	83.3	8.3	0.35 max	8.3	0.10 max	0.08 max
4	75	12	10	3.0	0.15 max	.....
5	65	15	18	2.0	0.15 max	.....

(a) Other elements: iron, 0.08% max; zinc and aluminum not to exceed 0.005% when determined on a 10-g sample.

Pure or improperly alloyed lead, cadmium and copper are dissolved by certain of these acidic compounds. Under such conditions the bearing gradually disappears, with the development of increasing clearance that may lead to complete failure. When the metals are properly inhibited by alloying, there is no reasonable chance for corrosion. Only corrosion-resistant metals should be employed in installations where acidic oils may be present. Many bearing alloys susceptible to corrosion are used extensively, but the engineer must make sure that noncorrosive conditions continue.

Sometimes corrosion may attack the various constituents selectively. Thus a particular oil may attack the lead of a copper-lead bearing.

As in all chemical reactions, the activity increases rapidly with temperature. Instances are known where, at temperatures below 240 F, a given bearing is commercially satisfactory, but not at 280 F in the same application.

Structure. Certain chemical and metallurgical features will be discussed in this section without reference to crystal arrangement. It was believed at one time that two metallographic constituents, "hard crystals in a soft matrix", were essential to a bearing material. The fallacy of this view is well demonstrated by the current widely used practice of employing pure tin, lead, cadmium, silver and even copper, as a bearing surface. Tin, lead and cadmium are very weak and therefore are applied as thin layers (usually electroplated) where strength requirements are not high. Another disagreement with the "hard crystal" theory is indicated by copper-lead, which consists of islands of soft lead in a matrix of hard copper.

When heavier loads are to be supported, the material is strengthened by alloying elements. Or again, if a high-strength material such as copper or silver is used, the anti-seizure characteristics may be improved by the addition of lead. Therefore, most bearing materials do have two or more constituents. However, tnese constituents do not contribute to bearing performance in the manner postulated by the older theory. Rather, alloying additions are made in order to produce specific effects on the bearing properties desired in a particular application.

The crystal size, as shown by metallographic examination of polished specimens, is not important if kept within the limits easily produced by modern casting technique. A possible exception is lead-base alloy with appreciable arsenic content. Very slow cooling of all babbitt materials will produce large crystals, which tend to lower fatigue strength and which may cause a mottled surface after use.

Compositions and Properties of Bearing Materials

Tin-Base Alloys. The tin-base bearing materials, known commercially as "babbitt metals" or "babbitts", are substantially alloys of tin, antimony and copper, to which may be added as much as 30% Pb for the purpose of reducing their cost. Zinc, aluminum, arsenic, bismuth and iron should be limited in amount.

The compositions of tin-base bearing alloys, as published in ASTM Tentative Specification B 23-46T, are presented in Table I.

The compositions of tin-base bearing alloys, according to SAE specifications, are shown in Table II. It may be noted that the limits for chemical composition are closer for metal in ingot form than for bearings, because of the possibility of changes in composition as a result of casting.

Table II. Chemical Compositions of Tin-Base Bearing Alloys (SAE)

Element	Composition, percentage[a] [b]					
	SAE 10		SAE 11		SAE 110	
	Bearing	Ingot	Bearing	Ingot	Bearing	Ingot
Sn, min.....	90.0	90.75	86.0	87.25	87.75	89.0
Sb.....	4.0–5.0	4.25–4.75	6.0–7.5	6.5–7.0	7.0–8.5	7.25–8.25
Cu, max.....	4.0–5.0	4.25–4.75	5.0–6.5	5.5–6.0	2.25–3.75	2.25–3.5

(a) Lead content limited to 0.35% max, but 0.60% Pb is permissible in finished bearings backed with steel or bronze, provided a lead-tin solder has been used in bonding the bearing material to the backing.
(b) Other elements (max): 0.08% Fe, 0.10% As, 0.08% Bi, no Zn or Al.

The presence of zinc in these bearing metals is not generally favored. According to Freeman and Brandt,[1] arsenic increases the resistance of these alloys to deformation at all temperatures, while zinc has a similar effect at 100 F, but causes little or no change at room temperature. Zinc has a marked effect on the microstructure of certain of these alloys.[3] Small quantities of aluminum, even less than 1%, will modify the microstructure of these alloys.

Bismuth is objectionable because, in combination with tin, it forms a eutectic that melts at 279 F, so at temperatures higher than this, the strength of the alloys is decreased appreciably.

In high-tin alloys (such as ASTM Grades 1, 2 and 3, and SAE 10, 11 and 110) lead is limited to 0.35%. This is because of the deleterious effect of lead on the strength of

Table III. Compositions and Physical Properties of Tin-Base Bearing Alloys

ASTM Alloy Grade	Specific Gravity	Composition, %				Compression Tests[a] Yield Point,[b] psi		Compression Tests[a] Ultimate Strength,[c] psi		Brinell Hardness[d]		Melting Point		Temp of Complete Liquefaction		Proper Pouring Temp	
		Cu	Sn	Sb	Pb	20 C	100 C	20 C	100 C	20 C	100 C	°F	°C	°F	°C	°F	°C
1	7.34	4.56	90.9	4.52	none	4400	2650	12,850	6950	17.0	8.0	433	223	700	371	825	441
2	7.39	3.1	89.2	7.4	0.03	6100	3000	14,900	8700	24.5	12.0	466	241	669	354	795	424
3	7.46	8.3	83.4	8.2	0.03	6600	3150	17,600	9900	27.0	14.5	464	240	792	422	915	491
4	7.52	3.0	75.0	11.6	10.2	5550	2150	16,150	6900	24.5	12.0	363	184	583	306	710	377
5	7.75	2.0	65.5	14.1	18.2	5050	2150	15,050	6750	22.5	10.0	358	181	565	296	690	366

(a) The compression-test specimens were cylinders 1½ in. long and ½ in. in diam, machined from chill castings 2 in. long and ¾ in. in diam.
(b) Values for yield point were taken from stress-strain curves at a deformation of 0.125% reduction of gage length.
(c) Values for ultimate strength were taken as the unit load necessary to produce a deformation of 25% of the length of the specimen.
(d) Tests were made on the bottom face of parallel machined specimens cast at room temperature in a steel mold 2 in. in diam by ⅝ in. deep. Values listed are the average of three impressions on each alloy, using a 10-mm ball and applying a 500-kg load for 30 sec.

these alloys at temperatures of 302 F or more. Lead and tin form a eutectic that melts at 361 F. Bearings that exceed this temperature naturally become fragile as a result of the formation of a liquid phase within them.

The mechanical properties of ASTM Grades 1 to 5 have been investigated intensively by Freeman and Woodward.[5] The principal results of their work are shown in Table III.

Values for Brinell hardness number, limit of proportionality, yield strength in compression, and compressive strength (load per unit initial area required to compress test pieces 0.250 in. per in. of length) of representative Sn-Sb-Cu alloys are given in Table IV, taken from the work of Ellis and Karelitz.[6]

An important point brought out by Freeman and his collaborators is that the total deformation of the sample in the compression testing of babbitts is a function of the duration of application of the load—a point sometimes overlooked by those reporting and studying results of tests on materials as plastic as these alloys. What is true of the compression test is true also of other types of static tests. Still, the known limitations of static tests do not discount their value. A Brinell test, for example, wherein the load is applied for a standard time (for instance, 30 sec) is of considerable value for purposes of manufacturing control. Between the Brinell hardness numbers of the tin-base bearing materials and their properties in compression, the relationship is close enough to permit a fair estimate of the properties in compression to be made on the basis of Brinell tests alone. A knowledge of the properties of these alloys in compression, though useful, is not so important as an understanding of the beneficial effects on bearing life brought about by reducing the thickness of liners in bearings, particularly in those to be subjected to repeated stress. The type of relationship that exists between bearing life and thickness of babbitt is made clear in Fig. 1.[7]

Compared with other bearing materials, the tin-base alloys have relatively low resistance to fatigue, but their resistance is sufficient to warrant the use of these alloys in low-load situations. An important point is that these alloys are commercially easy to bond and to handle and have excellent antiseizure qualities. Further, they resist corrosion much better than lead-base bearing alloys.

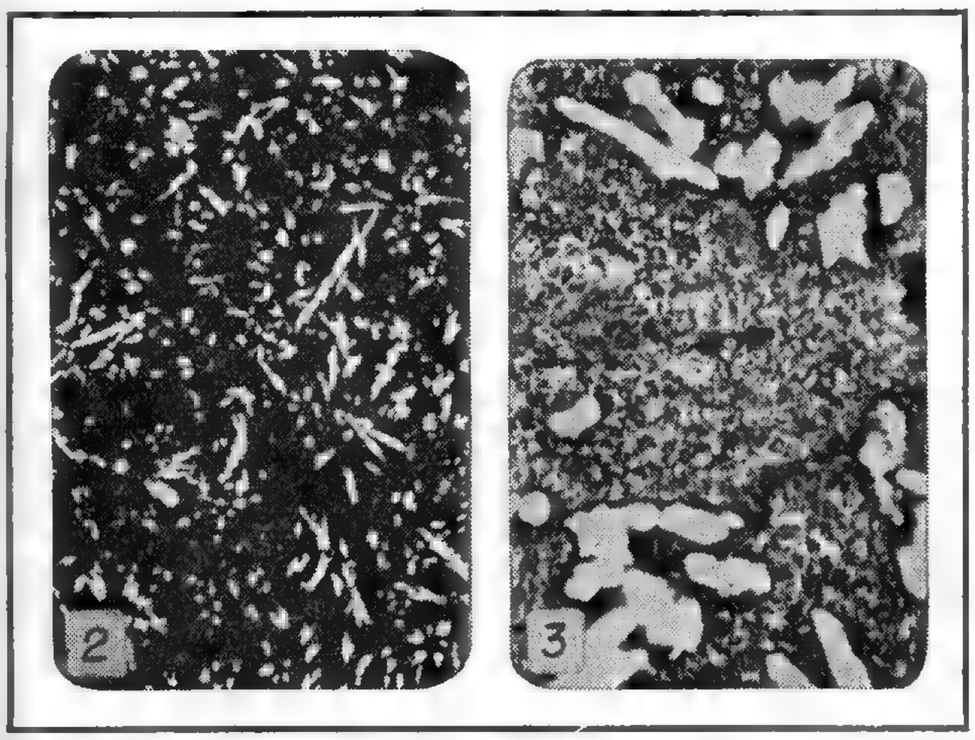

Fig. 2 Microstructure of tin-base bearing alloy containing 91% Sn, 4.5% Sb, 4.5% Cu (ASTM Grade 1, SAE 10) × 100. Etched with ferric chloride solution

Fig. 3 Same as Fig. 2 except × 500

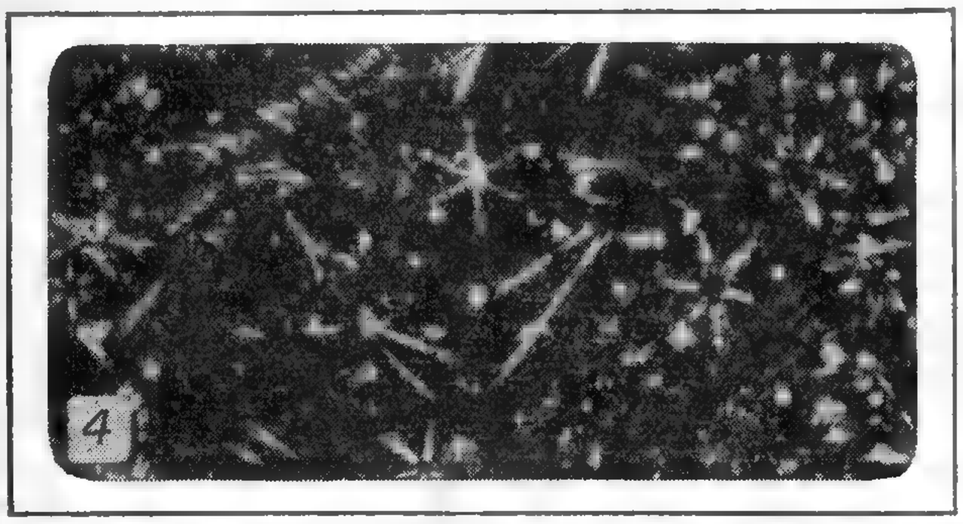

Fig. 4 Microstructure of strip-cast tin-base bearing alloy containing 89% Sn, 7.5% Sb, 3¼% Cu (ASTM Grade 2, SAE 110) × 500. Etched with ferric chloride solution

Structure consists of a tin-antimony solid solution matrix in which are embedded hexagonal dendrites and rodlike crystals of the eta (Sn-Cu) phase and very small round particles of the beta (Sb-Sn) phase, precipitated from solid solution.

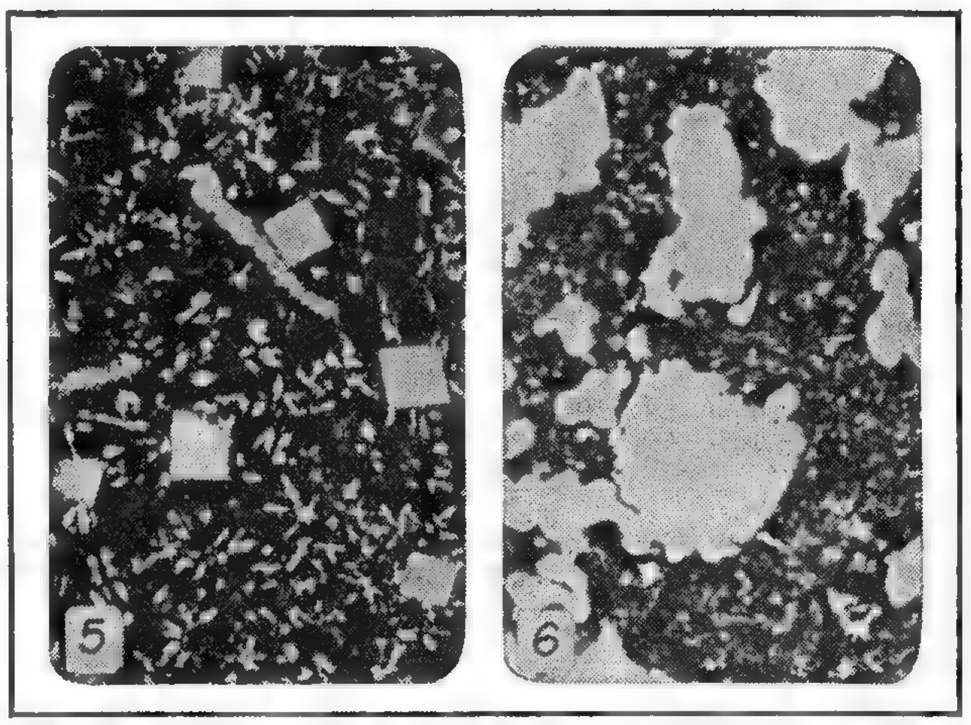

Fig. 5 Microstructure of tin-base bearing alloy containing 83.3% Sn, 8.3% Sb, 8.3% Cu (ASTM Grade 3) × 100. Etched with ferric chloride solution

Fig. 6 Same as Fig. 5 except × 500

Of the above alloys, ASTM Grade 2 (SAE 110) is most widely used in the automotive field at the present time. ASTM Grades 4 and 5 have a rather limited application and are relatively unimportant.

The structures of these alloys vary in accordance with their composition. Alloys that contain from about ½ to 8% Cu and less than about 8% Sb are characterized by a matrix (solid solution) in which needles of a copper-rich constituent and fine rounded particles of precipitated SbSn are distributed (Fig. 2 and 3). The proportion of the copper-rich constituent increases with copper content. ASTM Grade 2 (SAE 110) in the form of bearings has a structure of this type in which the needles often assume a characteristic hexagonal star-like pattern (Fig. 4). Alloys that contain from about ½ to 8% Cu and more than about 8% Sb exhibit primary cuboids of SbSn as well as needles of the copper-rich constituent in the matrix of solid solution (Fig.

Table IV. Effects of Antimony and Copper on Some Mechanical Properties of Sn-Sb-Cu Alloys at Room Temperature

Sb, %		Copper, percentage 0.5	1	2	4	8
2	Hardness	9.5	11.3	12.3	13.0	15.3
	Ultimate strength, psi	7,560	8,540	8,880	10,000	12,080
	Proportional limit, psi	1,580	1,590	1,960	1,860	2,200
	Yield strength, psi	4,380	5,160	5,880	6,880	7,220
4	Hardness	12.1	14.7	15.0	16.7	20.8
	Ultimate strength, psi	9,360	10,680	10,930	12,020	13,500
	Proportional limit, psi	2,355	2,490	2,450	2,890	3,155
	Yield strength, psi	5,660	7,080	7,060	8,300	10,840
6	Hardness	14.6	17.0	19.2	19.5	26.6
	Ultimate strength, psi	11,500	12,880	13,480	14,040	16,400
	Proportional limit, psi	3,390	3,140	3,380	3,540	4,795
	Yield strength, psi	7,100	7,500	8,800	9,700	12,660
8	Hardness	18.6	19.9	21.7	21.9	26.1
	Ultimate strength, psi	13,960	14,260	15,180	15,560	16,880
	Proportional limit, psi	3,230	3,605	3,790	4,520	4,070
	Yield strength, psi	8,640	8,860	9,920	11,340	13,480
10	Hardness	18.7	20.8	20.8	22.6	30.4
	Ultimate strength, psi	13,840	14,000	14,420	16,040	18,420
	Proportional limit, psi	3,560	3,630	4,460	4,880	5,670
	Yield strength, psi	8,240	9,440	9,780	11,920	14,580

5 and 6). In alloys that contain about 8% Sb and from about ½ to 8% Cu, rapid cooling has the effect of suppressing the formation of the cuboids of SnSb. This is particularly true of alloys containing the lower percentages of copper. (Study of the article on Cu–Sb–Sn in the CONSTITUTION OF ALLOYS Section of this Handbook, will assist in the interpretation of the above structures.)

Table V. Chemical Compositions of Lead-Base Bearing Alloys (ASTM B 23-46T)

ASTM Alloy Grade	Composition, percentage[a] Tin %	Antimony %	Lead %	Copper %	Arsenic %	Iron %
6	20	15	63.5	1.5	0.15*	0.08*
7	10	15	75	0.50*	0.60*	0.10*
8	5	15	80	0.50*	0.20*	...
10	2	15	83	0.50*	0.20*	...
11	..	15	85	0.50*	0.25*	...
12	..	10	90	0.50*	0.25*	...
15	1	15	rem	0.60*	1.40*	...
16	10	12.5	rem	0.60*	0.20*	0.10*
19	5	9	rem	0.50*	0.20*	...

* Maximum

(a) Other elements: zinc and aluminum not to exceed 0.005% when determined on a 10-g sample.

Alloy Grade 9 was discontinued in 1946

Lead-Base Alloys. The lead-base bearing alloys, also known commercially as "babbitt metals" or "babbitts", are of two types:

1 Alloys of lead, tin, antimony and, in many instances, arsenic.
2 Alloys of lead, calcium, tin and the alkaline earth metals.

Many alloys of the first type have been known for centuries in the form of type metal, and were probably employed as bearing materials because of some of the properties they were already known to possess. The advantages of arsenic additions in this type of lead-base bearing alloy have been generally recognized only during the last ten years. Alloys of the second type were developed in the early part of the present century.

Typical of the Pb-Sn-Sb-As alloys are the various grades of the ASTM Tentative Specifications for White Metal Bearing Alloys already referred to. The compositions of these alloys are listed in Table V.

The three SAE Specifications that cover lead-base bearing alloys are given in Table VI.

The properties of lead-base bearing materials[5] referred to in the ASTM specifications are quoted in Table VII.

In the absence of arsenic, the microstructure of these alloys consists of cuboid-shaped primary crystals of SbSn or of antimony embedded in a ternary mixture of Pb-Sb-SbSn in which lead forms the matrix. The amount of these cuboids per unit volume of alloy increases as the antimony content increases. If the antimony content is more than about 15% in these alloys, the total amount of the hard constituents increases to such an extent that the alloys become too brittle to be useful as bearing materials.

The main advantage of adding arsenic to these alloys consists in the improvement of their mechanical properties, particularly at elevated temperatures.[2] All lead-base babbitts are subject to softening or loss of strength during

Table VI. Chemical Compositions of Lead-Base Bearing Alloys (SAE)

Element	Composition, percentage[a] SAE 13 Bearing	SAE 13 Ingot	SAE 14 Bearing	SAE 14 Ingot	SAE 15 Ingot
Sn	4.5 – 5.5	4.75– 5.25	9.25–10.75	9.75–10.25	0.9 – 1.25
Sb	9.25–10.75	9.75–10.25	14.0 –16.0	14.75–15.25	14.50–15.50
Pb	86.0 max	85.5 max	76.0 max	75.25 max	remainder
Cu	0.50 max	0.50 max	0.50 max	0.50 max	0.60 max
As	0.60 max	0.60 max	0.60 max	0.60 max	0.80– 1.10

(a) Other elements: zinc and aluminum not to exceed 0.005% in a 10-g sample.

prolonged exposure to the temperatures (200 to 300 F) at which they serve as bearings in internal-combustion engines. The addition of arsenic minimizes this softening. Under suitable casting conditions, the arsenical lead babbitts—for example, ASTM 15 (SAE 15)—develop remarkably fine and uniform structure (Fig. 7). They also have excellent fatigue strength. (*See* Table VIII; note, however, that results from rotating-beam fatigue tests cannot be translated directly into bearing-fatigue performance.)

The arsenical babbitts are giving satisfactory service in many applications. The use of these alloys increased greatly during World War II, particularly in the automobile industry and in Diesel engines. The alloy most widely used is ASTM Grade 15 (SAE 15), containing 1% As. The automobile passenger-car bearings of this alloy are usually made from continuously cast bimetallic (steel-babbitt)

Table VII. Composition and Physical Properties of Lead-Base Bearing Alloys[a]

ASTM Alloy Grade	Specific Gravity	Composition, % Cu	Sn	Sb	Pb	Yield Strength in Compression,[b] psi 20 C	100 C	Compressive Strength,[c] psi 20 C	100 C	Brinell Hardness Number[d] 20 C	100 C	Melting Point °F	°C	Temp of Complete Liquefaction °F	°C	Proper Pouring Temperature °F	°C
6	9.33	1.5	19.8	14.6	63.7	3800	2050	14,550	8050	21.0	10.5	358	181	531	277	655	346
7	9.73	0.11	10.0	14.5	75.0	3550	1600	15,650	6150	22.5	10.5	464	240	514	268	640	338
8	10.04	0.14	5.2	14.9	79.4	3400	1750	15,600	6150	20.0	9.5	459	237	522	272	645	341
10	10.07	0.12	2.05	15.7	82.0	3350	1850	15,450	5750	17.5	9.0	468	242	507	264	630	332
11	10.28	0.19	0.09	14.8	84.7	3050	1400	12,800	5100	15.0	7.0	471	244	504	262	630	332
12	10.67	0.12	0.11	9.9	89.4	2800	1250	12,900	5100	14.5	6.5	473	245	498	259	625	329
15[e]	10.05	0.5	1.0	15.0	82.5	....	....	.....	....	21.0	13.0	479	248	538	281	662	350
16	9.88	0.5	10.0	12.5	77.0	....	....	.....	....	27.5	13.6	471	244	495	257	620	327
19	10.50	...	5.0	9.0	86.0	....	....	15,600	6100	17.7	8.0	462	239	495	257	620	327

(a) The compression-test specimens were cylinders 1.5 in. long, 0.5 in. in diam, machined from chill castings 2 in. long, 0.75 in. in diam.
(b) Values were taken from stress-strain curves at a deformation of 0.125% reduction of gage length.
(c) Values were taken as the unit load necessary to produce a deformation of 25% of the length of the specimen.
(d) Tests were made on the bottom face of parallel machined specimens cast at room temperature in ■ steel mold 2 in. in diam by 0.625 in. deep. Values listed are the average of three impressions on each alloy, using a 10-mm ball and applying a 500-kg load for 30 sec.
(e) Nominal arsenic content, 1.0%

Table VIII. Mechanical Properties of Some Lead-Base Bearing Alloys

Composition, percentage	ASTM Alloy Grade	Endurance Limit,[a][b] psi	At 77 F[b] Tensile Strength, psi	Elongation, % in 2 in.	At 212 F[c] Tensile Strength, psi	Elongation, % in 2 in.	At 302 F[c] Tensile Strength, psi	Elongation, % in 2 in.	At 392 F[c] Tensile Strength, psi	Elongation, % in 2 in.
12.75 Sb, 0.75 Sn, 3 As	..	4400	9,800	1.5	6700	4	4200	10	1900	70
15 Sb, 1 Sn, 1 As	15	4300	10,350	2	6400	9	3740	26	1260	95
15 Sb, 5 Sn	8	3900	10,000	5	5400	27	2900	55	1200	100

(a) Rotating-beam test at room temperature; 20,000,000 cycles at 2000 cycles per minute
(b) Test specimens chill cast
(c) Test specimens chill cast to size and held at the testing temperature for 20 minutes before testing

strip. When properly handled, the alloy will withstand the considerable strain that results from forming the bimetallic strip into bearings. Diesel engine bearings are often cast as individual bearings, either by centrifugal casting or by gravity casting methods.[9] In applications where higher hardness is required and where the formability requirements are not so severe (for instance, in rolling-mill bearings) an alloy that contains 3% As has been used successfully. The bond between arsenical lead babbitts and copper alloy backs is often of poor quality.

Copper is said to be effective in preventing segregation, but, mainly because it is the apparent cause of frothing when alloys of low tin content are being poured, it is limited in these alloys to 0.5% max (*see* Tables V and VI).

For many years the lead-base bearing alloys were considered low-cost substitutes for the tin-base alloys. There is not much difference between the antiseizure characteristics of the two groups of alloys. During the last decade it has been found that when the lead-base alloys are used in reduced thicknesses (0.030 in. or less) the resistance to fatigue is at least equal to that of the tin-base alloys, if not better. Bearings of any of these alloys remain serviceable longest when made 0.005 in. thick or less. The superiority of the lead-base over the tin-base alloys becomes more marked as operating temperatures increase. This accounts for the fact that automotive engineers generally favor lead-base alloys of compositions that approximate SAE 14 and 15, referred to in Table VI, and ASTM Grade 15, referred to in Table V.

Table IX. Chemical Compositions of Cadmium-Base Bearing Alloys

Element	Composition, percentage SAE 18	SAE 180
Cadmium	98.4 min	98.25 min
Nickel	1.0 to 1.6	.....
Silver	0.01 max	0.5 to 1.0
Copper	0.20 max	0.4 to 0.75
Tin	0.02 max	0.01 max
Lead	0.05 max	0.02 max
Zinc	0.05 to 0.15	0.02 max

The resistance to fatigue of bearing materials depends, to a great extent, on the design of the bearing. The strength and rigidity of the supporting structure, the thickness of the backing metal (steel or bronze), the thickness of the bearing material, and the character of the bond between the bearing material and the backing, are all factors of consequence in bearings for use in high-speed reciprocating engines, such as the main and connecting-rod bearings of automobile and aircraft engines. Resistance to fatigue is of somewhat less importance in bearings that operate under more or less static load; for example, journal bearings in locomotive tenders and passenger and freight railway cars. These bearings are lined to a thickness of ¼ in. unless otherwise specified. (*See* ASTM Specifications for Car and Tender Journal Bearings, Lined—ASTM Designation: B 67-46). In such bearings as these, resistance to abrasion, antiseizure characteristics, deformability, compressive strength and resistance to corrosion are of greater significance than resistance to fatigue. The lining metal generally employed in car and tender journal bearings (ASTM B 67-46) conforms to the following requirements for chemical composition:

Tin, per cent	as specified
Antimony, minimum per cent	8.0
Tin and antimony, per cent	10 to 14
Arsenic, maximum per cent	0.2
Copper, maximum per cent	0.5
Sum of tin, antimony, lead, and arsenic, min per cent	99.25
Other impurities, maximum per cent	0.75

Pouring temperature and rate of cooling exert a profound influence on the microstructure and properties of lead-base alloys, particularly when they are used in the form of the relatively heavy liners employed in railway journals. High pouring temperatures and slow cooling rates, such as result from the use of overhot mandrels, promote segregation and the formation of a coarse structure. A coarse structure may cause brittleness, low compressive strength and low hardness. Low pouring temperatures (620 to 650 F) are therefore to be recommended. Since these alloys remain relatively fluid, almost to the point of complete solidification (about 465 F for most of these lead-base alloys) they are easy to manipulate and can be handled with no great loss of metal from drossing.

The use of the lead-base babbitts containing calcium and the alkaline earth metals, is confined almost entirely to the railway field although these babbitts are employed also in certain Diesel bearings.

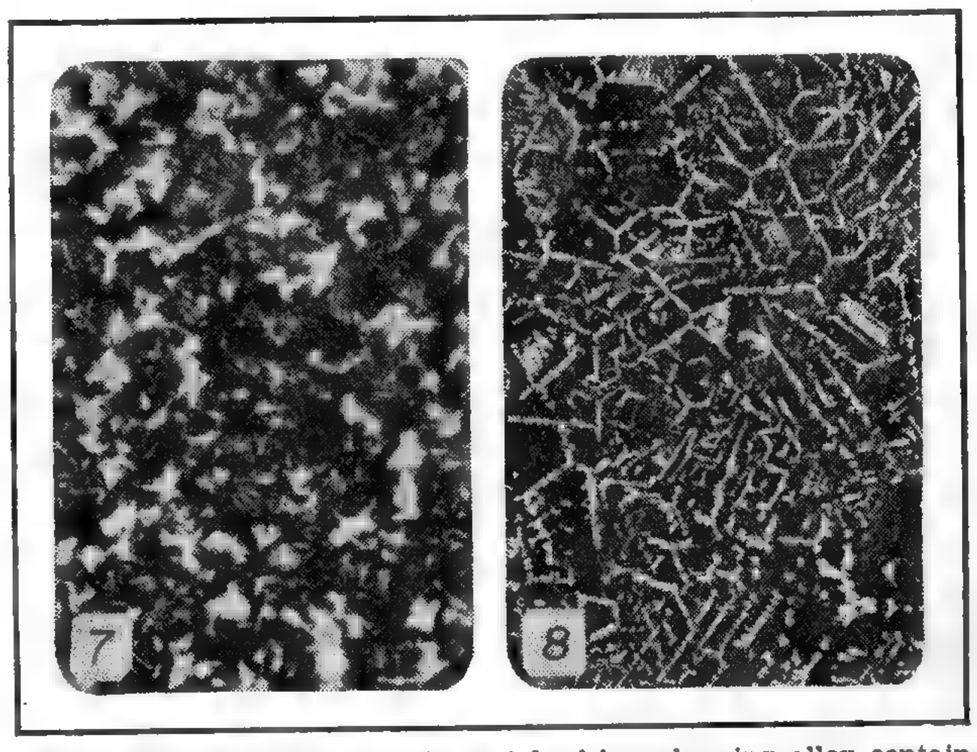

Fig. 7 Microstructure of strip-cast lead-base bearing alloy containing 82.5% Pb, 15% Sb, 1% Sn, 1% As (ASTM Grade 15; SAE 15) × 1000. Etched with ferric chloride solution

Structure consists of primary dendrites of lead and primary particles of antimony and of the beta (Sb-Sn) compound; matrix is a eutecticlike structure

Fig. 8 Microstructure of a die-cast cadmium-nickel bearing alloy containing 1¼% Ni (SAE 18) × 100. Etched with ferric chloride solution

Structure consists of large dendrites of $NiCd_7$ compound embedded in a matrix of nearly pure cadmium

One of the most widely used of these alloys contains 1.0 to 1.5% Sn, 0.50 to 0.75% Ca and small amounts of various other elements. The strength of this alloy approximates that of the alloy that contains 90% Sn, 8% Sb and 2% Cu, referred to in Table IV. The Brinell hardness number is about 20, and the solidus is 610 F. The liquidus is probably near 640 F. The pouring temperature varies from 930 to 970 F. This is relatively high and accounts for the formation of a larger volume of dross than is encountered when melting the lead-base Pb-Sb-Sn alloys. Care must be taken to avoid contamination of the alloy by antimonial lead-base babbitts, and vice versa. The resistance to wear and the deformability are of the same order as those of the other lead-base babbitts. Most compositions of this type of alloy are subject to corrosion by acidic oils.

Table X. Chemical Compositions of SAE 48 and SAE 480 Copper-Lead Bearing Alloys

Element	Composition, percentage SAE 48	SAE 480
Copper	67.0 to 74.0	60.0 to 70.0
Lead	25.0 to 32.0	30.0 to 40.0
Silver	1.5 max	.....
Zinc	0.1 max	.....
Phosphorus	0.025 max	.....
Iron	0.35 max	0.35 max
Tin	.....	0.05 max
Other elements	0.15 max	0.3 max

Cadmium-Base Alloys. In all likelihood the limited availability of cadium has been the main reason why cadmium alloys have not been more widely employed in the manufacture of bearings. Within the last 12 years, cadmium alloys hardened by nickel (SAE 18) or by silver and copper (SAE 180) have come to the fore because of having greater resistance to fatigue than the babbitts. Compositions are listed in Table IX.

These alloys are readily corroded by some oils; however, attack can be retarded by the diffusion of indium into the

bearing surfaces from an electrodeposited layer of the metal.

The main advantage of SAE 18 over SAE 180 is that it bonds readily with steel. Because of the nickel in the alloy, the bond is strong and ductile. The structure of a die-cast cadmium-nickel bearing alloy (SAE 18) is shown in Fig. 8.

Copper-Lead Alloys. Copper-lead alloys are used extensively both in the automotive and aircraft fields and in the field of general engineering.

In the aircraft and automotive fields these alloys are used almost exclusively in steel-backed bearings, a majority of which (for the automotive field) are blanked from steel strip continuously coated with alloy in automatically controlled machines. This same general method of manufacture is used in the production of most steel-backed babbitt bearings. Typical alloys are SAE 48 and SAE 480, of which the compositions are listed in Table X.

SAE 48 was designed originally for aircraft engine bearings. It is now being adopted by automotive engineers. Figure 9 shows the structure of SAE 48 in the form of a gravity-cast bearing. SAE 480 is used exclusively in general automotive practice. The tolerance for lead in SAE 480 is purposely made broad enough to cover the several compositions now in commercial use. Closer tolerances can be specified by the purchaser of these alloys.

Copper-lead alloys that contain about 30% Pb and as much as 5% Ag, have been used in the automotive industry. Another type of bearing has an intermediate layer of 25% Pb copper-lead cast on a steel back and a thin plated overlay of lead-tin alloy. Figure 10 shows the structure of the copper-lead layer in a bearing of this type. Although the field experience with these three-layer bearings is as yet limited, they have already proved their exceptionally high resistance to fatigue.

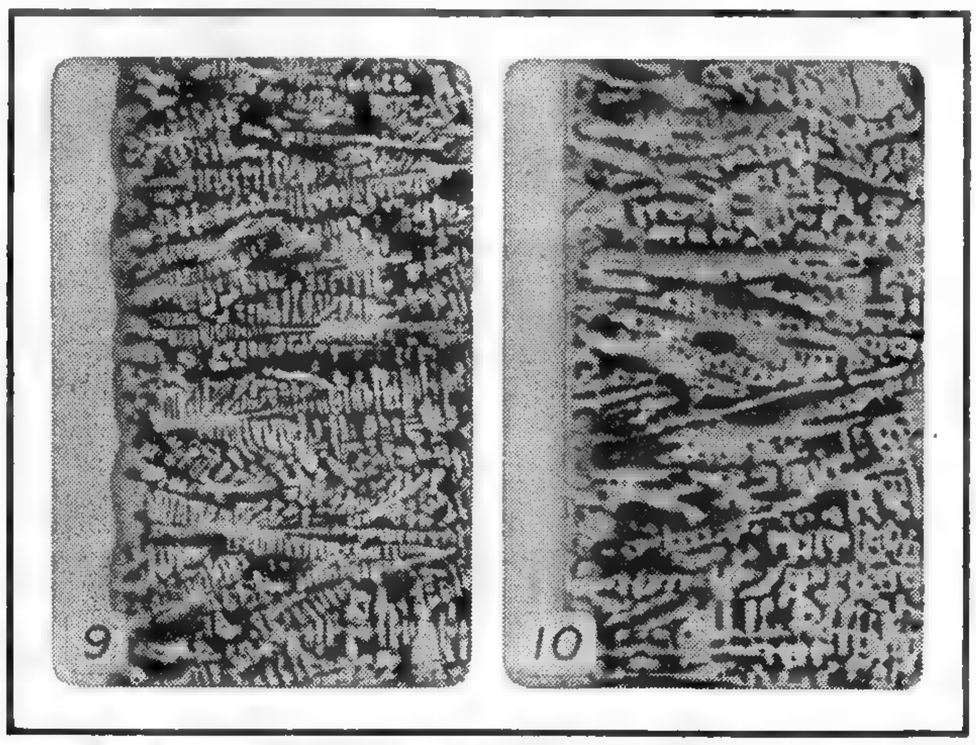

Fig. 9 Microstructure of a gravity-cast copper-lead bearing containing 28.5% Pb, 1¼% Ag, remainder copper (SAE 48) × 100

Bond between copper-lead alloy and steel is shown. The structure consists of copper dendrites that are approximately perpendicular to the bond surface. The space between the dendrites is filled with lead.

Fig. 10 Microstructure of a strip-cast copper-lead bearing containing 25% Pb, 0.25% Sn, remainder copper, × 100

This alloy is used as the intermediate layer in a three-layer bearing construction. Micrograph shows the bond between copper-lead alloy and steel. The structure consists of copper dendrites that are approximately perpendicular to the bond surface. The space between the dendrites is filled with lead.

The higher the lead content of the copper-lead alloys, the lower is the fatigue strength and the higher the antifrictional characteristics. Silver and tin may be substituted for part of the copper in order to increase fatigue strength. To prevent seizing, a thin coating of lead alloy is sometimes plated over these bearing materials. This lead, of course, wears away in time. Like the cadmium-base alloys, these alloys are easily corroded by certain oils. In fact, corrosion is a major problem with copper-lead alloys. For protection, indium can be diffused into the bearings by suitable heat treatment after the bearings are electroplated with indium.

Copper-lead bearings are also made by applying copper-lead powder to steel strip that is passed continuously through furnaces where the mixtures are simultaneously sintered and bonded to the strip. In these bearings the somewhat elongated and recrystallized copper grains tend to lie parallel to the surface of the strip, whereas in cast copper-lead strip bearings, the copper dendrites are essentially perpendicular to the surface of the strip.

Table XI. Approximate Mechanical Properties of Sand-Cast Copper-Lead Bearings Containing 30 and 40% Pb

Property	30% Pb	40% Pb
Tensile strength, psi	8000 to 9000	7500 to 8500
Elongation, % in 2 in.	6 to 8	6 to 8
Compressive strength,(a) psi	3000	2500
Brinell hardness number	22.5 to 32.5	20 to 30

(a) 0.001 in. compression on sample 1 in. high and 1 in. in diam

In the field of general engineering, alloys of copper and lead have found application as bearings, but a wider application as bushings. The hardness and the compressive and tensile strengths of these alloys decrease as the lead content is increased. Table XI presents *very approximate* limits for the mechanical properties of sand-cast bearings of these materials.

The properties of these alloys are profoundly affected by the method of manufacture and by the size of the casting section. They have good antiseizure characteristics and can be used with some success in situations where lubrication is uncertain or intermittent. Although copper-lead bearings are used without special support in some installations, it is general practice in the automobile field to apply these alloys as a thin layer on a steel shell.

Table XII. Chemical Compositions of Tin Bronze Castings (ASTM B 22-46T)

Element	Composition, percentage — Class A	Class B	Class D
Copper	79 to 82	82 to 85	86 to 89
Tin	18 to 20	15 to 17	▮ to 11
Zinc	0.25 max	0.25 max	1.0 to 3.0
Lead	0.25 max	0.25 max	0.30 max
Nickel	.....	.....	1.0 max
Iron	0.25 max	0.25 max	0.15 max
Phosphorus	1.0 max	1.0 max	0.05 max

In slowly cooled castings, such as sand castings, lead may segregate, so tin, nickel, manganese and other elements are added to reduce this segregation. These elements increase the strength of the basic alloy and provide materials that are used considerably in engineering.

Tin Bronzes and Leaded Tin Bronzes. *Tin Bronzes.* The bearing bronzes are substantially alloys of copper with from 5 to 20% Sn and a small percentage of residual phosphorus, that is, phosphorus remaining after deoxidation of the alloys with 10 or 15% phosphor copper. These alloys are sometimes referred to as "phosphor bronzes".

Table XIII. Required Mechanical Properties of Tin Bronze Castings (ASTM B 22-46T)

Property	Alloy — Class A	Class B	Class D(a)
Deformation limit,(b) psi	24,000 min	18,000 min	.....
Permanent set,(c) in. per in.	0.04 to 0.12	0.10 to 0.20	.....

(a) Tensile strength, 36,000 psi min; elongation in 2 in., 18% min
(b) Load that produces a permanent set of 0.001 in. in a cylindrical test specimen 1 sq in. in cross-sectional area and 1 in. high
(c) Under a load of 100,000 psi

When zinc is used instead of phosphorus, ▮ to 6% Zn may be used in the bronze, which is then quite generally referred to as "gun metal" (Government bronze, composition G, Admiralty bronze or zinc bronze).

Phosphor bronzes are chosen where load-carrying capacity at low speeds is of paramount importance, while gun metal is preferred where complicated castings are specified and where difficulties may be encountered in the foundry.

Typical of the phosphor bronzes are two of the alloys covered by the ASTM Tentative Specifications for Turntables and Movable Bridges (B 22-46T). The compositions and specified mechanical properties of tin bronzes, are shown in Tables XII and XIII.

These cast tin bronzes are ordinarily used for the following purposes:

Class A. For contact with hardened steel disks at low speeds under pressures not greater than 3000 psi, as in the disk bearings of center-bearing swing bridges.

Class B. For contact with hardened steel disks at low speeds under pressures not greater than 2500 psi, as in the disk bearings of turntable and center-bearing swing bridges; for contact with steel that has a tensile strength of not less than 60,000 psi, at low speeds under pressures not greater than 1500 psi, as in trunnions and movable bridges; and for bearing and expansion plates under pressures not exceeding 2500 psi.

Other alloys of this type are covered by the ASTM Tentative Specifications for Tin Bronzes and Leaded Tin Bronze Sand Castings (B 143-46T). The chemical and tensile requirements for these alloys are quoted in Tables XIV and XV.

Table XIV. Chemical Compositions of Tin Bronze and Leaded Tin Bronze Sand Castings (ASTM B 143-46T)

	Composition, percentage							
	Tin Bronze				Leaded Tin Bronze			
	1A[a]		1B[a]		2A[a]		2B[a]	
Element	Min	Max	Min	Max	Min	Max	Min	Max
Copper	86.0	89.0	86.0	89.0	86.0	90.0	85.0	89.0
Tin	9.0	11.0	7.5	9.0	5.5	6.5	7.5	9.0
Lead	...	0.30	...	0.30	1.0	2.0	...	1.0
Zinc	1.0	3.0	3.0	5.0	3.0	5.0	3.0	5.0
Nickel	...	1.0	...	1.0	...	1.0	...	1.0
Iron	...	0.15	...	0.15	...	0.25	...	0.25
Phosphorus	...	0.05	...	0.05	...	0.05	...	0.05

(a) The chemical requirements of SAE Specifications 62, 620, 621 and 622 conform to those for alloys 1A, 1B, 2B and 2A, respectively.

These specifications also cover two leaded tin bronzes, to which reference will be made below. Alloys 1A and 1B (Table XIV) are frequently referred to as 88-10-2 and 88-8-4 respectively. They are important both because of their good casting characteristics and because of their strength, toughness, bearing qualities and, in particular, their resistance to corrosion in sea water.

Phosphorus and zinc together in the same alloy confer no useful properties that cannot be obtained by one element or the other alone. However, phosphorus is commonly employed as a deoxidizer in making gun metal. On the other hand, zinc is rarely, if ever, added intentionally to phosphor bronze. Phosphorus must be used with discretion in making gun metal because it has a great effect on the freezing range of the alloy. As might be expected, variations in the freezing range affect the casting characteristics of the material. Sound sand castings can never be produced consistently unless uniform conditions are maintained in the foundry. In summary it may be said that gun metal should contain preferably no more than a trace of phosphorus, and phosphor bronze should contain no zinc.

Table XV. Required Tensile Properties of Tin Bronze and Leaded Tin Bronze Sand Castings (ASTM B 143-46T)

	Tin Bronze		Leaded Tin-Bronze	
Property	1A	1B	2A	2B
Tensile Strength, min, psi	40,000	40,000	34,000	36,000
Yield Strength,[a] min, psi	18,000	18,000	16,000	16,000
Elongation in 2 in. min, per cent	20	20	22	18

(a) Yield strength determined as the stress producing an elongation under load of 0.5%, that is, 0.01 in. in a gage length of 2 in.

In general the substitution of zinc for tin in bronze results in an improvement in ductility and the sacrifice of a measure of strength and hardness. In instances where strength and hardness are essential it may be desirable to limit the use of zinc, but when zinc is allowed by specification, the engineer can be sure almost invariably of a consistent output of sound, clean castings.

Lead usually, though not always, decreases the hardness and strength of gun metal. However, machinability is improved by the addition of a small amount of lead; ½% Pb will render gun metal free-cutting. It is better practice to keep the lead content below ½% in foundry production, because of the danger of exceeding this amount as a result of the pyramiding of lead from scrap returns. It will be noted that, in the above specifications for castings of tin bronze, the lead content is limited to either 0.25 or 0.30% max.

Iron increases the hardness of gun metal and is objectionable because of its tendency to produce hard spots that may seriously reduce machinability.

Nickel is beneficial rather than detrimental to the casting properties of the tin bronzes. It does not affect adversely their resistance to abrasion or corrosion, and tends to reduce grain size. Generally it is not added to 88-10-2, but is commonly present in 88-8-4 to the extent of from 0.50 to 0.75%.

Table XVI. Chemical Compositions of Leaded Tin Bronzes (SAE)

	Composition, percentage			
Element	SAE 791, Rolled or Wrought	SAE 792, Cast Lining	SAE 793	SAE 794
Copper	remainder	remainder	83.0 min	68.5 to 75.5
Tin	3.5 to 4.5	9.0 to 11.0	3.5 to 4.5	3.0 to 4.0
Lead	3.5 to 4.5	9.0 to 11.0	7.0 to 9.0	21.0 to 25.0
Zinc	1.5 to 4.0	0.5 max	4.0 max	3.0 max
Antimony	.....	0.5 max	.....	.....
Nickel	.....	0.5 max	.....	.....
Iron	0.1 max	0.35 max	0.35 max	0.35 max
Other elements	0.2 max	0.4 max	0.3 max	0.4 max

SAE 791 to 794 may be indented and graphited.

SAE 792, 793 and 794 are the cast, or cast and rolled, bronze liners for a rolled split bushing made with a steel backing, usually SAE steel 1010 or 1015. These materials may be rolled and annealed to any desired specification for hardness. When rolled, antimony is 0.25% max to prevent rolling difficulties.

SAE 793 and 794 are liners for steel-backed, split bearings similar in construction to SAE 792.

Leaded Tin Bronzes. The wrist-pin alloys and miscellaneous bushing alloys covered by SAE Specifications 791 to 794 (Table XVI), are typical of low-leaded tin bronzes. Other compositions are those mentioned in Table XIV and the alloy referred to as "Class C bronze" in ASTM Specification B 22-46T, which also covers Classes A, B and D in Table XII. Composition of Class C bronze is essentially the same as that of SAE 792, given in Table XVI.

Class C bronze, as well as other leaded tin bronzes, is used for ordinary bushings in machinery, but is employed specifically in bearing and expansion plates under pressures not greater than 1000 psi. Eash[11] found that a copper alloy containing 8% Ni, 10% Pb, 2% Sn and 1% Sb, appeared to be a promising substitute for Class C bronze when used in the sand-cast condition.

Table XVII. Chemical Compositions of Aluminum-Base Bearing Alloys

	Composition, percentage				
Element	750[13]	XA750[14]	XB750[15]	XB80S	Al-Cd-Si[16]
Tin	6.5	6.5	6.5	6.5	...
Copper	1.0	1.0	2.0	1.0	...
Nickel	1.0	0.5	1.2	0.5	...
Silicon	...	2.5	...	1.5	4.0
Magnesium	...	...	0.8	...	...
Cadmium	...	...	...	...	1.2

Probably the most complete account of the mechanical and wearing properties of the leaded tin bronzes is that contained in two papers published by French and collaborators.[10] These workers observed: "There is a considerable range of chemical composition within which the variations in mechanical and wearing properties [of these alloys] are small. This includes a range of from 15 to 25% Pb and from around 4 to 7% Sn. Since alloys within the entire range have given reasonably good performance in locomotive and journal bearings, there does not seem to be justification for the wide variations in specifications now used by different carriers for parts subjected to similar service." Since these remarks were published (1928), some progress

Table XVIII. Physical and Mechanical Properties of Aluminum-Base Bearing Alloys

Alloy Form Condition	750-T5 Permanent Mold Casting Heat Treated	750-T101 Permanent Mold Casting Cold Worked	XA750-T6 Permanent Mold Casting Heat Treated	XA750-T91 Permanent Mold Casting Cold Worked	XB750-T5 Permanent Mold Casting Heat Treated	XB80S-H12 Sheet Cold Worked	Al-Cd-Si Permanent Mold Casting As Cast
Tensile strength, psi	22,000	23,000	22,000	23,000	30,000	25,000	20,000
Yield strength, psi[a]	10,000	16,000	10,000	17,000	20,000	23,000	7,500
Elongation, per cent[b]	12	8	10	7	5	6	10
Brinell hardness	45	50	45	50	70	50	40
Endurance limit, psi[c]	9000	....	9500	....	....	....	....
Density	2.88	....	2.83	....	2.88	....	....
Thermal conductivity[d]	0.44	....	0.40	....	0.43	....	....
Coeff of thermal expansion[e]	0.0000135	....	0.0000132	....	0.0000133	....	....

(a) Offset, 0.2%. (b) Gage length four times the diameter. (c) Based on 500,000,000 cycles using R. R. Moore rotating-beam machine. (d) Cgs units, calculated from electrical conductivity. (e) Per °F, temperature range 68 to 392 F.

has been made towards attaining uniformity of composition in the leaded tin bronzes.

Other important observations by these workers were:

1 Leaded tin bronzes that contain less than about 4% Sn are unsuited for general bearing service, since they have low resistance to deformation and wear rapidly in the absence of lubrication. However, some of the alloys—for example, those high in lead—can serve satisfactorily for special service that involves low loads.

2 Bronze with from 8 to 10% Sn and 12 to 15% Pb seems better adapted than bronze with around 4 to 6% Sn, for service where the chief requirements are resistance to pounding and static stress.

3 In alloys with a nearly constant ratio of copper to tin, an increase in the lead content produces a general improvement in wearing properties, but this is more marked between 0.25 and 12% Pb than between 12 and 25% Pb. Concurrently, resistance to pounding, notch toughness and tensile strength decrease.

4 In alloys with a nearly constant ratio of copper to lead, increase in tin from 0.7 to about 5% results in a marked decrease in the wear produced by rolling and sliding friction without oil, and a general improvement in the wearing properties. Further increase in tin from about 5 to 10% does not greatly modify the wearing properties but does result in improved tensile strength and resistance to pounding. An improvement in notch toughness results when tin is increased to about 7%, which represents the proportion of this element above which appreciable amounts of brittle alpha-delta eutectoid appear in the structure of these alloys. With high tin, a slight decrease in notch toughness occurs.

5 As a general rule, chill-cast bronzes wear faster and have lower notch toughness than corresponding sand-cast bronzes. However, the chill-cast alloy has better resistance to pounding and higher tensile strength at all temperatures between 70 and 600 F. There are a few exceptions to this rule, for details of which reference should be made to the papers mentioned above.[10]

6 The addition of 4% Zn to these bronzes has, in general, a small effect on the properties referred to above. The work of French and his collaborators seems to justify the conclusion that the effects of zinc up to 4% are ordinarily small and may be insignificant in comparison with changes in properties occasioned by variations in foundry practice.

Silver. Electroplated bearings of three-layer construction[12] have been adopted in the aircraft industry. These bearings consist of steel shells electroplated with silver, which are then machined to very close dimensional tolerances and finally precision-plated to size, first with lead and then with indium or tin. This type of bearing has greater fatigue strength and higher load-carrying capacity than any other type used in aircraft at present (1947). Optimum fatigue strength and highest antiseizure properties are obtained only by using silver of the highest purity. Before use, the bearings are annealed so that the indium or the tin will diffuse into the lead. This annealing should be controlled carefully, so as to obtain the best results from the bearings in service.

Aluminum-Base Alloys. Since 1937 several aluminum alloys have been developed with mechanical and physical characteristics specifically adapted to meet the requirements of bearing applications. One of these materials, alloy 750,[13] has advanced to a commercial status and is being used to an increasing extent, particularly in heavy-duty engines. Alloy XA750[14] has been employed in a number of experimental applications, with promising results. Alloy XB750[15] is preferred for applications requiring higher strength. An Al-Cd-Si alloy[16] has performed favorably in a number of tests.

Aluminum bearings have been used chiefly in the form of homogeneous, single metal parts, which are preferably of relatively heavy section and are usually produced as permanent mold castings. The cast material may be used

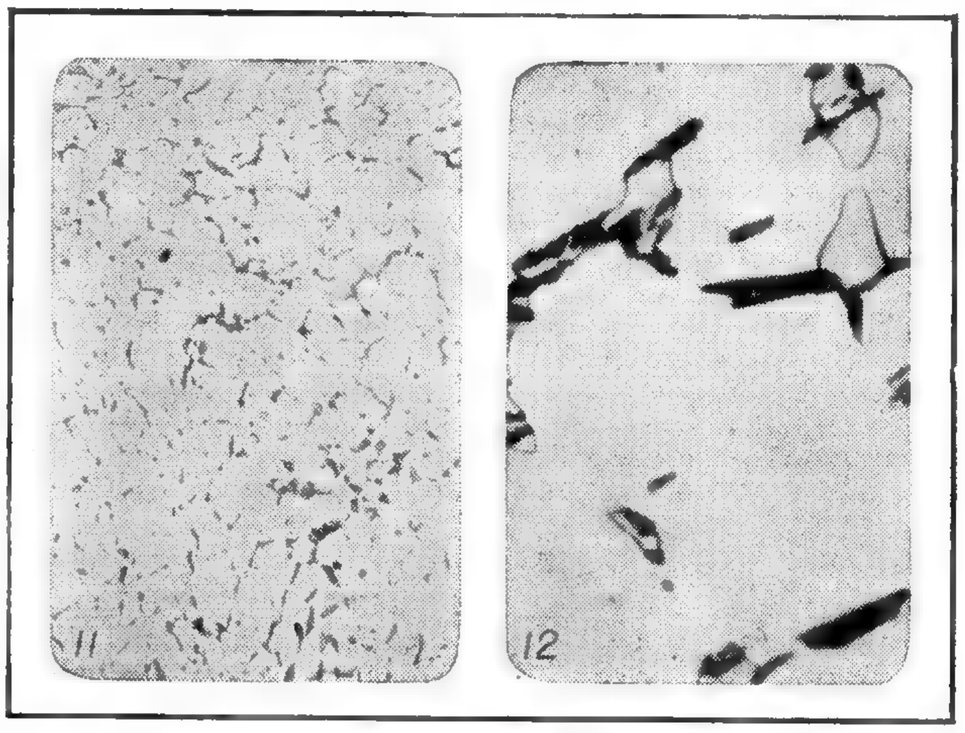

Fig. 11 Microstructure of permanent mold cast aluminum-base alloy 750–T5 in the heat treated condition, × 75

Fig. 12 Same as Fig. 11 except × 750. Outlined light particles, tin; acicular dark phase, $NiAl_3$; matrix, aluminum solid solution

in the heat treated condition or may be strengthened by cold working treatments. Recently alloy XB80S has been made available in the form of sheet, the mechanical properties of which are controlled by the final cold reduction. The Al-Cd-Si alloy also can be produced as sheet. When

Table XIX. Bearing-Fatigue Resistance and Antiseizure Properties of Various Bearing Materials Used in Alternating Load Applications

Except for the aluminum alloys, the materials are evaluated as steel-backed bearings under similar conditions. Aluminum alloys are evaluated as relatively thick, cast bearings.

Antiseizure Properties	Bearing-Fatigue Resistance: *Low*	*Low-Medium*	*High-Medium*	*High*
Very Poor				Tin bronzes Aluminum bronzes without lead
Poor				Silver 80–10–10 leaded bronze 88–4–4–4 leaded bronze 25% leaded bronzes
Medium		35% Pb copper-lead	28% Pb copper-lead with silver 25% Pb copper-lead with less than about 1% Sn	Aluminum-base alloys: 750 (cast) XB80S (rolled)
Good	Lead-base babbitts Tin-base babbitts	Cadmium-base alloys		

these aluminum alloys are used in ferrous housings, difficulties may result from differences between the coefficients of expansion of the two metals. Processes have been developed recently for bonding the aluminum bearing alloys to steel backing strip for thin automotive bearings.

The nominal compositions of the aluminum bearing alloys are listed in Table XVII.

The alloys have heterogeneous structures composed of a soft, low-melting constituent (tin or cadmium) and one or more relatively hard phases distributed throughout the aluminum solid solution matrix of moderate hardness (Fig. 11 and 12). These materials are characterized by high load-carrying capacity, high resistance to fatigue and excellent resistance to the type of corrosion encountered in bearing applications. However, the antiseizure properties are medium and the characteristics of embeddability are low, causing increased troubles at high surface speeds. Such troubles are experienced also with other hard bearing materials at high surface speeds.

Typical mechanical and physical properties of the aluminum-base bearing alloys are summarized in Table XVIII.

Fatigue Resistance, Antiseizure and Other Properties of Various Bearing Materials Used in Alternating Load Applications. Table XIX presents a classification that is necessarily crude. The antiseizure properties are very difficult, if not impossible, to measure in the laboratory. The ratings given are based on accumulated experience with materials that were in actual use as bearings. The resistance to fatigue can be measured quite accurately, but the fine differences are not considered here. It can be seen from the table that the stronger materials generally have poorer antiseizure characteristics. It is to be noted that the different materials, except the aluminum alloys, are evaluated as steel-backed bearings under similar conditions, for example, with the same thickness of layer. Solid aluminum bearings should be as thick as possible to provide the best performance. Table XIX refers to the results of tests on relatively thick aluminum alloy bearings.

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Industrial Poisoning by Metals

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POISONING by metals, though less common than other hazards to health in industry, is frequent enough and severe enough to have made the toxicology of metals important in some of the industries that produce and fabricate metals. The poisoning discussed in this article is chiefly that resulting from inhalation or ingestion of metal fumes and dusts. Dangers from radioactive metals are not mentioned here. Some of the other hazards incidental to the processes used in refining and working metals, are mentioned; however most of the pertinent information on such hazards is included in the articles that deal with technical processes in this Handbook.*

Toxicity of the nonferrous metals is discussed below in the alphabetic order of the metals. A summary in tabular form is presented on page 759.

Aluminum. Aluminum is a metal of very low toxicity. Small amounts have been ingested daily by a sizable section of the American public ever since the introduction of aluminum cooking utensils. Aluminum is now commonly cast, machined and welded with no trouble or special risk except that of fire.

Water-soluble fluoride salts are being used to some extent in the molding sand for aluminum castings. When hot aluminum is poured into the sand, it causes the evolution of a certain amount of fluoride salts and some free hydrofluoric acid, which can cause fluorosis. Similarly, there is a definite fluoride exposure during shakeouts, especially if the sand and casting are hot.

The risk of developing silicosis while cleaning castings is about the same as in iron foundries (*see the article* "Blast Cleaning of Metals"). During World War II, many tons of both magnesium and aluminum were cast, apparently without bad results. However, it is early to give the process a clean bill of health, and until it has been proved safe, special attention should be directed toward the ventilation of the working areas in both aluminum and magnesium foundries. (*See* Magnesium, page 757.)

Beryllium.[1,2,3] Numerous reports of poisoning by the fumes and dusts that accompany the concentration and purification of beryllium can be found in medical journals. Two types of lung disease are recognized as results of exposure to beryllium. The first of these, encountered among workers exposed to moderately high concentrations of beryllium dusts, consists in an acute inflammation of the lungs, which terminates in a few weeks in complete recovery or death. The second type of lung disease caused by beryllium is encountered among workers exposed to low concentrations of beryllium for long periods, and consists in a delayed, chronic inflammation of the lungs that clinically resembles the disease known as sarcoid. This condition may not be noticeable until many months after exposure is terminated, and may persist for months or years, ending in recovery or death from intercurrent infection. Intermediate types of lung involvement may be encountered.

The mechanism by which beryllium produces lung disease and the degree and type of exposure required are not understood as yet. Prevention of poisoning depends on control of exposure to the dusts and fumes encountered in industries using beryllium. Recent reports indicate that beryllium in any form is toxic, even in extremely low concentrations, and that extreme precautions are necessary in its handling. No safe working limits can be given at present.

Cadmium.[4-9] Most reported instances of industrial cadmium poisoning have followed the breathing of freshly formed cadmium oxide fume generated by the overheating and oxidizing of cadmium. This happens most frequently when cadmium-plated steel is mistaken for galvanized iron

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* *See, for example,* "Blast Cleaning", "Cyaniding", "Metal Spraying", "Radiography", "Welding", "Powder Metallurgy".

and is welded without any special precautions. This type of poisoning may result also from any other process that greatly overheats cadmium and permits the resulting cadmium vapor to burn. Cadmium boils at 778 C but oxidation begins at considerably lower temperatures, which accounts for the characteristic olive-drab streaks around vessels in which cadmium has been heated carelessly.

The ingestion of cadmium in food or drink can also result in poisoning, but such instances are usually non-industrial in origin. They may follow the taking of acid foods and beverages prepared in cadmium-lined containers. An overdose of cadmium by mouth produces a severe gastrointestinal upset with nausea, vomiting, diarrhea and abdominal cramps.

Cadmium compounds may be handled with relative impunity, provided they are not heated sufficiently to produce cadmium oxide fumes. Inhaled cadmium oxide fumes have a delayed but devastating effect. During the first several hours of exposure there may be no discomfort, or the worker may notice mild irritation of the eyes, dryness in the throat and a feeling of tightness in the chest. These symptoms are generally not sufficient to drive him from the contaminated atmosphere; consequently exposure is continued. About four to eight hours after exposure has begun, the toxic effects of the metal become severe and coughing, soreness in the chest and difficulty in breathing are noted. These disorders may progress to severe pain in the chest; bluish discoloration of skin and lips because of insufficient oxygenation of the blood; and in the lungs a collection of blood-tinged fluid that is coughed up and expectorated. Abdominal pain, nausea and vomiting may follow. Death occurs in a considerable proportion of cases, yet those workers who do recover are generally entirely well in a few weeks.

Cadmium poisoning should be suspected if any worker develops evidence of severe lung irritation several hours after exposure to fumes produced during the overheating or welding of plated metals. Inquiry should be made concerning the breathing of any brown or yellow fumes before the onset of symptoms. If possible, air should be analyzed for cadmium under conditions simulating the exposure. If a piece of work is suspected, the parts should be examined to determine whether they are cadmium-plated.

The treatment of acute cadmium intoxication is a serious emergency. The slightest delay can be disastrous. The affected worker should be removed from the contaminated atmosphere and placed at *complete* rest, no matter how mild his symptoms, because the effects of the poison are delayed. The slightest exertion may aggravate the condition seriously. Oxygen and sedatives should be administered if necessary. In general, further treatment should be similar to the measures employed for severe gassing by substances such as chlorine or phosgene.

Adequate ventilation should be provided whenever cadmium-coated metal is welded or overheated. The recommended maximum allowable concentration of 0.1 mg of Cd per cubic meter of air seems desirable when cadmium oxide fumes are encountered; but this limit is probably needlessly low if applied to cadmium in dusts resulting from the handling of unheated cadmium compounds. Respirators may be effective in preventing serious exposure when the fumes cannot be controlled by ventilation, but the use of respirators is not advocated. If adequate ventilation cannot be supplied, then the operation should be discontinued or modified. Certainly the use of cadmium-plated containers for the preparation or storage of food or drink should be prohibited.

Chronic poisoning after prolonged exposure to cadmium hydroxide, has been reported in French publications, but seems unknown in this country. It is said to be characterized by a prolonged latent period, during which yellow discoloration of the tooth enamel is the only evidence of intoxication, followed in four to eight years by weakness and lancinating pain localized in precise bony areas that give evidence of specific bone changes when X-rayed.

Chromium.[10–13] Metallic chromium and its trivalent salts are nontoxic under all ordinary circumstances, but chromium trioxide or chromic acid and the various chromates and dichromates are systemic poisons as well as powerful local irritants.

Industrial chromium poisoning follows contact with one or more of these hexavalent chromium compounds through exposure to an atmosphere that contains the material in the form of vapor, mist, spray or dust; through direct contact with solutions that contain the material; or through handling the dry substance in the form of crystals or fine powder. Exposure is most prevalent in the electroplating industry but is also encountered in a considerable number of trades involving exposure to chrome.

Industrial chrome poisoning is characterized by lesions of the skin or mucous membranes. The most common skin lesion is the chrome ulcer or "chrome hole", which may be single or multiple. It is a slowly developing, indolent, painless ulceration of the skin and underlying tissues, with indurated and undermined edges that produce a characteristic "punched out" appearance. Penetration is deep and healing is slow, generally leading to extensive and distinctive scarring. Exposure may also produce a more diffuse raised or blistered rash over the fingers, hands, arms, and face, and occasionally on the feet and chest. Finally, the mucous membranes of the nose and throat may be severely irritated or ulcerated. This frequently leads to perforation of the nasal septum. Such perforations may develop after only one week of exposure and they are permanent. Systemic chrome intoxication may occur, characterized by gastrointestinal and kidney involvement, asthma and muscular twitching, but such intoxication is too rare to be important industrially.

Chrome poisoning can best be prevented by avoiding exposure. All operations involving the production of chromate or dichromate dust or mist should be sufficiently well ventilated to ensure a concentration of not more than 1 mg of chromic acid anhydride in 10 cu m of air. Plating tanks should be ventilated by exhaust slots along each side, rather than by an overhead hood. Operations that involve the handling or grinding of dusts should be mechanized as much as possible, and local exhaust ventilation should be used extensively.

Chrome workers should be trained to practice careful personal cleanliness, and adequate sanitary facilities must be provided. Each man should wash, and change his clothing when leaving work. All cuts and scratches should be treated immediately and protected by waterproof plaster or protective ointments. Frequent medical inspection of the skin is desirable. Protective clothing should be supplied wherever possible, and care must be taken to prevent chromate solutions from entering boots or gloves and remaining in intimate contact with the skin for long periods. Protective ointments may also be useful in preventing chrome lesions.

Copper. Copper is unimportant as an industrial health hazard. Copper oxide fumes may induce metal fume fever, but such fumes are rarely encountered, since the vapor pressure of copper is low (for example, less than 0.0001 atm at a temperature 300 C above the melting point). Copper sulfate in powder or liquid form may irritate the skin, producing a troublesome chronic eruption. Chronic poisoning by copper has been reported as a cause of hemochromatosis, or bronzed diabetes; but at present almost all authorities agree that systemic copper poisoning occurs rarely if ever and that its etiological role in hemochromatosis is in doubt.

Lead.[14–23] All forms of lead are potentially toxic, but poisoning most commonly occurs after the inhalation of lead fumes and very fine lead dusts. The risk of serious lead poisoning increases with reduction in particle size and increase in the rate of solution. Thus, the mining and concentration of galena (lead sulfide) gives no trouble at present, but the careless smelting and roasting of the concentrates can easily cause lead poisoning. A skilled welder of lead does not burn or volatilize the metal, because he controls the flame temperature carefully, but the novice may use too hot a flame and get lead poisoning.

The entrance of lead into the body does not mean that lead poisoning has occurred or will occur. Practical experience and systematic investigation have demonstrated that certain levels of occupational lead exposure and absorption are compatible with normal healthy existence and activity. Furthermore, the finding or existence of excessive

lead absorption and excretion in an individual who feels reasonably well and continues his work, does not constitute lead poisoning. Even poor appetite, constipation, a lead line and stippling are not considered symptoms. Lead poisoning should not be diagnosed unless the effects of lead absorption are sufficient to cause the individual to lose his sense of well-being and to complain of being ill.

Lead may enter the body by inhalation or ingestion. Either route may end in lead poisoning, but inhaled lead is decidedly more toxic than swallowed lead. All body tissues are exposed to lead after its absorption. The blood, muscles, kidneys and nervous system may be seriously injured by exposure to lead while the bones, liver and intestinal tract remain relatively unaffected by its presence. Lead enters the circulation at a variable rate, depending on the degree, type and severity of exposure. It is removed from the circulation by the intestines, which excrete it in the feces; by the kidneys, which excrete it in the urine; and by the skeletal system, which stores it in considerable amount in the mineral structure of the bones. The concentration of lead in the blood stream is determined by the relative rates at which it is absorbed and excreted or stored.

Interruption of lead absorption by the halting of exposure usually produces a gradual decrease in the amount of circulating lead. However, the return of lead from the bones to the circulation may maintain a toxic level for some time after exposure has been discontinued, and the sudden release of lead from the bones may produce an abrupt rise in levels of circulating lead, with the occurrence of toxic symptoms, even in the absence of further lead absorption. This phenomenon is generally encountered during periods of intercurrent illness, such as pneumonia, and may seriously impede recovery.

The amount of lead present in the circulation and in tissues other than the bones, may be estimated from the daily fecal and urinary lead excretion. The relation between the rate of lead excretion and the occurrences of lead intoxication is not absolute, but it is generally accepted that the excretion of more than 1.1 mg Pb in the feces in a 24-hr period, or the presence of a urinary lead concentration above 0.15 mg per liter is indicative of amounts in the blood and tissue sufficient to produce lead poisoning.

The recognition of early or mild lead poisoning is obviously an important means of preventing advanced or severe involvement. Lead poisoning can be detected best in its incipient state by regular and systematic investigation of exposed workers. The following investigations are useful in establishing the existence of lead poisoning.

1 Inquiry into the time and place of exposure to lead, with substantiation of conditions.
2 Careful examination of the worker for any symptoms or signs of lead poisoning.
3 Examination of the blood, with particular attention to the number of basophilic stippled red blood cells.
4 Analysis for lead in a chemically clean 24-hr specimen of urine or of a blood sample. If it is impractical to obtain a 24-hr sample, a reasonable estimate of the lead excretion can be made from a single specimen, preferably one passed early in the morning on arising. In calculating the total daily excretion, the relation of the sample volume to the 24-hr urine output should be estimated, and the total values figured on this basis. The finding of more than 0.10 mg Pb per liter of urine in a 24-hr specimen, or of a whole blood concentration in excess of 0.05 mg Pb per 100 ml in an individual with symptoms of lead poisoning, clinches diagnosis.

Industrial lead poisoning is prevented by reducing workers' lead absorption to the lowest possible level by the use of proper ventilation and housekeeping; and by regular periodic examination for evidence of lead intoxication of workers unavoidably exposed to these lowest possible levels. Such workers should be subjected to a careful physical examination, with elimination of unfit individuals. In addition, lead workers should be re-examined periodically while at work; the frequency of examinations may be varied according to the degree of exposure. Laboratory studies should be performed at least every six months, and oftener if the exposure is severe or if symptoms develop. Complete blood counts should be performed along with routine urinalyses and the special examinations outlined.

Workers with evidence of early lead intoxication should be removed from exposure until such evidence disappears. Most authorities believe that this waiting period can be accelerated by the use of deleading therapy under competent medical supervision. Indiscriminate, unsupervised deleading should be avoided. Individuals who show signs of lead intoxication repeatedly, after relatively slight exposure, should be transferred to other employment.

Recovery from lead poisoning is usually complete, leaving no disability of any sort.

Magnesium.[24–27] In the handling and use of magnesium and magnesium alloys, no toxic effects are caused by the metal itself; however, certain of the materials used in processing, particularly in founding, may impair health.

Magnesium is ordinarily used in the form of alloys that contain from 90 to 98% Mg. Since magnesium oxidizes at elevated temperatures and burns when heated above the melting point, protective agents or inhibitors are used in certain production operations. The protective agents may be used in several different ways in the foundry: (1) as fluxes on molten metal, (2) as agents added to molding sand, (3) as furnace atmospheres for heat treatment.

The fluxes used in melting and treating the metal may give rise to considerable amounts of acid fumes—principally hydrochloric acid—if the fluxes have picked up moisture from exposure to air or if hot sludge from the pots is exposed to the air. During periods of high humidity, the fumes can be very irritating to the nose and eyes, so that control measures may be necessary.

The common inhibitors mixed into the molding sand are sulfuric acid, boric acid, sulfur, and various fluorides. These fluorides will give rise to fluoride fumes. Practical experience has shown that concentrations in excess of about 10 mg per cu m, measured as HF, are likely to cause a prickling sensation in the nose, running of the nose, and slight nosebleeds. The nosebleeds may recur frequently for some days. Considerable apprehension has been felt that heavy exposures to fluoride fumes might cause fluorosis, a serious malady, but practical experience has not shown these fears to be justified. However, it may be too early (1947) to be sure that some fluorosis will not result, since many years may be required for the development of this condition. It would be common sense to insist that all workers who are exposed to fluoride fumes be examined routinely by a competent physician; and to design the magnesium foundry so that fluoride concentrations are kept below 3 mg per cu m, the ASA limit.

Sulfur dioxide may arise from the following sources: burning sulfur from the flux used in pouring operations; or sulfur dioxide gas used for flushing molds before pouring, and for maintaining suitable atmospheres in heat treating furnaces. This gas may readily cause acute irritation and pain in the nose, chest and eyes, but seldom causes serious injury. Difficulty is readily avoided by having adequate ventilation in the foundry and by using heat treating furnaces that are gastight.

It is possible to contract a mild type of metal fume fever from breathing freshly generated magnesium oxide fumes, but the required dosage is so heavy that it would seriously reduce visibility, and so far it has not been a problem.

Manganese.[28, 29] Poisoning by manganese is very rare and has been limited entirely to industry. Either breathing fine manganese dusts or swallowing manganese compounds in food or drink, can affect the central nervous system and produce disability that may be serious, total and permanent. Inhalation of manganese dust is the principal danger and, as far as is known, manganese poisoning does not occur if the dust from operations is controlled.

Manganese paralysis resembles Parkinson's disease (paralysis agitans) and can easily be mistaken for it, though the causes and sequelae of the two are entirely different. Manganese poisoning occurs only after prolonged and repeated exposures to finely divided dusts rich in manganese. Industrially such exposures are generally limited to the milling or grinding of manganese compounds, such as the oxides. Theoretically, it would be possible to breathe toxic doses in the manufacture or welding of manganese steels, of ferromanganese and spiegeleisen; but actually such poisoning has been virtually unknown up to the present. Special apprehension has been expressed for men welding manganese steels, but again, the results have not warranted these fears.

Safe concentrations in air have been set at ▮ mg (as Mn) per cu m, a limit easily maintained in industrial operations. Where ventilation is impracticable, occasional exposures to manganese dusts can be avoided effectively by the use of dust respirators.

Mercury.[30, 31] Industrial poisoning from mercury is seldom encountered at present. It may occur among miners working ores that contain native quicksilver, or among those engaged in refining the ore if old-fashioned furnaces with inadequate condensers are used. Laboratory workers have been affected through the careless overheating of mercury or electrical contacts, or through poor housekeeping. A possible source of mercury poisoning is the handling of wet-cell plates from the reclaiming of Zn:Hg batteries.

Acute mercury poisoning is well known and, though often caused by the accidental or deliberate ingestion of bichloride of mercury in the home, is almost never encountered in industry. Industrial mercurialism is a chronic, slowly progressing disease, produced ordinarily by the inhalation of small amounts of mercury vapor over a long period of time. It is characterized by muscular tremors (hatter's shakes), inflammation of the mouth with loosening of the teeth, an excessive flow of saliva, and psychic irritability and depression. One, two or all of the above symptom complexes may be present in a given instance.

Chronic mercurialism may be curbed by withdrawal of the worker from the contaminated atmosphere. Prevention depends on careful housekeeping methods to reduce the concentration of mercury to less than the accepted safe level of 0.1 mg per cu m of air.

Molybdenum.[32] Industrial exposure to molybdenum is encountered during nearly all stages in the mining, refining, and alloying of this metal. Miners are exposed to molybdenite dust, MoS_2; refiners to calcium molybdenite, and steel mill workers to molybdic oxide arising from hot billets of molybdenum steel during rolling. No injury has been reported from any of these exposures. Fairly extensive investigations of the toxicity of molybdenum, conducted at the Industrial Hygiene Laboratory of the National Institute of Health, reveal that the toxicity of molybdenum is of a relatively low order and that chronic poisoning by this substance is unlikely, since it is eliminated from the body fairly rapidly when exposure is discontinued. Reasonable care to avoid gross overexposure to molybdenum dusts or fumes should prevent effectively the occurrence of any ill effects from this substance.

Nickel. Nickel in the form of pure metal or nickel salts is toxicologically unimportant. No specific health hazards exist in the nickel industry, and no special precautions are necessary in handling this metal. Men engaged in nickel plating may develop an eczematous vesicular dermatitis ("nickel itch") affecting primarily the hands and arms, after contact with nickel sulfate or nickel cyanide solutions employed in the electrolytic bath. Some authors attribute this effect on the skin to the caustic action of nickel salts. Isolated and poorly substantiated reports of poisoning by nickel dusts are encountered in technical publications.

An exception to the general harmlessness of nickel compounds is nickel carbonyl. This poisonous gas (boiling point, 43 C) may produce effects ranging from headache, giddiness, unsteady gait and nausea to severe dyspnea, cyanosis, fever, cough, and delirium, followed by gradual recovery or death, either immediately or in three to eleven days. The Mond process for the production of pure nickel, involves the generation of nickel carbonyl and is performed carefully under controlled conditions that prevent escape of the gas.

Precious Metals. Industrial poisoning by the precious metals (gold, silver, platinum, palladium, iridium, osmium, rhodium and ruthenium) is virtually unknown. Serious poisoning by silver and gold have been reported frequently, following their administration as therapeutic agents in medicine; and it is theoretically possible that industrial poisoning by some of the precious metals could occur.

These substances are handled with extreme care, however, because of their intrinsic value, so opportunities for inhaling or ingesting their fumes or dusts are uncommon.

Selenium.[33] It is well established that the ingestion of selenium, as in fodder for cattle, can produce serious gastrointestinal damage not unlike metallic poisoning in general. Some industrial poisoning by selenium has been reported in the earlier technical publications, but it was limited largely to the refining of elemental selenium and tellurium from sludges collected in the electrolytic refining of copper. Garlic breath, like that from tellurium, has been ascribed to selenium, but it is certainly much less troublesome than with tellurium.

Industrially, selenium has not proved to be a toxic problem. Selenium is now being used extensively in the manufacture of photoelectric equipment and rectifiers. It is distilled under vacuum and condensed on disks that are handled manually. No toxic symptoms result if working conditions are good and suitable ventilation is provided.

Tellurium.[34, 35] The inhalation or swallowing of tellurium dusts or fumes can cause a garliclike breath that persists for some days or even weeks, after exposure has ceased. No other ill effects may be experienced and there is no evidence that organic injury necessarily follows. The feeding of very large doses of elemental tellurium can produce severe intestinal damage and even death, but in industry exposures are far too slight to cause real harm.

Industrial exposures to tellurium occur when pellets of the element are added to molten metals to produce alloys. Some tellurium is volatilized, oxidizes, and the fumes rise and mix with those from the ladle. Prevention of the garlic breath can be accomplished readily by means of proper ventilation, eliminating exposure to the fumes.

Thallium.[36, 37, 38] Industrial poisoning from thallium is infrequent. The symptoms are mild and disappear entirely after the termination of exposure. No deaths have been reported. The possibility of serious poisoning from the careless handling of thallium or thallium salts in industry, must be considered, however, because this substance is highly toxic. Many instances of serious or fatal poisoning following the accidental or therapeutic ingestion or external application of this substance, have been reported. One gram of thallium is considered capable of causing death in the average adult, and thallium salts have been shown to be more toxic than lead salts. The infrequent occurrence of industrial thallium poisoning is probably related to the relatively high cost of thallium and to the consequent care with which it is handled.

The characteristic sign of thallium poisoning is rapid loss of hair within a period of about three weeks after intake of the substance. This is preceded and accompanied by a variety of nonspecific symptoms from the gastrointestinal and nervous systems. Dermatitis and kidney damage may also occur. After the substance has been withdrawn, all symptoms disappear and hair returns.

Except for careful handling of thallium, no specific health measures appear to be necessary. Workers who develop symptoms in the gastrointestinal or nervous system, or whose hair suddenly begins to fall out, should be withdrawn from contact with thallium or its salts until the symptoms have disappeared.

Tin. Poisoning by tin is almost unknown. The innocuous nature of this metal is attested to by the complete absence of tin poisoning among the general population, all of whom ingest considerable quantities of tin dissolved from the linings of tin-plated cans.

Vanadium.[39, 40] Vanadium fumes are capable of producing moderately severe toxic reactions. Workers exposed to vanadium pentoxide, in factories producing vanadium and ferrovanadium, develop conjunctivitis, nasal irritation, and fairly severe bronchitis with an irritating cough. Gastrointestinal disturbances with nausea and vomiting may occur but are infrequent. Fumes containing vanadium anhydride are extremely irritating and produce a reaction similar to that experienced after the inhalation of zinc oxide fumes. No permanent ill effects and no nervous system involvement have been reported.

Zinc.[41–44] Poisoning from zinc is limited to two sources: (1) the ingestion of food or drink heavily contaminated with zinc and (2) the breathing of fairly heavy concentrations of freshly formed zinc oxide fumes. There is no evidence of any cumulative or additive effect from either of these sources.

Zinc oxide fumes are formed when metallic zinc is

heated to temperatures considerably below its boiling point (906 C). For instance, the vapor pressure of zinc is 0.1 atm at 720 C. Any process that produces this oxide is a potential source of metal fume fever, known industrially by various names, such as "spelter shakes", "zinc shakes", "brass chills", and "galvo". An attack of metal fume fever is characterized by a rise in body temperature, an increase in the white blood cell count, and a cough, varying from a trifling irritation to paroxysms that induce vomiting. The reaction is usually accompanied by a distinct sweetish taste. About eight hours after exposure, chills may occur and the body temperature may rise to 103 or 104 F. The temperature then gradually subsides and usually is normal the next morning, but the high white blood count (leucocytosis) persists for an additional 12 to 24 hours. The experience may remind the patient of his reaction to an inoculation against typhoid fever. It is probably because of the absorption of proteins from the respiratory tract, but just why zinc oxide should have this effect while other fairly inert oxides do not, is as yet unexplained. A similar but much less severe reaction follows the inhalation of heavy concentrations of magnesium oxide from burning magnesium ribbon. Reactions ranging from severe to fatal follow the inhalation of fresh cadmium oxide, but no reaction at all is induced by breathing freshly formed ferric oxide or aluminum oxide.

Metal fume fever from zinc oxide is an unpleasant experience that lasts only a few hours. There is no cumulative effect and the patient is not made susceptible to more serious respiratory maladies such as tuberculosis or pneumonia. It has been shown that temporary resistance to a second attack of metal fume fever is acquired as a result of the first attack and lasts apparently as long as the white corpuscle count remains elevated. This acquired resistance (not true immunity) probably explains the fact that severe attacks of metal fume fever are unlikely to occur on successive days.

Metal fume fever is most likely to trouble workers engaged in the smelting of zinc, the manufacture of zinc oxide and zinc powder, the manufacture of the brasses—especially those high in zinc—and the welding (gas or electric) of galvanized iron.

In the welding of ordinary steel, solid fume particles evolve to the extent of about 4% of the weight of the rods burned. Welding on galvanized iron produces more fume—about 9% of the weight of the rods burned. From these figures may be calculated the ventilation necessary to keep the total fume concentration (as weighable solids) below 30 mg per cu m, the figure adopted by the Navy and Maritime Commission in their Health and Safety Standards during World War II. However, this figure is not low enough to ensure good visibility for the crane operator in a large machine shop; 10 mg would be better.

In general, prevention of zinc fume fever is easy—keeping average concentrations to which workers are exposed below about 15 mg of ZnO per cu m per 8 hr. This specification works no special hardship on the manufacturer and is easily attained. For short exposure, respirators of a quality approved by the Bureau of Mines are entirely practicable.

Poisoning occurs sporadically from food or drink contaminated with zinc. The commonest cause is the dissolving of zinc by acid or fruit juice, such as lemonade. Obviously, liquid foodstuffs should not be stored in zinc or zinc-lined containers, but galvanized iron sheets are well adapted to the lining of refrigerators, bins for grain storage, water reservoirs and the like, for which they have been used for years.

There is no specific treatment for metal fume fever. Palliative measures, such as hot baths, hot drinks and the like, relieve the patient somewhat, but do not alter the course of the attack.

Poisoning by ingested zinc is self-limiting. Treatment consists of the general supportive measures employed in any severe gastroenteritis.

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Industrial Poisoning by Metals

Metal	Acute Poisoning: Frequency and severity	Acute Poisoning: Principal route of entry of metal	Acute Poisoning: Principal organic systems affected	Chronic Poisoning: Frequency and severity	Chronic Poisoning: Principal route of entry of metal	Chronic Poisoning: Principal organic systems affected
Lead	Rare, severe	Inhalation (and ingestion)	Intestinal tract, respiratory tract	Fairly common, mild to severe	Inhalation or ingestion	Blood, intestinal tract, nervous system
Mercury	Rare, severe	Inhalation or ingestion	Kidneys or intestinal tract	Occasional, mild formerly frequent and severe	Inhalation	Teeth, gums, nervous system, intestinal tract
Cadmium	Rare, severe often fatal	Inhalation	Respiratory tract, general systemic reaction	Not reported in U. S. A.	.....	.....
Zinc	Frequent, mild	Inhalation	General systemic reaction	.....	.....	.....
Nickel	Rare, severe from Ni carbonyl	Inhalation	Lungs	.....	.....	.....
Manganese	.....	.....	.....	Rare, severe, permanent	Inhalation or ingestion	Central nervous system
Tellurium	Fairly common, not serious	Inhalation	Causes garlic breath	Fairly common, not serious	Inhalation	Causes garlic breath
Selenium	Rare	Inhalation	Causes garlic breath and systemic poison	.....	.....	.....
Thallium	Rare, mild	Inhalation, skin absorption and ingestion	Loss of hair, effect on nervous system	.....	.....	.....
Beryllium	Moderate, severe	Inhaling fumes or dusts	Lungs	Moderate, severe	Inhaling fumes or dusts	Lungs
Vanadium	Occasional, mild	Conjunctival naso-pharyngeal irritation	Eyes and respiratory tract	.....	.....	.....

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ALUMINUM AND ALUMINUM ALLOYS

Prepared under the chairmanship of

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Aluminum Company of America

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Aluminum (99.0+ Al)	810	Al – 4 Cu – 3 Si	826
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Al – 5.5 Cu – 0.5 Pb – 0.5 Bi	812	Al – 7 Cu – 2 Si – 1.7 Zn	828
Al – 4 Cu – 0.6 Mn – 0.6 Mg – 0.5 Pb – 0.5 Bi	813	Al – 7 Cu – 3.5 Si	828
Al – 4.4 Cu – 0.8 Si – 0.8 Mn – 0.4 Mg	813	Al – 10 Cu – 0.2 Mg	829
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Al – 4 Cu – 0.5 Mg – 0.5 Mn	815	Al – 12 Si – 1.5 Cu – 0.7 Mn – 0.7 Mg	830
Al – 4 Cu – 2 Ni – 0.5 Mg	816	Al – 4 Cu – 2 Ni – 1.5 Mg	831
Al – 4.5 Cu – 1.5 Mg – 0.6 Mn	817	Al – 4.5 Cu	832
Al – 4.5 Cu – 0.8 Mn – 0.8 Si	818	Al – 4.5 Cu – 2.5 Si	833
Al – 12.5 Si – 1.0 Mg – 0.9 Cu – 0.9 Ni	818	Al – 3.8 Mg	834
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Al – 2.5 Mg – 0.25 Cr	820	Al – 8 Mg	834
Al – 1.3 Mg – 0.7 Si – 0.25 Cr	820	Al – 10 Mg	835
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The Aluminum Industry

By Junius D. Edwards*

ALUMINUM as an element was discovered in 1825 and the commercial history of it covers only 60 years. It is one of the principal metallic products of the electrochemical industry.

Occurrence. The principal ore of aluminum, bauxite, comprises the hydrated oxides of aluminum, $Al_2O_3.3H_2O$ and $Al_2O_3.H_2O$, together with associated impurities, such as the oxides of iron, silicon and titanium. Bauxite is produced by the weathering and alteration of aluminum silicate rocks, and is widely distributed around the world, usually in tropical and semitropical regions, where the weathering processes have proceeded at an accelerated pace. At the present time, the principal supplies of bauxite come from the United States, Suriname, British Guiana, France, Hungary, Italy, Jugoslavia, Russia, and the Netherlands' Indies. Bauxite is thus not a rare ore, and its principal value, when delivered in refined form for the electrolytic production of aluminum, lies in the transportation charges and chemical refining costs incident to its purification. The bauxites used for the production of aluminum contain about 50 to 65% alumina; about four pounds of bauxite is necessary, therefore, to produce one pound of aluminum. It has been esti-

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mated that enough bauxite is in sight to supply the world with aluminum for the next several centuries.

Extraction or Refining Methods. In the electrolytic reduction of aluminum oxide, any impurities, such as the oxides of iron, silicon and titanium, are reduced along with the alumina. Therefore the alumina used is first refined by removal of these impurities. It is essential to start with raw materials of the highest purity, and this includes not only the alumina but the carbon electrodes and the fused electrolyte employed in the process.

The Bayer process is almost universally employed for the purification of bauxite. In this process the bauxite is digested with caustic soda solution, under pressure, and the alumina is dissolved out as a solution of sodium aluminate. The residue, known as "red mud", contains the oxides of iron, silicon and titanium, and is separated by settling and filtration. Aluminum hydrate is separated from the solution of sodium aluminate by seeding and precipitation and is converted to the oxide, Al_2O_3, by calcination.

The electrolytic reduction process is based on the discovery by Charles M. Hall that molten cryolite dissolves alumina, and that aluminum can be separated continuously from the molten solution at about 1000 C by electrolysis. The electrolytic reduction takes place in large cells that consist of a steel shell lined with carbon, forming an inner cavity in which the cryolite electrolyte is held. The carbon anodes, dipping into the electrolyte, introduce the current which separates the metallic aluminum electrolytically and provides the heat that keeps the bath liquid. Molten aluminum deposited on the bottom of the cell is withdrawn from time to time, as it collects. This primary aluminum of commerce ranges in purity to about 99.9%, depending on the care and skill with which the raw materials have been prepared and the reduction process carried out. Aluminum of purity as high as 99.99% can be produced by the Hoopes electrolytic refining process, in which aluminum is dissolved electrolytically from a molten aluminum-copper alloy and is deposited in a layer of pure aluminum, acting as cathode and floating on the molten electrolyte that separates the anode from the cathode layers. The production of a pound of aluminum requires about 10 kwhr of electrical energy, so cheap electric power is essential for the commercial production of aluminum.

Principal Products. The aluminum sheet of commerce, usually designated 2S, has a nominal purity of about 99.2%. It is, in fact, an alloy containing small amounts of iron and silicon, and its strength is substantially increased thereby. Another commonly used wrought alloy, known as 3S, contains 1.2% Mn. The principal elements used in the production of aluminum alloys are copper, silicon, manganese, chromium, magnesium and zinc. Since the invention of duralumin and the discovery and explanation of heat treatment effects in aluminum alloys, a series of heat treatable aluminum alloys has been developed. In certain wrought forms, tensile strengths above 80,000 psi are now obtainable. The alloys that can be heat treated are frequently referred to as the "strong alloys of aluminum" and greatly extend the field of application of aluminum.

Uses. Aluminum and its alloys can be worked and fabricated by the usual metal working processes, such as rolling, stamping, spinning, drawing, extruding, and forging, and can be produced in the form of castings by the sand, permanent mold, or die-casting processes. Except for magnesium and beryllium, aluminum is the lightest of the structurally useful metals. In the transportation field, it is not only the lightness of aluminum and its alloys, but the high mechanical properties obtainable by alloying and heat treating, which make aluminum suitable for light-weight structures.

Aluminum and its alloys can be joined by riveting, welding and brazing. Welding is done by torch methods, or electrically by arc and electric-resistance welding methods. There are some limitations, however, to the welding of heat treated alloys, because the heat of welding removes some of the effects of heat treatment.

Aluminum has good electrical conductivity, about 61% that of copper, volume for volume; weight for weight, the conductivity of aluminum is about double that of copper. High electrical conductivity, combined with good resistance to weather and with adequate mechanical properties, accounts for the use of more than 1,250,000 miles of aluminum cable, reinforced with steel.

Aluminum is also a good conductor of heat. This property is utilized in such varied applications as cooking utensils, and pistons and cylinder heads for internal combustion engines.

Aluminum is a good reflector for radiant energy throughout the spectral range, from ultraviolet through the visible range and into the infrared. It is being employed in thin films on the reflectors of the most modern telescopes, it is widely used for light reflectors in the illuminating industry, and its high reflectivity for infrared radiation is giving it a unique field of usefulness for thermal insulation. The

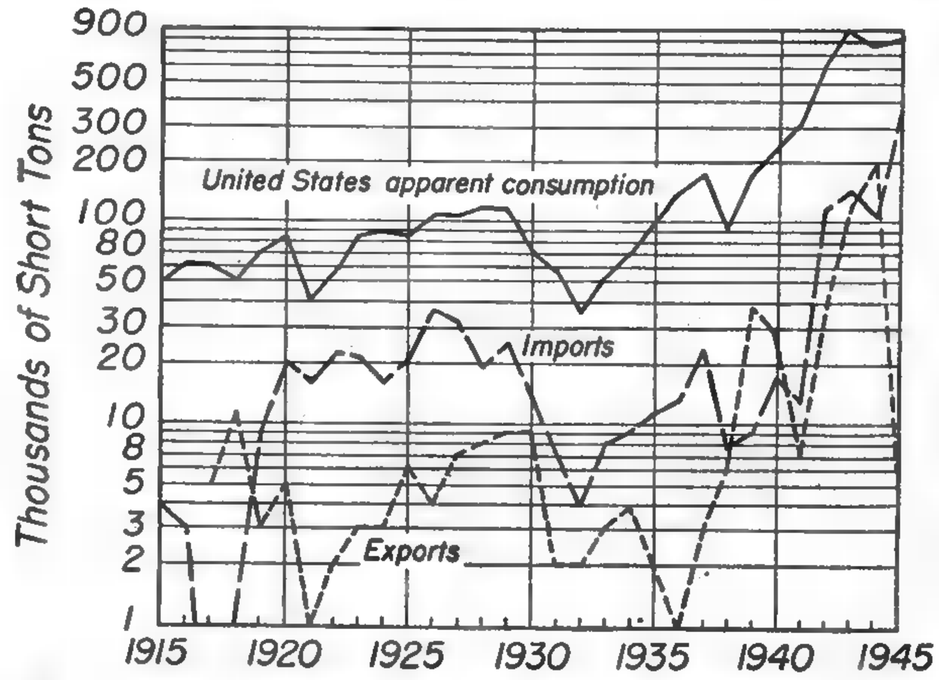

Fig. 1 Trends in imports, exports, and apparent consumption of aluminum, 1915 to 1945. (U. S. Bureau of Mines Minerals Yearbook, 1945)

usefulness of aluminum as a practical light reflector has been extended by the Alzak process, which includes electrolytic brightening to develop maximum reflection, coupled with an electrolytic oxide coating to provide a glasslike, transparent, weather-resistant and cleanable surface. In the thermal insulation field, aluminum foil, with its high reflectivity for thermal radiation and its low radiating power or emissivity for the same type of radiation, gives a high insulating effect to a structure comprising sheets of aluminum foil separated by air spaces.

In contact with moist air aluminum forms a thin, impervious film of oxide, which helps protect it against further attack. Aluminum can be electrolytically oxidized to give it a thicker oxide film of great hardness and resistance to corrosion. These anodic oxide films can be colored by the

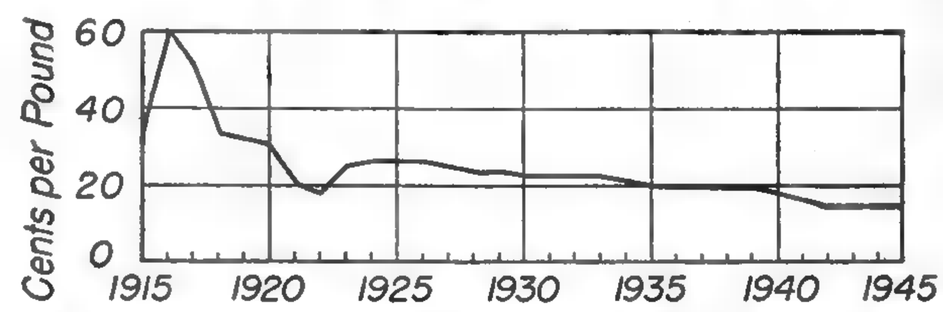

Fig. 2 Trend in average quoted price of aluminum, 1915 to 1945. Price is for No. 1 virgin ingot, 98 to 99% Al at New York, through 1929. Thereafter for "99% plus" virgin ingot, as reported by American Metal Market. (U. S. Bureau of Mines Minerals Yearbook, 1945)

absorption of dyes or by impregnation with inorganic pigments.

Aluminum has a high heat of combustion, and this affinity for oxygen is the basis of the thermit welding process, in which the reaction between finely divided aluminum and metallic oxides, such as iron oxide, produces a molten ferrous alloy at a high temperature.

Another chemical use of aluminum is as a deoxidizer in the manufacture of iron and steel. Gas-free steel ingot is produced by exploiting the great affinity of aluminum for oxygen.

In finely divided flakes aluminum makes an excellent paint pigment, supplied as either aluminum powder or aluminum paste. Aluminum paint made with this pigment

forms a durable and protective coating for both metal and wood. Relatively impervious to penetration by moisture, and opaque to sunlight, this coating conceals and covers well, remaining protective over extended periods, even under conditions of severe exposure.

Statistics. During the war, aluminum production facilities were expanded sevenfold to supply the material needs of the Air Force, Army and Navy. In the postwar era much less aluminum will be needed for aircraft and other military applications. However, civilian uses for aluminum will undoubtedly show substantial increases, because manufacturers and metal workers have gained extensive experience and familiarity with this metal during the war. Research and development have provided a sound fundamental knowledge of aluminum, on which to base these extended applications of the metal. Statistics regarding the trend in consumption and price of aluminum for the period from 1915 to 1945 are given in Fig. 1 and 2.

The pattern of postwar aluminum consumption has differed significantly from the prewar period; the principal change has been in the increased use of aluminum for building construction. One producer (Alcoa) reports the following shipments for 1946, according to industries:

Aluminum Consumption in 1946

Building products	18%
Transportation (land, sea and air)	14
Cooking utensils	11
Machinery (general and electrical)	6
Household appliances	6
Power transmission	5
Aluminum fabricators for further processing	25
All other uses	15

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The Production of Finished and Semifinished Aluminum Alloy Castings

By H. J. Rowe*

ALTHOUGH the properties and inherent characteristics of the aluminum alloys themselves account for the use of aluminum castings in many applications, in other instances the variety of commercial processes by which such alloys can be cast provides important economic advantages. Selection of the most satisfactory casting process became especially important during the war, because of the effect on conservation of production man-hours, machining man-hours and materials. Judicious selection is equally important today because of the effect it can have on the cost of producing a particular item.

Casting Processes

The selection of the casting process best suited to any particular application depends on both technical and economic considerations; that is, on such features of functional design as the size and shape of the part, limitations of section thickness, the dimensional tolerances desired, and the surface finish required. The number of parts required and the amount of subsequent machining and finishing are also factors to be considered. Because each casting process possesses certain distinctive design requirements, it is easier to design a part to be made by a particular process than to modify it later. A designer can benefit greatly by determining the requirements of the process, preferably after consultation with the ultimate producer, before setting up the design.

Sand Casting. Because it is widely adaptable, the sand-casting process is still the best known and most frequently used. It is employed for production in small quantities and for production of parts requiring intricate coring, as well as for production of large parts. Castings weighing from a few ounces to 500 lb are common products of the sand foundry and castings weighing as much as 7000 lb have been produced successfully.

The sand-casting process for production of aluminum alloy castings differs in no essential way from that used for production of castings made of other metals, both nonferrous and ferrous. To produce the expendable sand mold, a suitable pattern is employed, with the required allowances for shrinkage and subsequent finishing. When cores are required, they are produced in core boxes and it may be necessary to provide core driers. Such equipment is somewhat lower in initial cost than equipment for certain of the other processes discussed later, but sand-casting equipment provides a more limited life. Production rates are controlled by the type of pattern equipment as well as molding equipment, and may range from a few parts per day for large castings using loose pattern equipment, to several hundred per hour for small castings using metal match-plate pattern equipment.

The minimum thickness of section that can be cast in aluminum depends largely on the size, pressure requirements and intricacy of design of the casting. Although sections of the order of ⅛ in. have been satisfactorily provided in small sand castings, $\frac{3}{16}$ in. is generally considered the minimum for castings of small and medium size.

The surface of sand castings will vary in smoothness, depending on the physical characteristics of the sand. Relatively smooth surfaces can be obtained with fine sand, but the use of such sand is limited to rather small castings. For larger castings somewhat coarser sand is desired, because the increased permeability of the mold makes for a sounder casting. In general, aluminum sand castings have smoother surfaces than sand castings of the other metals.

Dimensional tolerances in sand castings will vary with the size of the casting, the type and accuracy of pattern equipment, and the molding technique used. Tolerances of plus or minus $\frac{1}{32}$ in. can generally be maintained for small castings, but greater tolerances are required for larger castings. Hence, sand castings must normally be machined to meet close dimensional tolerances, and allowance for such machining is necessary. Normal practice is to provide about ⅛ in. for such finishing on small and medium-sized castings. Large castings usually require ¼ in. or more as allowance for finishing, particularly on surfaces cast in the cope of the mold.

The sand-casting process permits the use of a number of aluminum alloys, providing a variety of physical and mechanical properties, in both the as-cast and heat treated conditions. (*See* pages 824 to 840.) The selection of alloy, although normally influenced by these properties, should also take casting characteristics into consideration. These vary sufficiently to have frequently an important influence on the cost and utility of the final part. Such factors as hot shortness, pressure tightness, tendency toward solidification shrinkage, and susceptibility to gas absorption are frequently controlling factors in the selection of an alloy. The most common of the sand-casting alloys are rated in Table I with regard to these characteristics.

Casting in Permanent Molds. Castings produced by the permanent mold process, or gravity die-casting process, as it is called in England, are known for their metallurgical superiority. For this process, metal molds and cores are used; the casting alloy is poured into the mold cavity under a normal gravity head, as it is in the sand-casting process. A variation, known as the semipermanent mold process, employs dry sand cores instead of metal cores. This difference greatly increases the possible applications for the permanent mold by overcoming many of the restrictions that

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are imposed on the design by metal cores. The chill imposed by the metal mold results in a refinement of grain and reduction in porosity in the final castings, with a consequent substantial improvement in the strength as compared with that of similar sand-cast parts. Permanent mold and semipermanent mold parts weighing from a few ounces to 20 lb are common foundry products, but permanent mold parts weighing as much as 250 lb, and semipermanent mold castings weighing as much as 500 lb have been produced.

Mold equipment usually consists of two or more parts suitably hinged or mounted on slides for ready opening and closing. This equipment is constructed from a good grade of dense cast iron and has cavities machined to the desired contour. Metal cores, when required, are usually machined from alloy steel. Sand cores are of the same general type as those used for sand castings and require the same material and equipment for production. The cost of such molds depends on their complexity and the casting tolerances desired. Normally this cost exceeds that of the best pattern equipment but can be justified where requirements of production are sufficient. Rates of production are controlled by the time required for the metal to solidify and the complexity of the mold operation. For small simple parts, permitting the use of multiple-cavity molds, production rates as high as 100 parts per hr can be obtained, although in specific instances even higher rates have been attained.

As with sand castings, it is difficult to state the minimum thickness of section that can be provided by the permanent mold process, because of the effect of size and intricacy of

Table I. Relative Casting Characteristics of Common Alloys for Sand Casting
Numbered in order of preference. (1, Best)

Alloy	Nominal Composition	Hot Shortness	Pressure Tightness	Shrinkage Tendency	Gas Absorption
43	5% Si	1	1	1	1
108	4% Cu; 3% Si	2	1	1	3
113	7% Cu; 2% Si; 1.7% Zn	3	2	1	3
122	10% Cu; 0.2% Mg	3	2	3	5
142	4% Cu; 2% Ni; 1.5% Mg	4	4	3	4
195	4.5% Cu	5	3	3	3
214	3.8% Mg	3	5	4	3
220	10% Mg	3	5	5	3
355	5% Si; 1.3% Cu; 0.5% Mg	1	1	1	2
356	7% Si; 0.3% Mg	1	1	1	2

the casting. Although sections of the order of $\frac{1}{10}$ in. can be provided in certain castings, $\frac{1}{8}$ in. is usually considered the minimum. The minimum diameter of holes cored with metal cores is considered to be $\frac{3}{8}$ in., but holes as small as $\frac{1}{4}$ in. in diam are produced in some parts.

With proper control of mold coatings, which are essential for this process, casting surfaces can be produced superior to those provided by sand. Often these surfaces do not require further processing.

For minimum mold and casting cost, dimensional tolerances and draft allowances should be as liberal as possible, particularly where close limits are not required. Possible tolerances depend on the size and complexity of the casting and the location of the dimension involved, in relation to moving members of the mold. In general, lower tolerances are practical than those possible with sand castings; plus or minus 0.020 in. is common for small castings. Tolerances are usually figured as plus or minus $\frac{1}{64}$ in. for the first inch or less, plus 0.001 to 0.002 in. for each additional inch of length, depending on whether the dimension is affected by moving parts of the mold. With such tolerances and the smoother surfaces provided, allowances for machine finish can also be reduced for permanent mold castings. A finish allowance of $\frac{1}{32}$ in. to $\frac{1}{16}$ in. is generally adequate, depending on the size of castings.

As with sand castings, the alloy for permanent mold castings should be selected after a consideration of the foundry characteristics, as well as of the physical and mechanical properties. (*See* pages 824 to 840.) Because metal molds resist the contraction of the casting more than sand molds, freedom from hot shortness is one of the essential requirements in selecting an alloy. Pressure tightness and tendencies toward solidification shrinkage are among the other characteristics to be considered. Porosity resulting from absorption of gas is not usually a problem with permanent mold castings, since the chill imposed by the mold results in the metal retaining more gas in solution and effecting a finer dispersion of any gas that is released. Table II rates these characteristics for the common permanent mold alloys.

Table II. Relative Casting Characteristics of Common Alloys for Permanent Mold Casting
Numbered in order of preference. (1, Best)

Alloy	Nominal Composition	Hot Shortness	Pressure Tightness	Shrinkage Tendency
43	5% Si	1	1	1
A108	5.5% Si; 4.5% Cu	2	3	1
C113	7% Cu; 3.5% Si	3	2	1
122	10% Cu; 0.2% Mg	3	3	3
A132	12% Si; 2.5% Ni; 1.2% Mg; 0.8% Cu	1	1	4
142	4% Cu; 2% Ni; 1.5% Mg	5	4	4
B195	4.5% Cu; 2.5% Si	4	4	3
A214	3.8% Mg; 1.8% Zn	5	5	5
355	5% Si; 1.3% Cu; 0.5% Mg	1	1	1
356	7% Si; 0.3% Mg	1	1	1

Die Casting. Another casting process of importance for aluminum alloys is the die-casting process, known particularly for the accuracy and uniformity of reproduction that it provides. In this process a metal mold or die and metal cores are used, either or both of which may be water-cooled. The molten metal is injected into the die under pressure. Two general methods are used to accomplish this: air injection, using so-called "gooseneck" machines; and metallic plunger injection, using so-called "cold chamber" machines. Injection pressures in gooseneck equipment are limited to about 750 psi, while in cold chamber equipment, pressures of 3000 to 15,000 psi are commonly used, although pressures exceeding 20,000 psi have been employed. For illustrations of gooseneck and cold chamber machines, see the article on "Casting and Production of Zinc Alloys", page 1078.

The size of die castings is limited only by limitations of casting design and equipment, improvements in which are being made continually. Castings have been produced that weigh from a fraction of an ounce to 20 lb with over-all dimensions of 36 by 12 by 9 in. Dimensions in one direction may exceed these considerably, since castings up to 84 in. in length have been produced.

The die-casting process itself, as employed with aluminum alloys, is similar in most respects to that employed for the die casting of other metals. With aluminum alloys, heat treated alloy steel dies are used, the designing of which is best done by trained engineers who are experienced with aluminum die-casting problems. There is no substitute for this experience in providing a satisfactorily operating die assembly. The cost of this equipment will vary with the size and complexity of the casting, and often is no greater than the cost of equipment for other casting processes for equal daily production. Production rates for die castings also vary with size and intricacy of casting and dies, and size of machine used; large machines operate more slowly than small machines. With both gooseneck and cold chamber machines, operating speeds up to 150 cycles per hr may be attained if the part is simple and the die is of small or medium size. It is frequently practicable to produce a number of castings in a die simultaneously, thereby permitting increased piece production per cycle.

Because of the nature of the die-casting process, sections can be provided that are somewhat thinner than can be made with other casting processes. In fact, it is generally preferable to maintain sections in die castings as thin and uniform as possible, consistent with the size and complexity of the casting, the alloy used, and the requirements of strength and rigidity. Under favorable conditions, castings having a major dimension of 6 in. can be produced with sections of 0.045 in. in thickness. For castings with a largest dimension of 15 in., a section thickness of 0.080 in. is about minimum. Larger castings require somewhat heavier sections, but sections thicker than 0.150 in. are rarely needed for satisfactory castings.

The die-casting process permits the casting into position of inserts of various metals to serve as bushings, studs and liners. Holes and cavities can also be provided by coring, thus reducing machining operations and making for lighter castings with superior metallurgical properties as a result of the increased chill provided by the steel cores. The use of such cores requires a draft allowance, minimum requirements for which are given in Table III, together with the maximum limitations of depth usually imposed.

Table III. Draft and Depth Limits for Cores

Approx Diameter of Hole	Draft Required on Diameter per Inch of Depth	Maximum Depth
1/10 in. (min diam) to 1/8 in. incl	0.020 in.	3/8 in.
1/8 in. to 1/4 in. incl	0.016 in.	1/2 in. to ▮ in. depending on size
1/4 in. to 1 in. incl	0.012 in.	2 in. to 8 in. depending on size
More than 1 in.	0.012 in. to 0.030 in. (depending on size and design)	Depends on size and design

The surface smoothness of die castings is superior to that of any other forms of aluminum casting, a condition that makes for low-cost polishing operations. The surface detail possible with die castings is excellent; in fact the reproduction of engraved or ornamental designs is one of the outstanding advantages of the process.

Tolerances as low as plus or minus 0.0015 in. per lineal inch of dimension, but not less than plus or minus 0.002 in. on any dimension, are provided commercially by die castings. On large castings, this tolerance can be reduced further to plus or minus 0.0010 in. for each additional inch over 10 in. Dimensions affected by the parting line of the die or other die parts movable with respect to each other, usually require an additional tolerance of 0.010 in. or less, generally on the plus side.

With such dimensional accuracy, smooth surfaces and ability to cast external threads and core holes, subsequent machining of die castings is reduced to a minimum. The rapidly chilled surface skin of die castings accounts for their excellent mechanical properties, and makes excessive machining actually undesirable, since the result will be a disproportionate loss in strength. Excessive machining may also reduce the resistance of the casting to leakage under pressure.

As with the die design, the selection of alloy for die castings is best left to the producer of die castings, whose experience will permit him to recommend materials that will present the fewest production problems and insure the most satisfactory castings. Not all alloys suitable for other casting processes are satisfactory for the production of die castings. Many alloys are too hot short or do not have mold-filling characteristics satisfactory for die casting; others introduce operational problems that would affect the ultimate cost of casting. The most important of these characteristics are rated in Table IV for the common die-casting alloys. Their mechanical and physical properties will be found on pages 824 to 840.

Table IV. Relative Casting Characteristics of Common Alloys for Die Casting

Numbered in order of preference. (1, Best)

Alloy	Nominal Composition	Hot Shortness	Mold-Filling Capacity
13	12% Si	1	1
43	5% Si	2	3
85	5% Si; 4% Cu	3	2
218	8% Mg	4	4
360	9.5% Si; 0.5% Mg	1	1
380	8.5% Si; 3.5 Cu	2	2

Casting in Other Metal and Refractory Molds. Several additional casting processes adaptable to aluminum alloys have attained commercial significance. Most of these are modifications of the previously mentioned processes designed to provide improved casting tolerances. As such, these processes took on important roles during the war, since they provided a source of small precision castings with a minimum of man-hours spent in machining.

Because the initial cost of castings produced by these processes is higher than that of castings produced by the more common processes, their applications during postwar years will probably be limited. However, they do offer certain advantages which cannot always be provided by the other processes and which will undoubtedly dictate their use for certain castings of a specialty type.

Casting in Plaster Molds. The process of casting in plaster molds, perhaps the most common of the specialty processes, is a refinement of the sand-casting process. In plaster molds, the normal molding sand is replaced by refractory materials providing smoother surfaces and greater accuracy in the mold. Gypsum plasters are the most common molding materials for aluminum alloy castings. Molds of such materials must be processed subsequently by heating to remove excessive water and to put the plaster in a condition to receive metal. A mold is capable of producing only one casting, after which it is discarded. The process is generally confined to small castings that weigh less than about 2 lb, but considerably larger castings have been made.

Metal match-plate pattern equipment and suitable metal core boxes, if cores are required, are essential to this process for best results. Such equipment, because of the accuracy generally required, costs more than similar equipment for sand castings, but less than that required for permanent mold castings. For larger production jobs, such equipment can best be used in a mechanized setup permitting production rates nearly equal to those of the permanent mold process. Metal for such molds is usually poured under gravity conditions, although moderate pressures are sometimes applied after pouring, in order to provide improved casting detail.

The refractory nature of the molding material used for this process results in slower solidification of the metal than in normal sand or metal molds. This is an advantage in that it permits casting of sections thinner than practicable in sand or permanent molds and approaching those of die castings. It is, however, a disadvantage in that it makes for lower mechanical properties than are provided under conditions of greater chilling. Because of segregation in some alloys under conditions of slow cooling, the type of alloy adapted to this process is also limited. Aluminum-silicon alloys, such as No. 43 and 355, have found most favor.

Plaster mold castings have a surface finish superior to that of sand castings and generally comparable with the finish on permanent mold castings or even superior. The tolerances provided are as good as those possible with permanent mold castings and often approach those of die castings. For this reason, machining requirements are generally low; the higher cost of casting is frequently offset by elimination of machining costs.

*Precision Investment Casting.** This process is an adaptation of the so-called "lost-wax" process commonly used for the casting of jewelry from the precious metals. It affords the intricacy of design possible in sand castings with precision approaching that of die castings. A refractory type of mold or investment is used, ordinarily of gypsum plaster for the casting of aluminum. An expendable wax pattern is employed instead of the usual permanent pattern. The heating of the mold to develop the required condition to receive metal, melts out the wax pattern, providing the required mold cavity. Molds can be used only once, since they are broken up to remove the casting. At present the process is normally confined to very small castings, although statuary of considerable size has been produced by this method for a number of years.

A master mold for the production of the wax patterns is the essential equipment required for precision investment casting. When considerable production is involved, this master mold is preferably of metal and designed to permit production of the wax patterns by injection methods. Although the initial cost of this equipment is frequently lower than that of equipment for the other casting processes, the use of the equipment and subsequent production of the molds requires skilled operators, thus making for a final casting cost exceeding that of other types of castings. This type of casting is usually poured to provide metal under pressure, using the centrifugal process or vacuum

* For a general description of this process, see the article on page 54.

or some means of applying pressure after the metal is poured. The production rate for precision investment castings is relatively slow compared with other processes.

As with other casting methods employing refractory materials, casting sections approaching those of die castings can be produced. Because most castings produced by this method are of very small size and light section, the effect of the slow cooling imposed by the mold is not sufficient to affect greatly the mechanical properties or choice of alloy. Most of the aluminum casting alloys can be used for the small castings. For larger castings, it is preferable to use aluminum-silicon alloys, such as No. 43, 355 or 356.

Depending on the accuracy of the master mold and the selection and control of the wax and mold materials, this process can yield castings of great dimensional accuracy, often approaching the accuracy of die castings; and because there are no moving members in the mold or die to interfere, accuracies in some instances may be superior. The use of pressure to fill the mold cavity insures a sharpness of detail approaching that of die castings; hence, subsequent machining is reduced to a minimum.

Centrifugal Casting. This process consists of pouring molten metal into a revolving mold, utilizing the centrifugal force developed to force the metal into the mold cavity. Centrifugal casting has been popular for various ferrous and nonferrous alloys because the metal is cleansed of oxides and inclusions by centrifugal action, and improved mechanical properties result. Because of the small difference in specific gravity between the usual oxides and inclusions associated with aluminum alloys, the possibility of a similar separation by centrifugal action is limited. Whether mechanical properties can be improved beyond those provided by the normal casting procedures is therefore questionable. Centrifugal casting of aluminum alloys has seen limited use to date (1947) and it remains to be shown whether this process offers anything further than a means of pouring metal under pressure.

Centrifugal castings are of three general types: (1) true centrifugal castings that are substantially symmetrical around an open center and are rotated about the central axis; (2) semicentrifugal castings, which are similar to (1) and are also rotated about the central axis, but in which central cores are used to form the contour of the bore; (3) centrifuged castings that are unsymmetrical or without a central hole and are rotated in a horizontal plane along the perimeter of a circle concentric with the axis of rotation. Molds for any of these types may be of sand, refractory or metal, although the lower strength of sand molds limits their use. Metal molds are preferred for high production but refractory molds of material such as gypsum plaster, have proved satisfactory for small castings.

Equipment requirements for molds into which metal is to be cast centrifugally are essentially the same as for similar molds used for comparable gravity castings; therefore the costs of equipment should be much the same. The limits of size for centrifugal castings must still be determined, since most production to date (1947) has been confined to rather small castings.

Because of the effect of the metal pressure, resulting from centrifugal force, on section thickness, smoothness of surface and sharpness of detail, centrifugal castings should provide tolerances somewhat superior to those produced in similar mold equipment under gravity. Of particular importance would be the possibility of casting thin sections at low metal temperature, a condition that should reflect favorably on mechanical properties. Alloy limitations, if any, have not been established, and any of the standard casting alloys for the comparable gravity process would be considered suitable. In producing true centrifugal castings, alloys that are normally considered hot short should be cast with less difficulty.

General Casting Considerations

In addition to those casting considerations that have been specifically mentioned under the various casting processes, there are other general considerations that apply to all processes. Knowledge of these should be helpful when the design, manufacture and use of castings are considered.

Casting and Equipment Design. Some features of design necessitated by the service requirements or functional requirements of a casting are discussed on page 523 in this Handbook. However, other features, if properly considered during the designing of a cast part, will aid the foundry in obtaining higher quality and greater economy. Most of these can be established only by discussion with the ultimate producer of the casting, since they may depend on his particular type of equipment and production methods. Usually the functional requirements of a casting can be achieved by several designs, and a review of these by the foundry, prior to the setting of the final design, will frequently permit great savings in equipment and process.

Certain of the characteristics of aluminum alloys simplify casting and equipment problems; other characteristics make necessary the use of practices that differ from those used with other metals. The low specific gravity of aluminum is an advantage because it produces lower mold pressures and, in the making of sand castings, permits lighter sand ramming and lighter mold equipment. On the other hand, the low density makes it somewhat more difficult for aluminum alloys to rid themselves of their oxides or to drive off mold gases than it is for the heavier metals; therefore in gravity cast molds, permeability and venting of molds assume greater significance.

The strength of aluminum alloys is quite low at temperatures just below that at which the metal solidifies. This characteristic is called "hot shortness" and, as indicated previously, will vary with alloy composition. Although selecting a suitable alloy will overcome problems of hot shortness in many instances, it is desirable that designs and casting methods should minimize any resistance to contraction while a casting is passing through the range of temperature associated with hot shortness.

The relatively high solidification shrinkage of approximately 3.5 to 8.5% for aluminum alloys also requires consideration from the standpoint of design and equipment. Means of compensating for this reduction in the volume of metal are required and can be facilitated if this characteristic shrinkage is considered during the design stages.

Although all the aluminum casting processes permit the use of metal inserts within certain limitations, the permanent mold and die-casting processes are particularly adapted to their use. Cast iron or steel are the most suitable materials for such inserts, but copper and brass are commonly used when proper care is taken to prevent their solution in the molten aluminum. The use of inserts often permits a design that is more economical to produce as an integral part than as an assembly of several parts.

Melting and Handling of Metal. Melting is the initial step in the production of all types of castings. Melting equipment and melting and handling procedures can reflect greatly on casting procedures as well as on the final quality and cost of the castings. Therefore the selection of equipment and the establishment and control of procedures must be given careful consideration.

Certain characteristics of aluminum alloys are important factors in establishing requirements of equipment and procedure. Molten aluminum alloys possess a marked tendency to absorb hydrogen. The liberation of this hydrogen during the freezing of the metal in a casting is the cause of the so-called pinhole or gas porosity. In the melting or handling operations, any source of water vapor particularly, or of any other material that will form hydrogen as a result of chemical reaction with the molten metal, is a potential source of gas porosity. Important sources of gas are moisture in the atmosphere above the metal, moisture formed as a product of combustion of the melting fuel, and moisture or other hydrogen-forming material combined with, or absorbed in, the oxide film on the surface of the metal to be melted.

Several factors are important in the control of the gas content of aluminum alloys. Evidence indicates that the gas absorption will be greater, the higher the temperature of the metal, the longer the time it is held at temperature, the higher the absolute humidity of the atmosphere, and the more direct the exposure of the molten metal to products of combustion. The envelope of oxide which always surrounds the metal, has been found to offer considerable protection against gas absorption and, as long as this envelope remains unbroken, the absorption of gas is relatively

slow. Preheating the metal to be melted, to about 900 F prior to submerging it in a molten bath, effectively eliminates gas resulting from any hydrogen-forming materials on the surface. Consideration of these factors provides the means of controlling the gas content of the metal. Use of low melting temperatures, avoidance of long holding periods, minimum agitation of the molten metal, control of combustion products, and preheating of solid material before melting, will generally provide metal sufficiently low in gas content for the various casting applications.

A second characteristic of aluminum alloys, important from the standpoint of melting and handling, is the readiness with which they combine with oxygen to form oxides and dross. The formation of an oxide envelope during melting is an advantage in preventing further oxidation of the metal and, as mentioned above, in preventing rapid absorption of hydrogen. Also, because of this protective oxide, it is not generally necessary, during the melting of aluminum alloys, to use a flux cover such as must be used with certain of the other metals. However, dross that is formed as a result of oxidation may be trapped in the molten metal and, if not removed, may constitute a defect in the final casting. Therefore, excessive agitation of the metal should be avoided while the metal is molten in the furnace, as well as during any transfer from furnace to pouring ladle, or during the pouring operation.

Furnace equipment for remelting aluminum alloys for foundry use should be selected not only on the basis of capacity and efficiency, but also from the standpoint of a design that will provide a minimum of gas absorption and of oxidation. The furnaces that best fulfill these requirements are the ones in which the metal is melted without coming in contact with the heating medium. Pot-type furnaces, heated indirectly by gas or oil, are the most commonly used. Cast-iron pots, suitably coated with a protective wash, are generally used with such furnaces, although nonmetallic pots of graphite or various vitreous and refractory materials offer certain advantages for some conditions of melting. Pots of these nonmetallic materials are particularly useful for melting aluminum-silicon and aluminum-magnesium alloys, where a minimum of iron pickup is desired. Electric induction furnaces, developed specifically for aluminum, are being employed in some foundries. Such furnaces provide desirable melting conditions for many foundry applications.

Proper control of temperatures is necessary for metal of the highest quality. As mentioned previously, both gas absorption and oxidation increase with the temperature of the molten metal. Holding the metal at even moderately high temperatures also tends to coarsen the grain structure of the resulting casting; the higher the holding temperature, the shorter the time required to produce an inferior structure. Therefore, to insure obtaining metal of maximum quality, melting or holding furnaces should be equipped with suitable thermoelectric devices for controlling or indicating temperature. See the article "Pyrometry", page 174 in this Handbook.

Under proper conditions of melting, fluxing of the metal while it is molten is not always necessary; hence, when a flux is used, it should be considered a supplement to good melting and handling practices, and not an agent to offset the effects of an otherwise inferior foundry technique. For the most part, the fluxing of metal for foundry use is confined to situations that require reduction in oxides and gas beyond that provided by ■ good melting and handling practice. Various solid and gaseous fluxes are used for this purpose; aluminum chloride, zinc chloride, chlorine gas, and nitrogen gas are among the materials most commonly used. The solid materials are usually prepared in aluminum foil capsules and immersed near the bottom of the melt. The gaseous materials can be introduced by means of carbon or refractory tubes extending to the bottom of the melt. In using any of these fluxes, care must be taken to insure that they are dry and, where necessary because of their toxic nature, to provide adequate ventilation. Various proprietary fluxes for aluminum are used to some extent; the most common of these fluxes act as a drying agent for the surface dross, facilitating removal of dross during skimming.

Finishing of Castings. One of the important economies to be realized by the use of aluminum castings results from the ease with which they can be finished. The light weight, which facilitates handling during the finishing operation; the smoothness of the cast surfaces and absence of burnt-in sand; the nonabrasive character of the metal; and the ease and speed with which the metal can be trimmed, machined or ground—all make for economy in finishing. Operations normally performed in the foundry, consist of core knock-out (where sand cores are involved), chipping, die trimming, sawing and grinding to remove gates, and polishing and abrasive blasting when required for surface appearance. Standard tools for use with aluminum are available for this purpose.

Aluminum castings are also excellently suited for various ornamental and protective finishes. Ordinarily applied by the manufacturer of the finished product, such finishes are produced by mechanical, chemical or electrochemical means, depending on the ultimate effect desired. Mechanical finishes, produced by polishing, buffing or satin finishing, are applied with the ordinary types of polishing equipment. Other desirable finishes may be obtained with rotating wire brushes, fiber bristle brushes, tumbling with various abrasive and cleaning mixtures, and hand rubbing. These and other types of finishes are discussed in detail in another article (*see* page 789).

Machining of Castings. Aluminum alloy castings are readily machined, although for best results certain practices must be followed that are different from those generally used for other metals. Details concerning the machining practices recommended for aluminum will be found in the article on page 786.

Heat Treatment of Castings. The mechanical properties of many of the aluminum alloys can be greatly improved by heat treatment and a number of such treatments have been developed for castings (*see* page 775). In addition, heat treatments are available that provide improved dimensional stability by reducing stresses and growth. These treatments are applied principally to sand and permanent mold castings, although castings produced in refractory molds or by centrifugal casting can be so treated when desired. Heat treatment finds limited application with die castings because of the blistering that may occur as a result of gas holes, and the possible loss of desired dimensional accuracy.

The Production of Aluminum Alloy Ingots for Working

By W. T. Ennor*

THE production of aluminum alloy ingots that are subsequently to be forged, extruded or rolled, involves converting aluminum and alloy pig, ingot and scrap to molten metal of satisfactory chemical composition and metallurgical quality, and casting this metal into ingot molds.

Melting. Melting equipment and practices are influenced by several inherent characteristics of aluminum: the low density, high specific and latent heats, relatively low melting temperature, high reflectivity, rapid oxidation to form a protective film, solution of hydrogen by molten aluminum, small differences in density among molten aluminum, oxide film and refractory inclusions, and the solubility of iron and silicon in aluminum.

Equipment. Many types and sizes of melting furnaces are in common use, but the fact that ingots for working are normally produced in large tonnages of standard shapes and sizes has resulted in a trend toward furnaces of

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high capacity and melting room layouts designed for continuous operation. Auxiliary holding furnaces or crucibles may be provided so that casting can be continuous, even though melting requires a recurring cycle of charging, melting, stirring and fluxing.

Reverberatory melting furnaces of 10,000 to 50,000-lb capacity are most commonly used. The fuel may be gas, oil, coal or coke. Smaller furnaces may be of either the reverberatory or the pot type. These pot furnaces are heated by combustion of gas or oil between a refractory shell and inner container. Cast-iron, graphite or refractory pots may be used.

Furnaces of the radiant type are little used because the high reflectivity of aluminum causes poor efficiency. Electric induction furnaces have a number of theoretical advantages and are receiving increased attention.

Refractories for furnace lining must be selected with careful consideration of wearing tendencies that result from the charging and furnace cleaning procedures employed; of thermal shock induced by the heating and cooling cycles used; and of the importance of avoiding silicon pickup in the alloys melted.

Cast-iron or steel tools are used for charging the furnace, stirring and skimming. Cast iron is dissolved by molten aluminum at a slower rate than steel, but in order to decrease solution, either metal should be coated periodically with a slurry of lime, mica, or other similar material.

Specialized auxiliary furnaces for melting finely divided and dirty scrap, and equipment for handling and recovering aluminum from skimmings, are found in most melting rooms producing ingots for working.

Melting and Alloying Practices. The major operations to be carried out in melting are charging, melting, stirring and fluxing. A batch system may be used whereby the entire furnace charge is melted and poured off as a unit; but continuous or, more accurately, semicontinuous melting, where a portion of the melt is removed periodically and replaced by a new charge, is a less expensive and more common practice. In order to shorten the cycle in the melting furnace and to provide a quiet, properly treated bath for withdrawal to a casting unit, metal may be transferred to a holding hearth in the same furnace or to a separate furnace, immediately after stirring or fluxing.

Charges ordinarily consist of a mixture of aluminum pig, scrap, remelted scrap, pure metals, and rich alloys of other metals with aluminum; but previously prepared or purchased ingot of the proper composition may be used to avoid the necessity for close attention to composition.

When alloying is done, metals with low melting points—such as magnesium, zinc, lead, bismuth and tin—are commonly added directly to the molten aluminum and stirred in. Magnesium is submerged below the surface of the molten aluminum to prevent burning. Such metals as manganese, iron, nickel, titanium and chromium dissolve so slowly that they are introduced as rich alloys or hardeners, normally containing from 2 to 10% of the metal in aluminum. Copper and silicon may be introduced directly, but their solution is moderately slow; consequently, rich alloys are frequently used.

Scrap may be added directly to the furnace charges, or previous melting and casting as small ingot may be desirable because of size, shape, cleanliness or doubtful chemical composition.

The composition of the completely molten bath is made uniform by manual stirring, which must be thorough, yet with the least possible disturbance of the surface oxide. The amount of oxide or skim that is formed will vary with the alloy and with the components used in the charge. If this oxide cover becomes very thick, it should be skimmed off. It should also be pushed aside from the area where metal is to be charged or ladled.

The metal bath may be fluxed with chlorine or aluminum chloride to float particles of oxide to the surface. Chlorine, as well as inert gases such as nitrogen and helium, will remove dissolved gas. A third use of chlorine and aluminum chloride, as well as salt fluxes of various chloride and fluoride mixtures, is to dry up the surface dross so that less entrapped metal will be removed during skimming.

It is unfortunate that variations in metal temperature and in soaking time have opposite effects on the two major melting problems of cleanliness and dissolved gas. Increases in bath temperature and in length of time held at temperature are beneficial from the standpoint of cleanliness, since nonmetallic inclusions are thus given a better opportunity to rise to the surface or sink to the bottom. However, the solution of gases, principally hydrogen formed by reaction with the bath of water vapor carried into the furnace by air and combustion gases, increases with metal temperature and time at temperature. The practice that is adopted will depend on many factors, including equipment, moisture content of the gases in the furnace, condition of the metal charged, fabricating difficulties, and requirements of the product. Since high temperatures also result in higher losses through oxidation and tend to coarsen the grain structures of the ingot, the practice generally preferred is to use metal temperatures as low as 1300 to 1400 F and to rely on fluxing, careful handling of the metal, and a final short soaking to give proper metal cleanliness.

Furnaces must be drained and cleaned periodically, and iron pots and tools must be coated with a protective wash. The walls and hearths of refractory furnaces are scraped to avoid excessive build-up of various deposits.

Casting. A poor product can be made from a good ingot, but a good product cannot be made from a poor ingot. Satisfactory ingot stock is essential for success in any metal working operation.

With an available supply of metal of the desired composition and metallurgical quality, a casting method must be used that will produce ingots of proper size, structure and surface quality. Ingot shape, cross-sectional area and length vary greatly; for instance, from short 4 by 4-in. wire bars and from 2 by 12-in. sheet ingots to ingots 20 in. thick, 48 in. wide and 8 ft long or more. Square cross sections are most common for ingots that are to be rolled into rod and bar, and rectangular shapes with high ratios of width to thickness, for sheet rolling. Round ingots are required for extrusion and some forging and pressing uses, and hollow round ingots for extrusion of tubing. These wide variations in size and shape greatly influence casting problems and the selection of the method to be used.

A study of ingot structures must include the subjects of crystal size and shape, constituent structure, porosity, inclusions, and uniformity of composition throughout the ingot. A fine equiaxed crystal structure is preferred and may be secured by suitable melting and casting practices, or in some instances by the addition of a grain refiner, such as titanium. Porosity resulting from liberation of gas or from improper feeding of solidification shrinkage will result in the blistering of fabricated products in annealing or solution heat treatment, and also may cause both cracking during working and low mechanical properties in the product. Dross or refractory inclusions have similar effects and are particularly serious in machining or in drawing to fine wire. Nonuniform composition will result in low mechanical properties in areas low in alloying elements.

The quality of the surface of aluminum alloy ingots may be impaired by cold shuts caused by improper or very slow transfer of metal into the mold; by included dross resulting from agitation during pouring; and by liquation when liquid having a low melting point is exuded through the partially solidified ingot surfaces.

The two principal requirements for a successful casting process are (1) the introduction of the metal quietly and uniformly without the inclusion of dross and the formation of cold shuts, and (2) the withdrawal of heat from the ingot at a fast enough rate and in a proper direction to produce a structure that is satisfactory for the intended use. The many procedures that have been used for transferring metal and withdrawing heat cannot be discussed here, but a brief description of the two methods in most common use will show the application of these casting principles.

Tilt-Mold Ingots. Until recent years, the most important type of aluminum and aluminum alloy ingot was the tilt-mold ingot, still extensively used. A heavy cast-iron book mold (a mold with hinges at one vertical corner or side and having diagonally opposed clamping devices) is mounted on trunnions, so that it can be rotated at a closely controlled rate around a horizontal axis at one of the top

corners or faces. Pouring is started when the mold is raised nearly horizontal, and while the mold is being lowered to a vertical position, the metal is introduced from a crucible slowly and without turbulence.

It is possible to avoid agitation and inclusions of oxide film by using equipment designed and operated properly; and the combination of slow pouring and water cooling of the bottom portions of the mold makes freezing possible from bottom to top in order to insure proper feeding to the solidifying metal in the lower regions. These features are the only characteristics distinguishing the tilt-mold process from ingot-making processes generally used in the steel and copper industries.

In the casting of strong aluminum alloys, the tilt-mold ingot has the disadvantages of a coarse constituent structure, a tendency toward fine porosity, considerable inverse segregation with low content of alloying elements at the ingot center, and relatively poor hot working characteristics. Because of the deep pool of metal still remaining molten in the mold when pouring is completed, and because of the high solidification shrinkage of aluminum, it is necessary to add the metal slowly and carefully with hand ladles for a long period in order to prevent a deep head-end pipe. These disadvantages, which increase in importance with increases in ingot size and in amount of alloying elements, have resulted in limiting the applications of the process. At present the tilt-mold process is used only for pure aluminum and the simpler alloys in quite wide ranges of shapes and sizes, and for strong alloys in small sizes to be worked by extrusion.

Directly Chilled Continuous Ingots. Recently, extensive use has been made of processes whereby metal is continuously introduced into a short, thin water-cooled mold; a shell is frozen by withdrawal of heat through the mold; the shell is withdrawn from the mold at a constant rate; and solidification is completed by direct application of water below the mold. By the use of lowering rolls and saw, the process can be carried out continuously for long periods, or a lowering mechanism may be provided to give intermittent operation for the casting of individual ingots of the desired length. In the intermittent method it is common practice to cast simultaneously two or more ingots from a single source of metal supply and with the same lowering mechanism.

This process, with extremely rapid withdrawal of heat by the application of water directly to the ingot, gives rapid cooling through the freezing range and therefore a fine constituent structure. The shallow freezing zone results in better feeding of solidification shrinkage and in greatly decreased inverse segregation of alloying elements. Since the shallow pool of molten metal freezes with only slight head-end shrinkage, the heading operation can be eliminated.

Ingots made by this process have excellent hot working characteristics, but the surfaces are ordinarily heavily liquated and may contain shallow cold shuts. This frequently necessitates scalping either the ingot or the partially fabricated product. Another disadvantage of the process is that many alloys tend to crack during cooling, as a result of high residual stresses.

The Hot Working of Aluminum Alloys

By John H. Alden*

THERE are two principal objectives in the hot working of aluminum alloys. The first objective, applicable to cast ingots of various types, is to deform plastically the as-cast structure, thereby converting it to a wrought structure and thus making it more workable and more adaptable to subsequent hot or cold working operations. The second objective is to obtain increased plasticity by using elevated working temperatures, thus permitting the economical manufacture of intricate parts or thin sections some of which could not be made by cold working.

Preheating of Ingots. Hot working of cast ingots is preceded by suitable heating of the ingot. With the more complex alloys, it is desirable to remove the cored cast structure or to dissolve and disperse certain constituents, or to do both. This is accomplished by heating the cast ingots to an elevated temperature and soaking them at such a temperature for a suitable period. The ingots may be hot worked directly thereafter, or they may be cooled to room temperature and reheated to the hot working temperature. Table I shows typical preheating treatments for some aluminum alloy ingots.

Table I

Preheating Treatments for Aluminum Alloy Ingots

Alloy[a]	Ingot Metal Temperature	Soaking Time at Metal Temp
3S, 4S	950 to 975 F	4 to 6 hr
14S, 17S, 24S	900 to 950 F	4 to 12 hr
A 51S, 52S, 53S, 61S, 63S	900 to 950 F	0 to 8 hr

(a) Chemical compositions of these alloys are listed on page 793.

With pure aluminum and some alloys, when it is not necessary to effect constituent changes in the as-cast structure, the ingots are merely heated to the desired hot working temperature just before performing the work.

Sheet and Plate. Ingots for the manufacture of sheet and plate are ordinarily wide and long in relation to their thickness, and those used in newer mills weigh several thousand pounds. When ingots show liquation, other surface segregation or cold shuts, they are usually scalped prior to working. Sheet ingots of the less easily workable alloys may be hot rolled to some intermediate thickness before scalping. The checks, cracks and other surface imperfections are then removed and the ingots are reheated and further hot rolled to slabs.

Modern mills for the hot rolling of sheet ingots are generally 4-high, although 3-high and 2-high mills are used extensively in the industry. There are a few installations where the hot mill is equipped with vertical edging rolls to roll the ingot edges, but ordinarily the edges of sheet ingot are unsupported and therefore are susceptible to edge cracking, particularly in the harder alloys.

This hot rolling or breakdown operation produces slabs for subsequent hot continuous rolling or cold rolling. When the hot mill slabs are to be cold rolled, the usual practice is to roll them on the hot mill down to thicknesses of ¼ to ½ in. If, however, the slabs are to be continuously rolled subsequently, the hot mill operations are stopped at thicknesses of one inch or slightly less.

In producing slabs for making Alclad sheet, the cladding is accomplished in the hot rolling operation. Slabs of the cladding alloy are strapped to a scalped ingot of the core material and the assembly is heated for rolling. The straps are removed after the assembly is placed on the hot mill table, and hot rolling is then done in a manner similar to that used with nonclad sheet ingots.

High-speed 4-high hot continuous mills, similar to those employed in the steel industry, were installed in several aluminum sheet mills just prior to and during the war. Hot mill slabs slightly under 1 in. thick are rolled on these mills to thicknesses ranging from 0.080 to 0.200 in. After continuous rolling, the stock is coiled or is sheared to straight lengths.

Slabs produced by these practices in hot mills and slabs and coils from continuous mills are ready, after annealing, for subsequent cold rolling into sheet.

Rod, Bar, Wire and Rolled Shapes. In the production of aluminum rod, bar, wire and rolled shapes, modern practice

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involves preheating, as for sheet ingots, before breaking down the ingot on a blooming mill. Ingots as large as 20 by 20 in. in cross section are rolled on such mills.

Blooming mills used for aluminum are similar to those employed for steel* and are generally 2-high reversing mills of about 5000-hp capacity. Since hot steel is more plastic than aluminum at hot rolling temperatures, reductions employed on aluminum blooming mills are somewhat less than on steel, but the types of passes are similar. Roll surfaces are smoother than the cogged surfaces often used on steel.

Depending on the alloy and the particular type of ingot employed, the ingot is often scalped prior to hot rolling. If the ingot is rolled unscalped, the bloom is generally scalped or local defects are removed by suitable conditioning tools. Temperatures employed during blooming-mill operations are shown in Table II. After inspection, blooms are ready for further hot rolling into wire, rod, bar and rolled shapes, or are used as stock for hot forging operations.

In the manufacture of wire and smaller sizes of rods, the blooms are further rolled to suitable size on continuous mills or train mills. For wire, such hot rolling is generally continued until the rod material is ⅜ in. in diam, at which size the metal is coiled, annealed and stocked for subsequent drawing. For medium sizes of rod and bar, hot rolling is stopped at a size a little larger than the finished dimensions. The metal is then annealed and cold rolled or drawn to finish size. Larger sizes of rod and bar are hot rolled to finish size on train mills.

Structural shapes are hot rolled to finish size. Designs of roll passes are similar to those used on steel, but the lower plasticity of the aluminum necessitates more passes to produce a given section. The principal problem in rolling aluminum shapes is the attainment of proper lateral flow so that the extremes of the section are just filled. Overfilling causes fins and underfilling causes surface cracking along the edges. As a rule, structural shapes are furnished in the heat treated condition.

The metal is subjected to compression and receives a large amount of plastic deformation during the extrusion operation. Frequently recrystallization takes place during the process of extrusion, and many sections emerge from the die at temperatures above the recrystallization temperature; therefore, extrusion of some alloys may develop a coarse grain structure. In addition, the extruded section is highly fibrous in structure, parallel to the direction of extrusion. As a result, tensile properties of the product are often higher than those obtained on other hot worked products or on some cold worked products. The size of the particular section has a pronounced bearing on the properties, and in a complex section containing portions of varying thicknesses, the properties may vary widely.

Extrusion speeds vary from 1½ to several hundred feet per minute, depending on the alloy, the section being produced and the temperature conditions employed. The upper limit of speed is usually dictated by the surface quality or dimensional requirements.

In the extrusion of tube blooms, tool setups must be carefully controlled to avoid too much eccentricity in the bloom. After extrusion the blooms are sawed to the desired length, are annealed, and are then ready for cold drawing into seamless tubing.

Forging.* Hot hammer forging is used for the manufacture of many aluminum parts. Hammers employed are similar to those used on steel, the largest being 35,000 lb. The forging stock, either round or square, is cut to suitable length and then heated to proper forging temperature. In making hammer-forged parts, a liberal flash is generally allowed.

The use of press forging is increasing rapidly. In this type of forging, the deformation takes place somewhat more slowly. Since press forgings are ordinarily made to close tolerances, it is important that ■ slug of accurate size be used in order to obtain uniformity in the finished piece.

Forging techniques and die design for both types of forging are similar to those employed for steel and, for that matter, are also similar to brass forging. Compared with the common steels, aluminum alloys require about 30% more energy or power to form a given forging properly from a given size of slug. Hot forging temperatures are shown in Table II.

Table II. Typical Hot Working Temperatures for Aluminum Alloys

Alloy[a]	Sheet and Plate: Breakdown, deg Fahr	Sheet and Plate: Continuous Rolling, deg Fahr	Extrusion, deg Fahr	Blooming Mill Breakdown, deg Fahr	Hammer Forging, deg Fahr	Press Forging, deg Fahr
2S, 3S, 4S, 52S	750 to 925	300 to 850	750 to 900	750 to 850	680 to 840	680 to 840
14S, 17S, 24S	750 to 850	600 to 850	650 to 850	775 to 850	760 to 820	800 to 860
18S, 25S	.....	.....	.....	800 to 870	760 to 820	800 to 860
32S, A51S, 53S, 61S, 63S	750 to 850	700 to 900	700 to 900	800 to 890	800 to 860	820 to 880

(a) Chemical compositions of these alloys are listed on page 793.

Extrusions. The extrusion process is employed for producing a wide variety of sections, ranging from round rods to very complicated and diversified cross sections. This process is also employed for producing tube blooms for the manufacture of cold drawn seamless aluminum tubing. Extrusion presses in this country range as high as about 5500 tons in capacity, and reports have been received of 12,000-ton presses in Europe.

In the extrusion operation, the cast cylindrical ingot is heated to the desired temperature and delivered to the press. The extrusion cylinder is heated by electricity or gas to minimize the loss of heat from the ingot. The ram of the press is fitted with a dummy block somewhat smaller than the cylinder diameter. As the ingot is extruded, this clearance between the dummy block and the cylinder leaves in the cylinder some of the original ingot surface. Furthermore, a certain length of the ingot is left unextruded and this is removed before charging another ingot. Temperatures employed in the extrusion of aluminum alloys are shown in Table II.

Lubrication. The hot working of aluminum alloys requires more power than the hot working of steel. Also, the fact that aluminum does not scale necessitates the presence of a film of suitable lubricant between the aluminum surface and the rolls or other hot working tools. For most hot rolling operations, large volumes of a soluble oil emulsion are employed, serving the dual function of roll cooling and lubricating. For extrusion, no lubricant is needed, except on the surface of mandrels for the extrusion of hollow blooms. Such mandrels are usually lubricated with a suspension of graphite in light mineral oil. In hot forging operations various die lubricants are employed, including graphite suspensions, tallow, and other specialized kinds. They must be carefully selected, however, to avoid adhesion of the metal to the forging die.

* *See* "The Hot Mechanical Working of Steel", page 343.

* For discussion of the principles of forging, see articles on pages 36 to 41 in this Handbook.

The Cold Working of Aluminum Alloys

By John W. Hood*

COLD working, as covered in this discussion, is limited to those processes employed in the fabrication of the basic products—plate, sheet, foil, rod and bar, wire, tubing, and impact extrusions—in which the aluminum alloy is at approximately room temperature when the process begins. Hot working is employed for the breakdown or roughing operations, and in some instances even for the finishing operations. However, cold working is employed for various reasons in the fabrication of the foregoing basic products made of aluminum and aluminum alloy.

Purposes of Cold Working

In the cold working of all aluminum products one or more of the following objectives is attained:

Increase in Strength and Hardness at the Expense of Ductility. Aluminum and its alloys, like other metals, strain harden during cold working, especially at low temperatures. The increase in the tensile strength, based on the strength of the alloy in the annealed (or heat treated) temper, is directly proportional to the amount of cold work expressed as the fractional reduction of the initial cross-sectional area. This direct proportionality applies throughout most of the range normally used in commercial manufacturing operations. For higher reductions, the tensile strength increases more rapidly than would be indicated by this relationship.

The yield strength of annealed (or heat treated) material, that is, the stress which produces a permanent set of 0.2%, is increased rapidly by the first small amounts of cold work. Succeeding reductions produce relatively less effect until, after about 20% reduction in cross-sectional area, the rate of increase in this property parallels quite closely the increase in tensile strength.

The elongation decreases with increasing amounts of cold work and, as in the yield strength, the first small amount of cold work produces a relatively greater effect (in this instance, a decrease) than subsequent reductions of equal amount. The first reduction of 20% usually reduces the elongation to about ⅓ of its initial value or even less; after a reduction of about 60%, further cold working causes little additional change in this property.

This principle is utilized in the fabrication and control of tempers of the aluminum alloys that cannot be heat treated, as illustrated by the typical mechanical properties of 2S (99% Al min) listed in Table I.

The principle of strain hardening by cold work is employed also in the heat treated alloys (1) in flattening after solution heat treatment, and (2) in producing higher strengths than are available from heat treatment alone. The effect of cold work on the typical tensile properties of 24S sheet* $\frac{1}{16}$ in. thick, after solution heat treatment and aging at room temperature, is shown in Table II.

Refinement of Grain Structure. The amount of strain hardening or cold work in the metal prior to a heating operation is one of the important factors affecting the temperature of recrystallization and the grain size. In general, it is considered good practice to specify not less than approximately 50% reduction in cross-sectional area by cold working or its equivalent between annealing or heat treating operations, in order to prevent the development of excessively large grains. The amount of reduction required for obtaining a specific grain size varies with the composition of the alloy and many other factors beyond the scope of this article.

Straightening or Flattening. Straightening and flattening operations are employed normally for all tempers of aluminum alloys, except for the annealed temper or for material that is to be formed immediately after solution heat treatment. It is expected that maximum workability is required in these latter tempers and the normal forming operations to be imposed will preclude the necessity for straightening prior to forming.

Except for the extremely large sizes, straightening and flattening operations are performed cold and are usually controlled so as to introduce a minimum amount of strain hardening. However, some strain hardening may result, since straightening and flattening can be accomplished only by stressing the metal beyond the elastic range in order to produce permanent set.

In addition to hand bending and hammering, which represent the earliest forms of straightening and are still employed, other methods in general use involve equipment designed for straightening and flattening specific products.

Staggered roll levelers are employed for flattening sheet and plate. These devices bend the metal back and forth in successively decreasing amounts as it passes between the rolls. Contact of the sheet or plate with the driven rolls develops sufficient friction to hold the metal in tension.

Roll straighteners that act on the metal by a combination of flexing, rolling and stretching are also in common use for straightening rod and tubing. The rolls are located at angles that cause the rod or tubing to rotate. Flexing is accomplished by the position and shape of the driven rolls. The gripping of the metal in the rotating rolls causes it to flow circumferentially; therefore this action is employed also to shape and size the metal.

Stretchers are in general use for straightening and flattening sheets, tubing, rod, bar and wire. Tensile stresses

Table II. Effect of Cold Work on 24S-T4 Sheet

Designated Temper	Yield Strength, psi	Tensile Strength, psi	Elongation, per cent in 2 in.
24S-T4[a]	44,000	67,000	21
24S-T3[b]	46,000	68,000	19
24S-T36[c]	57,000	73,000	13

(a) Solution heat treated, aged at room temperature, not flattened
(b) Solution heat treated, aged at room temperature, flattened by combination roll and stretcher leveling
(c) Solution heat treated, aged at room temperature, cold rolled sufficiently to reduce thickness approximately 6%

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*Nominal composition: 4.5% Cu, 1.5% Mg, 0.6% Mn, remainder Al.

Table I. Mechanical Properties of Commercially Pure Aluminum (2S) in Various Tempers

Alloy and Temper[a]	Approximate Reduction in Area, per cent[b]	Yield Strength (Set = 0.2%), psi	Tensile Strength, psi	Elongation, Per Cent in 2 In. Sheet Specimen (1/16 in. thick)	Elongation, Per Cent in 2 In. Round Specimen, (½-in. diam)	Brinell, 500-kg load, 10-mm ball	Shearing Strength, psi	Endurance Limit, psi
2S-O	..	5,000	13,000	35	45	23	9,500	5000
2S-H12	20	13,000	15,000	12	25	28	10,000	6000
2S-H14	40	14,000	17,000	9	20	32	11,000	7000
2S-H16	60	17,000	20,000	6	17	38	12,000	8500
2S-H18	80	21,000	24,000	5	15	44	13,000	8500

(a) Designation of symbols: O, annealed; H18, fully cold worked (hard); H12, H14, H16 = intermediate degrees of cold working between O and H18.

(b) These reductions vary widely with alloy composition, type of product and method of fabrication, and should be considered only as illustrative of relative orders of magnitude.

are applied through suitable jaws attached to each end of the metal. Machines for stretching are normally operated by hydraulic power so that the load may be applied gradually and may be controlled properly as the metal is elongated. Because of the marks remaining from the gripping of the jaws, it is necessary to remove the ends of the stretched pieces after stretching. Together with the time required for loading and unloading, the removal of ends may make this method of straightening more costly than roll flattening and straightening.

Increase in the Accuracy of Dimensions. Some products, particularly plate, rod and bar, are hot worked nearly to the finish dimensions and are then cold finished to obtain greater accuracy of dimensions.

Improvement in Surface Appearance. In the fabrication of certain products, such as sheet, tubing, bar and rod, bright finishes are attained as a result of the proper choice of lubricant, tool or roll shape and surface, together with the burnishing effect obtained by cold reduction. In general, the brighter surfaces are obtained in the harder tempers and with the greater reductions, provided lubrication is ample to prevent discoloration caused by overheating or by adhesion of the metal to the tools.

Control of Characteristics of Metal Flow During Subsequent Forming Operations. The tendency of sheet metal to draw "ears" or to develop a scalloped edge during a cylindrical drawing operation is caused by preferred orientation of grains. Metal that has random grain orientation draws symmetrically with an edge of uniform height from the base of the drawn shell. Random orientation of grains is obtained in the process of fabrication, by the proper balance of recrystallization and cold work. For this reason the amount of reduction by cold work between annealing operations is often an important factor in the successful use of sheet.

Certain alloys exhibit a tendency to develop "Lüder's lines" or flow lines on the surface when stretched. Such a tendency is pronounced in the annealed temper. The introduction of slight amounts of strain hardening by compressive cold work will minimize the tendencies during subsequent stretching operations. This compressive cold work may be introduced by roll leveling, cold rolling or by other methods, and the resistance to the development of Lüder's lines is roughly proportional to the amount of strain hardening thus introduced.

Cold Worked Products

Dimensional ranges and notes on the cold working of specific products are given here.

Plate. By definition, plate is material ¼ in. or more in thickness. This product is usually rolled hot to gage but may be finish rolled cold, particularly for plate less than ½ in. thick, or for the intermediate tempers of the alloys that cannot be heat treated. In the "as-rolled" temper of the alloys that cannot be heat treated, the mechanical properties may vary widely because such a temper may be finish rolled either hot or cold.

Sheet. By definition, sheet is material within the range of thickness from 0.005 in. to and including 0.249 in. The cold rolling methods employed for sheet are divided into two general classifications; namely, the flat roll and the strip roll methods.

In flat rolling, the sheets are handled in relatively short lengths and remain flat. In the lighter gages, that is, approximately 0.040 in. or less, the sheets are finish rolled in packs of two or more.

In strip rolling, the sheets remain in relatively long lengths and are wound in coils between successive passes in order to facilitate handling and application of tension. The sheet is guided into the rolls and kept reasonably flat as a result of suitable tension applied by steel bar "bridles" equipped with guides, or by brakes applied to the unwind reel. Upon emerging from the rolls, the sheet is coiled on a reel or by means of a 3-roll coiler for heavier thicknesses.

Because the flatness of the sheet is controlled by means of tension provided in strip rolling, much greater reductions per pass are possible than in flat rolling. It is the normal practice to make the largest reductions on the first pass after annealing and to use progressively smaller reductions for subsequent passes.

The greater amount of work per pass introduced by the strip rolling operation entails the use of more lubrication than in flat rolling. Therefore the surfaces of strip-rolled products supplied in the as-rolled or intermediate tempers are normally oily, whereas flat rolled products are relatively free from oil.

Various finishes are applied to aluminum sheet products, ranging from bright to dull, as determined by the intended use. The finish produced is determined by the type of grind applied to the rolls and is influenced also to a considerable degree by the control of auxiliary equipment, lubrication, roll temperatures and annealing methods.

Foil. By definition, foil is material not more than 0.005 in. thick, and is available commercially as thin as 0.00025 in.

Foil rolling is a continuation of the rolling methods for strip sheet to thicknesses 0.005 in. or less. Because of the more fragile nature of the metal in the foil thicknesses, control of tension, lubrication and roll shapes must necessarily be more accurate than for the heavier gages of sheet.

The thickness of foil is controlled by adjusting the speed of the rolls rather than by varying the roll opening. In finishing to thicknessess less than approximately 0.001 in., it is customary to finish roll in packs of two sheets engaged in the rolls at the same time. This accounts for the variation in the luster on the two sides of the lighter gages of foil. The thickness of foil is measured by weighing a sample of known area on a carefully calibrated balance. It is common practice to express the thickness in terms of covering area, as square inches per pound as well as in thousandths of an inch.

Rod and Bar. These are defined as products falling within the following approximate size limitations: rod, ⅜ to 3 in. in diam, inclusive; rectangular bar, 0.081 to 1½ in. thick, inclusive, 4 in. wide max; hexagonal bar, ⅜ to ■ in. inclusive, distance across the flat surfaces.

Rod and bar are normally produced by hot rolling to final dimensions, although where better surface finish and closer dimensional tolerances are required, the final reductions are made cold. These products are specified as rod and bar, cold finished. The cold reductions may be made by drawing through dies, cold rolling, roll straightening or combinations of these processes, depending on the finished sizes, the results required, and economical considerations.

Wire. Supplied in various forms, wire is defined within the following approximate size limitations: diameters, 0.005 to 0.374 in. inclusive; wire-flattened, 0.010 to 0.187 in. thick, 0.030 to ■ in. wide; wire-flattened and slit, 0.010 to 0.080 in. thick, 0.125 to 4.75 in. wide.

Wire is drawn from larger sizes of rod to the desired dimensions by successive cold reductions through dies made of chilled cast iron, tungsten carbide, diamond, or through "Turk's-head" dies. "Flattened" and "flattened and slit" wire are produced, as the names imply, by rolling a round wire flat, and slitting the flattened wire to the required width. Flat sections with round or square edges can be produced by this method.

Tubing. This form is manufactured in sizes ranging from approximately ⅛ to 12 in., outside diameter, and with wall thickness from 0.010 to ½ in., depending on the outside diameter.

Tubing is manufactured by bench drawing or otherwise reducing from extruded blooms to the required finished dimensions. The drawing process consists essentially of pulling the tube through a hole in a die, thus reducing the outside diameter, while a mandrel inside the tube controls the inside diameter.

Another tube-reducing process employs dies with tapered grooves. These dies are rocked back and forth over the tube, compressing the metal of the tube against a mandrel which governs the inside diameter. The tube is fed through the dies intermittently and is rotated, so as to distribute the working action over the entire circumference of the tube.

The process is determined by the finished size of

tube, the type of finish and the accuracy of dimensions required.

Impact Extrusions.* These are manufactured commercially within the following approximate size limitations: diameter or distance across flats, ¾ to 5 in. inclusive; minimum bottom thickness, 0.020 to 0.075 in. inclusive; minimum wall thickness, 0.010 to 0.281 in. inclusive; maximum length, 4½ to 10 in. inclusive. The limits of any one dimension are determined by the alloy and the other dimensions.

Impact extrusions are cup-shaped objects produced by striking a high-speed impact blow with a punch into a die cavity containing a cold slug of metal, approximately the shape and size of the outer cross-sectional dimension of the shell. The die cavity is of the same size and shape as the outside of the desired part, and the punch is of the same size and shape as the inside of the part to be produced. The impact is sufficient to cause the metal to fill the die cavity and to flow or squirt upward out of the die and around the punch. Speed is the important characteristic of this method of cold working. The movement of metal takes place in a fraction of a second. Collapsible tubes, commonly used as containers for toothpaste, shaving cream and similar commodities, are examples of products made by this process.

*For a description of the process of impact extrusion, see the article "Extrusion of Lead and Lead Alloys", page 947.

The Forming of Aluminum Alloys

By L. J. Weber*

ALUMINUM is one of the most workable of the common metals. The principles of forming all metals are basically the same, but for each metal there is a difference in the amount of permissible deformation, the details of tool design, annealing procedures and such. The data and procedures discussed here are those which have been found most satisfactory in commercial practice.

General Sheet Metal Practice for Aluminum. Forming operations, such as bending, rolling, flanging, beading, curling, crimping and hammering, can be classified under general fabrication of sheet metal. Bending is the basic operation in most sheet metal work. During bending, the metal on the outside of the bend is stretched while that on the inside is compressed. If breaking occurs or if the metal is severely strained during or after the forming operation, a larger bend radius should be used, or the alloy or temper should be changed to provide material with better bending characteristics. Tables I and II show bend radii for the different aluminum alloys and tempers that have been used successfully with a variety of types of forming equipment. These tables should be used only as a guide to determine the approximate radius for each specific job.

Bending may be done on the ordinary folding brake or bar folder, using approximately the same technique as for other metals. The power brake with the proper tooling will produce a variety of shapes. The tools that are used most widely are V-dies with punches that have suitable radii. For relatively thin metal, a block of rubber retained in a steel channel section may be used as the die. As the sheet is forced into the rubber, the metal assumes the shape of the punch, which is designed with the proper radii for obtaining the desired contour.

Edging, beading or curling rolls are often employed to produce a beaded or half-round edge. The rolls employed are usually specifically designed to meet the requirements of the job. Many complicated shapes can be formed by utilizing roll molding machines where the material travels through successive rolling operations in a single machine.

Curved surfaces or cylinders may be fabricated by roll forming. In the production of cylinders by this method, an area remains flat, approximately equivalent to the distance between the lower front and the back roll. This flat area may be minimized by preforming the ends of the sheet to the proper radius before the sheet is fed into the forming rolls.

The Drawing of Aluminum. Aluminum is drawn on the same type of equipment that is used for other metals. Many shallow draws are made on single-action presses because of the high speed at which such presses can be operated. If no blank-holder is used in the drawing operation, the metal must be thick enough to avoid wrinkling. With thin metal, a blank-holder is usually required, and an air cushion is sometimes attached to the press, or springs are built into the tools to provide the necessary pressure against the blank-holder to avoid wrinkling.

Deeper draws require the double-action press, which has an outer ram where a blank-holder is attached and an inner ram where the punch is attached. When a shell is being drawn, the outer ram, with the blank-holder attached, descends first and exerts pressure on the outer edge of the blank; the inner ram, to which the punch is attached, then descends and forces the metal into the die. The pressure on the blank-holder must be adjusted to permit the blank to slip and, at the same time, prevent the formation of wrinkles. If the blank is held too tightly it will break. To obtain a smooth shell of metal that is uniform in thickness it is always necessary to adjust the pressure on the blank-holder with care.

The proper temper of the common aluminum alloys is determined by the article to be drawn. For severe draws, annealed sheet is used, but for less severe draws, the intermediate tempers or even full hard temper may be used.

Heat Treatable Alloys. When heat treatable alloys are required, severe draws are usually made from annealed sheet. For less severe draws, the sheet may be given the solution heat treatment, and the aging may be retarded by keeping the sheet at a low temperature (minus 20 F will virtually prevent aging in most alloys) until the drawing operation is performed. Very shallow shapes may some-

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Table I. Bend Classification for Making a 90-Deg Cold Bend in Aluminum and Aluminum Alloy Sheet

The minimum permissible radius varies with the nature of the forming operation, the type of forming equipment, and design and condition of tools. The minimum working radius for a given material, or hardest alloy and temper for a given radius, can be ascertained only by actual trial under the contemplated conditions of fabrication.

Alloy and Temper(e)	Bend Classification(a)	Alloy and Temper(e)	Bend Classification(a)
2S-O	A	24S-O(b)	B
2S-H12	B	24S-T4(b)(c)	J
2S-H14	B	24S-T36(b)	K
2S-H16	D		
2S-H18	F	52S-O	B
		52S-H32	C
3S-O	A	52S-H34	D
3S-H12	B	52S-H36	F
3S-H14	C	52S-H38	G
3S-H16	E		
3S-H18	G	61S-O	B
		61S-T4(c)	
4S-O	B	61S-T6	F
4S-H32	C		
4S-H34	D	75S-O(b)	D
4S-H36	F	75S-W(b)(d)	E
4S-H38	G	75S-T6(b)	K
14S-O(b)	B		
14S-T4(b)(c)	H		
14S-T6(b)	K		

(a) For corresponding bend radii see Table II.
(b) Alclad 14S, 24S and 75S can be bent over slightly smaller radii than the corresponding tempers of the uncoated alloy.
(c) Immediately after quenching, these alloys can be formed over appreciably smaller radii.
(d) As long as 2 hr after quenching.
(e) For nominal compositions of these alloys, see page 793.

Table II. Approximate Radii Required for 90-Deg Bend, in Terms of Thickness, t

	Approximate Thickness					
B & S Gage	26	20	14	8	5	2
Inch	0.016	0.032	0.064	0.128	0.182	0.258
Inch	1/64	1/32	1/16	1/8	3/16	1/4
Bend Classification						
A	0	0	0	0	0	0
B	0	0	0	0	0 to 1t	0 to 1t
C	0	0	0	0 to 1t	0 to 1t	½t to 1½t
D	0	0	0 to 1t	½t to 1½t	1t to 2t	1½t to 3t
E	0 to 1t	0 to 1t	½t to 1½t	1t to 2t	1½t to 3t	2t to 4t
F	0 to 1t	½t to 1½t	1t to 2t	1½t to 3t	2t to 4t	2t to 4t
G	½t to 1½t	1t to 2t	1½t to 3t	2t to 4t	3t to 5t	4t to 6t
H	1t to 2t	1½t to 3t	2t to 4t	3t to 5t	4t to 6t	4t to 6t
J	1½t to 3t	2t to 4t	3t to 5t	4t to 6t	4t to 6t	5t to 7t
K	2t to 4t	3t to 5t	4t to 6t	5t to 7t	5t to 7t	6t to 10t

times be formed in the full heat treated *T* temper, but difficulties are often encountered because of breakage caused by the high strength of the alloy and the comparatively low elongation.

Alloys that develop their maximum properties by aging at an elevated temperature are frequently drawn in the as-quenched or *W* temper. The time that elapses between the solution heat treatment and drawing should be kept at a minimum since these alloys do harden to some extent at room temperature. The desired strength is then obtained by heating the formed parts to the proper aging temperature for the necessary period.

Successive Reductions. Long experience has indicated that the successive reductions given in Table III are nearly optimum for drawing cylindrical shells. Tools designed to give these reductions will usually operate satisfactorily. Although higher reductions may be used occasionally, great care should be taken to avoid making the draws too critical, because otherwise the loss in scrap, as well as the loss of time in production, will quickly exceed the expense saved in tooling.

Table III. Reduction in Diameter for Deep Shells

Operation	Suggested Reduction
Blank ..... (D)	.....
First draw ..... (D_1)	0.40D
Second draw ..... (D_2)	$0.20D_1$
Third draw ..... (D_3)	$0.15D_2$
Fourth draw ..... (D_4)	$0.15D_3$

Apparently the best results are obtained when the radius of the die is no less than four times and no more than fifteen times the original thickness of the metal. The radius of the punch should be at least four times the thickness of the sheet. If the radius is too sharp, the resistance to the flow of metal may cause fractures. If the radius is too large, wrinkling may occur in the sidewall of the shell.

Usually the drawing tools are designed so that the original thickness of the sheet is changed very little. This practice differs from that for brass and steel, which may be reduced in thickness as much as 50%. For this reason, it is often necessary to rework tools designed for brass and steel, when these tools are to be used to draw aluminum alloys.

Dimensions of Dies. In rectangular shapes, the greatest flow of metal occurs at the corners and must be controlled to prevent wrinkles and fractures. Provisions for this flow can be made by varying the radius of the draw. Ideally, the dimensions of the original blank should be such that there is just enough metal to obtain the desired shell. Care used in developing the blank often means the difference between success and failure in drawing. The suggested dimensions of dies for drawing rectangular and cylindrical shapes are given in Tables IV and V respectively.

Lubricants. A lubricant for drawing has two important functions: (1) it allows the blank to slip readily between the blank-holder and die; (2) it prevents galling and scratching while the movement takes place. Mineral oils or compounded mineral oils are most often used. Water-soluble drawing compounds have been tried but have been found less satisfactory. Some of the oils that have proved suitable in production operation are the following:

Light draws .....Light lubricating oil
Medium draws .....Mixture of light and heavy lubricating oil
Severe draws .....Heavy lubricating oil or a mixture of 50% mutton tallow and 50% paraffin
Very severe draws....Mixture of 30% mutton tallow and 70% paraffin

It should be remembered that the proper choice of lubricant for a particular plant is a matter of experience and depends on factors such as tool design, tool materials and sheet thickness.

The Stretch Forming of Aluminum. The use of stretcher presses for forming parts has increased considerably during the past few years. In this operation the edges of the sheet are clamped tightly; then a punch of desired shape is pushed up against the sheet by means of a hydraulic ram. The metal is actually stretched over the punch and thus takes the required shape. This method of forming can be used for making long, sweeping contours where sharp radii are not used.

Molding and extrusions can also be formed by this method. The ends are not clamped fixedly as with sheet but instead are clamped in jaws attached to air cylinders or hydraulic cylinders. A variation in pressure can be applied on these cylinders to obtain a part that is satisfactory in shape without causing wrinkles.

The Forming of Aluminum by Means of a Drop Hammer. Drop hammers are especially suitable for small production runs, since the dies and punches are usually made from soft alloys and are therefore both cheap and easy to produce. The parts that are made on drop hammers are usually shallow and have liberal radii.

Table IV

Dimensions of Dies for Drawing Rectangular Shapes

First draw .....Add 2.2 times blank thickness to punch dimension
Second draw .....Add 2.2 times blank thickness to punch dimension
Final draw .....Add 2.0 times blank thickness to punch dimension

Table V

Dimensions of Dies for Drawing Cylindrical Shapes

First draw .....Punch diameter plus 2.2 times thickness of blank
Second draw .....Punch diameter plus 2.3 times thickness of blank
Third and succeeding draws .....Punch diameter plus 2.4 times thickness of blank
Final draw of tapered shells .....Punch diameter plus 2.0 times thickness of blank

Guerin Process. Forming with rubber, also commonly known as the Guerin Process, is a procedure that was employed frequently for forming airplane parts during the war. The tool setup is usually inexpensive and a number of parts can be formed at one time. This process is especially useful in flanging and forming shallow parts.

Bending Tubes and Shapes. In the bending of tubing or shapes, the material on the outside of the bend is stretched and that on the inside is compressed. Therefore the metal must be ductile enough to permit both stretching and compression to take place.

The size and shape of the tubing also govern the bends

that can be made. The sharpness of bend depends on the diameter of the tubing and on the ratio of wall thickness to diameter. The thinner the wall of the tubing, the more tendency there is for rupture on the outside of the bend. Extremely thin-walled tubing has a tendency to fail by buckling on the inside of the bend. Besides fracturing and buckling, another difficulty that must be overcome in this bending is the tendency of the tubing to flatten or distort at the point of the bend. The curves in Fig. I give bend radii that can be used as a guide for forming aluminum tubing.

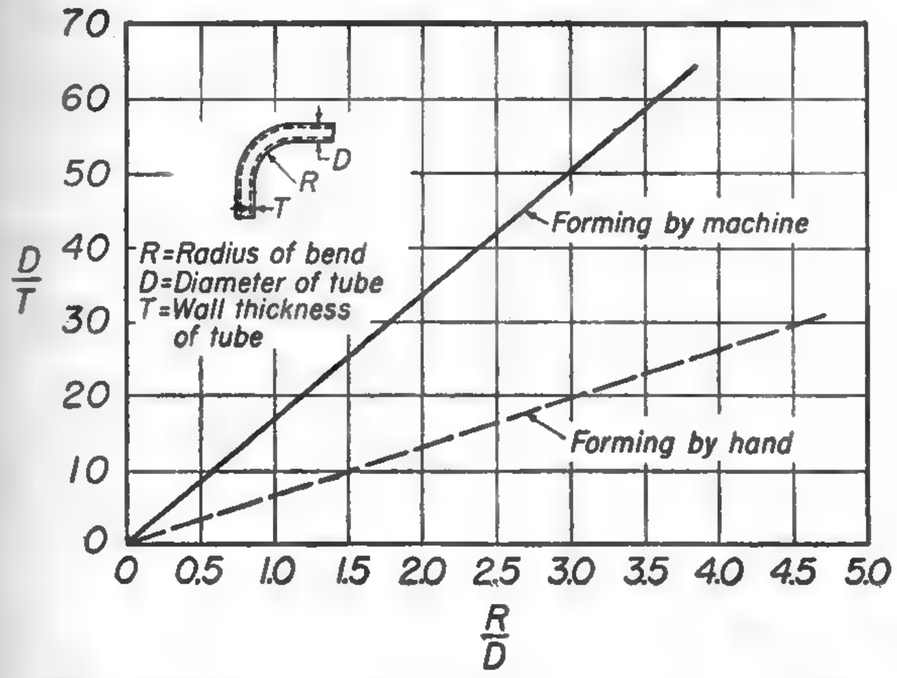

Fig. 1 Suitable bend radii for round aluminum alloy tubing (alloys 2S-H14, 3S-H14, 61S-T4, 52S-H32, 24S-O)

The essential parts of mechanically operated machines for bending tubes and shapes are the hub, follow block, clamp and mandrel. The tube is slipped over the mandrel (which is mounted on a rod that is long enough to accommodate various lengths of tubing) and is placed between the follow block and the hub, both grooved to fit the tube. The clamp blocks then hold the tube against the hub in order to make the bend when the hub is rotated. The mandrel supports the inside of the tube during bending, and must be located so that its point of curvature is exactly even with the center line of the hub. If the mandrel is ahead of this point, the tube will break; if the mandrel is too far back, the tube will flatten. Since the tube must slide against the blocks as it is being bent, lubrication must be provided.

The Heat Treatment of Aluminum Alloys

By C. F. Nagel, Jr.,* P. V. Faragher* and W. E. Sicha*

SINCE the data sheets concerning the individual aluminum alloys give the temperature ranges for heat treatment and the physical properties thus obtained, this article will discuss the heat treatment processes and the general principles involved.

Heat treatment improves the mechanical properties of several wrought or cast aluminum alloys. At least the principal hardening constituents in all these alloys are substances that have distinctly higher solid solubility in aluminum at elevated temperatures than at room temperatures. Heat treatment is simply a means of distributing the alloying ingredients more efficiently so that they can perform more effectively their function of hardening the metal.

Aluminum alloys that are susceptible to heat treatment solidify too rapidly in the production of castings and ingots to permit attainment of equilibrium conditions. The dendrites formed during early stages of solidification consist of solid solution, which varies in composition from the core to the outer layer of the dendrite arms.[1] An appreciable percentage of the added hardening elements is present in the form of eutectic or relatively large particles of a rich alloy. These conditions exist in spite of the fact that the total amount of the hardening elements may be completely soluble in solid aluminum at temperatures just below the melting point, for equilibrium conditions.

Working of the aluminum alloy ingots tends to break up the cast structure and thereby increase the rate of solution of the soluble alloying constituents when the metal is subsequently heated. Also, solution is more rapid in castings with a small grain size and fine dendritic structure. In general the heat treating temperature is made as high as possible without melting any of the eutectic material that is present in a particular alloy. The alloy is held at the high temperature long enough for solution and diffusion to take place and produce, as nearly as practicable, a homogeneous solid solution. The alloy is then rapidly cooled or quenched so that there is not time for the hardening elements to precipitate from solid solution during the cooling period, in accordance with their lower solubility at lower temperatures. This process is called "solution heat treatment". Such treatment increases all the mechanical properties.

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Following solution heat treatment, the dissolved alloying constituents tend to precipitate from solid solution in accordance with their true solubility relations at room temperature and to coalesce into larger particles. The rate of this precipitation varies both with the alloy and with the temperature. Even with 24 S (4.5% Cu, 1.5% Mg, 0.6% Mn, remainder Al), which ages rapidly at room temperatures, holding at subzero temperatures suppresses the precipitation almost indefinitely. When the material is brought back to room temperature, age hardening proceeds at the normal rate. In contrast, 25 S (4.5% Cu, 0.8% Mn, 0.8% Si, remainder Al) ages very slowly at room temperature and must be held at slightly elevated temperatures to bring about any substantial change in mechanical properties. Other wrought alloys show appreciable increases in properties after aging at room temperature, and they reach a substantially stable condition in most instances within a matter of days; but if subjected to an artificial aging treatment, they show a marked further increase in yield strength together with some increase in tensile strength.

The aging that occurs at room temperature in solution heat treated casting alloys is usually most marked in the first few days after quenching and proceeds at a slower rate over a period of several weeks. This aging is substantially completed in three months or less in most casting alloys. Precipitation is greatly accelerated by aging at slightly elevated temperatures. Aging generally increases the tensile and yield strengths and hardness but reduces the ductility.

It should be noted that during aging or "age hardening" at room temperatures, or artificial aging (commonly called "precipitation heat treatment") at slightly elevated temperatures, even the larger particles formed are usually too small to be resolved by the optical microscope. By prolonged heating it is possible, in all solution heat treated aluminum alloys, to enlarge the precipitate to a size visible under the microscope. Particles of the size that results from aging treatments are more effective in hardening the metal than are the atoms of alloying constituents that are present in solid solution, and these particles are also more effective than the larger particles that result from prolonged heating or "overaging".

The foregoing paragraph outlines the theory presented by Merica and his associates to explain the facts observed in the heat treatment of aluminum alloys. This theory may not describe completely the phenomena that occur, but with the slip interference theory of Jeffries and Archer,

which pictures the particles as keying the crystal planes against slip, it gives a mechanical analogy that is easy to remember and explains the nomenclature in common use for these processes.

Thermal Treatment Processes. Three basic types of thermal treating processes are commonly applied to aluminum alloys:

1 Solution heat treatment consists in heating the alloy to a temperature at which certain constituents go into solution, usually in the range from 900 to 1000 F, and then quenching the metal to maintain these constituents in solution during the period of cooling.

2 Precipitation heat treatment consists in heating the alloy at a slightly elevated temperature, usually in the range from 250 to 400 F, to accelerate precipitation and agglomeration of the constituents in supersaturated solid solution.

(*a*) Such a precipitation treatment usually follows solution treatment.
(*b*) A precipitation treatment may be applied to material that has not received solution heat treatment. Certain fabricating processes for wrought alloys hold hardening constituents in solid solution in concentrations appreciably greater than the equilibrium solubility at room temperature. Similarly, the cooling rates that prevail in the production of commercial castings retain a degree of supersaturation of the solid solution at room temperature.
(*c*) Casting alloys that have received solution heat treatment may be overaged by application of a precipitation treatment at a temperature somewhat higher than the temperature range noted above. Overaging results in precipitation in excess of that which imparts maximum hardness and strength.

3 Annealing consists in heating to a temperature intermediate between the solution and precipitation heat treating temperatures to attain essentially complete precipitation and to remove residual strains.

Thermal Treating Practice.* *Furnaces for Solution Heat Treatment.* Wrought aluminum alloys are commonly heat treated in molten salt baths or in air furnaces, but the casting alloys are almost invariably heat treated in air furnaces. The salt bath consists either of fused sodium nitrate or, if the bath is also to be used for annealing, a mixture of equal parts of sodium and potassium nitrates. Provision should be made for the proper circulation of the bath throughout the immersed load of metal, to insure uniform temperatures in all parts of the bath. Gas, oil or electricity may be used to heat the bath, which is held in a steel or cast-iron tank.

By far the largest tonnage of aluminum alloys is heat treated in air furnaces, which may be heated electrically or by gas, oil or radiant tubes; the type of heating selected usually depends on local conditions. For best results artificial circulation should be provided. Furnaces in which products of combustion are circulated can be used satisfactorily if the atmosphere contains a sufficiently high percentage of carbon dioxide and is free from sulfur compounds and excessive moisture.[2] If electrical heating is used, the units should be of the type that has a low input of energy per unit of area. The baffles used to direct the air circulation may also serve to minimize direct radiation to the charge.

Furnaces for Precipitation Heat Treatment. Precipitation heat treatment is carried out in a furnace or oven usually heated electrically or by gas. Provision should be made for circulating the air in order to obtain a uniform temperature throughout the furnace, as well as more rapid transfer of heat.

Furnaces for Annealing. Furnaces for annealing are heated ordinarily by oil or gas but electric furnaces are also used. The permissible temperature range for annealing is wider than for solution or precipitation heat treatment.

Pyrometric Equipment. Since accurate temperature control is essential for best results, all pyrometers should be calibrated at regular and frequent intervals. Automatic temperature recorders are desirable, if not essential, to provide a record of the heating period, as a means of insuring that the material has been heated for the required time within the desired temperature range and that it has not been overheated. Furnace operation is simplified by equipment that regulates the temperature automatically, but manual control is possible. For further information about pyrometry see the article on page 174.

Solution Heat Treatment. Aluminum alloys in large tonnage are heat treated successfully without difficulty. Therefore, the following detailed instructions and precautions should not be interpreted to mean that proper heat treatment is a difficult process that cannot be carried out under commercial conditions. Proper practices are necessary for satisfactory results, but with ordinary care the required methods are established readily on a normal operating basis.

The temperature of the salt bath or of the furnace should not be higher at any time during the period of heat treatment than the maximum temperature specified for heat treatment of the alloy. This maximum temperature is chosen so as to be as high as possible without exceeding the melting point of the eutectic that is present in the alloy. If this eutectic is melted during heat treatment, the mechanical properties and usually the surface appearance of the alloy are seriously injured.

If the alloy is not heated to the minimum temperature specified, the full mechanical properties will not be developed and, in some instances, the resistance to corrosion of the resulting product will be below standard.

It is not possible to obtain satisfactory results by heat treating different parts of a piece of metal in succession. A piece must be uniformly heated throughout and quenched in all parts in the same operation.

The heating time is measured from the time the coldest part of the load reaches the minimum of the temperature range for heat treatment as determined from a temperature survey of a production load. The time at temperature will vary with the nature of the product and the alloy. Thick massive sections of wrought alloys require heating periods as long as a few hours; for thin sheet a few minutes may be sufficient. Relatively long heating periods are required for solution heat treatment of casting alloys.[1] The actual periods of time required will be determined from experience in operating the equipment with the various types of material to be heat treated. The consistent development of satisfactory mechanical properties is the criterion of correct heat treatment.

For clad wrought alloy products, the minimum possible time should be used in order to avoid the diffusion of the alloying constituents of the core through to the surface.[3] Since different thicknesses of metal require different times of heating, it is preferable not to heat treat clad products of very different thickness in the same load.

Quenching. After the alloy has been heated for the required time, it is removed and quenched. The time interval should be as short as possible between the removal of the load from the heating bath or furnace and the complete immersion of the metal in the quenching medium; in any event the interval should not exceed a few seconds for wrought alloys. Particularly for thin material, the use of guard sheets will minimize the loss of heat during the period of transfer. In quenching castings commercially, a time interval of considerably less than one minute can be realized between removal from the furnace and immersion in the quenching medium.

Allowing the metal to cool in the air is equivalent to quenching from a lower heat treatment temperature, and both mechanical properties and resistance to corrosion may be impaired. Quenching wrought alloys in hot water, in oil, or in air, may develop the required mechanical properties, but the resistance to corrosion is usually inferior to that of material quenched in cold water. However, in some instances, such practice may be necessary to avoid warping. Relatively slow cooling from the solution treatment may be permissible for forgings made of 53 S (0.7% Si, 1.25% Mg, 0.25% Cr, remainder Al) and 14 S (4.4% Cu, 0.8% Si, 0.75% Mn, 0.35% Mg, remainder Al), since the resistance to corrosion of these materials seems to be influenced less by cooling rate than that of some of the other heat treated wrought alloys. The quenching rate does not ordinarily influence the resistance to corrosion of aluminum casting alloys, but relatively rapid quenching in boiling water contributes to maintenance of the desired mechanical properties.

If the metal has been heated in a nitrate bath, it must

* For general information concerning furnaces and salt baths, see the articles on pages 267 to 283.

be thoroughly washed to remove the salt completely, since otherwise nitrate may initiate corrosion of the metal. For this purpose, warm water (150 F) may be used after the metal has been quenched in cold water, because of the greater solubility and higher rate of solution of the salt at higher temperatures.

Precipitation Heat Treatment. The rate of precipitation from supersaturated solid solution and agglomeration into larger particles varies for different alloys and also depends on the temperature. If the temperature of the material is raised moderately after quenching, the rate of precipitation is increased. Moreover, with proper choice of temperature, the resulting tensile and yield strengths are very much higher than those developed by room temperature aging, and the elongation is appreciably lower. Also the increase in yield strength is substantially greater than the increase in tensile strength.

The first effect of aging at elevated temperatures is a small loss in tensile and yield strengths but, as the process is continued, these properties increase, pass through a maximum and then decrease to values intermediate between those of the "as-quenched" and annealed conditions. The elongation decreases at first quite rapidly, then more slowly to a constant value. The time required to reach the maximum strength decreases as the aging temperature is raised, but the value for the maximum strength also decreases. At still higher aging temperatures the strength decreases continuously from the start.

For precipitation heat treatment in industry, the temperature must be high enough to permit development of the desired properties within a reasonable time, from the standpoint of economy and efficiency of plant operation, but not high enough to result in too great a sacrifice in the properties that can be obtained in the alloy. Also the aging period must not be so short that variations such as result from differences in time required for all parts of the load to come to temperature, cause appreciable variation in the properties that are obtained.

In general, the properties are the same whether the precipitation heat treatment is begun immediately after quenching or after aging at room temperature for any period of time. There is some evidence that there may be a small improvement in the properties of 75 S (5.5% Zn, 2.5% Mg, 1.5% Cu, 0.3% Cr, 0.2% Mn) if artificial aging is not begun during the interval between 2 hr and 2 days after quenching, but the improvement is not sufficient to complicate production schedules with such a requirement.

For some wrought alloys, the response to artificial aging is greatly enhanced if the material is strain hardened after solution heat treatment and prior to precipitation heat treatment. For 24 S (4.5% Cu, 1.5% Mg, 0.6% Mn) the increase in tensile and yield strengths is more than doubled by reductions of 6% by cold work prior to artificial aging.

Annealing. The annealing practice varies, depending on the condition or temper of the alloy. The strain hardening resulting from working wrought alloys that were originally in the soft temper, may be removed and the alloy completely softened by heating to a temperature in the range of 640 to 670 F. Heating to temperatures higher than 670 F causes partial solution heat treatment and consequently prevents complete softening; at temperatures lower than 640 F, annealing may not be complete. Casting alloys are usually annealed when in the "as-cast" condition by heating for 2 hr at 650 F.

This same practice, when applied to the wrought alloy that has been subjected to the solution heat treatment, will remove most of the effects of heat treatment as well as any subsequent strain hardening, so that the alloy is suitable for all but the more severe forming operations. However, if the heat treated alloy must be completely annealed, it must be heated for 2 hr at 750 to 800 F, then slowly cooled (not faster than 50 F per hr) until a temperature of 500 F has been reached. The rate of further cooling to room temperature is not important.

Nomenclature. The condition of heat treatment is designated by appending to the alloy number the letter T and a number that identifies the specific heat treatment. The suffix W also is a heat treatment designation, used to indicate the unstable condition immediately after solution heat treatment. For temper designations, see page 808.

Nitrate Hazard. Fused nitrate baths are commonly used in the heat treatment of steel as well as of aluminum, and it is important to guard against certain dangers in their operation. Care should be taken to prevent contact of the fused salt with carbonaceous or organic material (wood, charcoal, coke, oil or cloth) or with red hot iron or steel. Articles to be heat treated, or sludge, should not be allowed to lie on the bottom of the tank, especially if the tank is underfired, since they are likely to cause the tank to be burned through as a result of local overheating. It is important to guard against the possibility of combustible gases accumulating around the tank, and it is desirable to have at some distance from the tank a shutoff valve for the heater, which can be operated in an emergency.

Extra sacks of nitrate should be stored in a dry place and at a distance from the tank. Care should be taken not to put anything wet into the nitrate bath. If fresh salts to be added to the bath are at all wet, it is best to make the addition when the bath is frozen. In the melting of a solid bath, the salt must melt freely at the sides of the tank before melting at the bottom, to avoid generation of pressure and possible explosion. In controlling a nitrate fire, it is vitally important not to use water or any fire extinguisher containing water. Perhaps the best fire extinguisher is dry sand, a supply of which should be kept near the tank.

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Joining Aluminum Alloys

By E. C. Hartmann,* G. O. Hoglund,* M. A. Miller* and P. T. Stroup*

THE METHODS described in this section for joining aluminum alloys include riveting, welding by gas, metal-arc, carbon-arc, tungsten-arc, atomic hydrogen and resistance methods, brazing by torch, furnace, or dip processes, diffusion bonding, resin bonding and soldering.

Riveting

Of the numerous wrought aluminum alloys available today, five are used commercially in the form of rivets for joining aluminum alloy structures. These various rivets are described as follows:

* Aluminum Company of America, New Kensington, Pa.

Rivets of Commercially Pure Aluminum (2 S). Rivets of commercially pure aluminum are soft and are used only for nonstructural joints in constructions involving the low-strength aluminum alloys. They are not heat treated either during manufacture or subsequently by the user, but are employed in an intermediate cold worked temper, just as when they come from the heading tools. They are readily driven cold and in the driven condition will develop an average shear strength of about 11,000 psi.

A17 S Alloy Rivets. This alloy contains nominally 2.5% Cu, 0.3% Mg, with the remainder aluminum. Rivets of A17 S are heat treated as the last step in their manufacture and are employed without subsequent heat treatment by the

user. They are driven cold and develop an average shear strength of 33,000 psi in the driven condition. In sizes ⅜ in. or less in diam, they are readily driven with ordinary equipment and can be cold driven in even larger sizes, especially if suitable squeeze riveters are available. Of all aluminum alloy rivets, those of A17 S are the most widely used in aircraft and they have been used successfully also in other types of structures where the parts to be joined are of aluminum alloy 14 S, 17 S or 24 S.

17 S Alloy Rivets. This alloy consists nominally of 4% Cu, 0.5% Mn, 0.5% Mg and the remainder aluminum. Rivets of 17 S alloy are always heat treated before use. Ordinarily they are heat treated at the plant of the manufacturer before shipment and are subsequently heat treated again by the user just before use, in order to make them soft enough to be headed easily. The treatment consists of heating the rivets to a temperature of 930 to 950 F and quenching in cold water. The rivets harden gradually at room temperature, reaching their full strength after about four days, but for a period of 1 to ▮ hr after quenching, they are soft enough to be headed without difficulty. This age hardening can be postponed and the soft condition greatly prolonged by storing the rivets at low temperature immediately after quenching. After removal from the cold storage, which is often a simple dry-ice chamber, the rivets resume their normal rate of room temperature aging. When used in the larger sizes, 17 S rivets can be successfully hot driven, if heated within the temperature range from 930 to 950 F and driven promptly after removal from the heating medium, so as to obtain a quench in contact with the material into which they are being driven. These rivets are generally stronger than A17 S rivets, but their shear strength depends somewhat on the driving condition as shown in Table I. Rivets of 17 S have been used widely in construction of aircraft and are used also in general structural applications involving parts made of 14 S, 17 S, and 24 S alloys.

Table I. Average Ultimate Shear Strengths for Driven Aluminum Alloy Rivets[a]

Rivet Alloy	Driving Procedure	Shear Strength, psi
2 S	Cold, as received	11,000
A17 S-T3	Cold, as received	33,000
17 S-T31	Cold, as received	39,000
17 S-T31	Cold, immediately after quenching	34,000[b]
24 S-T31	Cold, immediately after quenching	42,000[b]
53 S-T61	Cold, as received	23,000
17 S-T41	Hot, 930 to 950 F	33,000[b]
53 S-T41	Hot, 960 to 1050 F	18,000[b, c]

(a) These values are for rivets driven with cone-point heads. Rivets driven with heads that require more pressure, may be expected to develop slightly higher strengths.

(b) Immediately after driving, the shear strengths of these rivets are about 75% of the values shown. On standing at ordinary temperatures the rivets age harden to develop their full strength; this action is completed in about four days for rivets of 17 S and 24 S, and in about two weeks for rivets of 53 S.

(c) This shear strength is for rivets driven at temperatures from 960 to 980 F. The shear strength increases about 1000 psi for each increase of 12 F in driving temperatures. Thus, if the range of driving temperature is carefully maintained at 1030 to 1050 F, an average shear strength of 24,000 psi will be developed in the driven rivets.

24 S Alloy Rivets. These rivets have a nominal composition of 4.5% Cu, 0.6% Mn, 1.5% Mg, with the remainder aluminum. Before use they are always heated within the temperature range from 910 to 930 F, then quenched in cold water and aged at room temperature. They are supplied in the heat treated temper but should be heat treated again by the user just before driving, in order to make them soft enough to be headed satisfactorily. Rivets of 24 S alloy remain soft enough for driving for only about 90 minutes after quenching if held at room temperature; so, like rivets made of 17 S, they are usually stored at low temperature to prolong the period during which they can be headed satisfactorily. Typical driven rivets in this alloy will develop a shear strength of about 42,000 psi after about four days of aging at room temperature. These rivets are the strongest and most difficult to drive.

53 S Alloy Rivets. The nominal composition of this alloy is 0.7% Si, 1.3% Mg, 0.25% Cr, with the remainder aluminum. These rivets are heat treated by the manufacturer before shipment and are generally driven cold by the user without subsequent repetition of heat treatment. They are somewhat easier to drive than A17 S rivets and can be upset cold with ordinary driving equipment in sizes as large as ½ in. Typical cold driven rivets of this alloy develop a shear strength of about 23,000 psi. Sizes larger than ½ in. can be driven cold, especially if suitable squeeze riveting equipment is available. Where such equipment is not available, however, the rivets may be driven hot successfully by heating them to temperatures within the range from 960 to 1050 F and driving promptly after removal from the heating medium, so as to obtain a quench in contact with the material through which the rivet is being driven. The shear strength of such rivets is a function of the driving temperature and of the duration of aging after driving, as shown in Table I. Rivets may be obtained that are intended specifically for hot driving and are made of 53 S-T4 rather than 53 S-T61, because the former temper is cheaper and gives equally good results when driven hot.

Rivets of 53 S-T61 alloy and 53 S-T4 alloy have been most widely used in marine construction in conjunction with plates and shapes of 52 S, 53 S, and 61 S alloys, because in combination with these alloys the rivets exhibit excellent resistance to salt water and other types of corrosive action.

Table II. Reduction in Shear Strength of Aluminum Alloy Rivets as a Result of Use in Thin Plates and Shapes

Ratio of Rivet Diameter to Plate Thickness,[a] D/T	Percentage Loss in Shear Strength: Single Shear	Double Shear
1.5	0	0
1.6	0	1.3
1.7	0	2.6
1.8	0	3.9
1.9	0	5.2
2.0	0	6.5
2.1	0	7.8
2.2	0	9.1
2.3	0	10.4
2.4	0	11.7
2.5	0	13.0
2.6	0	14.3
2.7	0	15.6
2.8	0	16.9
2.9	0	18.2
3.0	0	19.5
3.1	0.4	20.8
3.2	0.8	22.1
3.3	1.2	23.4
3.4	1.6	24.7
3.5	2.0	26.0
3.6	2.4	27.3
3.7	2.8	28.6
3.8	3.2	29.9
3.9	3.6	31.2
4.0	4.0	32.5

(a) Thickness of thinnest plate in single shear joint. Thickness of middle plate in double shear joint.

Reduction in Shear Strength. Table II shows the reduction in shear strength of rivets which occurs with increasing ratio of rivet diameter D to plate thickness t.

Rivet Holes. Rivet holes in aluminum alloy structures may be either drilled, punched, subdrilled and reamed, or subpunched and reamed. In general, the reamed holes are much to be preferred, especially if the reaming is done in assembly, to give the holes exact coincidence. The correct clearance to use in the rivet holes depends largely on the class of work. The best clearance is the smallest one that will allow the rivet to be inserted easily without delay and is usually about 2 to 3% of the shank diameter. Hot rivets require slightly more clearance than cold ones because it is harder to handle them, and delay while inserting them into the holes must be minimized.

Flush Riveting. Countersinking of aluminum alloy plates for flush riveting should be done with a clean, sharp tool, in conjunction with a stop to prevent the plates from countersinking too deeply. The dimpling operation consists of pressing a depression into the sheet and using this recess to receive the countersunk head of the rivet.

Preparation of Faying Surfaces. For maximum resistance to corrosion, all faying surfaces in aluminum alloy riveted joints should be painted before assembly. The usual procedure is to treat the joints with one of the phosphoric acid solvent compounds and then to apply one coat of zinc chromate primer to each of the faying surfaces. The paint should be dry before the joint is assembled. The zinc chromate pigment is recommended because it imparts a corrosion-inhibiting effect to the paint in addition to the ordinary covering protection. If required, a sealing compound containing zinc chromate may be used in the joint.

Methods of Driving. Virtually all driven heads on small rivets are flat heads upset by means of pneumatic hammers or squeeze riveters. In the aircraft industry the usual procedure is to apply the pneumatic hammer to the manufactured head of the rivet and to upset the driven head against a suitable flat bucking bar or block, held firmly against the end of the shank of the rivet. An equally acceptable procedure, however, is to apply the hammer to the shank end of the rivet and to hold a suitably shaped bucking bar against the manufactured head of the rivet. In fact, this second procedure is to be preferred where the parts being riveted are quite stiff or likely to be damaged by the battering action of the pneumatic hammer.

Where flush surfaces are required, the usual practice in aircraft riveting is to insert a countersunk manufactured head into the countersunk hole and upset a small flat head on the shank end of the rivet. An equally acceptable and often preferable procedure, however, is to use some other style of manufactured head, insert the rivet from the nonflush side of the work, and upset the shank end to fill the countersunk hole. To obtain satisfactory results with this type of driving, it is necessary to leave a portion of the driven countersunk head protruding above the work and to dress this head off flush.

The intermediate sizes of rivets for purposes of this discussion range from ¼ to ½ in. in diam and are suitable for joining shapes and plates that range in thickness from ⅛ to about $\frac{7}{16}$ in. Generally, aluminum alloy rivets in this range of sizes may be driven without heating; pneumatic hammers should be used not exceeding the size corresponding approximately to a 1 to $1\frac{1}{16}$-in. bore and a 6 to 8-in. stroke. For accessible locations, squeeze riveting is preferable to riveting with a pneumatic hammer, and should be employed if the equipment is available. In riveting with a pneumatic hammer, the recommended procedure is to hold

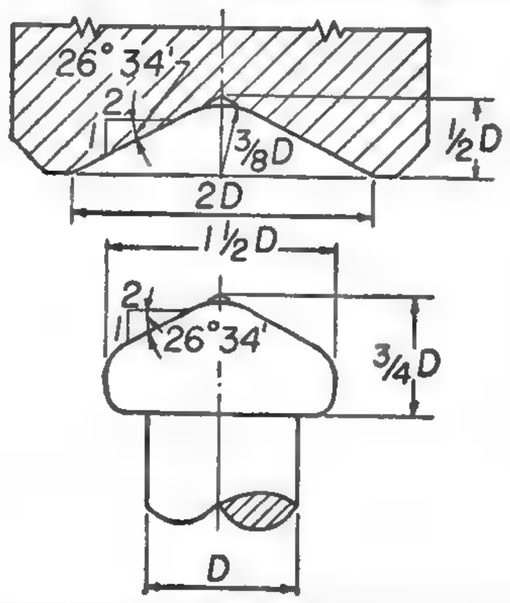

Fig. 1 Nominal dimensions of cone-point head and rivet set

the bucking bar against the manufactured head of the rivet and to upset the driven head with the pneumatic tool. If the work is not countersunk, a cone-point head of the type shown in Fig. 1 is recommended, because it requires much less pressure to drive than other types of heads, such as the round head or button head. A small flat driven head of the type used in the aircraft industry is also satisfactory if desired. Where countersunk heads are used, a 60-deg included angle of countersink is recommended, with the hole countersunk a little less than the thickness of the outside plate. In the driving of countersunk rivets, a tight rivet is usually obtained if the rivet is inserted from the side of the work that is not countersunk and is upset to fill the countersink with a slight excess of metal, which can be removed to give whatever degree of flushness is required for the particular job.

If large rivets are to be driven without heating, it is usually necessary to employ squeeze riveters, a practice that results in excellent rivets. When the cone-point and 60-deg countersunk types of driven heads are used, as described in connection with the driving of intermediate-size rivets, a squeeze riveter capacity of 30 to 40 tons is required for handling the ¾-in. rivets in the various aluminum alloys.

The use of squeeze riveters is limited by the accessibility of the part to be riveted and by the size and reach of the squeeze riveters available for a particular job. Where squeeze riveters cannot be used, it is ordinarily necessary to apply heat in driving the larger sizes of rivets, in order to make them soft enough to be upset by the pneumatic hammers. The usual procedure for hot driving aluminum alloy rivets is to heat the rivets within the normal commercial heat treating range as indicated earlier, remove them quickly from the heating medium, and insert them in the holes with a minimum loss of time so as to quench the rivets in contact with the material into which they are being driven. This procedure usually calls for an electrically heated circulating-air furnace that has good temperature control to

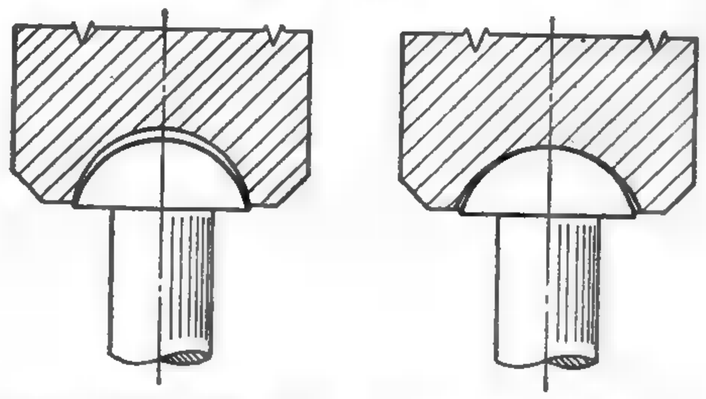

Fig. 2 (*Left*) Incorrect fit of the bucking tool on the manufactured rivet head. (*Right*) Correct fit. Clearances are exaggerated.

insure against underheating or overheating the rivets. Also this procedure requires having the furnace near the work in order to minimize the time of transfer of the rivet from the furnace to the work.

Driving Tools. The tools used for driving aluminum alloy rivets are much the same as those used for riveting other metals. Smooth polished surfaces are best for the parts in direct contact with the aluminum alloy surfaces, so that a minimum of friction is offered to the flow of metal during the upsetting operation. Pneumatic hammers should be of ample size to upset the rivet without excessive hammering. Undersized pneumatic hammers tend to peen the rivet rather than to upset it. Bucking bars should have sufficient mass, preferably distributed close to the rivet head and concentric with it. The manufactured head of the rivet should be pressed tightly against the work piece during the upsetting operation. If this is not done, or if the bucking-up set does not have sufficient mass, the manufactured head will often be separated slightly from the work piece when the driving operation is finished.

Regardless of whether a pneumatic hammer or a squeeze riveter is used, the set that is held against the manufactured head during the driving operation should be slightly wider and shallower than the manufactured head so that the initial contact will be at the end of the head directly in line with the shank, as shown in Fig. 2. This practice will prevent the shank from being driven up into the head, and thus will minimize the tendency toward the formation of a crack or fold at the junction of the shank with the manufactured head.

Welding

The common welding methods that have been adapted to the joining of aluminum and aluminum alloys, include both fusion and electric-resistance welding processes. Fusion-welded joints are made by gas, metal-arc, carbon-arc, tungsten-arc or atomic hydrogen welding. Resistance-welded joints are made by spot, seam or flash welding. In each method, the metallurgical and physical characteristics of the aluminum alloys must be considered in order to obtain

economical results and sound joints. The following sections contain a general discussion of the essential characteristics of each welding method as applied to all these alloys.

Gas Welding. The commonly used gases for welding aluminum and aluminum alloys are oxyhydrogen and oxyacetylene. With respect to soundness, strength, speed and appearance, equally good results are obtained with either gas. Standard equipment in the way of torches, hose and regulators, is suitable for welding such materials. Some welding has also been accomplished with oxypropane derivatives and with mixtures of oxygen with natural gas. Good soundness and strength have been obtained in such welds, but the use of these gases does not appear to be economical, because of the comparatively low rate of welding.

When aluminum is being fusion welded with gas, it is important that a suitable flux be used to remove the oxide coating that forms on the surface of all aluminum alloys in the atmosphere. This coating does not melt at the welding temperatures and will prevent smooth coalescence of the weld metal unless a flux is provided that will melt at a temperature somewhat lower than the welding temperatures and will break down the surface skin of oxide, permitting the liquid metal from the rod to flow into the molten parent material. A number of good fluxes are available. These are applied either dry or mixed with tap water to the consistency of ■ thick paste.

Virtually all fluxes for aluminum welding contain chlorides and fluorides, with the result that in the presence of moisture, residual deposits left on the joints after welding will attack the base metal. Thorough cleaning is especially necessary on parts that are painted, since the presence of flux will raise the paint coatings over the welds. Such action can be prevented if, immediately after welding, the parts are cleaned by scrubbing the joints in boiling water. On tanks or parts where the joints are inaccessible, the flux can be neutralized by dipping for 10 to 15 minutes in a cold solution of 10% nitric acid mixed with 0.25% hydrofluoric acid. Other acid mixtures and commercial cleaners may also be suitable for this purpose.

The proper choice of filler material for gas welding is important, particularly in the joining of alloys that have comparatively large amounts of alloying constituent. Commercially pure aluminum and metal of higher purity are generally welded with the same grade of metal as the parent material. The same practice is satisfactory for the aluminum-manganese alloy (3 S). In welding the aluminum-magnesium alloys or the aluminum-silicon-magnesium alloys, ■ filler rod containing 95% Al and 5% Si (43 S) is commonly used. This rod has a melting point substantially lower than that of pure aluminum, and permits the dissipation of some of the stress set up by solidification shrinkage and the thermal contraction that occurs in the weld zone as it cools. Cracks in the weld and the transition zone can be minimized by the use of this rod on parts that are welded in jigs to hold proper alignment.

Arc Welding in General. Aluminum and the aluminum alloys can be fusion welded with the metal arc, carbon arc, tungsten arc and with atomic hydrogen. The advantage in these processes is that the highly concentrated heated zone obtained with the arc prevents excessive expansion of the parts that are being welded, thus lessening distortion. Furthermore, the preparation of the joints for welding is simpler and the rate of welding is faster.

Metal-Arc Welding. Because of the relative difficulty of controlling the arc, it is not practical to butt weld material that is less than 0.081 in. thick, or to fillet weld joints on plate that is less than ⅛ in. thick. The soundness of the welds, particularly in thin material, is not equal to that of torch welds. Arc-welded joints are equal in strength to torch-welded joints; however it is difficult to obtain liquid-tight or gastight joints in material less than ¼ in. thick.

The standard electrodes for welding aluminum are designed to be used for direct current. Ordinarily this current is obtained from a d-c motor-generator set used for welding steel. Current obtained by rectifying alternating current is also satisfactory for this purpose, but the standard 60-cycle alternating current is not suitable for use with the present electrodes. However, if high-frequency current is superimposed on standard 60-cycle alternating current, the standard electrodes will function satisfactorily.

The proper polarity should be determined by trial on the joints to be made. The capacity of the equipment and the size of electrode are determined by the thickness of the material to be welded. Table III provides approximate machine settings and electrode sizes for welding the various thicknesses of aluminum.

Table III. Electrode Size and Machine Settings for the Metal-Arc Welding of Aluminum

Thickness, inch	Electrode Diameter, inch	Current, amperes
0.081	⅛	55 to 65
0.102	⅛	65 to 75
0.125	⅛	75 to 85
3/32	⅛ or 5/32	85 to 100
1/16	5/32	100 to 125
¼	5/32 or 3/16	125 to 150
5/16	3/16	150 to 175
⅜	¼	175 to 200

Unless a suitable flux is provided, the oxide coating present on the electrode and the parent material will prevent coalescence of the weld metal. Consequently, successful results are most easily obtained by using a coated electrode on which a heavy coating is provided that functions both to remove the coating on the metal and to stabilize the arc. Since the 43 S alloy provides superior fluidity at the welding temperatures, this alloy is used for the filler material in all the electrodes that are commercially available.

Carbon-Arc Welding. Carbon-arc welding is an alternative arc-welding method suitable for all the weldable aluminum alloys in any thickness not exceeding approximately ½ in.

Equipment for making carbon-arc welds is the same as that used for metal-arc welds except that a-c as well as d-c power is suitable as a source of welding current. In manual welding, more training and experience are needed before an individual becomes adept at making fillet and butt welds. Welding is almost always done in the downhand position.

A filler rod coated with flux is necessary in carbon-arc welding and electrodes for metal-arc welding are frequently used. This is satisfactory with respect to strength and soundness, but it is more economical to use a rod specially prepared for carbon-arc welding with a thinner coating of flux. Such a filler rod will make 20 to 30% more footage of weld.

The carbon arc has also been adapted for automatic welding. The most suitable type of equipment is that in which the arc length is adjusted automatically and an a-c field is superimposed around the carbon.

The method has been used for seams and head welds in vessels such as chemical tanks and tank cars. No preparation of edges is required for butt joints ½ in. thick or less. Back-up below the joint and a clamping device are necessary to maintain alignment of the edges. Filler wire and powdered flux are fed to the weld automatically. The alloy of the wire should be the same as that used for other welding methods. It is ordinarily desirable to employ hard drawn wire instead of annealed wire in order to get a uniform feed in the wire-feed mechanism.

Tungsten-Arc Welding. The only fusion welding process found suitable for welding aluminum alloys without the use of a welding flux is tungsten-arc welding in an argon atmosphere. This process, introduced during World War II, widens the field for application of welding. Welds made properly by this method are relatively free from discontinuities such as oxide film, porosity, or lack of fusion. The characteristics of welds made by this method are a sound weld structure, uniformity in strength of the joints, improved ductility across welds in the heat treatable alloys, and smooth appearance.

The procedure is carried out with standard a-c welding equipment supplied with superimposed high-frequency current on the welding circuit to establish and hold a steady arc. Filler wire of the standard compositions is fed into the joint. The smooth coalescence and viscosity of the weld metal make it feasible to weld in the overhead and vertical position as well as downhand. High-purity argon is fed

through a cup surrounding the tungsten electrode, so that it blankets the arc and the molten metal.

Preparation of the surface for welding requires thorough cleaning and removal of the oxide coating. Dirt and grease are usually removed by solvent methods; then the edges and the surface near the weld are cleaned further with a wire brush. No cleaning is required after the weld has been made.

Atomic Hydrogen Welding. The atomic hydrogen process involves drawing an arc between two tungsten electrodes in a hydrogen atmosphere. The arc, independent of the work material, can be handled in much the same manner as a welding torch and may be moved away from or toward the joint, according to the need. This flexibility is valuable in making many types of joints.

In the atomic hydrogen process a good grade of aluminum flux should be used; a number of such fluxes are available. When mixed with water to the consistency of a thin paste, the flux should be applied to both the filler rod and the seam.

As in gas welding, the choice of filler material is important in this process and follows the same rules. Where the thickness of the metal being welded is sufficient to allow the manipulation, the filler rod may be inserted into the molten pool and moved back and forth to assist in breaking up the oxide film that is present. Aluminum flows readily after reaching the molten state, so care must be used to keep the molten metal from falling through. To prevent this, particularly with plates thicker than $\frac{3}{16}$ in., it is desirable to back up the weld.

In atomic hydrogen welding, cracking may be avoided usually if a short weld, about an inch long at the beginning of a seam, is made and allowed to cool before proceeding with the remainder of the seam. Parts should be preheated to approximately 425 F before welding, and should be allowed to cool slowly after the weld is completed. Sawdust sprinkled near the seam will char at about the correct preheating temperature. A powdery layer of oxide and flux gradually accumulates on the electrode clamps and may cause the arc to flow between the tips of the electrode holder instead of between electrodes, with resulting damage to the tips. If the ends of the electrode clamps are dipped into water occasionally, this accumulation will be dissolved.

Welding of Castings. The welding of aluminum alloy castings is a useful and economical procedure for the foundryman and fabricator. One of the chief applications is in salvaging castings that have foundry defects. Another important use is in repairing castings that have been cracked or broken. The welding of castings is of interest to the fabricator also because aluminum alloy castings can be welded satisfactorily to wrought alloy sections, thus forming combinations of thick and thin metal.

In general, the welding of aluminum alloy castings requires a technique similar to that used for aluminum sheet and other wrought products. However, it is necessary to consider carefully the susceptibility of many castings to thermal strains and cracks, because of intricate design and varying thickness of section. In addition, many castings in highly stressed structures depend on heat treatment for strength, and welding, as previously indicated, tends to destroy the effect of the initial heat treatment. In these instances, unless the casting or assembly can be heat treated again, welding is not recommended. When it is possible to heat treat the casting or assembly after welding, the strength can be restored substantially.

The data for preparation of edges, machine settings, and general recommendations for gas welding, arc welding, and resistance welding apply to the welding of castings. Some additional precautions are sometimes required, in regard to chipping or removing defects. Since many castings have intricate shapes, preheating is frequently desirable to reduce differentials in temperature. In this connection, slow and uniform cooling to room temperature is as important as preheating for the elimination of thermal strains that occur because of changes in shape or section.

Castings should be designed so that the parts to be joined by welding have as nearly the same thickness as is practicable. Rather than to attempt the welding of a thick section directly to a wrought or cast part that has a relatively thin section, it is better to provide a gradual taper on the thick section and to weld at a point where the thickness approximates that of the lighter piece. Cast fittings to be welded to light-gage wrought parts, should be provided with flanges tapering to the thickness of the wrought section. Consideration of these factors in the design of castings will greatly facilitate the welding of assemblies involving light and heavy sections.

Resistance Welding. The aluminum alloys are joined in production by spot, seam and push or flash welding methods. Sound joints can be made by resistance welding if proper equipment is used; if the surface of the metal is prepared correctly; and if the proper machine settings are used in operating the equipment.

Equipment for spot welding aluminum is not basically different from that used for welding other metals, except that more rigid control of time and pressure is desirable and the current should be integrated in smaller steps. When timing is considered, best results are produced—particularly on light-gage material—with electronic equipment that ensures delivery of a definite number of cycles, and eliminates undesirable transients in the secondary circuit by making and breaking the current at the zero point on the a-c wave. Good results can also be obtained with timers of the contactor type, controlled either mechanically or electronically. Experience has shown also that mechanisms utilizing hydraulic or pneumatic pressure are superior for spot welding the aluminum alloys, because duplication of pressure at the tips can be obtained most accurately. Current in the secondary circuit must be relatively high in equipment for spot welding the aluminum alloys, because of the high thermal and electrical conductivity of these materials. This factor of machine design should be considered in the preparation of machine specifications, in order to ensure that sufficient current is available.

The electrical demand in the spot welding of aluminum may be reduced by the use of a magnetic-energy-storage type of equipment that stores the welding energy in an inductor transformer by establishing a direct current between 100 and 400 amp in the primary winding of this transformer. When the current is interrupted by a magnetic contactor, a high value of current is established in the secondary circuit, and through the work that is being welded. This current decays to a low value in from 0.01 to 0.05 sec. Equipment incorporating this process is also provided with an electrode force system that permits the welding force to be varied during the welding operation. The combination of a short-time welding-current impulse and a varying force results in welds of excellent appearance and of sound structure.

The direct current used in the primary of the inductor transformer is ordinarily obtained by rectifying a three-phase 440 or 220-v shop supply. The maximum demand for power with this type of equipment is about one-tenth that of a-c equipment, welding the same thickness of material, because the energy is obtained by drawing a lower power for a much longer time.

The condenser-energy-storage equipment utilizes static condensers to store the energy used for welding. The three-phase shop power is stepped up in voltage and rectified so as to charge the condensers to a voltage from 1000 to 3000 v. When this bank of charged condensers is connected to the primary of the special welding transformer, an impulse of welding current rises rapidly to its maximum value and decays to zero at a somewhat slower rate. For welding with this equipment, a constant high value of welding force is generally used. Occasionally a higher force is used at the end of the welding procedure, to provide a forging action on the solidified weld metal. Welds produced with this type of equipment are excellent in appearance and very sound in structure. Also, the maximum demand on the power system is about one-tenth of that required when a-c welding equipment is used for joining the same thickness.

For all these forms of welding equipment, the power required depends on both the material to be welded and the throat area of the welding machine. To obtain adequate power and reduce the cost of the welding equipment, it is advisable to use a machine with the shortest length of arms and the minimum arm spacing compatible with the shape of the work pieces to be welded.

Preparation of the surface of the material is significant,

particularly with respect to welding cost. The oxide coating of some alloys is sufficiently resistant to passage of the welding current to cause surface heating that will alloy the welding tip materials with the parts. This is particularly true of the heat treated alloys, in which the thermal operations required during heat treating increase the thickness, and consequently the resistance, of the surface oxide coatings. From any alloy that wears away the tip excessively, the oxide coating should be removed with steel wool, emery cloth, or a chemical etch before welding.

In setting up a welding operation it is essential to use welding tips that will maintain consistent distribution of current and pressure during successive welds. The common method of dressing tips with a file is not suitable for spot welding the aluminum alloys. Good results in practice have been obtained by machining the tip to a contour that can be restored periodically with a fine grade of emery held in the fingers. A tip with a hemispherical end is ordinarily employed. Materials for tips to be used in spot welding should have a conductivity greater than 75%, and a hardness exceeding Rockwell B 60. To make proper machine settings it is essential to calibrate the current and pressure delivered by a machine.

Table IV

Machine Settings for Spot Welding Aluminum Alloys

Gage B & S No.	Gage Inch	Time, cycles	Current, amperes	Electrode Pressure Min, lb	Electrode Pressure Max, lb
26	0.016	4	14,000	200	400
24	0.020	6	16,000	300	500
22	0.025	6	17,000	300	500
20	0.032	8	18,000	400	600
18	0.040	8	20,000	400	600
16	0.051	10	22,000	500	700
14	0.064	10	24,000	500	700
12	0.081	12	28,000	600	800
10	0.102	12	32,000	800	1000
8	0.128	15	35,000	800	1200

In seam welding, a special application of spot welding, rolls are used for electrodes and the current is applied intermittently. Machine characteristics, as outlined above, apply as well to seam-welding equipment, except that successful results have been obtained only with electronic timing devices. In the making of liquid-tight or gastight joints, the timing cycle is adjusted so that the current is on not more than 30% of the time. By adjustment of the timing cycle and the speed of the rolls, overlapping or intermittent welds can be made. Machine settings for seam welding depend on the gage, temper and alloy to be welded.

Electric Butt Welding. The common alloys, 2 S and 3 S, and high-purity aluminum are more readily electric butt welded, but all the wrought alloys can be welded by this method if a welding machine of proper design is available.

Simple cylindrical and rectangular sections of aluminum can be push welded. The parts to be welded are clamped in dies and pressure is applied before the application of power causes melting at the surface of the aluminum and softening of the metal near the plane of contact. The joint is held under pressure by the dies so that the molten and soft metal are squeezed out of the joint. Power is cut off after a predetermined die travel or application of a definite number of cycles of current. The weld freezes rapidly because of conduction of heat away from the joint.

Push welds require excellent fit between the pieces being welded and between the pieces and the clamping dies. Equipment for such welding is characterized by high current capacity and rapid free movement of the movable die.

The flash butt-weld process is adaptable to welding complicated extruded shapes of aluminum as well as the simpler cylindrical and rectangular shapes. Parts to be welded are clamped in dies and power is applied before the parts are allowed to come in contact. A motor-driven cam imparts an accelerated motion to the movable die, and thus brings the dies together. Flashing is continued from ½ to 1½ sec, during which time from ¼ to ¾ in. of aluminum is flashed from the parts being welded. The flashing period is terminated when the power is cut off almost simultaneously with a sudden increase in velocity of the moving die. The ends of the parts being welded are forced together and the weld freezes rapidly bcause of conduction of heat to the dies.

Good fit between the parts being welded is not necessary. Dies should fit the aluminum sections well enough to provide mechanical support for projections or thin sections, and clamping pressure must be high enough to prevent slippage during the final push-up period.

The relations among welding time, die motion, die spacing and welding current are varied for each section and each alloy of aluminum that is welded.

The weldable aluminum alloys are grouped as shown in Table V, and special characteristics of welding as applied to these groups are described in the following.

High-Purity Aluminum. Occasionally it is necessary to use material of purity higher than that of commercially pure aluminum, in order to obtain greater resistance to certain types of chemical attack. As a typical example, many

Table V. Process Chart for Welding Aluminum Alloys

Metal or Alloy	Gas	Arc	Spot	Seam	Butt or Flash
High-purity aluminum	A	A	A	A	A
Commercially pure aluminum (2 S)	A	A	A	A	A
Al-Mn alloy (3 S)	A	A	A	A	A
Al-Mg-Cr alloy (52 S)	B	A	A	A	A
Al-Si-Mg alloys (53 S, 61 S, 63 S)	B	A	A	A	A
Al-Cu-Mg-Mn alloys (14 S, 17 S, 24 S, A17 S)	No	B	B	B	A
(Alclad 17 S, Alclad 24 S)	No	B	A	A	A

A, welds can be applied generally on a commercial basis.
B, commercial welding depends on design or special technique.
No, commercial welding is not feasible.

of the storage or fermenting tanks employed in the brewery industry are made of aluminum having a purity of 99.5%.

Fusion welding of high-purity aluminum requires no special treatment with regard to welding technique as far as equipment, preparation of joints, or machine settings are concerned. In order to produce welds that have resistance to corrosion comparable with that in the parent material, a filler wire of the same composition as the parent material should be used. This requirement is frequently fulfilled by shearing strips from the parent material. If joints in these materials are to be made by metal-arc or carbon-arc welding, special flux-coated electrodes with a filler material of high-purity wire should be obtained.

Welds in these materials are characterized by comparatively high ductility and dressing operations are usually carried out by hammering. A tensile strength across the welds equal to the strength of the annealed temper of the parent material is obtained in fusion welded joints, regardless of the temper of the material prior to welding. Sound welded joints can be made in any of the commercial forms of these materials.

Resistance welding of these materials is easily accomplished by spot, seam or butt welding and no special practices are required. The ability of these welds to withstand corrosion is not inferior to that of the parent metal.

Some difficulty may be experienced if spot or seam welding is attempted as a method of joining high-purity aluminum in the soft temper to material that is heavier than 0.100 in. thick. The cause of the trouble is that the hardness of these materials in the soft temper is not sufficient to prevent the welding electrodes from deforming the surface, with consequent spreading of the current and pressure distribution during the welding cycle. This results in weak and inconsistent welds—but not in the intermediate or hard tempers of these materials.

Commercially Pure Aluminum (2 S). Commercially pure aluminum, readily weldable by all methods, is widely used for making dairy and chemical tanks wherever the mechanical properties are adequate.

This material can be both gas welded and arc welded, and commercially parts have been welded that range in thickness from 0.020 to 1 in. Butt welds are characterized by high ductility in the welds and excellent resistance to impact or shock loading. A strength equal to the tensile strength of the annealed material is obtained in the welds.

Commercially pure aluminum is generally employed as a

filler material when making welds, and considerable testing and practical use have indicated that resistance to corrosion of such welds is substantially equal to that of the parent material. Metal-arc welding is usually done with standard flux-coated electrodes containing 43 S filler rod. However, where maximum resistance to chemical attack is important, a special coated electrode should be used, containing commercially pure aluminum filler material.

All the commercial forms of commercially pure aluminum are spot, seam, or butt welded in production. No special technique is required for welding these materials, and because of the excellent surface present on commercially pure aluminum, this is probably the most economical alloy to use with regard to cost of resistance welding. It is also common practice to use resistance welding for joining together articles made of commercially pure aluminum and for cast parts in which the composition has been varied to improve mechanical properties or casting qualities.

The remarks concerning the welding characteristics of the annealed temper, above, apply also to commercially pure aluminum.

Al-Mn Alloy (3 S). This alloy is substantially the same as commercially pure aluminum from the standpoint of welding, except that the mechanical properties of both the parent material and the welded joints are higher.

Fusion welding of this alloy is widely practiced where a higher strength is required than can be obtained in welded parts made from commercially pure aluminum. The previous remarks about filler wire and resistance to corrosion apply as well to this material.

Resistance welding of this alloy is similar to that of commercially pure aluminum. The strength of the welds, however, is higher.

Al-Mg-Cr Alloy (52 S). By the alloying of aluminum with magnesium and chromium, a material is available that has considerably higher mechanical properties than can be obtained in the materials mentioned in preceding paragraphs. This introduces problems that are discussed below, particularly from the standpoint of fusion welding.

In fusion welding, this material is more sensitive to the application of the welding heat, and as a result of thermal contraction and solidification shrinkage, cracks may occur when the weld cools. This condition is minimized if the filler material that is used has a lower melting point than the parent material, and virtually all gas welding is done with a 43 S filler rod. Cooling cracks are less likely when the parts are thin enough for welds to be made in one pass. Consequently, most commercial applications have been made on material less than ¼ in. thick. Welded joints in thicker parts usually require preliminary trial to determine a method that will cause the least stress in the welds during the cooling period.

The strength of welds in this alloy is generally equal to the strength of the annealed material, but the elongation in the welds is less than that obtained in commercially pure aluminum or the aluminum-manganese alloy.

The above remarks do not apply to joints made by the metal-arc or carbon-arc welding processes, in which the welding heat can be concentrated within a narrow zone and difficulties from cracking as the weld cools are virtually eliminated. The standard arc-welding technique using a 43 S filler wire in the electrodes is commonly employed for arc welding alloy 52 S.

This alloy can be spot, seam, or butt welded readily, and because of the high strength and hardness, no difficulty is experienced with any temper. Some of the commercial forms, particularly the annealed sheet, are covered with an oxide coating that will cause wear of the welding electrodes unless it is removed by mechanical or chemical means before welding. The strength of spot and seam welds in this alloy is higher than that obtained with the materials previously mentioned. The spot welding of this alloy has been practiced widely for assembling airplane gasoline tanks.

Al-Si-Mg Alloys (53 S, 61 S, 63 S). For strength, these alloys rely on operations in which the material is treated thermally so that the metallurgical structure is arranged to obtain comparatively high mechanical properties. The application of welding heat may partially obliterate the heat treated structure and lower the properties.

All these alloys can be joined with the welding torch so that sound welds with consistent strength are obtained. However, in this method of welding, the heat affects a width in the parent material from two to five times the thickness of the material. After welding, a repetition of the heat treatment will increase the strength of the joint, but because of the cast structure in the weld, a strength equal to that of the parent material is not obtained. The strength of a gas-welded object made of these alloys is usually not predictable, since the annealing effect of the welding heat depends on the amount and location of the welds in the parts. Mechanical tests are usually performed on the welded parts to determine the suitability of the welded assembly for the service intended.

The welding technique is substantially the same as for other materials and the resistance to corrosion of welded joints is good. Filler wire of 43 S is ordinarily used.

In arc welding, less difficulty is experienced from cooling cracks when these alloys are assembled with the metal arc or carbon arc, because of the comparatively narrow zone affected by the welding heat. However, the strength of the welds is approximately the same as that obtained with the gas torch, and the previous remarks made in connection with gas welding apply as well to arc-welded joints. Flux-coated electrodes containing 43 S filler wire are used for arc welding these Al-Si-Mg alloys.

For these alloys resistance welding is widely used, particularly where structural sections are spot welded to sheet panels to stiffen the panels. Sheet of 52 S alloy is commonly spot welded or seam welded to extruded shapes made of one of the Al-Si-Mg alloys. High mechanical strength is obtained with this combination and the resistance of the welds to corrosion is as good as that of the parent material.

Because of the heat treatment of these alloys, an oxide coating is usually present on the surface, which interferes with the passage of the welding current. Before welding, in order to prevent surface heating between the parts and the welding tips, mechanical or chemical cleaning operations are performed on the surface that contacts the welding tips. Occasionally, it is desirable also to remove the coating from one or both of the faying surfaces.

Al-Cu-Mg-Mn Alloys (14 S, 17 S, 24 S, A17 S, Alclad 17 S, Alclad 24 S). This group of materials includes the aluminum alloys in which the strength is increased to a maximum by heat treatment. With two exceptions, the effect of welding is to reduce the resistance to corrosion and the mechanical strength. Consequently, these materials are not used extensively in welded parts.

In view of the fact that no greater strength can be obtained when welding these alloys than can be obtained with 61 S and 53 S, and that the resistance to corrosion is substantially lowered by gas welding, these alloys cannot be recommended for joining by gas welding.

The previous remarks about gas welding apply as well to metal-arc and carbon-arc welds made in these alloys. However, these alloys can be arc welded in a limited number of instances when the welds can be placed at locations in the structure where the stresses are low. Because of the effect of the welding heat on the structure of the alloy, it is suggested that welded parts be tested before use or that the problem be submitted to an organization familiar with handling these alloys.

Spot, seam or butt welding can be used for assembling these alloys with good results in regard to static mechanical strength. Insufficient information is available to permit making general conclusions concerning the qualities of resistance welds under shock or vibrational loading.

Exposure tests of resistance welds made in these alloys have indicated, with the exceptions mentioned below, that the resistance to corrosion of the welds is not equal to that of the parent material. It follows that, under corrosive conditions, protective paint is essential to prevent deterioration in the joints.

In some applications, particularly aircraft structures, it is important that the resistance to corrosion of spot welds should be as good as that of the parent material in the high-strength alloys. Such resistance is obtained by providing a surface of high-purity aluminum on the alloys, thus protecting the material from corrosive influences. For this purpose, Alclad 17 S and Alclad 24 S

have been produced, and considerable testing of spot welds exposed to corrosive conditions has indicated that welds having corrosion resistance equal to that of the parent material can be produced in these alloys.

Brazing

Methods of Brazing. Aluminum brazing differs from welding, in that special fluxes and filler materials, having a melting point lower than that of the alloys being joined, are used for making the joints without melting the parent parts. The parts produced are similar to welded parts in the sense that the product is 100% aluminum alloy, a circumstance beneficially reflected in the matching of color and also in strength, resistance to corrosion, and ability to be anodically coated and electroplated.

The three procedures most widely applied in brazing aluminum are torch brazing, furnace brazing, and flux-bath or dip brazing. Torch brazing is similar to gas welding in that the heat required for melting the filler material is applied to the joint locally with a welding torch, using either oxyhydrogen, oxyacetylene or oxy-natural gas flames. Furnace brazing is done by applying a flux to the work pieces, assembling the parts and raising the temperature of the entire assembly or batch of assemblies in a furnace to a point that will cause the filler material to melt and flow into the joint without melting the parent parts. Dip brazing is accomplished by assembling the parts and dipping a particular area or the complete unit into a bath of molten flux held at a temperature higher than the melting point of the filler material but lower than the melting point of the parent alloys.

Materials Available. A number of fluxes are available for the brazing processes. Alcoa No. 33 flux is used for torch brazing all alloys and furnace brazing the alloys that can be brazed and heat treated. Alcoa No. 30 flux is used for furnace brazing where maximum flow of metal is required, particularly on heavy sections, at temperatures higher than 1100 F.

Several types of aluminum brazing sheet are available. This brazing sheet is a duplex product consisting of an aluminum alloy core with a thin layer of aluminum brazing alloy on one or both surfaces. When the sheet is properly heated to a temperature higher than the melting point of the coating alloy and lower than the melting point of the core, in the presence of an appropriate flux, a portion of the coating melts and flows into the nearest capillary spaces. Where aluminum brazing sheet can be used, the advantage is that no preplacement of brazing alloy is necessary, in the form of wire rings, washers or such. The proper fluxes, filler alloys and brazing temperatures are shown in Table VI for various materials to be brazed.

Design of Joints. Lock-seam, tee, line-contact, or lap joints, rather than butt or scarf joints, are ordinarily used with brazing. When added filler metal is used, clearance between the parts is necessary for the flow of the filler material. Clearances are of the order of 0.006 to 0.010 in. for laps smaller than 0.25 in. and as great as 0.025 in. for longer laps. For brazing sheet, the principle of line contact should be employed; that is, the sheet should touch the part to which it will be brazed along a line.

Alloys 2 S, 3 S and metal of higher purity are the only ones of the wrought alloys not adapted to heat treatment, for which commercial brazing processes have been developed. Since brazing temperatures are higher than annealing temperatures, designs involving the use of alloys that cannot be heat treated must be based on the annealed temper of the material. Alcoa 53 S, 61 S and No. 21 and 22 brazing sheet are the alloy products that can be heat treated, for which satisfactory brazing techniques have been developed. The temperature of brazing can also effect the heat treatment so that quenching after brazing, followed by artificial aging, will produce the maximum properties.

Brazing Technique. The parts to be brazed, as well as the filler material, must be thoroughly cleaned and freed from dirt and oil in order to obtain satisfactory results. The removal of foreign material is usually sufficient cleaning for torch-brazed joints. However, before furnace brazing or dip brazing, it is best to use a chemical cleaning method. A satisfactory procedure is to immerse the parts for about 30 sec in a 5% solution of sodium hydroxide at 150 F, then to rinse in water, to dip in a solution of 10% or more nitric acid, and finally to rinse thoroughly in water again.

Furnace brazing consists in assembling the parts with filler material in place, applying flux, and putting the assembly in a furnace operating at the required temperature, for a period sufficient to cause the flux and filler material to melt and flow into the joints. The brazing flux is usually applied by dipping the parts into a suspension of three parts of flux in one or more parts of distilled water, or by brushing or spraying this material onto the parts.

Dip brazing differs from furnace brazing in that it is not necessary to apply the brazing flux in a separate operation. Held in a suitable rack, the assembly, with brazing alloy in place, is dipped into molten flux. As in furnace brazing, the temperature is such that the brazing alloy melts and flows into the joints without melting the parent parts. A nickel pot that is heated externally or a ceramic pot that is heated internally may be used to hold the flux.

It is always necessary to remove the flux from the parts after brazing. Immersion in boiling water immediately after the brazing operation, generally removes most of the flux. If such a treatment is likely to distort the parts, they should be cooled first to room temperature and then immersed in boiling water. After most of the flux has been removed in boiling water, the parts are immersed in an acid solution and are then rinsed thoroughly. Suitable acid solutions are concentrated nitric acid, 10% nitric acid plus 0.25% hydrofluoric acid, or 10% nitric acid plus 10% sodium dichromate.

Mechanical Properties and Resistance to Corrosion. The wrought alloys that cannot be heat treated will be in the annealed temper after furnace or dip brazing. The wrought alloys suited to heat treatment may be quenched from the brazing operation and artificially aged or may be cooled in air, then heat treated again and allowed to age. Alloy 61 S, for example, when quenched from the brazing operation and afterward artificially aged, will exhibit a tensile strength of 45,000 psi, a yield strength of 40,000 psi and an elongation of 9% in 2 in. Under the same conditions, Alcoa No. 21 and 22 brazing sheet will develop a tensile strength of 35,000 psi, a yield strength of 29,000 psi and an elongation of 9% in 2 in.

Torch-brazed aluminum alloy joints have essentially

Table VI. Filler Alloys, Temperatures and Fluxes for Brazing Various Aluminum Alloy Products

Material Being Brazed	Filler Alloy	Brazing Temperature, deg Fahr	Brazing Flux	Type of Brazing
2 S, 3 S, 406	43 S wire	1160 to 1185	No. 33	Torch
	No. 711 brazing sheet	1160 to 1185	No. 30, 34, 53	Furnace
	No. 713 brazing sheet	1160 to 1185	No. 34, 53	Dip
53 S	No. 717 brazing wire	1060 to 1090	No. 33	Torch
61 S	No. 717 brazing wire	1060 to 1090	No. 33	Furnace
			No. 34, ■	Dip
No. 1, 2 brazing sheet	Present as coating	1160 to 1185	No. 34, 53	Furnace
			No. 34, 53	Dip
No. 11, 12 brazing sheet	Present as coating	1090 to 1140	No. 34, 53	Furnace
			No. 34, 53	Dip
No. 21, 22 brazing sheet	Present as coating	1090 to 1120	No. 34, 53	Furnace
			No. 34, 53	Dip

the same tensile and flexural fatigue properties as torch-welded aluminum joints in the same alloys.

In general, the resistance of brazed joints to corrosion is comparable to that of welded joints in the same alloys.

Diffusion Bonding

The methods of affecting a bond between two similar or dissimilar metallic surfaces, without the presence of a liquid phase, is termed "diffusion bonding".

For the diffusion bonding of aluminum parts, the first requisite is to have a minimum of oxide film on the surface. The parts are then brought into intimate contact by the suitable application of high pressures, and are heated to an elevated temperature in order to permit some deformation at the joint. The period of time required for permitting this deformation to take place, decreases with increasing temperature and pressure. The exact conditions of time, temperature and pressure depend on the surface preparation and the alloy used. Suitable pressures are of the order of 5,000 to 10,000 psi, with temperature in the range from 800 to 900 F and deformation from 25 to 50%. One production unit has operated under these conditions with a time cycle of 30 sec per assembly.

It is necessary to remove as much of the oxide film as possible and to permit deformation during bonding, so that the remaining oxide is broken up and extended, thus permitting intimate contact of metal against metal. Experience indicates that a chemical treatment of aluminum surfaces, with or without subsequent scratch-brushing, greatly reduces surface oxide film. When the surfaces are relatively free from oxide film they should be brought together as soon as possible, under conditions that will not cause reoxidation.

Resin Bonding

Resin bonding may be broadly defined as a process of making joints between metal and metal, or metal and nonmetal, by means of organic adhesives or resin cements, usually with the application of heat and pressure. The bonding may be carried out in the range from room temperature to about 500 F, depending on the adhesive used and the character of the surfaces to be bonded. The process can therefore be classified with low-temperature joining methods. Because the adhesives are organic in nature, the strength of resin-bonded joints decreases with any increase in temperature above room temperature.

Three basic types of cements are used for the resin bonding of aluminum alloys. Vulcanizable cements contain natural or synthetic rubber, alone or in combination with synthetic resin materials. Thermosetting cements are based on types of plastics that will not resoften, with or without additions of synthetic rubbers. The thermoplastic cements are generally solutions of plastic materials that will soften reversibly.

The surfaces to be bonded must be free from foreign matter, grease and such, but not necessarily free from uniform and stable oxide films. Solvent or vapor degreasing is sufficient in some instances; in others, particularly with the heat treatable aluminum alloys, it is desirable to use a chemical treatment—for example, a cleaner of the phosphoric acid type. Thermoplastic cements may be applied to the clean dry surfaces in the form of a solid, a hot melt or from solution; thermosetting and vulcanizable cements are almost always applied from solution, although films or tapes can sometimes be used. Solutions are applied by brushing, dipping, spraying, roller coating or like operations. The solvent is permitted to evaporate at room temperature or higher. The faying surfaces are then brought together, while subjected to the recommended temperature for the particular adhesive being used, under sufficient pressure to permit the cement-coated surfaces to come into contact and fuse or bond together. For thermoplastic cements, the characteristics of flow are such that with relatively thick films, the pressure may be quite low and the period of time only that required to bring the bond to the joining temperature. The heat-setting cements generally require pressures between 25 and 500 psi, temperatures from 200 to 400 F and time periods of 10 to 30 min. A common method for obtaining such conditions is to place the parts together between electrically heated platens in a hydraulic press.

It is always advisable to design resin-bonded joints so that the principal stresses are in shear. Furthermore, it must be borne in mind that although the failing load of an assembly will be proportional to its width parallel to a simple lap joint, the failing load will not be proportional to the amount of overlap at the joint, because of unbalanced strains. Such unbalanced strains may be minimized by using scarf, strapped or double lap joints. The failing stress of resin-bonded assemblies that contain simple lap joints, will increase with increasing thickness of the component sheets; for example, from 2500 psi for sheet 0.028 in. thick to 5300 psi for sheet 0.192 in. thick. In resin-bonded joints in work pieces made of Alclad 24S-T4, 0.064 in. thick, the tensile shear strength decreases from about 5000 psi for a 0.25-in. overlap to about 3800 psi for a 1.0-in. overlap. Scarf joints in 0.064-in. Alclad 24S-T4 have given shear strengths of 6400 to 6700 psi.

Some adhesives are associated with rather severe corrosion at faying surfaces, when lap joints are immersed in sea water for several months; other adhesives fail without visible corrosion. A few adhesives resist an exposure to sea water quite satisfactorily for at least a year. In applications where high resistance to corrosion is needed, it is advisable to paint the resin-bonded joint.

Soldering

Any ordinary soldering iron (soldering copper), heated by gas or electricity, may be used on aluminum in the same manner as on the other materials, such as copper, brass and iron, except that before the copper tip is used, it should be tinned with ordinary lead-tin solder, and that an aluminum solder must be used for the joining. As for other metals, flame or torch methods may be used for soldering aluminum, with the added precaution that the flame should be directed on the side of the part opposite the joint or near the joint, so that the heat to melt the solder is supplied by conduction, and so that the flame does not come in direct contact with the flux and solder; a hot plate is particularly useful in this connection. A small quantity of the flux is applied to the joint or to the solder wire and the joint is made by means of a soldering iron, flame or hot plate. No rubbing is needed; the technique resembles that for other metals.

For accessible surfaces, it is common practice to cause the molten solder to wet or to alloy with the aluminum by a method involving mechanical abrasion or friction. In general, the solder is melted on the aluminum surface and the surface is rubbed or otherwise abraded beneath the molten solder in order to remove the oxide film and to allow the solder to adhere to the surface. Mechanical friction can be produced by a soldering iron, scraper, steel wool, wire brush, or sometimes by the solder stick itself. After the surfaces are alloyed to the solder, they may be joined together by placing them in contact and subjecting them to heat; additional solder may be added if required. Aluminum surfaces that have been properly alloyed to an aluminum solder by any of the common methods may then be joined by ordinary soft solders and fluxes.

Soldered joints can be used for joining tubing, sheet, extruded shapes or any of the commercial forms of 2S or aluminum of higher purity—3S, 53S and 61S. Alloy 52S has rather poor soldering characteristics unless the parts are cleaned before applying the solder; a brief dip in 5% hydrofluoric acid has been found suitable for such cleaning. Alloys such as 56S, which contain substantial amounts of magnesium as an alloy constituent, have poor soldering characteristics.

Soldering can also be used for joining other metals to aluminum, either directly or by plating the aluminum first with copper. For example, joints can be made to copper, brass, iron, steel, nickel and other metals. Applications such as the joining of copper sleeves to transmission line fittings have been successful for many years.

The resistance to corrosion of soldered joints is the most important single factor to be considered before the

use of soldering is attempted for purposes of production. Since all solders are composed of metals possessing solution potentials different from that of aluminum, corrosion failure of the joint may occur in the presence of an electrolyte. Many salt-type fluxes leave a residue that accelerates corrosion, and for this reason such fluxes should not be used. The life of the joint will depend almost entirely on the conditions to which it is exposed. Experience indicates that if a joint can be kept dry, it will last indefinitely. When resistance to corrosion is important, brazed, welded or riveted joints should be considered, or a paint coating should be applied to the soldered joint.

Machining Aluminum Alloys

By R. L. Templin*

ALUMINUM and most of its commercial alloys have good machining characteristics, but these characteristics differ somewhat from those of the other commonly used metals. Although the tools ordinarily used for cutting steel will often give satisfactory results with aluminum and its alloys, best results will be obtained by following the methods described here.

Free-machining aluminum alloys are produced with machining characteristics that make them better suited than the other aluminum alloys for many of the operations performed by machine tools that are used for high production.

The following instructions are divided into two parts. The first part describes recommended tools and procedures for general machine-shop practice; the second part deals specifically with automatic screw-machine practice.

General Machine Practice

Tool Materials. Since their performance on aluminum is generally satisfactory, plain high-carbon tool steels are widely used for machining aluminum and most aluminum alloys. For quantity production work, however, high speed tool steels have replaced plain high-carbon tool steels to a large extent. Tools tipped with cemented tungsten carbide show marked superiority over both high-carbon and high speed tools. Cutting edges of carbide-tipped tools remain sharp much longer without regrinding, and they produce a better surface finish. In fact, tungsten carbide tools are necessary for best results with aluminum alloys of a high silicon content.

Tool Shapes in General. In the following description of tool shapes, a wide range of rake angles is indicated. In general, the larger rake angles are employed for finishing tools and for the aluminum alloys that are not free-cutting; this includes the softer materials, which require tools with exceptionally acute and keen cutting edges. On the other hand, rake angles in the lower range are used for roughing cuts and for machining the alloys that have free-cutting characteristics. Tools similar to those used for machining steel may often be employed successfully.

Top Rake. The top rake of the tools for cutting aluminum generally varies from 20 to 50 deg, depending on the type of tool used and the kind of stock to be machined. Finely finished surfaces may be produced with tools that have a top rake angle in the higher end of the range, but such tools can be used only in a machine that is sturdy and free from vibration, with no lost motion in its feeding mechanism. For some operations it may be necessary to use a top rake smaller than indicated by the above range, but a negative rake should never be used.

Side Rake. A side rake between 10 and 20 deg assists greatly in the cutting action of the tool, since it tends to produce a slicing action, enabling the tool to cut the metal more freely. Planer finishing tools have been ground with a side rake as great as 40 deg, in order to take full advantage of the good cutting characteristics of aluminum.

The cutting-tool angles previously described apply to the machining of aluminum in general. Although there are some tools to which they may not be adapted, these angles can produce the best results with many types of tools. Specific values for the different angles are governed by the work to be done and by the requirements of the machine in which the tool is used.

Clearance. The angle of clearance should be about 8 to 10 deg. This angle, plus the top rake angle indicated, leaves about 30 to [illegible] deg for the total included angle of the cutting edge of the tool.

Clearance is important and must be carried around the side of the tool that advances into the work material. If this clearance is too small, the side of the tool will rub against the stock and generate heat; if the clearance is too large, the tool may dig into the stock and chatter.

Tool Finish. It is essential that the cutting edges be keen, smooth, and free from grinding-wheel scratches, burrs or wire edges. Great emphasis must be given to this requirement, because success in machining aluminum and its alloys depends on the condition of the cutting edges to a large extent. Keen edges may be obtained by finish grinding on a fine abrasive wheel, then lapping, or hand stoning with a fine oilstone. Care must be taken so that neither the angles nor the contour of the cutting edge are appreciably modified during the finishing operations.

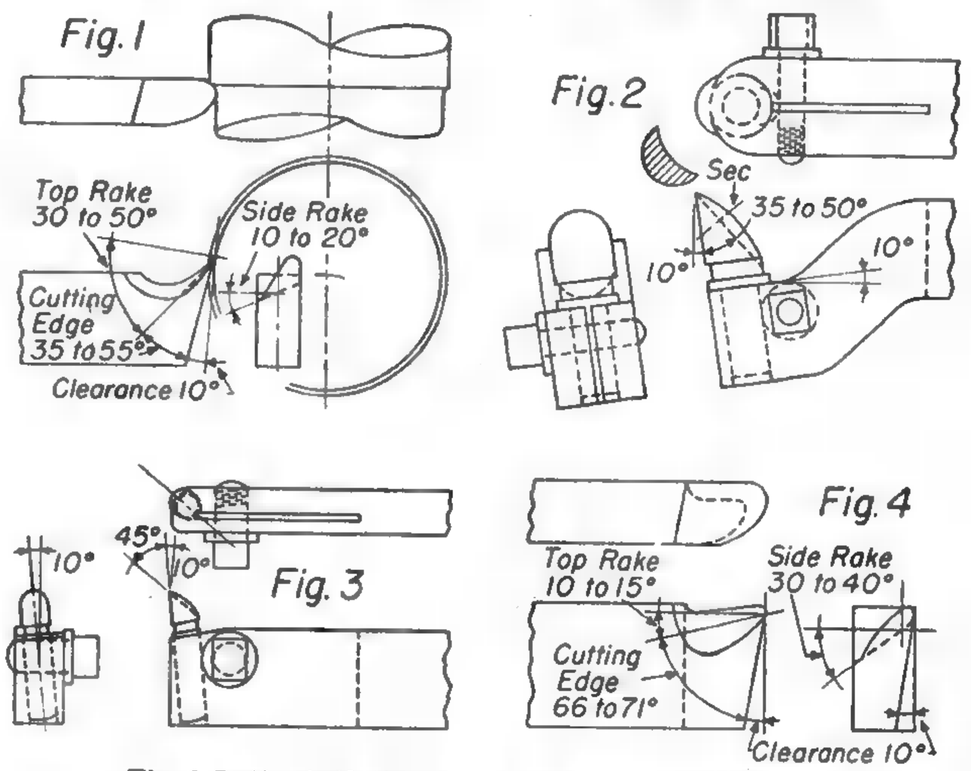

Fig. 1 Lathe tool that may be used with aluminum
Fig. [illegible] Lathe tool recommended for use with aluminum
Fig. 3 Planer and shaper tool for machining aluminum
Fig. 4 Planer tool for roughing aluminum

Lathe Tools. Outside turning tools, for use in a lathe when machining aluminum and its alloys, may be of the form shown in Fig. 1. However, when tools of this kind are prepared from the usual tool-bit stock, they require considerable grinding in order to produce the desired shape, and it is sometimes difficult to maintain the values for the different angles when regrinding. A better tool is shown in Fig. 2. The bit of this tool is machined from annealed high-carbon or high speed steel and is then hardened. For sharpening readily, the bit is held by its shank in the chuck or collet of a tool-grinding machine or lathe, and the outside diameter is ground off until a keen edge is obtained. After each grinding, the tool should be stoned as mentioned previously. When using such a tool and such a resharpening procedure, it is comparatively easy to maintain the desired shape throughout the useful life of the tool. Also, this tool has proved more economical than those ground from square or rectangular tool-bit stock, and it possesses certain adjustable features. When the clamp screw of the tool-bit holder is loosened, the bit may be rotated to various positions and may thus be ad-

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justed to different working conditions. Tools of this form may be used for both rough turning and finishing cuts; but where the same tool is employed for both, it should be restoned before being used as a finishing tool. With some modifications, either of these two forms of tools may be adapted for boring operations.

These tools, like most others suitable for machining aluminum and its alloys, tend to produce continuous chips, which are usually curled only a little when the tools are functioning properly. Where the character of the chips becomes a major problem, a reduction in the angles of top and side rake will tend to curl the chips more and break them up. The extent of adjustment that is possible while still obtaining the desired surface finish depends largely on the particular alloy that is being machined.

Parting tools for machining aluminum should have from 12 to 20-deg top rake and should be stoned so that the cutting edges are keen and smooth. With such tools the front clearance angle should be decreased to about 3 to 4 deg and light feeds should be used.

The angles of top rake and side rake recommended for outside turning tools should be interchanged for facing.

Planer and Shaper Tools. The tool shown in Fig. 2 can be readily adapted to planer and shaper work by using a holder, as shown in Fig. 3. Here again the tool may be used for both roughing and finishing work when machining aluminum; but a side cutting tool, as shown in Fig. 4, can be used to better advantage for heavier roughing cuts.

When aluminum is being finished in a planer or shaper, care must be used to prevent the tool from striking or rubbing on the finished surface during the return stroke; otherwise the work may be scratched and the thin edge of the tool broken.

Milling Cutters. In machining aluminum and its alloys, milling cutters, straddle mills, end mills and similar cutters work to best advantage if they are of the coarse-tooth spiral type that has a considerable amount of top rake on the cutting edges. In some instances milling cutters with nicked teeth help to decrease the chip size. Face-milling cutters should be designed so that the inserted teeth have appreciable top and side rake. The helical milling cutters, designed primarily for machining steel, work especially well with aluminum and its alloys if the cutting edges are provided with suitable top rake, that is, 10 to 20 deg. The same is true of staggered-tooth milling cutters.

Aluminum alloys may be milled at very high speeds. The speed at which metal can be removed is usually limited only by the equipment available. Milling operations have been satisfactorily performed on airplane spars of aluminum alloy at cutting speeds of 15,000 fpm or more in commercial production.

Threading Tools. Excellent threads may be chased even in the softest aluminum with an engine lathe using a single-pointed threading tool that has considerable top and side rake. Hand and machine taps will produce smooth and accurate threads in aluminum if they are of the spiral-flute, ground-thread type. Experience has shown that such taps should have preferably a right-hand spiral flute when intended for cutting a right-hand thread, and the spiral angle should be similar to that used in an ordinary twist drill. Taps that have a short spiral ground on the front end, such as the "gun" tap or spiral-pointed tap, will often work satisfactorily in aluminum where there is room for the chips to be forced ahead of the tap, and where the thread to be cut is not tapered; but taps of this type are not satisfactory for tapered threads or for use as bottom taps.

Thread chasers for self-opening die heads and collapsible taps should be ground with appreciable top and side rake. Certain types of these tools lend themselves more readily than others to modifications of cutting angles.

Twist Drills. Like all other cutting tools for aluminum, twist drills should have keen edges, and plenty of cutting compound should be used. The best drill for aluminum is one in which the flutes have a large spiral angle, that is, more twists per inch than the ordinary twist drill. Ordinary drills are suitable when the holes are not deep, less than six diameters. Twist drills with high spiral angles, as shown in Fig. 5, generally give better results for the softer alloys of aluminum. Polished flutes both improve the cutting action of the drill and assist greatly in removal of chips.

It may be necessary to withdraw the drill from the hole occasionally to dispose of the cuttings if the hole is deep in proportion to the diameter. A high speed and light feed are also helpful, especially for small drills. Examples of twist drills suitable for use on aluminum and its alloys are shown in Fig. 5.

Reamers. Reamers of the spiral-fluted type, like those generally used for machining steel, produce the best results on aluminum.

Saws. Since sawing is fundamentally a cutting operation, the principles that govern the shape of tools for machine cutting aluminum should be followed, as far as practicable, in the selection of saws for sawing aluminum.

Circular saws with chip-breaker teeth are better than the broad-tooth type. This type of saw has teeth so profiled that one cuts deep and the next cuts wide. Another

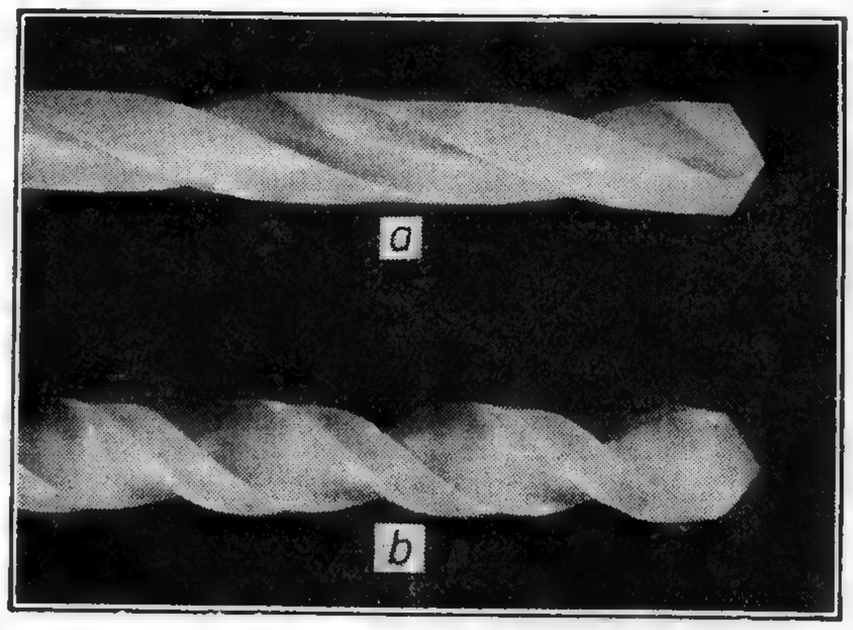

Fig. 5 Twist drills. (*a*) Double-fluted or standard twist drill, 24-deg spiral angle. (*b*) Special double-fluted twist drill, 47-deg spiral angle.

preferred type of saw blade has alternate side-rake teeth. The teeth are arranged alternately so that one cuts on one side and the next one on the opposite side of the saw cut. These teeth should have a side rake of about 15 deg.

For both types of blades, the top rake, or "hook", may vary up to about 45 deg. When such a large rake angle is employed, a tooth with a rather small included cutting angle results. Such teeth do not look very strong but experience indicates that, with other conditions correct, the teeth will serve longer without resharpening than when a small rake angle is employed. Obviously, with the use of a large rake angle, the sawing machine must be sturdy and free from vibration, the work piece must be securely clamped, and a positive feeding device must be provided. Where it is desired to feed the work material by hand, the saw teeth should have little top rake, if any; otherwise, the saw will enter the work too rapidly. Saw teeth for aluminum, however, should never have a negative rake.

It is important that proper clearances be provided on the sides of the teeth so that the teeth will not drag in the saw cut and cause the saw to overheat. Saws for cutting aluminum should have comparatively coarse teeth with curved gullets, free from sharp corners and burred edges, to prevent chips sticking.

Band saws of the high-speed metal-cutting type perform satisfactorily on aluminum. For light work, heavy-duty woodworking band saws may be used. Cutting speeds range from 2000 to 5000 fpm but higher speeds have been attained satisfactorily. For light work, band-saw blades made of spring-tempered steel are often used because the blades are readily resharpened. For heavy work, the flexible-back type of saw blade with hard teeth is preferred. Relatively coarse teeth—about 8 per in.— are preferable, although the number of teeth may be varied to suit sawing conditions. Relatively fine feeds are generally used to avoid large cuttings, but the feed will depend on the kind of work being done, especially on its size or shape.

A cutting lubricant or coolant is necessary for some classes of work, especially when sawing large heavy sections. Mineral-base lubricating oils, thinned with kerosene,

provide satisfactory lubrication when fed to the sides of the saw blade. Soluble-oil cutting compounds have also been found satisfactory. In some instances, an occasional application of paraffin wax or heavy grease will provide ample lubrication.

Hand hack-saw blades, of the "wavy-set" type, work especially well with aluminum.

Files. Files with single-cut coarse teeth, having considerable top rake, or "hook", work best on aluminum and its alloys. Such files, with deeply cut, curved teeth—about 10 per in.—are the best for general purposes. These files remove metal rapidly without loading the teeth, and produce a smooth finish. The long-angle lathe file is also excellent for filing aluminum, especially for fine work. Files of this type generally have a pitch of about 14 to 20 teeth per in. with single-cut teeth, cut at an angle of about 45 to 55 deg. This side rake angle permits the files to cut freely and helps to drive the cuttings from the teeth.

Ordinary files with single-cut fine teeth do not work well on aluminum, and those with double-cut teeth, whether fine or coarse, are no better, because the teeth load with cuttings.

Grinding Wheels. Good results are obtained with commercial grinding wheels of silicon carbide. The advice of the supplier should be obtained before selecting the proper grade of each commercial make of wheel.

Once a grinding wheel has been selected, three variables affect the quality of finish; namely, wheel speed, work speed, and grinding compound. A solution of soluble cutting oil and water serves well as a grinding compound. It is important that the fine grindings of aluminum be strained from the compound before reusing, in order to prevent deep scratches on the finished surface. Wheel speeds of about 6000 fpm have produced good results, but both wheel and work speeds can best be set by the experienced operator, according to his own judgment.

Rubber-bonded abrasive cutoff wheels can be used successfully for cutting the aluminum alloy products containing relatively large amounts of silicon, but such wheels tend to load when used in cutting the softer aluminum alloys. Cutoff wheels of this type should be operated at speeds of 9000 to 13,000 surface feet per minute and should be used with an abundant supply of cutting fluid, preferably a water-soluble oil, diluted with about 80 parts of water to one of oil.

Cutting Speeds and Feeds. Wide ranges may be used for cutting speeds and feeds in machining aluminum and aluminum alloys. The particular values for speed and feed usually depend on the character of the work, the type of tool, the lubricant, and the machine on which the work is done. Generally, aluminum can be machined to best advantage by using comparatively high speeds and fine to medium feeds. Ordinarily the finer the feed, the higher the speed should be. Extremely fine feeds should be avoided because they result in a rubbing rather than cutting action, and this is injurious to the tool.

A considerable amount of heat may be generated by tools that produce a tightly curled chip, and this may necessitate using a slower speed to prevent overheating the tool and the work material. When slow speeds and coarser feeds are used, a heavy cutting compound is preferred; this applies particularly to tapping operations. When the tools previously described are being used, the amount of metal removed from the stock in a given time may often be increased by an increase in the speed rather than in the feed.

When heavy, coarse-feed cuts are employed in engine lathe work, it is usual with aluminum, as with most other metals, for excessive friction to occur on the lathe centers because of the expansion of the metal with rise in temperature. Ball or roller bearing tailstock lathe centers help to decrease this trouble.

Cutting Lubricants. Some of the alloys of aluminum have been machined successfully without any lubricant or cutting compound, when the tools used have been of the form described; but in order to get the best results, some form of lubricant is desirable. Kerosene oil will often serve, but it works better ordinarily when mixed with pure lard oil. A satisfactory mixture for general purposes may be obtained by using equal parts of kerosene and lard oil. For heavy cuts and slow feeds, as in roughing work or tapping, pure lard oil has been found to give satisfactory results. For milling, sawing and drilling, the soluble cutting oils are satisfactory and more economical than the kerosene or kerosene and lard oil lubricants. Many of the proprietary cutting lubricants or compounds that are available commercially perform satisfactorily. A continuous and copious supply of lubricant should be fed to the tool in order to produce the best results.

Automatic Screw-Machine Practice

Stock. A number of aluminum alloys are commonly used for screw-machine stock. These may be divided into two general classes:

1 General-Purpose Alloys, 17 S-T4, 24 S-T4, 61 S-T6 and R 361-T. The choice between alloys 17 S-T4 and 24 S-T4 is based on mechanical properties; 24 S-T4 has higher strength. When these alloys are machined, the relatively long chips that are obtained sometimes, create a problem in chip disposal; but by the proper combination of feeds, speeds and tooling, the chips may be reduced considerably in size. The alloys 61 S-T6 and R 361-T are usually specified when the product is to be subject to severe conditions, requiring superior resistance to corrosion. Ordinarily the chips from these alloys are long and stringy and more difficult to handle.

2 Free-Machining Alloys for Use in Automatic Screw Machines. These alloys contain additions of lead and bismuth to impart free-machining characteristics. When the machining is done with tools that have little or no top rake, excellent finishes are produced and the chips are fine and broken. Currently, two alloys of this type are commercially available. Alloy 11 S has a nominal content of 5½% Cu and ½% each of Pb and Bi. This alloy is generally specified in the T3 temper, produced by cold working after a solution treatment. Alloy R 317, of more recent origin, has a composition similar to 17 S with small additions of lead and bismuth. It is usually supplied in the solution-treated and naturally aged temper.

Drills. Standard twist drills are ordinarily satisfactory for drilling holes that have a depth of 5 to 6 diam in aluminum alloys; but for deeper holes it is preferable to use straight-fluted drills or twist drills with less twist and with larger flutes, to provide greater chip clearance. Drills with a larger spiral angle, that is, more twists per inch, are preferred for the softer alloys. Generally, all drills used for aluminum should have narrow lands and large, smooth, highly polished flutes. These drills are usually ground with an included lip angle of 118 deg and a clearance angle of 12 to 20 deg. Sometimes a greater included angle is used so as to produce a narrow chip that will pass up the flutes more readily. Grinding the drill web thinner produces advantages as in drilling other metals. When a deeper hole is required, the drill must be withdrawn a sufficient number of times for removal of chips and proper application of cutting compound. It is usually safe practice to drill to a depth four times the drill diameter on the first entrance, 1½ to 2 diam on the second entrance, ¾ to 1 diam on the third entrance, and ½ to 1 diam on subsequent entrances.

Form and Cutoff Tools. Form and cutoff tools used in machining the free-machining alloys usually require ■ top rake from zero to 3 deg; for the other aluminum alloys better results will be obtained by using a top rake from 5 to 15 deg—the softer the alloy, the greater the top rake used. These larger rakes may be applied locally on the face of form tools for work involving large differences in diameter. In most instances a side clearance of ½ deg will aid in producing a smooth finish. Front clearance angles are determined by the design of the screw machine and the tools; the angles generally used in screw-machine practice are satisfactory for the aluminum alloys.

When used without support for the work material, the side pressure of the form-cutting tool will spring the stock and break it off, if the ratio of the formed length to the smallest diameter is too great. The limit for this ratio is 2½ for 17 S-T4 and 24 S-T4 and 2¼ for the other alloys. A front angle of 22 deg on a cutoff tool will usually reduce the cutoff burr to a minimum.

Box Tools. Holders for box tools are designed usually so that the tool is set with a clearance angle of 8 deg, but for some roughing tools this angle may be greater. The cutting face of the tool should be ground so that the bottom edge of the blade is parallel with the axis of the work piece. The cutting edge may be ground square with the tool shank, or with a slight angle, depending on whether or not a square shoulder is necessary on the work piece. For alloys other than the free-machining ones, a small groove or "hook" is ground just behind the cutting edge in order to produce a thin cutting edge and to provide considerable rake. This makes the tool cut more freely and forms the chips into helical coils that are guided out of the holder and away from the work. For long heavy cuts, the feeding cams may be notched with care to provide an interrupted feed to break the cuttings.

Threading Tools. Taps with "hook" as supplied by the maker may be used, but it is important that they be of the ground-thread type, with smoothly polished flutes to allow freer exit of the chips. Best results are obtained when the taps are provided with rakes from 10 to 15 deg, and with a clearance on the chamfer of about 3 to 5 deg. Thread chasers should be tapered or chamfered at least for two threads at the leading end of the tool so that they will start more easily.

Surface Speed of Stock. In general, aluminum alloys can be machined at the maximum spindle speed available in all standard types of automatic screw machines for turning, drilling, forming and cutting off. When tools that have cemented carbide tips have been used, aluminum alloys have been machined at 1000 fpm of stock surface, with no indication that such speed is excessive. How much this rate can be exceeded has not been determined. For threading and tapping operations, each type of machine has a suitable speed that is considered good practice for machining aluminum as well as all other materials. This speed is approximately one-third of that used for other operations.

The lighter weight of aluminum, about one-third that of other commonly used metals, is an advantage when high spindle speeds are employed. The lower inertia of aluminum causes less wear on the spindles, belts and motors, especially when quick changes in speed are involved.

Tool Feeds. Tool feeds vary with cutting conditions, as well as with requirements of tolerance and finish. Overlapping operations and the condition of the machine may require lower feeds than normal. The feeds shown in Table I are approximate and may need to be altered, depending on specific conditions. Generally, feeds approximately 15% higher than those given in Table I for aluminum alloys may be used for the free-machining alloys.

Table I. Approximate Feeds for Standard Tools in Machining Aluminum Alloys

Tool	Cut Width or Depth, in.	Diameter of Hole, in.	Feed per Revolution, in.
Box Tools, One chip finishing	1/32	.....	0.012
	1/16	.....	0.010
	1/8	.....	0.008
	3/16	.....	0.008
	1/4	.....	0.006
Center Drills	.....	Less than 1/8	0.004
	.....	1/8 and more	0.008
Cutoff Tools, Circular	3/64 to 1/16	.....	0.003
	3/32 to 1/8	.....	0.0035
	5/32 to 3/16	.....	0.004
Straight	1/16 to 1/8	.....	0.003
Drills	.....	1/16	0.004
	.....	3/32	0.006
	.....	1/8	0.009
	.....	3/16	0.011
	.....	1/4	0.013
	.....	5/16	0.014
	.....	3/8	0.015
	.....	1/2 and more	0.016
Form Tools	1/8 to 1/4	.....	0.002 to 0.004
	3/8 to 1/2	.....	0.0015 to 0.0035
	5/8 to 3/4	.....	0.0015 to 0.003
	1	.....	0.001 to 0.0025
Reamers	0.004 to 0.008	Less than 1/8	0.007 to 0.010
	0.009 to 0.012	1/8 and more	0.010

Cutting Compounds. Cutting compounds that are used for other metals are generally suitable for the aluminum alloys. A number of good commercial cutting oils, prepared especially for machining aluminum, give satisfactory results. Usually a light mineral oil is employed, with about 5% of fatty additions and with a viscosity from 45 to 55 Saybolt sec at 100 F. It is desirable to have a flash point higher than 260 F. As with all metals, it is essential that an ample supply of cutting oil be provided. A large volume flowing over the tools is more desirable than a high-pressure stream.

Finishes for Aluminum Alloys

By Junius D. Edwards*

ALUMINUM is a bright, silvery, corrosion-resistant metal which, for many applications, needs no special finishing by the user. Aluminum sheet, for example, can be purchased with a bright smooth surface or with "mill finish" of intermediate brightness. Aluminum extrusions are frequently employed just as they come from the die. Aluminum castings are generally used without any special surface finish except for necessary grinding and machining operations. There is, however, a wide variety of finishes that can be applied to aluminum for purposes of decoration and protection. These range from well-known mechanical procedures, such as polishing, scratch-brushing and sandblasting, to such unique finishes as anodic coating and electrobrightening.

Mechanical Finishes. Mechanical finishing operations are generally employed to remove appreciable amounts of metal and produce a uniform surface finish.[1] This finish may vary in smoothness from that left by grinding and sandblasting, to the high luster produced by polishing, buffing and coloring with a suitable abrasive, on wheel, disk or belt. In this way finishes are produced ranging from a highly diffusing surface to a mirrorlike surface. Sandblasting produces surfaces of varying degrees of roughness, depending on the fineness of the abrasive and the amount of pressure employed. This method is more commonly used for castings, since there is a strong tendency to warp sheet by blasting. However, with fine abrasive, a light dust blast applied to sheet can provide an attractive finish, particularly when used in combination with high-lighted areas. These mechanical finishing operations will not be described in detail, since they are much the same as for finishing other metals.*

Mechanical finishes do not, in themselves, add anything in the way of surface protection. Frequently, however, mechanical finishes are used as surface preparation for a final finishing operation, such as electrobrightening or anodic coating. In this way, a combination of surface preparation methods and other finishing techniques will give a product luster, texture, or color, combining serviceability and attractive appearance.

Cleaning and Etching. Cleaning is sometimes necessary for the removal of oil, grease, or other contaminants on the surface of aluminum. For production work, vapor degreasing or a dip into a solvent may be called for, or a simple chemical cleaning solution may be employed. Many alkaline solutions that will remove grease and oil from aluminum are not satisfactory for most cleaning purposes be-

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* *See* "Blast Cleaning of Metals", page 300 in this Handbook.

cause they either etch or discolor the surface. However, safe cleaners are available which can be used on aluminum without etching or discoloration.[3] A safe cleaner can be made from sodium carbonate and phosphates of sodium, suitably inhibited with sodium silicate to eliminate the etching action. Such a cleaner is usually employed at temperatures of about 140 to 180 F in order to accelerate the cleaning action. This treatment is followed by rinsing and drying. Excellent cleaning solutions are available.

Aluminum articles can be given a bright, frosted finish by a dip in a hot solution of caustic soda, followed by a dip in strong nitric acid. The caustic soda solution is used in concentrations from about 5 to 15%, and at room temperature or at temperatures of about 160 to 180 F for a period of about a minute. After this treatment the metal is rinsed in clear cold water. The next step in the procedure is immersion in strong nitric acid (1 part water, 1 part concentrated HNO_3, 38 Bé). Then the metal is given a final rinse in water and rapidly dried. The treatment with nitric acid neutralizes any traces of alkali and brightens the surface. When alloys containing substantial amounts of silicon are to be treated, it is necessary to add hydrofluoric acid to the nitric acid; one part of concentrated hydrofluoric acid (48% HF) to eight parts of concentrated nitric acid is a good proportion to use. After treatment in the caustic soda solution, the article is dipped into the cold nitric-hydrofluoric acid mixture for 15 to 30 sec, then again washed in water and dried.

Aluminum articles can be given a smooth, bright finish by immersion in a solution containing about 2% by volume of concentrated hydrofluoric acid and 10% by volume of concentrated nitric acid. The solution must not become too warm.

For removing films and stains from annealing and heat treating operations, a dip into a solution containing about 10% sulfuric acid and 3% chromic acid, operated at 160 F, will be found effective. This treatment removes far less metal than does caustic dipping, and it leaves the article (such as a pressing, forging or extrusion) with a bright attractive finish.

Anodic Oxide Coating of Aluminum. One of the outstanding characteristics of aluminum is the high protection afforded by the very thin, invisible film of aluminum oxide naturally formed on the surface. Oxide films of substantial thickness can also be formed by anodic treatment in certain electrolytes, usually of an acid character.[3] These anodic coatings are minutely porous, and during anodic treatment the current carried by the electrolyte in the pores converts the base metal into aluminum oxide. During formation, therefore, the oxide grows into the metal, leaving the first-formed oxide on the surface. The oxide coating is integral with the aluminum and this, in large part, accounts for its excellent adhesion to the base metal. The coatings are essentially amorphous aluminum oxide, but may contain sulfate or other substances adsorbed from the electrolyte.

The first anodic coating procedure to receive wide application was developed by Bengough and Stuart and employs a 3% solution of chromic acid as the electrolyte, at a temperature of about 100 F. In operation the voltage is raised from zero to 40 at the rate of about 8 v per min, and is maintained at full voltage for 30 to 60 min. This gives a current density of about 1 to 3 amp per sq ft. These coatings are relatively thin (0.00005 to 0.0001 in.) and their principal use has been as a base for paint on aluminum aircraft parts. The usual color is grayish green, resulting from the presence of reduced (trivalent) chromium in the coating.

The Alumilite process[1] presents a variety of procedures for producing anodic coatings on aluminum and adapting them to practical service conditions by sealing and coloring treatments. The electrolyte which has received the widest acceptance is an aqueous solution containing about 15 to 25% sulfuric acid. This electrolyte has the advantage of yielding clear transparent coatings on pure aluminum, and translucent or opaque coatings on metal of lower purity, such as 2 S sheet (99% min Al). During anodic treatment of aluminum alloys, the behavior of alloying constituents is important in determining the characteristics of the coating. Certain constituents may be anodically dissolved and removed from the coating, whereas others, unattacked or partially oxidized, may remain in the coating as occlusions. Removal of constituents or inclusions from the oxide during anodic treatment, may therefore affect the continuity and protective power, as well as the appearance of the coating. The thickness of the coating is primarily a function of the current employed (ampere-minutes) and is under control of the operator. Commercial coatings are usually produced in the thickness range of 0.0001 to 0.0008 in. The oxide forming the coating is intrinsically hard and the resistance of the coating to wear will usually increase with thickness.

A unique characteristic of these coatings is their submicroscopic porosity. These pores, which require the electron microscope for viewing, will admit solutions and thus provide a variety of ways in which the characteristics of the coating may be altered. If the pores of the coating are impregnated with a solution of a dye of suitable type, the dye becomes firmly adsorbed on the coating and colors it throughout the depth. A great variety of colors can be produced in this way and the dye-colored coatings have a semimetallic luster that is very attractive. These dye-colored coatings are not proof against fading in sunlight, although they are virtually permanent indoors. However, they are satisfactory for many outdoor applications where several years' service is sufficient. The pores are too small to admit solid particles, but after the coating is impregnated with two reacting solutions in turn (a solution of cobalt acetate, for example, and subsequently a solution of ammonium sulfide), a mineral pigment such as black cobalt sulfide can be precipitated within the pores. A variety of mineral pigment colors is available. When applied under proper conditions, they are very serviceable in outdoor applications.

For most purposes, however, the uncolored coating is desired, and for most applications it is necessary to make the coating nonadsorptive to prevent accidental staining. This is accomplished by a sealing operation. Sealing without coloration can be accomplished by treating the coating with hot water for a period of 10 to 30 min. Sealed coatings on cafeteria trays, for example, will not stain from contact with coffee and other colored fluids and foods. The coating may not only be sealed but may also be impregnated with a corrosion inhibitor by treatment with chromate solutions. The chromate, adsorbed in the coating, is effective in protecting against attack in many environments. Coatings sealed in this way form an excellent base for paint and have been used extensively in protecting aluminum alloy aircraft parts.

The Alumilite process provides other coating electrolytes, notably solutions containing both sulfuric and oxalic acids, to give especially hard and dense coatings for applications requiring these characteristics. Oxalic acid alone has also found application as an electrolyte.

When anodically coated articles are dusty or dirty, they can usually be cleaned by wiping with a damp cloth or with mild soap and water. Care should be taken, in the selection of a chemical cleaner, for many alkaline cleaners attack and dissolve the coating; however, safe cleaners are readily available.

Electrobrightening or Electropolishing. Electrobrightening or electropolishing of aluminum can be accomplished by suitable anodic treatment. The process most extensively used and one which introduced commercially electrobrightening or electropolishing of aluminum, is the Alzak process.[4] When a buffed aluminum surface is made anode in fluoboric acid electrolyte, a thin surface film of metal is removed with such uniformity that the specularity of the surface is not appreciably disturbed. As soon as embedded polishing materials and other dirt have been removed in this manner, the surface is ready for anodic coating in sulfuric acid electrolyte. If the aluminum is free from certain alloying constituents, a protective film of clear, transparent aluminum oxide is formed. The electrobrightened surface may have a reflectivity as high as 90%. The reflectivity will be reduced somewhat by the oxide coating, and the reduction is a function of the thickness of the coating. However, specular aluminum reflectors with a reflectivity of 80 to 85% can be made with oxide films as thick as 0.0004 in. The electrobrightening procedure may be employed in decorative finishes to provide an interesting contrast in luster and texture between brightened and dust-blasted surfaces.

Oxide Coating by Chemical Treatment. Artificial oxide coatings can be applied to aluminum by chemical treatment as well as by electrolytic treatment. So far it has not been possible, however, to make these coatings as hard and resistant to abrasion as those made by suitable anodic procedures. For many purposes, however, the "chemical" coatings are adequate and can be produced at lower cost.

One solution for the production of such a coating is made with sodium carbonate and potassium or sodium dichromate. When the proper ratio is maintained between carbonate and dichromate, the hot solution in contact with aluminum produces a grayish green coating, the thickness of which depends on the duration of treatment. The principal applications for this coating have been in the treatment of small parts, and in the surface treatment of aluminum articles that are to be painted subsequently. In these applications the coatings known as Alrok coatings[1] are usually impregnated with dichromate solution to lend added protection.

A substantial number of other coatings produced by chemical treatment are described in technical articles and patents. Several excellent proprietary procedures are available for the surface coating of aluminum alloys before painting. Other processes yield colored coatings of decorative value. With coatings of this type for use without paint or enamel, one problem is how to secure adequate thickness and wear resistance.

Electroplating. The electroplating of other metals upon aluminum has now received commercial acceptance. This has become possible through the development of special methods for treating the aluminum surface to leave it in satisfactory condition for subsequent plating by conventional methods.

An oxide film in itself is not a deterrent to successful electroplating of aluminum; several available methods of anodic treatment produce a porous oxide coating of appreciable thickness to which electroplates show good adhesion. Several etching methods also produce a satisfactory surface for electroplating. However, the method most generally applicable comprises immersion of the aluminum article in a solution of sodium zincate of controlled composition. A dark-colored film that contains zinc is deposited in a short time. After this treatment, other metals can be successfully electrodeposited. A commonly used finish comprises successive deposits of copper, nickel and chromium, although other metals may be applied over the copper. Brass, iron, silver or chromium can also be applied directly over the zinc immersion coating.

Silver plate is applied to electrical equipment to decrease contact resistance or to improve surface conductivity. Brass plate facilitates the vulcanization of rubber to the surface. Copper coatings are sometimes employed to permit assembly by soft soldering. Heavy chromium deposits are used to reduce friction and increase wear resistance. Chromium deposits applied directly to aluminum provide increased resistance in an alkaline environment. Zinc is used in threaded parts to prevent seizing where the presence of organic lubricants is undesirable. Tin may be employed to reduce friction between sliding surfaces.

Because of the unfavorable solution potential of aluminum with respect to certain electrodeposits, aluminum parts plated with such metals as copper or nickel should not be exposed to a corrosive environment unless the electroplate is heavy enough to be impervious (about 0.0015 in. of nickel). The thickness of electroplate on aluminum should therefore be about that used in plating on iron or zinc.

Painting of Aluminum. Paints generally show good adhesion to the natural oxide film on aluminum.[5] For severe service conditions, such as involve frequent wetting and drying, better adhesion can be secured by special treatment of the surface to increase its passivity. Of course it is necessary, as with other metals, to remove oil and grease films prior to painting; this can be done by wiping with cloths moist with solvent or by vapor degreasing.* A combined degreasing and chemical treatment is provided by a solution comprising phosphoric acid and suitable grease solvents, such as the alcohols (U. S. Army Corps of Engineers' Specification T1184-D). The grease solvent permits the phosphoric acid to wet the aluminum surface and, by reaction, a film of inert aluminum phosphate is formed in a few minutes. The surface is then thoroughly washed with clean water and dried, after which it is ready for painting. As indicated in other sections of this article, various chemical and electrolytic treatments also provide good surface preparation for painting.

The use of zinc chromate (zinc yellow) pigment in priming paints for aluminum has received general acceptance. This pigment is not pure zinc chromate but is a double compound containing potassium chromate of limited solubility. No doubt this sparingly soluble chromate exerts a protective action when water vapor penetrates the film. The priming coat usually employs a synthetic resin vehicle, offering high resistance to penetration by moisture.

Aluminum paint is an excellent top coat for most applications because of its low permeability to moisture; however, other color-pigmented coats can be applied if desired. Synthetic resin vehicles of high resistance to moisture and suitable distensibility should be employed where the service conditions demand protection as a primary consideration. Clear lacquers of the methacrylate resin or cellulose acetobutyrate type are recommended where a transparent protective finish is desired. Thick coatings of bituminous paint are quite effective for protecting aluminum that is to remain in contact with soil, cement or plaster.

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* *See* "Solvent and Vapor Cleaning", page 299 in this Handbook.

The Resistance of Aluminum Alloys to Corrosion

By E. H. Dix, Jr.* and R. H. Brown*

THE successful use of aluminum and aluminum alloys in many fields depends on the ability of these products to resist a variety of corrosive environments. For this reason it is important that the behavior of aluminum alloys in regard to corrosion should be well understood and that the limitations of the alloys under certain conditions in service should be recognized. Aluminum electric transmission lines and aluminum cooking utensils are perhaps the earliest applications that have stood the test of time. Aluminum has also become established as an architectural material; aluminum roofs more than 40 years old are known to be giving satisfactory service at present.

The high-strength aluminum alloys, most of which contain copper as the principal alloying element, have a lower order of resistance to corrosion than that of aluminum or the aluminum alloys used where strength is not the principal consideration. However, improvements in manufacture, especially heat treatment, and the development of satisfactory methods of protection have resulted in the successful use of these high-strength alloys under many corrosive conditions. For example, when the first aluminum airplanes were built after World War I, considerable corrosion of the thin, high-strength aluminum-copper alloy sheet was experienced. In contrast, the high-strength

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aluminum alloys (millions of pounds) used in the aircraft of World War II were almost free from difficulties caused by corrosion, even though the planes operated with little protective care.

Corrosion Behavior of Aluminum and Its Alloys. *Protection Afforded by Oxide Film.* Although aluminum is an active metal, it behaves as a very stable one because it is covered with a thin oxide film that is highly resistant and protective. Aluminum owes its commercial existence to this film. If the surface of aluminum is scraped sufficiently to remove the oxide film, in many environments a new film begins to form immediately.[1] Thicker, more protective and decorative oxide coatings can be produced by chemical and electrolytic treatments.[2,*] In conditions under which the protective film does not re-form readily, aluminum should be protected adequately or not used at all. Among such conditions are contact with strongly acid or alkaline solutions and contact with constantly moist corrosive materials that prevent free and uniform access of oxygen to the aluminum surface.

Contacts Between Dissimilar Metals. The highly anodic electrode potential causes aluminum to be dissolved sacrificially when in contact with most other metals in corrosive environments.[3] The electrode potentials of a number of aluminum alloys and some other metals[1,4] are given in Table I. Not only must the direct metallic contact with a more cathodic metal be avoided but also corrosion products of these metals must be kept from the surface of aluminum;[1] for example, copper picked up from copper or brass plumbing will plate out on aluminum cooking utensils and cause pitting unless removed by periodic abrasive cleaning. Rain splashing from copper or copper alloy surfaces onto an aluminum surface will also cause corrosion; for example,

Table I

Electrode Potentials of Various Metals and Alloys[a]

Metal or Alloy[b]	Potential, volts 0.1 N Calomel Scale[c]
Magnesium	— 1.73
Zinc	— 1.00
72 S, Alclad 3 S, Alclad 75 S	— 0.96
220–T4	— 0.92
56 S, 214	— 0.87
52 S, Aluminum (99.95% min)	— 0.85
4 S, B214	— 0.84
2S, 3S, A51S, 53S, 61S–T6, 63S, 406, Alclad 14S, Alclad 24S	— 0.83
13, 43	— 0.82
75S–T6, 360, 356	— 0.81
24S–T81, 25S–T6, 61S–T4	— 0.80
355–T6	— 0.79
14S–T6, 113, 355–T4	— 0.78
108, C113	— 0.77
85, A108	— 0.75
195–T6	— 0.73
B195–T4	— 0.71
14S–T4, 17S–T4, 24S–T4, 25S–W	— 0.68 to — 0.70[d]
Steel	— 0.58
Lead	— 0.55
Tin	— 0.49
Copper	— 0.20
Bismuth	— 0.18
Stainless steel	— 0.09
Silver	—0.08
Nickel	— 0.07

(a) Data from Aluminum Research Laboratories
(b) The potential of all tempers is the same unless temper is designated.
(c) Measured in an aqueous solution of 53 g NaCl + 3 g H_2O_2 per liter
(d) The potential varies with the quenching rate.

copper or bronze screens will cause pitting of aluminum window frames in all except very mild atmospheres. Stainless steel, in spite of its cathodic electrode potential, causes relatively slight electrolytic attack on aluminum alloys when in contact with them,[5] since the flow of current is limited by polarization. Zinc and cadmium are sufficiently close to aluminum alloys in electrode potential to be used successfully with them.

Electrode Potentials of Alloy Constituents. Because of the electrochemical nature of most corrosion processes, relationships among electrode potentials are important also in determining the resistance to corrosion of aluminum alloyed with other metals.[3] Table II gives the electrode potentials of aluminum and of some of the constituents found in the common aluminum alloys.

Table II. Electrode Potentials of Aluminum Solid Solutions and Constituents[a]

Solid Solution or Constituent	Potential, volts 0.1 N Calomel Scale[b]
α(Al-Mg) (Mg_5Al_8)	— 1.07
Al + Zn + Mg (4% $MgZn_2$) solid solution	— 1.07
β(Zn-Mg) ($MgZn_2$)	— 1.04
Al–4% Zn solid solution	— 1.02
Al–1% Zn solid solution	— 0.96
Al–4% Mg solid solution	— 0.87
α(Al-Mn) ($MnAl_6$)	— 0.85
Aluminum (high purity)	— 0.85
Al + Mg + Si (1% Mg_2Si) solid solution	— 0.83
Al–1% Si solid solution	— 0.81
Al–4% Cu solid solution	— 0.69
α(Al-Fe) ($FeAl_3$)	— 0.56
Al-Cu ($CuAl_2$)	— 0.53
Silicon	— 0.26

(a) Data from Aluminum Research Laboratories
(b) Measured in an aqueous solution of 53 g NaCl + 3 g H_2O_2 per liter

The impurities that occur in commercially pure aluminum—iron, silicon and copper—are cathodic to aluminum. However, the aluminum-iron constituent is ordinarily the only cathodic constituent present, because copper is always well within the limits of solid solubility and silicon is usually in solid solution either in the aluminum-iron constituent or in aluminum itself. The particles of the aluminum-iron or aluminum-iron-silicon constituent form cathodic points that weaken the oxide film besides promoting electrochemical attack; hence the resistance to corrosion of high-purity aluminum with a minimum aluminum content of 99.95% is higher—under some conditions markedly higher—than the resistance of commercially pure aluminum.

It will be observed that manganese and aluminum form a compound that has almost the same electrode potential as aluminum. This is true also of the constituent formed when magnesium and silicon are added in the ratio of the compound Mg_2Si. These alloying elements produce alloys that are comparable with commercially pure aluminum in their resistance to corrosion. Chromium and manganese behave similarly with respect to corrosion, but chromium is employed only as a minor alloying element, particularly valuable in improving the resistance to stress corrosion of several types of aluminum alloys.* Magnesium and silicon in solid solution in the ratio of the compound Mg_2Si do not affect the electrode potential of the alloy; however, most other alloying elements forming a solid solution with aluminum do alter its electrode potential. Magnesium and zinc, either individually or together, in solid solution in aluminum make the potential more anodic, whereas copper makes it more cathodic. Silicon, although cathodic to aluminum, has relatively little effect on its electrode potential when in solid solution, because of relatively low solid solubility. Both the aluminum-magnesium and the aluminum-silicon alloys have good resistance to corrosion. When magnesium is alloyed with aluminum in amounts that remain in solid solution under conditions of commercial manufacture, the alloys are as resistant as commercially pure aluminum and are even more resistant to salt water and some alkaline solutions, such as those of sodium carbonate.[6,7] The aluminum-magnesium constituent formed by magnesium in excess of the solid solubility, is anodic to the aluminum-magnesium solid solution and hence, under some conditions of thermal treatment, lowers the resistance to corrosion of the alloy.

Nickel and aluminum form a strongly cathodic constituent that usually has an adverse effect on the resistance of aluminum alloys to corrosion. However, nickel is employed primarily in alloys that require high strength and hardness at elevated temperatures, and in such application the resistance of the alloy to corrosion is of little

* *See* "Finishes for Aluminum Alloys", page 789.

* *See* "Stress Corrosion of Metals", page 227.

importance. Tin, bismuth and lead are also cathodic to aluminum. The latter two elements are used in free-cutting alloys of the aluminum-copper type and may lower the resistance to corrosion of these alloys under some conditions of exposure. Tin is an important element in aluminum alloys that are used for bearings. Although, under some corrosive conditions, these alloys may resist corrosion less effectively than certain other aluminum alloys, the aluminum alloys that are used for bearings resist remarkably well the action of the breakdown products of lubricating oils and are superior in this respect to most bearing materials. The aluminum-titanium constituent, although cathodic to aluminum, has not been found to have a detrimental effect on resistance to corrosion.

Copper in solid solution changes the electrode potential markedly in a cathodic direction. The aluminum-copper constituent is even more strongly cathodic to aluminum;[8] hence copper in excess of about ¼% may have an adverse effect on the resistance of aluminum alloys to corrosion. An exception to this generalization occurs in several alloys in which copper in combination with other elements is beneficial.

Effect of Heat Treatment. The microstructural condition produced as a result of thermal treatment has an important influence on the resistance to corrosion of aluminum-copper alloys.[9] The aluminum-copper solid solution produced by a solution heat treatment and rapid quench has the highest resistance to corrosion. Aging at room temperature, which causes precipitation of minute particles of submicroscopic size in uniform dispersion, does not lower measurably the resistance to corrosion. However, reheating or a slow quenching rate that produces localized precipitate surrounded by areas of depleted solid solution, results in a pronounced decrease in resistance to corrosion. The areas of depleted solid solution are anodic both to the remaining areas of solid solution and to the precipitated particles and, hence, in a corrosive environment, are dissolved out rapidly, resulting in so-called "intergranular" corrosion. Resistance to corrosion is restored to a point where it equals that of the rapidly quenched solid solution by further aging at elevated temperatures or a combination of controlled quenching and artificial aging, which causes more general precipitation and so equalizes the potential in the various solid solution zones. For a more detailed discussion of this subject, the reader may refer to the article "Stress Corrosion of Metals", on page 227 in this Handbook.

In the aluminum-magnesium-silicon alloys that contain magnesium and silicon in the ratio of the compound Mg_2Si, the resistance to corrosion is not affected by precipitation, because in this ratio the electrode potential is the same, whether these elements are in or out of solid solution.

Alclad Products. Relationships between electrode potentials are used to advantage in alclad products,[10,11] in which an aluminum alloy core is covered with a thin surface layer or layers of aluminum or of an aluminum alloy resistant to corrosion, both anodic to the core. Thus when these products are used in a corrosive environment, not only do the surface layers protect the core, by virtue of their high resistance to corrosion, but they also protect electrolytically areas of the core exposed at the edges by cutting, or elsewhere by abrasion or corrosive attack. This electrolytic protection is important in the high-strength alclad products because it preserves the initial strength of the product even under severely corrosive conditions. Alclad sheet is especially resistant to perforation since, as long as appreciable areas of coating remain, pitting does not progress beyond the interface between the coating and the core, but spreads out slowly instead, producing a shallow area of attack. This action is particularly desirable in relatively thin sheet because it permits exposure for a long period of time without risk of perforation.

Aluminum and alloys of the magnesium silicide type are suitable for coatings on the aluminum-copper high-strength alloys in which the copper remaining in solid solution, after heat treatment, makes the core so cathodic that the coating is anodic to the core. For alloy cores having about the same electrode potential as aluminum (such as 3 S, 4 S, 61 S-T6 and 75 S-T6) or having a potential even higher than that of aluminum (as in 56 S), a coating that contains 1% Zn or more may be used in order to achieve the desired electrolytic protection.

The Relative Resistance to Corrosion of Commercial Aluminum Alloys. The properties and characteristics, other than resistance to corrosion, of most of the alloys discussed in this section are described on pages 810 to 840. Tables III and IV show nominal compositions.

Table III

Nominal Composition of Wrought Aluminum Alloys

Alloy	Cu	Si	Mn	Mg	Zn	Ni	Cr	Pb	Bi
2 S .....99.0% Al (min)	...	...	...	...	...	...	...	...	...
3 S	...	...	1.2	...	...	...	...	...	...
4 S	...	...	1.25	1.0	...	...	...	...	...
11 S	5.5	...	...	...	...	...	...	0.5	0.5
14 S	4.4	0.8	0.8	0.4	...	...	...	...	...
17 S	4.0	...	0.5	0.5	...	...	...	...	...
18 S	4.0	...	...	0.5	...	2.0	...	...	...
24 S	4.5	...	0.6	1.5	...	...	...	...	...
25 S	4.5	0.8	0.8	...	...	...	...	...	...
32 S	0.9	12.5	...	1.0	...	0.9	...	...	...
A51 S	...	1.0	...	0.6	...	...	0.25	...	...
52 S	...	...	...	2.5	...	...	0.25	...	...
53 S	...	0.7	...	1.3	...	...	0.25	...	...
56 S	...	...	0.1	5.2	...	...	0.1	...	...
61 S	0.25	0.6	...	1.0	...	...	0.25	...	...
63 S	...	0.4	...	0.7	...	...	...	...	...
72 S	...	...	...	...	1.0	...	...	...	...
75 S	1.6	...	0.2	2.5	5.6	...	0.3	...	...
R303	1.2	...	...	2.5	6.5	0.1	0.25	...	...
R317	4.0	1.0	0.5	0.5	...	...	...	0.5	0.5
Clad Aluminum Alloys									
R301) .....core	4.5	1.0	0.8	0.4	...	...	...	...	...
R301) .....cladding	...	0.7	0.5	1.0	...	...	...	...	...

Alclad 3 S — core, 3 S; cladding, 72 S
Alclad 14 S — core, 14 S; cladding, 53 S
Alclad 17 S — core, 17 S; cladding, pure aluminum
Alclad 24 S — core, 24 S; cladding, pure aluminum
Alclad 75 S — core, 75 S; cladding, 72 S

Table IV

Nominal Composition of Aluminum Casting Alloys

Alloy	Cu	Si	Mg	Zn	Ni or Cr	Mn
13	...	12.0	...	...	...	...
43	...	5.0	...	...	...	...
85	4.0	5.0	...	...	...	...
108	4.0	3.0	...	...	...	...
A108	4.5	5.5	...	...	...	...
113	7.0	2.0	...	1.7	...	...
C113	7.0	3.5	...	...	...	...
122	10.0	...	0.2	...	...	...
A132	0.8	12.0	1.2	...	2.5 Ni	...
142	4.0	...	1.5	...	2.0 Ni	...
195	4.5	0.8	...	...	...	...
B195	4.5	2.5	...	...	...	...
214	...	...	3.8	...	...	...
B214	...	1.8	3.8	...	...	...
218	...	...	8.0	...	...	...
220	...	...	10.0	...	...	...
355	1.3	5.0	0.5	...	...	...
356	...	7.0	0.3	...	...	...
360	...	9.5	0.5	...	...	...
380	3.5	8.5	...	...	...	...
406	...	...	...	...	...	2.0
Allcast	3.0	5.0	...	...	...	...
Red X-8	1.5	8.0	0.3	...	...	0.3
Red X-13	1.5	12.0	0.7	...	...	0.7
40E	...	...	0.5	5.25	0.5 Cr	...

High-Purity Aluminum. For the reasons previously stated, high-purity aluminum, under most conditions of exposure, surpasses the other forms of aluminum in resistance to corrosion. This resistance increases with increase in purity.

Commercial Aluminum. Aluminum of commercial purity also has a high resistance to corrosion, which is comparable, except in special instances, with that of the most resistant alloys. The wrought product 2 S is used for a large number of miscellaneous applications where good resistance to corrosion is required, as well as for such products as cooking utensils and equipment for the handling of chemical solutions.

Aluminum-Manganese Alloys. The wrought aluminum-manganese alloy 3S possesses a general resistance to corrosion comparable with that of 2S. Among the applications illustrating the resistance of 3S to corrosion are roofing and siding, cooking utensils, and tanks and tubing to handle water and a number of chemicals. A cast aluminum-manganese alloy, 406, because of good resistance to corrosion, is used for pipe fittings in connection with 3S or Alclad 3S pipe.

Aluminum-Magnesium Alloys. All the aluminum-magnesium alloys possess a high order of resistance to corrosion. The alloy 52S resists atmospheric weathering very well, and because of exceptional resistance to sea water, has been used rather extensively for marine applications. This alloy has been used considerably in equipment for the chemical industry and is used also for heavy-duty cooking utensils and the bulk processing of foods. Another alloy, of higher magnesium content, 56S, is used for corrosion-resistant wire products.

The casting alloy 214 is used for ornamental castings where a white color is desired, for cooking utensils, for the bulk processing of foods, for a number of fittings for equipment in the chemical industry, and also for marine applications. A related alloy, B214, which contains some silicon as an alloying element, is used for similar applications and especially for pipe fittings for marine use. The die-casting alloy 218 resists corrosion and tarnish very well, and for that reason is used for hardware fittings and for various parts in aircraft and ships. The sand-casting alloy 220 is used for aircraft and marine castings and for frames of railroad cars.

Aluminum-Manganese-Magnesium Alloys. The wrought aluminum-manganese-magnesium alloy 4S is used in many of the same applications as 3S or 52S, because the resistance to corrosion of these alloys is similar.

Aluminum-Silicon Alloys. The casting alloy 43 is able to resist both atmospheric weathering and a wide variety of waters, chemicals and food acids. Its uses under corrosive conditions include fittings in refrigerators, carburetor bodies, cooking utensils, architectural and ornamental parts, pipe fittings, marine fittings, and a wide variety of food-handling equipment. The die-casting alloys, 13 and 360, and the heat treatable alloy 356, are comparable with 43 in their resistance to corrosion. The alloy 356 is used for such applications as liquid-cooled engine cylinder blocks, pump parts, aircraft and marine fittings, and castings for the chemical industry. The heat treatable casting alloy, 355, because of its copper content, is somewhat less resistant to corrosion than alloy 356. However, it is used for a large number of aircraft parts, liquid-cooled cylinder heads for aircraft, impellers for superchargers, water jackets and fuel-pump bodies. Red X-8, an alloy of related composition, has found use in the same type of applications. The wrought alloy 32S, and the casting alloys A132 and Red X-13, which contain higher silicon than the alloys previously mentioned, compared favorably with them in resistance to corrosion.

Aluminum–Magnesium Silicide Alloys. The wrought aluminum–magnesium silicide alloys are important because their general resistance to corrosion is comparable with that of the wrought alloys that are not heat treatable (2S, 3S, 4S and 52S) and their strength after heat treatment is considerably higher. The resistance to corrosion of the wrought aluminum–magnesium silicide alloys is independent of temper. For many uses these alloys do not require paint as protection. The alloy 53S has been employed for structural purposes where a high degree of resistance to corrosion is required and, to a considerable extent, for equipment used in the handling and processing of chemicals and beverages. The alloy 61S is only slightly less resistant to corrosion than 53S and is satisfactory for structural applications under severe conditions of exposure. It is used also for processing and handling beverages and chemicals, except where the copper content is undesirable. Extruded parts made of 63S are widely used for architectural purposes. This alloy is comparable with 53S in resistance to corrosion and has a brighter color. The forging alloy A51S, which contains silicon in excess of the magnesium silicide ratio, has resistance to corrosion in the T4 temper comparable with that of 53S, but artificial aging to the T6 temper decreases this resistance. Nevertheless, resistance to corrosion of A51S-T6 is superior to the resistance of ■ number of other types of aluminum alloys of comparable strength.

Aluminum-Copper Alloys. The wrought aluminum alloys 17S-T4 and 24S-T4, which contain copper as the main alloying element, resist corrosion satisfactorily but are inferior in this respect to the alloys of the aluminum–magnesium silicide type, such as 53S and 61S. The resistance to corrosion of 17S-T4 and 24S-T4 is decreased by slow quenching from the solution heat treatment temperature, or by subsequent reheating. Thick sections of the alloy 24S in the artificially aged (T8) tempers have a resistance to corrosion comparable with that of similar sections of 24S-T4.[13] The wrought aluminum alloy 14S, which contains added silicon, is comparable in the T4 temper with 17S-T4 in resistance to corrosion. The commercially available products of 14S-T6 have the same order of resistance to corrosion as products of 24S-T4 that are similar in cross section. These aluminum-copper alloys have been widely used for aircraft construction and for general-purpose structures. In such applications they are always painted for protection. The forging alloy 25S has a lower order of resistance to corrosion than 17S-T4 and 24S-T4 but the millions of aircraft propeller blades made of this alloy have given satisfactory service in many climates. Because of their lead and bismuth contents, the free-cutting alloys 11S and R317 have a somewhat lower resistance to corrosion than 17S-T4, under some corrosive conditions. The alloy 11S is most resistant in the T3 temper.

The sand casting alloy 195 and the permanent mold alloy B195 (which also contains silicon as an alloying element) have good resistance to atmospheric weathering and are used for such parts as wheels and fittings for aircraft and fittings for railroad cars; but in general, protection against corrosion is recommended. The wrought alloy 18S, the casting alloy 142 (both of which contain nickel and magnesium in addition to copper) and the casting alloy 122, are possibly somewhat inferior to 195 in resistance to corrosion but are in the same general class. Except in cylinder heads for air-cooled engines, parts made of the latter alloys are seldom subjected to corrosive environments.

Aluminum-Copper-Silicon Alloys. With respect to resistance to corrosion, the alloys containing substantial amounts of both copper and silicon can be treated as a group. Their resistance to corrosion is comparable with that of the aluminum-copper alloys. The alloys 108, 113 and C113 contain copper in excess of silicon, whereas the alloys 85, Allcast, A108, and 380 contain silicon in excess of copper. They all resist atmospheric weathering fairly well, but for severely corrosive conditions paint is recommended as protection. As examples of their use, unprotected 108 is used for manifolds; A108, for ornamental grilles and reflectors; and C113, for agitators in washing-machines.

Aluminum-Zinc Alloys. Because of its anodic electrode potential, the aluminum-zinc alloy 72S is used as an alclad coating to protect electrolytically those alloy core compositions that have an electrode potential too anodic to be adequately protected by pure aluminum. The resistance to general corrosion of 72S is only slightly, if at all, inferior to that of 2S.

Aluminum-Zinc-Magnesium Alloys. The wrought alloy 75S is comparable with 24S-T4 in resistance to corrosion; hence, the same protective measures against corrosion are used. The alloy R303 can be classified in this group. The casting alloy 40E has good resistance to general corrosion.

Alclad Products. Alclad 17S-T4 and Alclad 24S-T4 sheet have been used extensively in aircraft construction for more than 15 years. As skin for the wings and fuselage, these alclad products resist atmospheric corrosion satisfactorily without paint or other protective measures. The alclad products currently available in the form of sheet and plate include Alclad 3S, Alclad 24S, Alclad 75S, Alclad 14S, and R301; in the form of tubing, Alclad 3S, with a coating on the inside surface only; and in the form of wire, Alclad 56S. Alclad 75S-T6, Alclad 14S-T4, and R301-W are comparable with Alclad 24S-T4 in resistance to

corrosion. The difference in electrode potential between coating and core of Alclad 14S-T6 and R301-T is smaller than in Alclad 14S-T4 or R301-W; consequently their resistance to corrosion is somewhat lower. Alclad 3S is used primarily where resistance to penetration under corrosive conditions is the chief consideration. Alclad 56S is used extensively for wire that is to be made into insect screen cloth.

Resistance to Atmospheric Exposure. In situations where air has free access to their surfaces, aluminum and the more corrosion-resistant aluminum alloys exhibit satisfactory weathering characteristics in rural, urban, industrial and seacoast atmospheres. In comparison with that of other metals, the resistance to industrial atmospheres is outstanding. The corrosion-resistant aluminum alloys also withstand seacoast atmospheres satisfactorily.[5]

The importance of the protective oxide film on the resistance of aluminum to corrosive environments, was discussed in the introduction to this article. When aluminum is exposed to the weather, moisture and dirt that collect on the surface cause breakdown of the weak spots in the protective oxide film, and tiny pits are formed. The metal from these pits is converted to a hydrated aluminum oxide, thus forming a thicker coating, which greatly retards further attack. At this stage of weathering, the aluminum surface presents a somewhat nonuniform, speckled appearance. In the course of several months or a year, depending on the atmospheric conditions, the appearance of the surface becomes more uniform; the color depends on the amount of dirt in the atmosphere. In industrial regions the color becomes ■ slate gray, whereas in clean, seacoast atmospheres the surface takes on more of an etched, whitish appearance. In dry, clean locations, such as Phoenix, Ariz., the bright metallic sheen remains almost untarnished for a period of years. Sheltered areas of the metal are likely to develop a thicker, rougher oxide coating than surfaces that are frequently washed with rain. When the appearance of the weathered surface is objectionable, the bright metallic appearance may be preserved by simple periodic cleaning with an abrasive cleaner, such as Bon Ami or steel wool and soap.

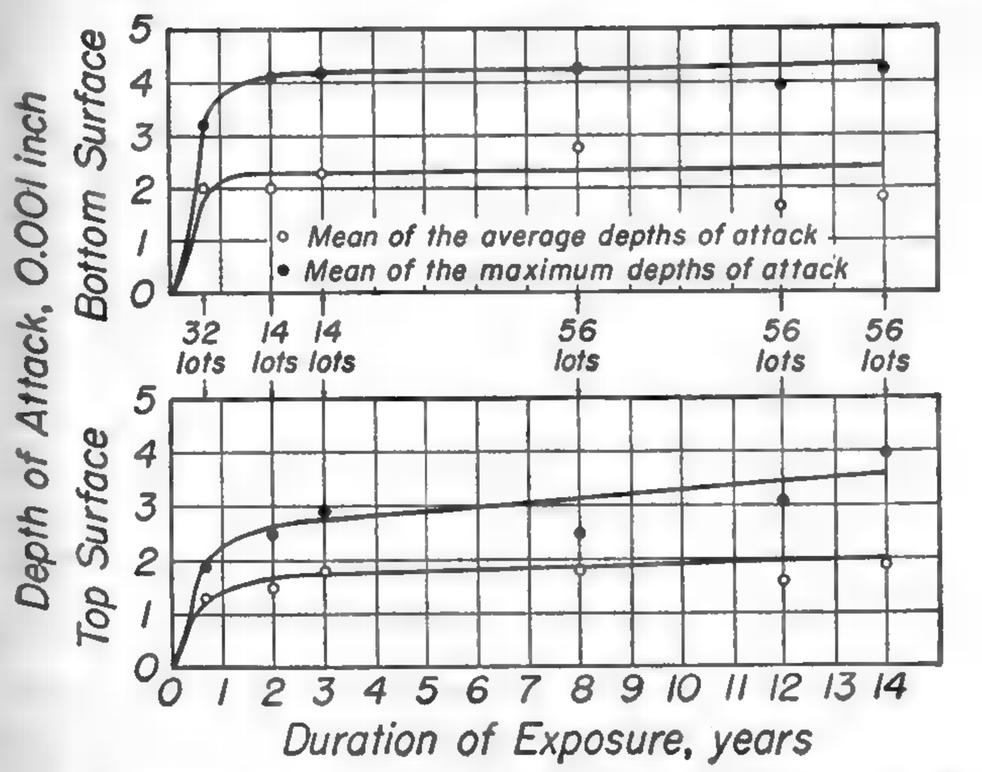

Fig. 1 Rates of corrosion of aluminum alloys during exposure to the industrial atmosphere of New Kensington, Pa. Alloys tested were 2S, 3S, 4S, 43S, 51S and Al plus 2 to 6% Mg. Specimens were in the form of sheet 0.064 in. thick. Panels were exposed at 45 deg, facing south. Fifty-six lots were tested.

The curves of Fig. 1 show the rate of attack by corrosion on the surfaces of a number of aluminum alloys exposed to an industrial atmosphere. The self-stopping action of this type of attack with free circulation of air, is well illustrated. Pitting to the depth of 0.002 to 0.003 in. occurs in the first year or so. After this period the protective oxide coating has become sufficiently thick for the rate of attack to progress much more slowly, and even after 10 to 20 years the depth of attack is not much more than about twice that in the initial period. In seacoast atmospheres, pitting may be more rapid in some locations, but this attack also is self-stopping and the maximum depth of pitting after a number of years is not more than twice that found in industrial atmospheres.[13]

The weathering of aluminum under conditions that permit free access of air to its surface has been described. Under conditions of exposure that prevent free circulation of air against the surface of the aluminum, the corrosion behavior is quite different; for example, where a constantly moist absorbent material is in contact with an aluminum surface. Even if the material is relatively inert, oxygen concentration cells are set up that accelerate the corrosion of aluminum.[14] The corrosion product that forms is mostly an aluminum hydroxide, which remains wet and gelatinous and thus offers little protection from further attack. However, occasional drying does permit the formation of a protective film that retards further attack temporarily. The influence of a moist absorbent material as just described is sometimes referred to as "poultice action". If the material forming the poultice is not inert but contains acid or alkaline material that may be leached out, the rate of attack is increased markedly; and if salts of heavy metals are also present, the attack is accelerated still further by electrolytic action. When it is known that the aluminum surface is likely to be subjected to poultice action, adequate protection should be provided by painting.

Another common condition that prevents free access of air to the surface occurs in crevices between contacting surfaces in joints. Moisture is carried into the joint by capillary action, and corrosion is accelerated by oxygen concentration cells set up because of lack of free circulation of air. Unless the joint is dried frequently, the corrosion product holds moisture and retards the formation of a protective film. The corrosion products of aluminum occupy several times the volume of the metal and, hence, exert sufficient pressure to spread the joint. This permits more moisture to enter the joint, and the corrosion process continues. Under such conditions, it is recommended that the contact surfaces be painted before assembly, even though in many instances the surfaces subjected to free circulation of air require no protection from paint. Where a joint is made between aluminum and a dissimilar metal such as iron or steel, the corrosion is greatly aggravated by electrolytic action between the metals. In such situations, it has been found desirable to spray the steel surface with aluminum or zinc and to impregnate the sprayed coating with a good paint. When the steel is covered thus, chances of electrolytic action are greatly minimized. The use of a permanently plastic joint compound to seal the joints from moisture, is recommended regardless of other protective measures. With a satisfactory compound, painting the contact surfaces may sometimes be omitted.

Many of the wrought alloys are commonly used without protection. These include alloys which do not respond to heat treatment (2S, 3S, 4S, 52S, Alclad 3S and Alclad 56S) and the heat treatable alloys of the magnesium silicide type (53S, 61S and 63S), as well as the Alclad high-strength alloys (Alclad 24S-T4, R301, Alclad 14S-T6 and Alclad 75S-T6). The wrought aluminum-copper alloys not in Alclad form, 75S-T6 and R303, as well as A51S, are ordinarily painted when exposed to the atmosphere.

Of the casting alloys, the aluminum-silicon alloy 43 has been used extensively in the construction of buildings without the protection of paint. The backs of spandrels made of 43 alloy have sometimes been painted. Although they are less frequently used, it now seems evident that the cast aluminum-copper or aluminum-copper-silicon alloys will also resist weathering satisfactorily without protection. The aluminum-magnesium alloys, 214 and 218, have a higher resistance to corrosion and a tendency to maintain a whiter appearance under conditions of atmospheric exposure; hence, these alloys are often used for highly ornamental work.

Resistance to Waters. Aluminum equipment is established as standard for storing and conveying distilled water of the highest purity.[15] During the initial period of contact, the reaction that takes place with the distilled water is

sufficient to form a protective film of hydrated aluminum oxide on the metal surface; but this action soon stops and, even with boiling water, the purity of distilled water is not affected to a practical extent by contact with these aluminum alloys. Commercially pure aluminum, 2 S, and such alloys as 3 S, 52 S, 43, 214, B214 and 406 have been used successfully. Equipment constructed of these alloys is coming into use also for storing and conveying demineralized waters, used in processes where contamination by even small traces of certain elements cannot be tolerated.

A considerable amount of aluminum equipment made of 2 S, 3 S, 52 S, 43, 214, B214 and 406, has been used to convey and store a number of lake, river and municipal waters —in some instances, at elevated temperatures. However, the variation in composition of waters from different sources is so great that it is not possible at present to predict their action on aluminum and, hence, to generalize regarding the mutual compatibility of aluminum alloys and miscellaneous waters. Alkaline waters have usually been found to have appreciable action on aluminum alloys, although there are exceptions to this generalization. In some instances this action has been prevented by the addition of suitable chemical inhibitors. Waters of high acidity, such as are often encountered in coal mines, are generally corrosive to aluminum, but in a number of situations, aluminum alloys have proved to be more resistant than other metals used in such service. When small amounts of cathodic metals such as copper and nickel are present in natural waters or have been picked up by contact with other metallic equipment, these waters have been found to be corrosive to aluminum. The heavy metal ions are reduced by aluminum and the deposition of the heavy metals on the aluminum surface causes the aluminum to pit. Because Alclad 3 S has been found to combat the pitting action successfully, this product is being used widely for the handling of such corrosive waters. Moisture in the form of water vapor causes very little action on aluminum alloys at temperatures as high as 300 F.

Aluminum alloys such as 2 S, 3 S, 4 S, 52 S, 53 S, 214, B214 and the alclad products, have been found to resist the action of sea water. The alloys 52 S, 214 and alclad products are outstanding in this respect.[5]

Aluminum Alloys for Chemical Equipment. Aluminum alloys have been used widely for processing, handling and storing different types of chemical solutions. The chemical industry has so many ramifications that only a general survey with a few specific examples can be given here. It should be emphasized that even small quantities of impurities in the chemical solutions, and other seemingly unimportant factors, may make the difference between success and failure of aluminum alloys in a given application.

Potentials in Various Solutions. The potentials given in Table I cannot be used to predict the resistance of aluminum to corrosion while in contact with dissimilar metals in many types of chemical solutions. Table V indicates that the potential of aluminum varies to a marked degree with the composition of the solution. In the use of aluminum in the chemical industry, the effect of the composition of the solutions on the potentials of aluminum must be considered carefully for each application if the galvanic effects resulting from dissimilar metals are to be avoided.

Acid Solutions. Organic. Nearly all organic acids can be used in contact with such aluminum alloys as 2 S, 3 S, 52 S, 53 S and 61 S; for example, at room temperature the rate of attack on aluminum by any concentrations of aqueous solutions of acetic acid, is not more than 0.0044 in. per year. The rate of attack increases markedly with increasing temperature; however, commercial glacial acetic acid does not attack aluminum appreciably even at temperatures as high as 120 F. Formic and oxalic acid solutions attack aluminum alloys at appreciable rates, so aluminum alloys are not generally used for handling these materials except in processes where it is necessary for the resulting products not to be discolored or for the solution to retain its water whiteness.

Acid Solutions. Inorganic. Dilute aqueous solutions of the mineral acids, such as HCl, H_2SO_4, H_3PO_4, and HNO_3, react with aluminum at appreciable rates. Aluminum alloys are used with these solutions to a limited extent, generally where it is desirable to maintain the water whiteness of the solution or to prevent the discoloration of the products that are being processed. Organic coatings have been applied to certain types of aluminum equipment for the handling of dilute mineral acids. Nitric acid, in concentrations greater than 80% by weight, has a negligible action on aluminum; consequently, aluminum alloys are used to make tanks and drums for fuming nitric acid. Salts that hydrolyze to give acid solutions can be handled in aluminum equipment. For example, aluminum alloys are used widely in contact with ammonium nitrate solutions and, in many instances, have been employed safely in contact with ammonium sulfate and ammonium aluminum sulfate solutions.

Alkaline Solutions. Aluminum is attacked by many aqueous alkaline solutions because of their solvent effect on the protective oxide film. There are notable exceptions, as indicated by the extensive use of aluminum equipment to handle and manufacture ammonia, not only in the liquid and vapor states, but also in aqueous solutions. After a minor initial action with these chemicals, a protective film is re-formed on the aluminum surface. For a similar reason aluminum alloys are usually satisfactory in contact with a number of organic amines. The addition of sodium silicate or sodium chromate can greatly minimize or even prevent the attack on aluminum by solutions of salts that hydrolyze to give basic solutions such as sodium carbonate and trisodium phosphate.

Table V. Effect of Composition of Electrolyte on the Potential of Aluminum[a, b]

Electrolyte	Potential, volts 0.1 N Calomel Scale
Reversible potential calculated from heat data for aluminum ion concentration of one molal activity	— 2.11
M[c] $AlCl_3$	— 1.11
M NaCl	— 0.85
M Na_2SO_4	— 0.50
M HCl	— 0.71
M HNO_3	— 0.88
M NaOH	— 1.47
M NH_4OH	— 0.80
Sat Sol[d] $Ca(OH)_2$	— 1.54
Sat Sol $Ba(OH)_2$	— 1.53
M Na_2CO_3	— 1.35
M Na_3PO_4	— 1.32
Sat Sol $CaCO_3$	— 1.04
Sat Sol $CaSO_4$	— 0.77

(a) Data from Aluminum Research Laboratories
(b) Alloy 2 S–O
(c) M indicates one gram molecular weight of the compound per liter of solution
(d) Sat Sol indicates saturated solution of compound

Neutral Salt Solutions. Neutral inorganic salt solutions cause very little action on aluminum, but the simultaneous presence of some of the cathodic metals and chlorides may cause appreciable acceleration of attack. The action of neutral solutions of chloride salts is slow unless they are contaminated with heavy metals such as copper, nickel and lead. Aluminum alloys are used for piping chloride brines from oil wells. At room temperature the accelerating effect of the presence of the heavy metal impurities can be inhibited by the addition of chromates. Aqueous solutions of neutral sulfates and neutral nitrates are not corrosive to aluminum.

Sulfur and Sulfur Compounds. Aluminum alloys are particularly resistant to the action of elementary sulfur, even when it is molten or in the form of vapor, and to the action of a number of sulfur compounds that corrode many other metals. Tests have shown that aluminum alloys resist "sour" crude oils containing large amounts of hydrogen sulfide. Processes to eliminate H_2S from the "sour" crudes use equipment made of aluminum alloys.

Stability of Chemicals. In the handling or processing of a number of chemicals, aluminum alloys are used not only because they resist chemical attack but also because they do not act to decompose the compounds catalytically. The decomposition of hydrogen peroxide is not accelerated by aluminum nor is the aluminum attacked; consequently,

Table VI. Aluminum Alloys for the Construction of Equipment for Processing or Handling Industrial Chemicals[a]

Process or Chemical	Equipment	Alloy
Acetic acid	Distillation columns, *condensers, receivers, storage tank cars, drums, piping, oxidizing kettles,* and the like	2S, 3S, 52S, 61S-T6, Alclad 3S, 43, 214, B214, 356,406
Acetic anhydride	Heat exchangers, reaction vessels, *piping, storage tanks,* drums, *tank cars*	As above
Ammonium nitrate	*Ammonia tanks,* reaction vessels, tanks, *evaporators, crystallizers,* piping, drums, *tank cars*	As above
Ammonium hydroxide	Absorbers, *condensers, dephlegmators, piping*	As above
Edible oils and fats	*Deodorizers,* bleachers; winterizing equipment, including stills, separators, *condensers,* traps, bleachers, filters, pumps, *tanks, piping;* drums, tank cars	As above
Fatty acids	*Condensers, storage tanks,* trays, filter presses, receivers, drums, *melting vessels*	As above
Formaldehyde	Scrubbers, *receivers, storage tanks,* condensers, drums, *tank cars*	As above
Glue and edible gelatin	Vats, *evaporators, tanks,* heat exchangers, cooling towers, pumps, chutes, screens, spreaders, molds, filters, *piping*	As above
Hydrogen peroxide	*Stills,* condensers, receivers, *storage tanks, piping,* pumps, *drums, tank cars*	99.6% Al, 2S, 52S, 43, 214, B214, 356
Naval stores	*Stills, condensers,* receivers, *storage tanks,* evaporators, *piping, drums, tank cars*	2S, 3S, 52S, 61S-T6, Alclad 3S, 43, 214, 356, 406
Refrigerants	*Compressors, heat exchangers, evaporators, receivers, tubing*	2S, 3S, 17S-T4, 24S-T4, 52S, 61S-T6, Alclad 3S, 43, 214, B214, 356, 406
Ammonia, Carbon dioxide, Freons (11, 12, 21, 22, 113, 114), Methyl formate, Sulfur dioxide		
Soda ash manufacture	Equipment for handling ammonia, carbon dioxide, and brines, including *heat exchangers,* stills, *piping,* receivers, *absorbers,* reaction columns	2S, 3S, 52S, 61S-T6, Alclad 3S, 43, 214, B214, 356, 406
Water Distilled De-ionized	*Storage tanks, piping, condensers, receivers, degasifiers*	As above

(a) The *italicized* items have been constructed of aluminum alloys. Laboratory tests indicate that aluminum alloys deserve consideration for the fabrication and service testing of the items not italicized.

pure aluminum containers are used for storage and shipment of this material.[16] It has been found that aluminum alloys such as 2S, 3S, 52S, 53S and 61S-T6 are not attacked by mineral and vegetable oils, nor do they catalyze the decomposition of these products.[17,18] Pure aluminum equipment is used to produce citric and gluconic acids from sugars by the fermentation process, not only because pure aluminum resists attack by these solutions, but also because it is one of the few metals that has no harmful effect on the organisms.

Refrigerants. Even if some water is accidentally introduced into the refrigerating system, a wide variety of refrigerants can be handled in equipment made of aluminum alloys such as 2S, 3S, 52S, 53S and 61S. These alloys are affected to a negligible extent and do not affect the refrigerant adversely. In tests that were conducted at a temperature of 45 C, employing either dichloro-difluoromethane (F12) with 5% added water, or ammonia with the same amount of water, in contact with 3S, the maximum rate of penetration was found to be less than 0.002 in. per year.[19] When 3S was in contact with either of the above materials, dry or with dry sulfur dioxide, the attack was much less.

Chemical Equipment. In Table VI the italicized items of aluminum equipment have given satisfactory service with the chemicals or in the processes listed. Laboratory tests indicate that the aluminum alloys listed deserve consideration and service testing for the items not italicized. Materials that are now being shipped in aluminum-tank cars are given in Table VII.

Table VII. Chemicals Now Transported in Aluminum-Tank Cars

Chemical	Alloys Used for Tanks
Acetic acid	3S, 4S
Acetic anhydride	3S, 4S
Ethyl acetate	Alclad 17S-T4
Fatty acid	3S, 61S
Formaldehyde	3S
Glycerin	61S
Hydrogen peroxide	2S
Naphthenic acid	3S
Nitric acid	61S
Water-white rosin	3S

Aluminum for the Preparation and Processing of Foods. Because of the mutual compatibility between foods and aluminum equipment, aluminum alloys are widely used in the preparation and processing of foods. Aluminum cooking utensils, generally made of 2S, 3S or 52S sheet, or 43 or B214 casting alloys, give excellent service. Alclad 3S has been found very satisfactory for teakettles, in spite of the severe service to which they are subjected. Directly fired or jacketed kettles, ordinarily made of 3S or 52S, are used extensively for the heating of foods and fruit juices in bulk. Aluminum equipment has been used satisfactorily for years for storing, processing, or handling a number of food products such as fruit juices, milk, fish, meats, various vegetables, wines and beer. The wrought alloys usually employed are 2S, 3S, 52S, 53S and 61S, and the cast alloys are 43, 214, B214, 356 and 406.

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The Metallography of Aluminum Alloys

By F. Keller*

THE methods in general use for the metallographic examination of aluminum alloys are similar to those employed for other metals, except that more care must be taken to avoid the formation of flowed metal and deep scratches during polishing. The polishing and etching procedures described here have been in use for many years and have been found generally satisfactory for all products and tempers of aluminum alloys.

Preparation for Macroscopic Examination. Macroscopic examination of aluminum products for soundness, cracks, inclusions, folds and seams, as well as for grain structure and grain flow, is aided by the use of etching practices that clean the surface, make defects more prominent and reveal the general macrostructure. The practices that should be employed depend on the character of the product and on the types of information desired.

In instances where only the surface structures of ingots, billets, forgings and other articles are of interest, no surface preparation other than degreasing is necessary before etching. In problems involving the use of the more active etching solutions, a fairly smooth saw cut will often provide a satisfactory surface. A reasonably good finish is necessary; otherwise the finer details of the macrostructure may be obscured. For some types of examination a fairly satisfactory finish can be obtained by surfacing the sample on an abrasive belt, provided excessive metal flow is avoided. The best preparation for macro-etching, however, consists in obtaining a smooth, uniform surface by machining the sample on a lathe or a shaper.

All oil, grease, dirt and other foreign materials should be removed by some suitable cleaning method before etching is attempted. Special cleaning is not required when a sodium hydroxide solution is used for etching, since this solution is an effective cleaner. When other etching solutions are used, the cleaning may be accomplished by a preliminary treatment in a 5% sodium hydroxide solution or by the use of other cleaning agents, such as carbon tetrachloride, ethylene dichloride or one of the proprietary cleaners.

Etching to Reveal Macrostructure. Etching is usually done by immersing the sample in the etching reagent, by swabbing with the reagent, or by pouring the reagent onto the surface. It is very important to apply the etching reagent to the surface as uniformly as possible. Different times of etching will be required for different alloys and different tempers of the same alloy. Under any circumstances, etching should be continued until the desired contrast is obtained, but prolonged etching should be avoided, since it may cause excessive roughening of the surface, thus obscuring some of the macrostructural features. In some instances, the use of the less active solutions is desirable to avoid excessive roughening. This is especially important when the specimens are to be examined at magnifications of 10 to 25 diam.

Etching Solutions for Revealing Macrostructure. The solutions in general use for revealing soundness, grain size, grain flow and grain structure on a macroscopic scale for various aluminum alloy products, are listed in Table I.

Preparation for Microscopic Examination. For microscopic examination, it is usually necessary to cut specimens of a convenient size for polishing. These can be obtained by sawing or shearing, but care should be taken to avoid overheating the specimen or altering the structure in any manner. The next step in the preparation of a metallographic specimen is the removal of all oil, grease, dirt and other foreign material. Specimens too small to be handled conveniently during polishing should be mounted in some manner. The mounting of specimens can be accomplished in several ways. For instance, with samples of sheet, a pack can be made by binding a number of pieces of sheet together by means of machine screws. In the making of a composite specimen of sheet or foil, the pieces assembled in the pack are sometimes separated by filler pieces of an aluminum alloy. Other

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Table I. Etching Solutions for Revealing Macrostructure

Solution	Concentration	Specific Use	Procedure
Sodium hydroxide	NaOH ..... 10 g Water ..... 90 ml	General-purpose macro-etch for cleaning surfaces, revealing unsoundness, cracks and gross defects	Dip sample 5 to 15 min in solution heated between 140 and 160 F; wash in water, remove deposit of etching products with conc HNO_3 and rinse with water. Can be used on original surface or after a reasonably good saw or machine cut.
Aqua regia—HF	HCl (conc) ..... 75 ml HNO_3 (conc) ..... 25 ml HF (48%) ..... 5 ml	For revealing grain structure of castings and of alloys of the 3 S, 52 S, 53 S and 61 S type	Apply by immersion or swabbing until desired contrast is obtained. Wash specimen with warm water to speed up drying. Special surface preparation not required.
Tucker's etch	HCl (conc) ..... 45 ml HNO_3 (conc) ..... 15 ml HF (48%) ..... 15 ml Water ..... 25 ml	General-purpose macro-etch for revealing structure of castings, forgings and such	Etch by immersion of part or sample until desired grain contrast is obtained; rinse with warm water and dry. Can be used after a reasonably good saw cut or machine cut.
Modified Tucker's etch	HCl (conc) ..... 10 ml HNO_3 ..... 10 ml HF (48%) ..... 5 ml Water ..... 75 ml	General-purpose macro-etch for revealing structure of all castings and forgings except high-silicon alloys	Etch by immersion or swabbing until desired grain contrast is obtained; rinse with hot water and dry. Can be used after a good machine cut.
Hydrofluoric acid	HF (48%) ..... 10 ml Water ..... 90 ml	General-purpose macro-etch for revealing structure of high-silicon alloy castings and forgings	Etch by immersion until desired grain contrast is obtained; rinse in hot water and dry. Use after a polish with alundum flour on broadcloth.
Flick's etch	HCl (conc) ..... 15 ml HF (48%) ..... 10 ml Water ..... 90 ml	General-purpose macro-etch for revealing grain structure of duralumin-type alloys	Apply by immersion or swabbing until good grain contrast is developed. Rinse with water and remove deposit of etching products with conc HNO_3; wash with warm water. For best results, a smooth machined surface or a surface obtained by rubbing on 180 Aloxite cloth is required.
Keller's etch	HF (48%) ..... 0.5 ml HCl (conc) ..... 1.5 ml HNO_3 (conc) ..... 2.5 ml Water ..... 95.0 ml	For revealing finer details of macrostructure of duralumin-type alloys and for showing grain contrast	Etch by immersion for 15 sec to 1 min; wash with warm water and dry. Do not remove etching products from surface. Samples should be carried through regular metallographic procedure to the final operation.

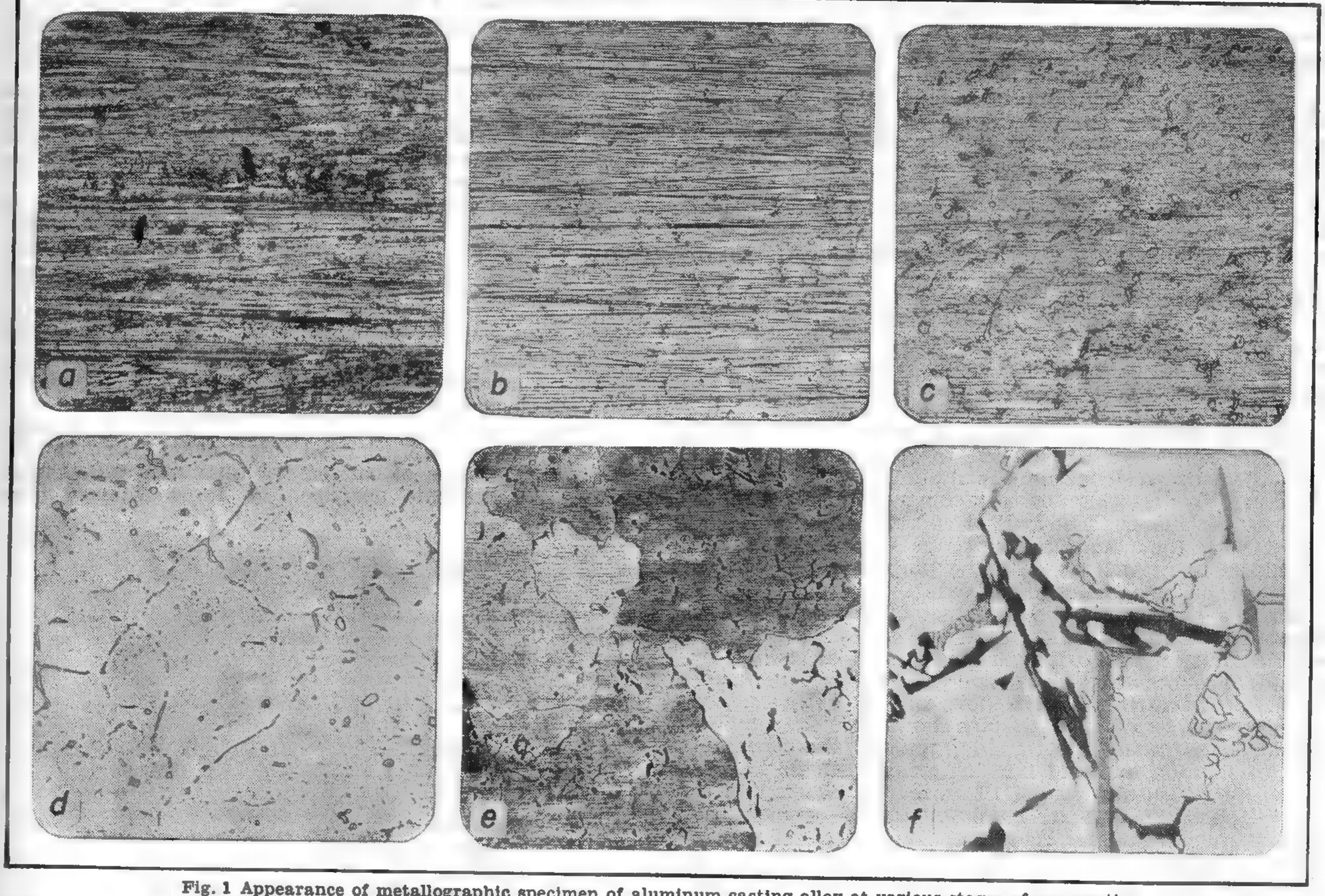

Fig. 1 Appearance of metallographic specimen of aluminum casting alloy at various stages of preparation

(*a*) Appearance of surface after file cut. ×100 (*b*) Surface after operations on emery papers. × 100 (*c*) Surface after operations with 600 alundum flour. × 100 (*d*) Surface after final polish with magnesium oxide. Unetched. ×100 (*e*) Structure revealed by etching with HF-HCl-HNO_3 solution. × 100 (*f*) Several different constituents as they appear before etching. × 500

metals should not be used as filler pieces in composite specimens. The pack should be clamped tightly to minimize capillary retention and subsequent exudation of solutions from crevices.

The general practice is to embed any small or irregular-shaped specimen in a mounting medium. The most economical and convenient method consists in placing the specimen in a ring of aluminum tubing and filling the ring with melted sulfur. Sulfur does not chip during polishing and is unaffected by the etching reagents commonly used. Other mounting materials, such as sealing wax or dental cement, may be employed. If a press for mounting specimens is available, Bakelite or one of the transparent or semitransparent plastics can be used. It is important to avoid any mounting material that will cause galvanic attack during etching or that is severely attacked during the etching procedure.

The following procedure is recommended for the preparation of specimens for microscopic examination:

1 Draw the specimen over a long-angle lathe file to obtain a plane surface and to remove any distorted metal from sawing operations.

2 Rub specimen on 180-grain Aloxite paper to remove file marks, and then successively on No. 0 and 000 metallographic emery papers that have been coated with a solution of paraffin and kerosene. This coating helps keep the specimen bright and prevents particles of abrasive from becoming embedded in the surface. The solution is made by dissolving 50 g of paraffin in one liter of kerosene. The specimen should be turned about 90 deg to the direction of polishing, at each step in the process.

3 Polish on a rotating disk covered with "kitten's ear" broadcloth or "Gamal" cloth, using a water suspension of 600 alundum flour or a similar material as the abrasive. A quantity of the abrasive is placed in a flask with water and is shaken until it is in suspension. In this way, the mixture can be conveniently supplied to the pad while the specimen is being polished. The polishing disk should be operated at about 250 to 300 rpm and the specimen should be held on the pad about 2 to 3 in. from the center of the disk. The pad should finally be washed free of the coarser particles of the abrasive by means of a stream of water from a wash bottle, and the polishing with this abrasive should be completed by using a suspension from which all the coarse particles have settled.

4 Polish finally on a rotating disk covered with "kitten's ear" broadcloth or "Gamal" cloth and operated at a speed of 150 to 200 rpm, using heavy magnesium oxide powder as the polishing medium. The pad should be kept moist with *distilled water* and a small quantity of the magnesium oxide should be worked into it with the palm of the hand. Any gritty particles or excess powder should be brushed off. During polishing, the pad should be kept moist by adding *distilled water* from a wash bottle as needed. Polishing should be continued until the striations from the alundum operation (3) are removed. As the polishing operation approaches completion, the pad should be washed nearly free of magnesium oxide and the specimen should be held on the slowly rotating pad while a copious supply of distilled water is used. The pressure and time required for polishing a specimen are influenced by both the composition and the temper of the specimen.

5 When a satisfactory polish has been secured, the specimen should be washed in a stream of warm tap water and dried by blowing the excess water from the surface. The polished surface should not be touched or rubbed against anything; otherwise the finish may be marred. Specimens will retain their finish indefinitely, provided they are kept in a place where dust and dirt from the

atmosphere will not collect on the surfaces. The proper appearance of the surface of an aluminum alloy at various stages in the preparation is illustrated by Fig. 1.

Several precautions must be taken to secure satisfactory results during the polishing of aluminum alloys. For example, there are several grades of magnesium oxide powder prepared specifically for metallographic use and employed successfully for polishing some metals; however, several of these products are somewhat alkaline and will etch an aluminum specimen. Magnesium oxide powder of this type should not be used. The use of *distilled water* with the magnesium oxide is very important. When ordinary tap water is used, hard carbonate particles may form and cause deep scratches that cannot be removed without going back to the operations on the abrasive papers. Finally, a new polishing cloth should be boiled for several hours to soften the fibers before it is used. When the cloth is not in use, it should be kept moist in distilled water that has been acidified slightly with hydrochloric acid.

Etching Solutions for Microscopic Examination. Metallographic specimens are etched to remove flowed metal from the polished surface and to aid in revealing the microstructure by coloring or attacking the various constituents or phases. The type of etching solution required varies with the magnification to be used in subsequent examination, as well as with the purpose for which the etching solution is being employed.

Etching is accomplished by either of two methods, immersion or swabbing. The practice of swabbing specimens with a dilute solution of hydrofluoric acid or sodium hydroxide has been found to give uniform or satisfactory results in removing surface flow and in outlining constituent particles. Experience has shown that the temperature of both specimen and etching reagent, the concentration of solution and the time of etching should be controlled to give useful results. Information concerning the etching solutions that are employed for the identification of constituents and for revealing the general microstructural features of various aluminum alloys is given in Table II. These are all aqueous solutions made by volume when acids are used, and otherwise by weight.

Constituents in Aluminum Alloys. In the metallographic examination of aluminum alloys, it is frequently necessary to identify the constituents that appear in the microstructure. In general, the constituents in aluminum alloys consist of (1) elements such as silicon that do not combine with aluminum to form compounds and therefore are present in the elemental state; (2) intermetallic compounds formed by ▪ combination of one or more alloying elements with aluminum ($CuAl_2$ and $FeAl_3$); (3) intermetallic compounds that are formed by a combination of two or more elements other than aluminum and that are stable in aluminum (for example, Mg_2Si); and (4) ternary or more complex constituents, as for instance, α(Al-Fe-Si) and Al-Cu-Fe-Mn.

Identification of Constituents. The first attempt to identify constituents should be made on the unetched specimen, using color and manner of occurrence as a means of differentiation. Some of the more common constituents, such as $CuAl_2$, Si, Mg_2Si and β Al-Mg, can be identified readily by their polishing characteristics, color and manner of occurrence. Others, more difficult to identify, are sometimes present and necessitate the use of various etching reagents.

For judging the color of constituents, it is advisable to employ light approximately the color of daylight. Addition of a Wratten 78A filter, which has a bluish tint, converts the light of a carbon-arc lamp with an Eastman neutral tint filter to approximately that of daylight. Any white light will give about the same results, although the use of the 78A filter will help in the separation of different constituents. Examination for identification is usually made at a magnification of 500 diam with a lens combination comprising a 4-mm objective and a 10× ocular.

Etching Chart. In Table III are given the etching characteristics of the principal constituents found in "as-polished" specimens of commercial aluminum alloys after the etching reagents described in Table II have been used.

Fig 2 Sand-cast 43 alloy (5% Si). × 500

Microstructure of Aluminum Alloys. Commercial aluminum alloys are generally of the hypoeutectic type and solidification begins with the separation of aluminum or aluminum-rich solid solutions as primary dendrites. During solidification of these dendrites, the alloying constituents tend to concentrate in the remaining liquid phase, producing a structural condition known as "coring" and a discontinuous or continuous network of constituents at interstices of the dendrites and along the grain bound-

Table II. Etching Solutions for Revealing Microstructure

Solution	Concentration	Specific Use	Procedure
Hydrofluoric acid	HF (48%) ..... 0.5 ml H_2O ..... 99.5 ml	General-purpose micro-etch	Swab with soft cotton swab for 15 sec.
Sodium hydroxide	NaOH ..... 1 g H_2O ..... 99 ml	General-purpose micro-etch	Swab specimen with solution for 10 sec.
Sodium hydroxide	NaOH ..... 10 g H_2O ..... 90 ml	General-purpose micro-etch	Immerse specimen for ▪ sec at 70 C and rinse in cold water.
Sulfuric acid	H_2SO_4 (conc) ..... 20 ml H_2O ..... 80 ml	For separating Al-Cu-Fe-Mn from Al-Fe-Mn or α(Al-Cu-Fe)	Immerse for 30 sec at 70 C and quench in cold water.
Nitric acid	HNO_3 (conc) ..... 25 ml H_2O ..... 75 ml	For separating α(Al-Fe-Si) from $FeAl_3$	Immerse for 40 sec at 70 C and quench in cold water.
Keller's etch	HF (conc) ..... 1.0 ml HCl (conc) ..... 1.5 ml HNO_3 (conc) ..... 2.5 ml H_2O ..... 95.0 ml	For revealing microstructure of heat treated duralumin-type alloys	Etch by immersion for 10 to 60 sec, wash with warm water and blow dry. Do not remove etching products from surface.
Modified Keller's etch	HF (conc) ..... 1.0 ml HCl (conc) ..... 1.5 ml HNO_3 (conc) ..... 10.0 ml H_2O ..... 87.5 ml	For separating 75S-W from 75S-T6 alloy	Etch by immersion for 10 to 60 sec, wash with warm water and blow dry. Do not remove etching products from surface.

Table III. Etching Characteristics of Constituents in Aluminum Alloys

Constituents	Reagent					
	0.5% HF, swab for 15 sec, wash in cold water	1% NaOH, swab for 10 sec, wash in running water	20% H_2SO_4 at 70 C, immerse specimen for 30 sec, quench in cold water	25% HNO_3 at 70 C, immerse specimen for 40 sec, quench in cold water	10% NaOH at 70 C, immerse specimen for 5 sec, rinse in cold water	0.5% HF, 1.5% HCl, 2.5% HNO_3, immerse specimen for 15 sec, rinse in warm water
Silicon	Outlined Unattacked Color lightened	Outlined. Unattacked Color slightly lightened	Unattacked Color lightened	Outlined Unattacked Color lightened	Outlined Unattacked Color lightened	Outlined Unattacked Color lightened
Mg_2Si	Colored bright blue	Outlined Color unchanged	Action violent Some particles dissolved, any left have a blue color	Colored brown or black	Outlined Color lightened	Outlined Colored blue to brown
$CuAl_2$	Outlined. Part of pinkish tinge removed. Constituent light and clear	Outlined. Part of pinkish tinge removed Constituent light and clear	Outlined. Part of pinkish tinge removed. Constituent light and clear	Colored brown or black	Pitted Colored light to dark brown	Outlined Constituent light and clear
β (Al-Mg)	Outlined. Slightly clearer and more watery Black pits appear in particles	Not outlined Unattacked Uncolored	Attacked vigorously resulting in pitting. Some particles dissolved	Heavy attack Particles grayish and watery	Outlined Unattacked Uncolored	Heavily outlined Attacked by pitting
$FeAl_3$	Slightly darkened Brown stains appear on large primary particles	Outlined Slightly darkened	Heavily attacked Particles often dissolved or deeply pitted Color darkened	Outlined, Contrast with Al-Fe-Si improved	Outlined Colored deep brown	Outlined Uncolored Slightly attacked
α (Al-Fe-Si)	Outlined Uncolored	Outlined Uncolored	Outlined Blackened and attacked	Outlined, Contrast with $FeAl_3$ improved	Attacked Blackened	Heavily outlined Darkened and roughened
β (Al-Fe-Si)	Blackened and attacked	Outlined Uncolored Unattacked	Outlined Slightly darkened and pitted	Outlined Uncolored Unattacked	Outlined Slightly darkened and attacked	Outlined Slightly darkened and roughened
Al-Mn	Outlined Slightly darkened	Attacked. Colored brownish or bluish but coloring is uneven	Outlined Uncolored Unattacked	Not outlined Unattacked Uncolored	Colored blue or brown	Outlined Unattacked Uncolored
$NiAl_3$	Outlined Colored blue and brown	Outlined Darkened slightly Uncolored	Outlined Darkened slightly Uncolored	Outlined Uncolored Unattacked	Colored blue to deep brown	Colored brown to black
Al-Fe-Mn	Outlined Colored brown (Sometimes bluish)	Outlined Particles pitted (Often a rough blue color on a few particles)	Outlined Unattacked Uncolored	Outlined Unattacked Uncolored	Colored deep brown to blue	Outlined Attacked Darkened
Al-Cu-Ni	Outlined Unattacked Darkened	Outlined Slightly darkened Unattacked	Outlined Slightly darkened Unattacked	Blackened Some particles dissolved	Outlined Unattacked Uncolored	Outlined Some large particles stained unevenly
α (Al-Cu-Fe)	Outlined Blackened	Outlined Unattacked Uncolored	Outlined Unattacked Uncolored	Outlined Unattacked Uncolored	Outlined Blackened Attacked	Blackened
β (Al-Cu-Fe)	Outlined Unattacked Uncolored	Outlined Slightly darkened	Outlined and uncolored. Often show black cores which are probably $FeAl_3$	Outlined Slightly darkened Unattacked	Pitted Colored light brown	Outlined Blackened
Al-Cu-Fe-Mn	Outlined. Colored light brown to black Usually appears roughened	Outlined Uncolored	Outlined Blackened	Outlined Unattacked Uncolored	Outlined Uncolored	Outlined Colored brown to black
Al-Mn-Si	Outlined. Colored light brown to black Usually appears roughened	Outlined Usually appears rough and attacked Slightly darkened	Outlined. Appears rough and attacked Darkened slightly	Outlined Appears rough Darkened slightly	Outlined Attacked Color not changed	Outlined Slightly darkened
Al-Cu-Mg	Outlined Blackened	Outlined Colored light brown	Outlined Attacked Blackened	Outlined Attacked Blackened	Outlined Unattacked Colored brown	Colored brown to black
$CaSi_2$	Colored blue Heavily outlined	Outlined Color unchanged	Outlined Colored blue Roughened	Outlined Unattacked Uncolored	Outlined. Blackened Attacked and roughened	Colored brown to blue Mottled
Al-Cu-Mn	Outlined Attacked Blackened	Outlined Unattacked Uncolored	Outlined Colored light brown	Outlined Unattacked Uncolored	Outlined Attacked Blackened	Attacked Blackened
$CrAl_7$	Outlined Unattacked Uncolored	Outlined Unattacked Uncolored	Outlined Unattacked Uncolored	Outlined Unattacked Uncolored	Outlined Colored blue to brown unevenly	Outlined Unattacked Uncolored
Al-Cr-Fe	Colored light brown Unattacked	Not outlined Unattacked Uncolored	Outlined Unattacked Uncolored	Not outlined Unattacked Uncolored	Small particles colored brown to black Large particles stained all colors	Outlined Colored light brown Unattacked

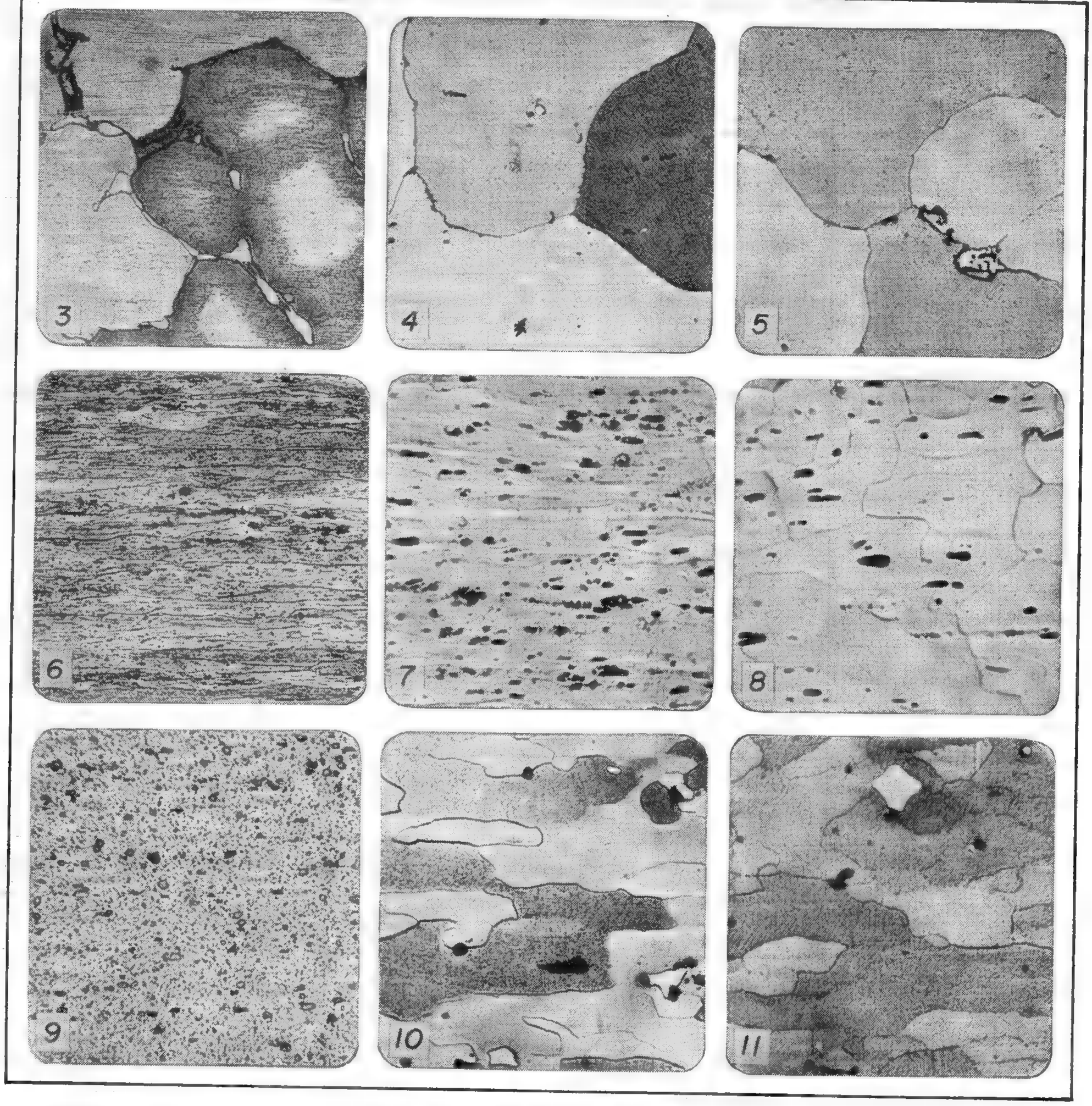

Fig. 3 to 11 Microstructure of aluminum alloys

Fig. 3 Sand-cast 195 alloy (4.5% Cu, 0.8% Si). × 250 Fig. 4 Heat treated 195 alloy casting. × 250 Fig. 5 Heat treated and aged 195 alloy casting. ×250 Fig. 6 Hot rolled 17 S alloy sheet (4% Cu, 0.5% Mg, 0.5% Mn). ×250 Fig. 7 Cold rolled 2 S alloy sheet (99.0% min Al). ×500 Fig. 8 Annealed 2 S alloy sheet. ×500 Fig. 9 Annealed 24 S alloy sheet (4.5% Cu, 1.5% Mg, 0.6% Mn). ×500 Fig. 10 Heat treated 14 S alloy sheet (4.4% Cu, 0.8% Si, 0.8% Mn, 0.4% Mg). × 500 Fig. 11 Heat treated and aged 14 S alloy sheet. × 500

aries. Further changes in structure result from different rates of cooling after solidification, and from various thermal and mechanical treatments. The constituents in aluminum alloys are found at the interstices of the dendrites and along grain boundaries in the as-cast condition, and are generally distributed throughout the matrix in material in the wrought condition. The microstructure of castings is governed largely by chemical composition, rate of solidification and thermal treatment. The microstructure of wrought products is influenced also by type and amount of working, as well as by the various thermal treatments that the products receive.

The structure of aluminum castings and of ingots is heterogeneous therefore, and is characterized by a dendritic pattern with a continuous or discontinuous network of microconstituents. Typical microstructures of two aluminum casting alloys in the as-cast condition are illustrated by Fig. 2 and 3. When an alloy of the type shown in Fig. 3 is subjected to a solution heat treatment, appreciable changes occur in the microstructure. The soluble constituent in the network will dissolve and the matrix will become a solid solution with no evidence of coring. The type of structure produced by heat treatment is shown in Fig. 4. The mechanical properties of an alloy of this type can be further improved after the solution treatment by employing a precipitation treatment, which will decrease

the grain contrast and may cause a noticeable precipitate along grain boundaries and within grains. The structure of the same alloy as in Fig. 3 is shown in Fig. 5 as it appeared after receiving a solution treatment and a precipitation treatment.

When cast aluminum ingots are made into various wrought products by rolling, forging, extruding or drawing, the macrostructure and microstructure are altered according to the type and degree of working, as well as by subsequent thermal treatments. Hot working breaks up the relatively large as-cast grains into fibers or fragments that may or may not recrystallize as new grains during working. The original cast grains are flattened and elongated according to the type and extent of working. Figure 6 illustrates the microstructure of a hot worked alloy of the 17 S type.

After the structure of aluminum alloy products has been refined by hot working, further working can be done below the recrystallization or annealing temperatures, causing additional refinement of the structure by breaking the grains into fragments and changing the constituent pattern. In cold worked material, work lines are frequently apparent in the microstructure, making it difficult to reveal any evidence of grain boundaries by etching. The microstructure of a cold worked aluminum alloy (2 S-H18) is shown in Fig. 7.

Annealing of cold worked aluminum alloys causes recrystallization and the formation of new grains from the grain fragments produced by cold working. With some alloys and with small amounts of cold working, it is not always possible to determine by metallographic examination whether or not recrystallization has occurred. Usually, however, annealed alloys are characterized by a more or less equiaxed grain structure that can be revealed readily by etching. A typical example of the structure of annealed aluminum sheet (2 S-O) is shown by Fig. 8. Besides causing recrystallization, the annealing treatment for heat treatable aluminum alloys must cause sufficient precipitation and agglomeration of the hardening constituents to produce the maximum degree of softening. The microstructure of 24 S-O alloy sheet, shown in Fig. 9, is characteristic of the type of structure obtained in a strong aluminum alloy in the annealed condition.

When an aluminum alloy of the heat treatable type is subjected to a solution heat treatment, marked changes occur in the microstructure. The most important change results from solution of the various hardening constituents during the heating cycle and subsequent retention of these components in solid solution as a result of the quenching operation. Thus, the microstructure of an aluminum alloy that has received a solution heat treatment is essentially that of a solid solution of the various elements in aluminum. This type of microstructure is illustrated by the micrograph of 14 S-T4 alloy shown in Fig. 10. It is typical of all aluminum alloys that have copper as their principal hardening component. After heat treatment, a few particles of the constituents will usually be apparent in the microstructure. These are residual particles of the soluble hardening constituents that have not been dissolved by the solution heat treatment, and particles of some of the relatively insoluble constituents that are present in the particular alloy.

Immediately after quenching from a solution heat treatment, the material will have a degree of workability and strength intermediate between that of the fully annealed condition and that of the heat treated temper. In the course of several days subsequent to quenching, some of the dissolved hardening elements will precipitate from solid solution as submicroscopic particles of the optimum size, number and dispersion to harden and strengthen the material appreciably. Most of the heat treatable aluminum alloys have, to a variable degree, this tendency to age harden at room temperature after a solution heat treatment.

The particles of precipitate that are responsible for the precipitation hardening of these alloys at room temperature are much too small to be resolved by the optical microscope; thus, they will not be apparent in the microstructure. Some aluminum alloys, however, do not age harden to their maximum strength at room temperature and must be given a precipitation treatment to cause the age hardening action to reach completion. This applies to alloys of the 14 S, 18 S, 25 S, 51 S, 53 S, 61 S and 75 S types. In these alloys, the tensile and yield strengths are further increased by the precipitation heat treatment following a solution heat treatment, but the ductility and workability are decreased. The effects of a precipitation heat treatment are usually evident in the microstructure, especially in alloys containing copper. After a precipitation heat treatment, alloys of the copper-containing type will show considerably less grain contrast on etching and will have very fine particles along the grain boundaries and within the grains. The structure of a precipitation hardened alloy of the 14 S type is illustrated by Fig. 11.

Properties of Aluminum-Copper Alloys

By E. H. Dix, Jr.* and J. J. Bowman*

OF the alloying elements used in aluminum alloys, copper was one of the earliest employed commercially and for many years has been the principal one, especially in this country. Even today copper is an important constituent of many of the most commonly used commercial alloys. When copper is the principal alloying element, two copper contents are of the greatest importance; namely, about 8% for castings and about 4% for both castings and wrought products. Alloys containing 4% Cu are nearly always used in the heat treated condition.

Casting Alloys. The commercial aluminum-copper casting alloys ordinarily contain controlled amounts of iron and silicon and sometimes small amounts of other elements, such as titanium or boron for special purposes. The casting and general foundry characteristics of these commercial aluminum-copper alloys are very good. The addition of copper decreases shrinkage difficulties and hot shortness progressively. Although the 8% Cu alloy is a good general-purpose alloy, its commercial importance is decreasing and the alloys containing about 4% Cu and substantial amounts of silicon are replacing it to a great extent. The commercial 4% Cu casting alloy is usually employed in the heat treated condition. Although considerably higher mechanical properties are possible with alloys of high purity, the high-purity alloys have achieved no importance commercially because the casting characteristics are inferior to those of alloys with controlled amounts of other elements.

Wrought Alloys. Binary alloys of high purity, containing as much as 10% Cu, have been successfully rolled, on a small scale, but since the difficulty of working increases with increase in copper content, the upper limit for practical production would be 5 to 6%. However, the commercial alloys ordinarily contain a nominal amount of not more than 4½% Cu with additions of manganese, magnesium or silicon. Such alloys belong to the important group generally known as "duralumin".

Heat Treatment. The solubility of copper in solid aluminum is 5.65% at the eutectic temperature (1018 F), and decreases to less than ¼% at room temperature. For this reason the aluminum-copper alloys are susceptible to age hardening. A solution treatment at a temperature in the range from 900 to 975 F puts most of the soluble copper into solution. Quenching from this temperature produces a supersaturated solid solution from which some precipitation occurs in finely dispersed form during natural aging

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after quenching, with the result that the strength and hardness increase and the elongation decreases. Additional precipitation, producing a further increase in strength and hardness, may be obtained by artificial aging in the temperature range from 300 to 400 F. In the commercial alloys, the addition of magnesium greatly increases the strength

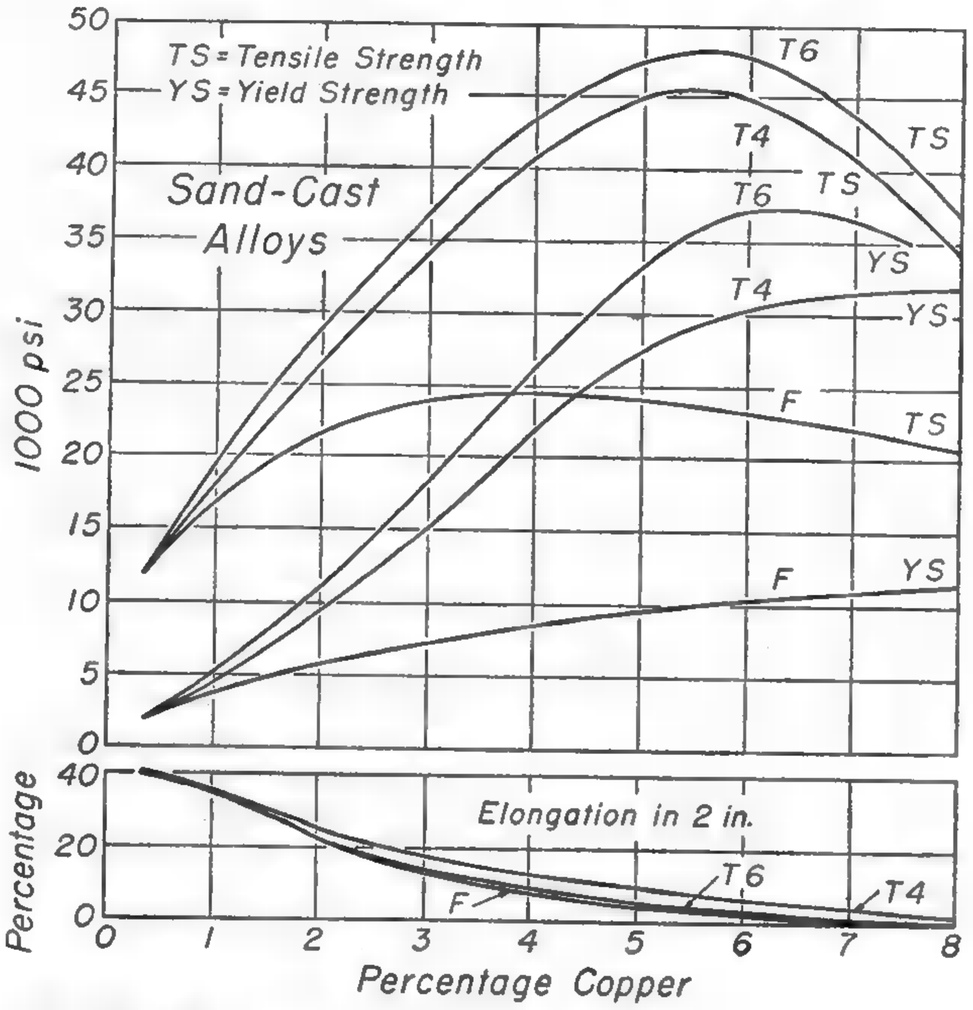

Fig. 1 Tensile properties of sand-cast aluminum-copper alloys of high purity. Tensile specimens cast to size, ½ in. in diam at reduced sections. *F*, as cast; *T4*, quenched in water after solution treatment at high temperature; *T6*, precipitation hardened after solution treatment.

obtainable as a result of heat treatment, and the addition of silicon increases the response to artificial aging. In one important commercial alloy the response to artificial aging is increased by cold work after the solution heat treatment.[1]

Mechanical Properties. The strictly binary aluminum-copper alloys are of little commercial importance, but the effect of copper as an alloying element can best be shown by a study of the properties of high-purity binary alloys.

The mechanical properties of high-purity aluminum-copper alloys are shown in Fig. 1, according to data obtained by testing sand-cast specimens;[2] and in Fig. 2, according to data obtained by testing specimens cut from rolled sheet.[2] From these curves, the effect of thermal treatments as well as of copper content can be seen. Additions of approximately 6% Cu give the maximum benefit of copper to the heat treated alloys.

Endurance Limit. The rotating-beam endurance limit (500 million cycles) of the aluminum-copper alloys increases with increase in copper content and, for a given alloy, is increased by solution heat treatment. Little if any improvement is obtained by subsequent artificial aging.[7]

Other Characteristics. *Density.* As would be expected, the densities of both the solid and liquid aluminum-copper alloys increase with the copper content. At 68 F the density of the sand-cast alloy containing 4% Cu is about 2.77 g per cu cm, and that of the 8% Cu alloy is about 2.86 g per cu cm. At 1290 F the densities for these alloys are, respectively, about 2.44 and 2.53 g per cu cm.[3]

Electrical and Thermal Conductivity. The electrical and thermal conductivities of aluminum are reduced by copper, an effect that is greater when the copper is in solid solution. For example, the electrical conductivity at 68 F is reduced from about 65% that of the standard annealed copper to about 37% for an alloy with about 5½% Cu quenched from a solution treatment.[4] The corresponding values for thermal conductivity are 0.57 and 0.35 cgs units.

Thermal Expansion. The coefficients of thermal expansion of aluminum-copper alloys decrease continuously with increasing copper content from about 0.000024 per °C (68 to 212 F) for pure aluminum to about 0.000020 for the 33% Cu alloy. The rate of decrease is greatest from 0 to 8% Cu.[5]

Lattice Parameter.[6] The aluminum-copper alloys, like pure aluminum, have a face-centered cubic lattice. The lattice parameter is decreased from 4.0413 for pure aluminum to 4.0305 × 10^{-8} cm for about 5% Cu in solid solution.

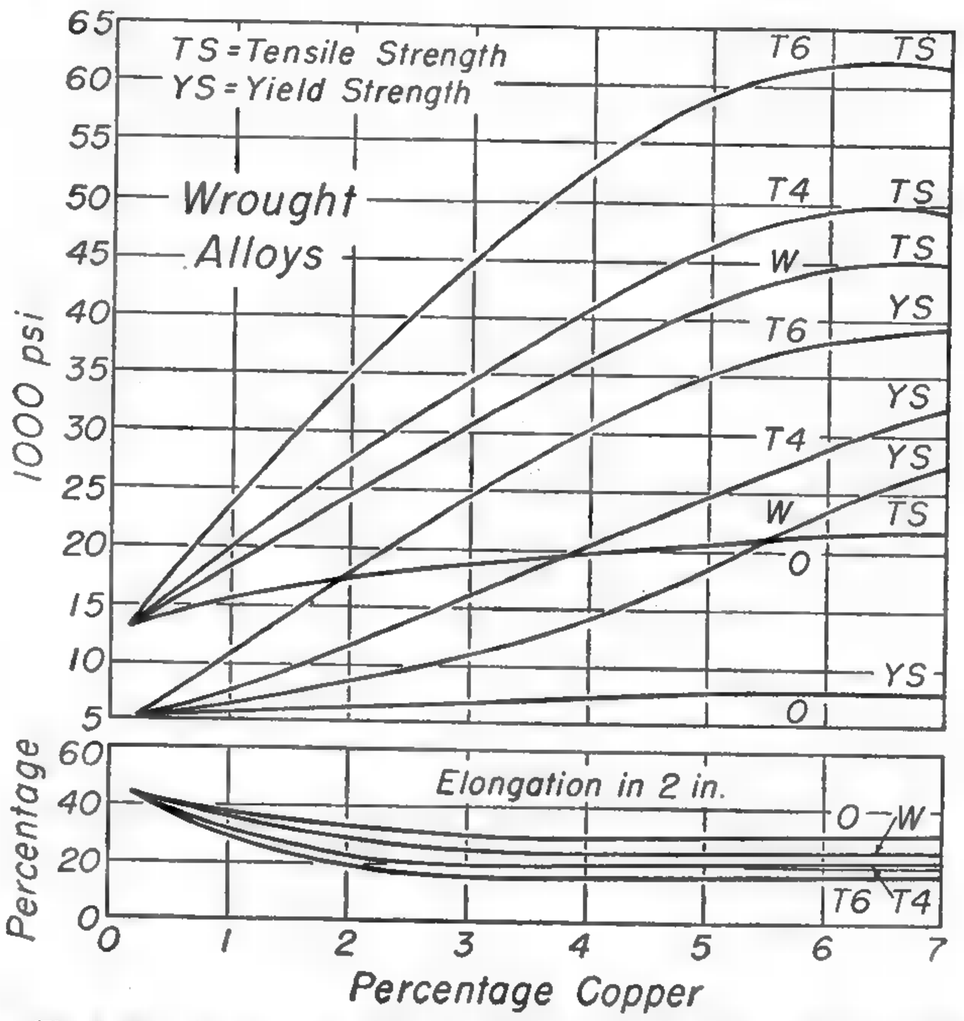

Fig. 2 Tensile properties of wrought aluminum-copper alloys of high purity. Standard ½-in. specimens from sheet $\frac{1}{16}$ in. thick. *O*, annealed; *W*, tested immediately after quenching in water from a solution heat treatment; *T4*, as in *W* but subsequently aged at room temperature until no further changes in properties were perceptible; *T6*, as in *T4*, followed by precipitation treatment at elevated temperature.

Resistance to Corrosion. The addition of more than about ¼% Cu lowers the high resistance of pure aluminum to corrosion. The resistance to corrosion of the aluminum-copper alloys is generally lower than that of the aluminum-silicon, aluminum-manganese, aluminum-magnesium and aluminum-magnesium silicide alloys, but is satisfactory for most applications, especially in relatively thick sections, as in castings.[8] Thin sheets of aluminum-copper alloy generally require protective coatings to resist severely corrosive conditions. The most effective protection is that obtained by the use of corrosion-resistant aluminum or aluminum alloy coatings which protect exposed areas of the core cathodically as in alclad products.

The resistance to corrosion may be affected greatly by heat treatment; the maximum resistance to corrosion of thin sections is obtained by a rapid quench and natural aging. Artificial aging or other reheating of thin sections of aluminum-copper alloys may reduce markedly the resistance to corrosion, although in heavy sections where rapid quenching is not possible, artificial aging generally improves the resistance to corrosion.

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Properties of Aluminum-Silicon Alloys

By L. W. Kempf*

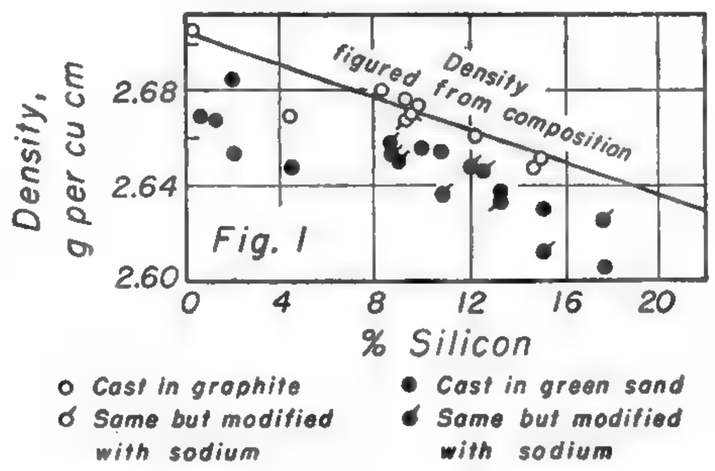
SILICON probably stands second to copper in importance as an ingredient in aluminum casting alloys. Attention was directed to the many advantageous properties of these alloys in 1921 when A. Pacz[1] discovered a method of modifying their structure and thus improving their tensile properties by treating the molten alloy with small amounts of sodium fluoride immediately before casting.[2,3] Probably the most generally valuable properties of the aluminum-silicon alloys are their excellent casting qualities, including superior fluidity and freedom from hot shortness. The strength and hardness obtained in the binary alloys are not at all remarkable. Other advantages of the silicon alloys are high resistance to corrosion, low specific gravity, low thermal expansion and high conductivity for heat and electricity. The chief use of the binary alloys is in castings containing about 5 to 13% Si.

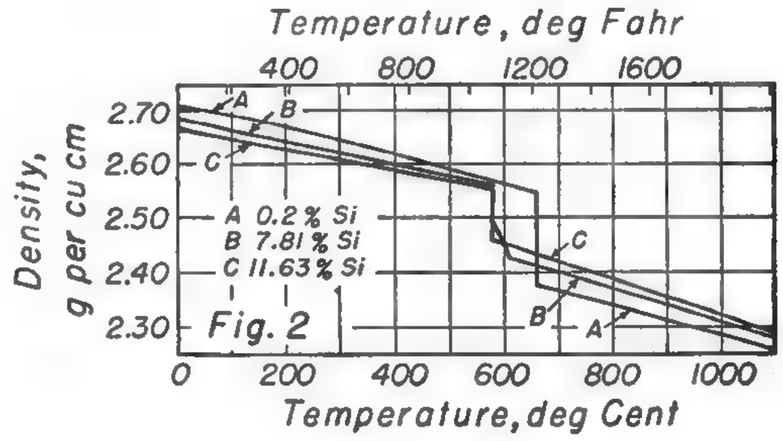
Density of Solid Alloys. Edwards[4] has determined the density of alloys containing as much as 18% Si. The diagram in Fig. 1 presents his data. These numerical values are approximately equal to the specific gravity. The influence of temperature on the density of alloys containing 0.2, 7.81 and 11.63% Si is given in Fig. 2.

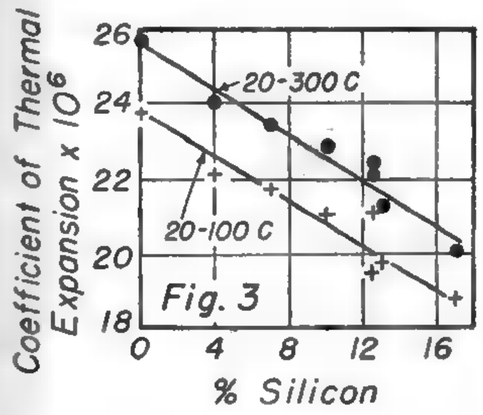
Thermal Expansivity. The coefficient of thermal expansion of silicon is less than one third that of aluminum, and the aluminum-silicon alloys have appreciably lower expansivity than pure aluminum. The variation in coefficient of expansion with silicon content is indicated in Fig. 3.

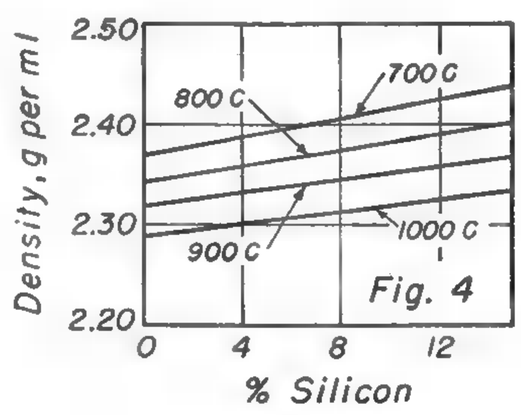
Growth. The solubility of silicon in solid aluminum varies with temperature from about 0.05% at 200 C (390 F) to 1.65% at 577 C (1070 F). Alloys quenched from a high-temperature solution treatment are of appreciably higher density than the same alloys in equilibrium at room temperature. The magnitude of this difference in density is small under all conditions but is greater the higher the degree of supersaturation. Thus with ordinary sand castings the rate of cooling is such that for all practical purposes, and especially for uses involving temperatures below 200 F, no changes can be detected. Changes in density have been estimated by measuring the linear change in dimensions accompanying reheating to elevated tempera-

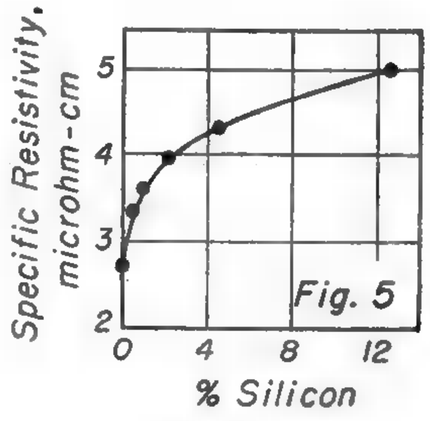
* Deceased

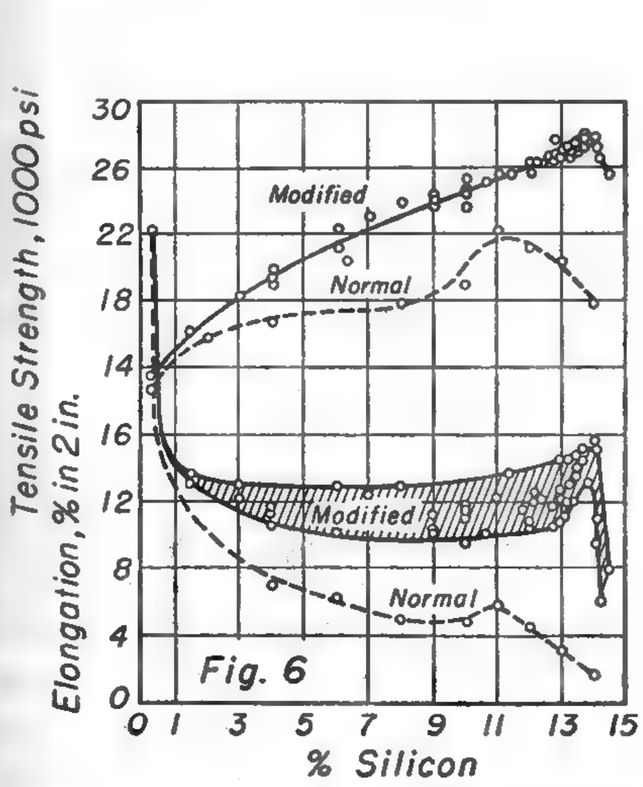


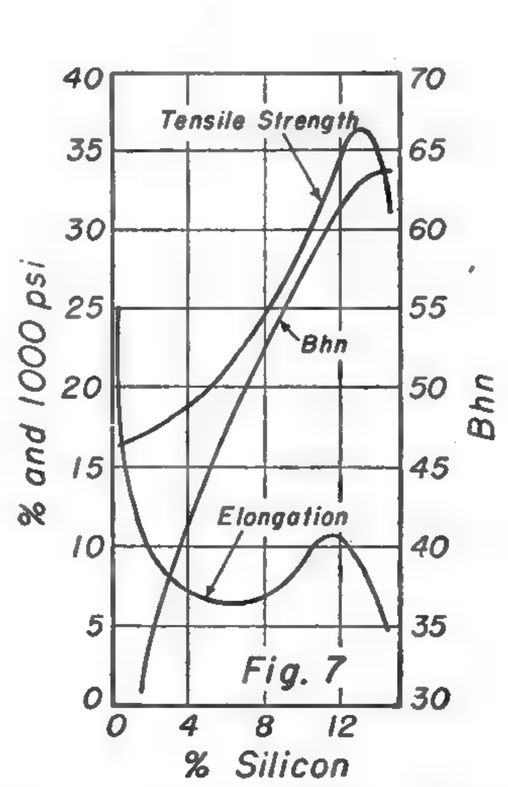












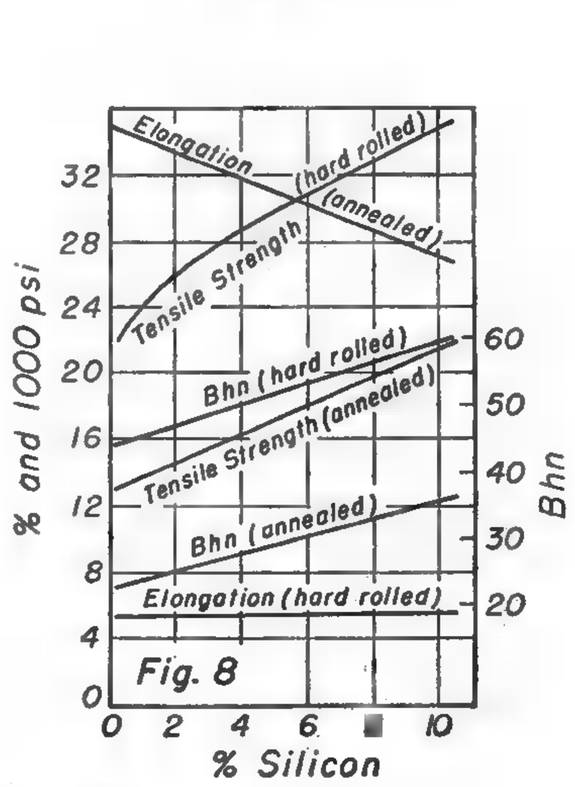


Fig. 1 to 8 Some physical and mechanical properties of aluminum-silicon alloys

tures of alloys quenched from high-temperature solution treatments. This change in dimension has been termed "growth" or "permanent growth". The maximum amount of growth observed in alloys containing more than about 1.7% Si quenched from near the eutectic temperature corresponds to a unit change of 0.0016 in lineal dimensions. Heating for 10 to 20 hr at 400 to 450 F is required to bring about equilibrium as regards growth. The time for attainment of equilibrium varies inversely with temperature in a logarithmic manner.

Density of Liquid Alloys. The density of liquid alloys, as determined by Edwards, is given in Fig. 4.

Solidification Shrinkage. The percentage of change in volume from a liquid at the melting point to a solid at the freezing point is known as "solidification shrinkage". Edwards gives the solidification shrinkage of pure aluminum as 6.6%, that of an alloy of 7.81% Si as 5.6%, and of an alloy of 11.63% Si as 3.8%. The change in solidification shrinkage with silicon content is illustrated in Fig. 2.

Pattern Shrinkage. The pattern shrinkage is usually determined by casting a straight cylindrical bar between a pair of graphite or metal plates that are rigidly maintained a known distance apart, and measuring the length of the bar when cold. Determinations by Edwards on alloys containing 12.55% and 22.4% Si give a shrinkage of 0.16 and 0.15 in. per ft respectively. The usual pattern shrinkage used in aluminum foundries for all aluminum alloys is $\frac{5}{32}$ in. (0.156 in.) per ft.

Electrical Resistivity. Increasing amounts of silicon increase the electrical resistivity of aluminum-silicon alloys, as indicated in Fig. 5. These data are from measurements by J. D. Edwards on sand-cast specimens. Some measurements by C. S. Taylor on high-purity alloys in wrought form are given in Table I.

Table I. Electrical Resistivity of High-Purity Aluminum-Silicon Alloys

Iron and Copper Less Than 0.05%

Silicon, percentage	Resistivity, microhm-cm[a]	Resistivity, microhm-cm annealed[b]
0.02 or less	2.68	2.68
0.06	2.778	2.778
0.14	2.847	2.770
0.16	2.860	2.769
0.23	2.947	2.776

[a] Heated 2 days at 495 C (925 F) and quenched in cold water.
[b] Heated 2 days at 495 C, quenched in cold water, and then annealed 100 days at 200 C.

Thermal Conductivity. The thermal conductivity of aluminum-silicon alloys[5] is affected in a marked manner, especially at high contents of silicon, by the particle size and distribution of the silicon. The smaller the particles of silicon, the higher the conductivity. The conductivity of sand castings in the condition of highest conductivity (annealed) decreases from about 0.39 cgs units for the 5% Si alloy to about 0.31 cgs units for the 13% Si alloy. Modification of the 13% Si alloy with sodium increases the conductivity to 0.39 cgs units. Similarly, the chill-cast 5% Si alloy, by virtue of its fine structure, has a conductivity of about 0.44 cgs units.

Elastic Properties. The yield strengths of aluminum-silicon alloys are generally lower than those of aluminum-copper alloys of approximately the same tensile strength. This characteristic of the silicon alloys limits their use in some applications, but it is an advantage in others where some slight bending or forming operations must be carried out on castings. Few reliable data have been published concerning the elastic limit, but isolated determinations and general experience would place the true elastic limit of all aluminum-silicon alloy sand castings containing as much as 14% Si, at not over 3000 psi. The yield strength of modified sand castings varies from about 10,000 psi at 8% Si to 12,000 psi at 14% Si. A typical yield point for the normal sand-cast 5% Si alloy is about 9000 psi. According to the determinations of Templin and Paul,[6] the addition of silicon to aluminum results in a fairly uniform increase of Young's modulus in tension from about 10,250,000 psi for the 5% Si alloys to about 11,100,000 psi for an alloy containing 13% Si.

Tensile Properties. Figure 6 gives the tensile properties of both normal and modified aluminum-silicon alloys in the form of sand-cast test bars ½ in. in diam.[2] These values represent laboratory determinations and the values given for modified alloys are those for material in which special care was taken to obtain the optimum effects of the modification process. Figure 7 indicates the variation in tensile properties with silicon content of chill-cast test bars.[7] Figure 8 gives the tensile properties of aluminum-silicon sheet, 0.08 in. thick, in the hard rolled and annealed conditions.

Fatigue Resistance. As given in the literature, endurance limits for cast aluminum-silicon alloys containing from 5 to 14% Si vary between 5700 psi and 9500 psi. Results are not concordant and the determinations were made on the basis of 5 to 50 millions of reversals. Determinations made in the Aluminum Research Laboratories on the basis of 500,000,000 cycles, with the R. R. Moore type of rotating-beam machine, place the endurance limit of the normal sand-cast 5% Si alloy at about 6500 psi. The value for the modified 13% Si alloy is about 6000 psi.

Corrosion Resistance. Comparative experience in various fields indicates that the aluminum-silicon alloys preserve a better appearance under the conditions of ordinary atmospheric corrosion than do the aluminum-copper alloys. The rate of loss in mechanical strength of either of the types of alloys under these conditions is very low. Under conditions of salt spray corrosion, aluminum-silicon alloys appear to be definitely superior to the aluminum-copper alloys or the aluminum-copper-zinc alloys. However, they are inferior to the aluminum-magnesium alloys under these conditions. Czochralski[8] presents data on relative loss in weight, in steam and nitric acid, of the modified 13% Si alloy, the 8% Cu alloy, and the 12% Zn-2% Cu alloy. All alloys were in the cast condition. Under these conditions the 13% Si alloy is superior to the 8% Cu, and the 12% Zn-2% Cu alloys.

Casting Properties. The aluminum-silicon alloys are especially fluid, fill molds better, and take sharper impressions than any of the other common alloys of aluminum. For the normal alloys, the fluidity increases with silicon content until this content reaches the composition of the eutectic, about 11.6% Si, and about 12 to 14% Si for the modified alloys. Alloys unusually free from hot shortness are those containing more than about 3% Si along with iron and copper in concentrations common in ordinary commercial virgin ingot. This valuable property improves with increasing silicon content until the eutectic composition is reached, but all the alloys containing from 5 to 13% Si can be cast readily without cracking. The 5% Si alloy is comparatively easy to feed, but as the silicon increases, the alloys become subject to a peculiar type of internal shrinkage, and careful feeding is necessary with alloys of high silicon contents. The ratio of volume of risers to volume of castings should, in general, be greater in the use of the 13% Si alloys than in the use of the 8% Cu alloy. Because of freedom from hot shortness and because of the characteristic tendency to form a sound outer layer or skin, the aluminum-silicon alloys are especially suitable for the production of castings that must be free from leaks.

Welding Rod. Some of the properties that make the aluminum-silicon alloys so valuable in the castings field have also been responsible for their wide use as welding rod. An alloy containing about 5% Si is widely used for welding both cast and wrought products. Such rod is utilized in the cast and wrought forms, depending on the preference of the operator and the type of welding.

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Properties of Aluminum-Magnesium Alloys

By W. E. Sicha* and F. Keller*

THE binary alloys of aluminum with magnesium attracted the interest of investigators as early as 1900. There have been numerous attempts to utilize for general purposes alloys containing as much as 10% Mg; alloys containing up to 30% Mg have been used for special purposes.

The aluminum-magnesium alloys are lighter than aluminum, have good physical properties, excellent resistance to corrosion and are easily machined. Certain fabricating difficulties encountered initially have been overcome and commercial exploitation of these alloys has progressed at a moderate rate.

Density. The densities of solid aluminum-magnesium alloys decrease continuously with magnesium content, as indicated by the curve of Fig. 1.

Thermal Expansivity. The coefficient of thermal expansion of magnesium is somewhat higher than that of aluminum, and the expansivity of aluminum-magnesium alloys increases with magnesium content according to Fig. 2.

Growth. The precipitation of magnesium constituent from a supersaturated aluminum solid solution is accompanied by a slight decrease in density. An alloy containing 10% Mg in solid solution showed a change in density corresponding to a unit linear expansion of 0.0015 after heating to approximately 400 F for a sufficient period of time to bring about complete stabilization.

Electrical and Thermal Conductivity. The electrical conductivity of aluminum decreases continuously with increasing magnesium content, as shown by Fig. 3. Determinations on which this curve was based were made on alloys quenched from a solution treatment at high temperature. Alloys treated so as to contain a minimum amount of magnesium in solid solution would ordinarily have appreciably higher electrical conductivities than this curve indicates.

A knowledge of the general relationship between electrical and thermal conductivity of aluminum alloys permits the estimation of thermal conductivity from electrical conductivity, as indicated in Fig. 3.

Casting Characteristics. Alloys containing as much as 5% Mg may be cast in ordinary green sand molds. When so cast, especially in heavy sections, alloys with magnesium concentrations greater than this may develop a dark, porous outer ring. The alloys form considerable dross when molten, a tendency that increases with magnesium content. These difficulties have been overcome successfully for commercial purposes, by the development of foundry technique. Inherently the aluminum-magnesium alloys are not particularly difficult to cast, since they are quite fluid and not especially hot short. Very little difficulty from cracking has been encountered in the relatively large castings. Pressure-tight castings are less easily obtained with the aluminum-magnesium than with the aluminum-silicon alloys.

Tensile Properties and Hardness of Sand Castings. The variation with magnesium content in mechanical properties of sand-cast aluminum-magnesium alloys is shown in Fig. 4.

The variation in solid solubility of magnesium in aluminum, from about 15% at the eutectic temperature of 451 C to less than 4% at room temperature, renders some of the alloys susceptible to improvement in tensile properties by heat treatment. The curves of Fig. 5 show the variation with magnesium content, in tensile properties and hardness of heat treated sand castings. These properties were attained with solution heat treated ½-in. diam test bars of low-impurity-content alloys, cast in green sand. Comparison of the curves of Fig. 4 with those of Fig. 5 indicates that heat treatment brings about a profound change in the properties of alloys containing more than 6% Mg.

Working Characteristics. Alloys containing as much as 2 or 3% Mg can be reduced from cast ingots by forging or rolling with little difficulty. When alloys contain more than about 3% Mg, breaking down cast ingots becomes increasingly difficult. This condition has precluded the commercial development and application of wrought alloys containing more than about 6% Mg.

Properties of Wrought Alloys. Figure 6 shows the change in tensile properties and hardness of aluminum-magnesium alloys with variation in the magnesium content. For alloys containing as much as 10% Mg, the data from which Fig. 6 was derived were obtained from forged bars. For more than 10% Mg the material from which the test specimens were taken was produced by extrusion. The specimens had been solution heat treated and the alloys were of high purity. It will be noted that tensile strength increases to a maximum at about 15% Mg, which is approximately the maximum solubility of magnesium in solid aluminum. As the magnesium content increases beyond this concentration, the tensile strength decreases quite rapidly. Brinell hardness and yield strength increase continuously with magnesium content. A relatively constant elongation of about 32% is noteworthy between 2 and 12% Mg.

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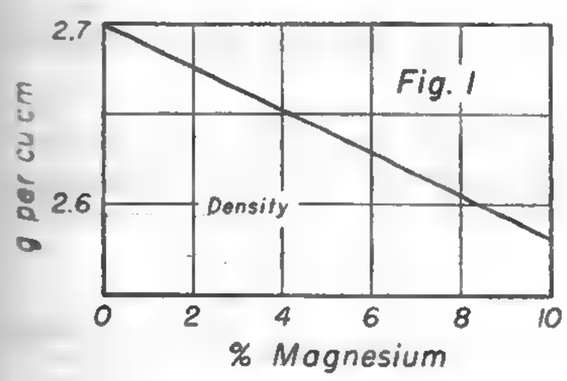

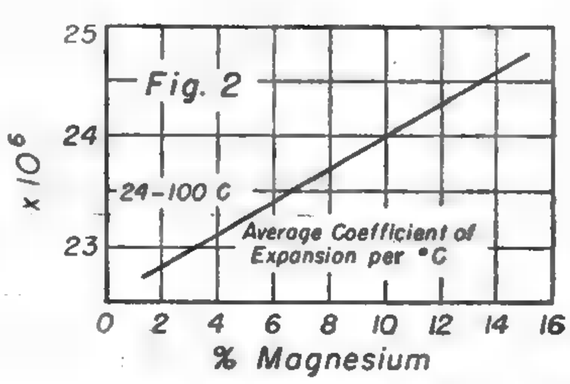

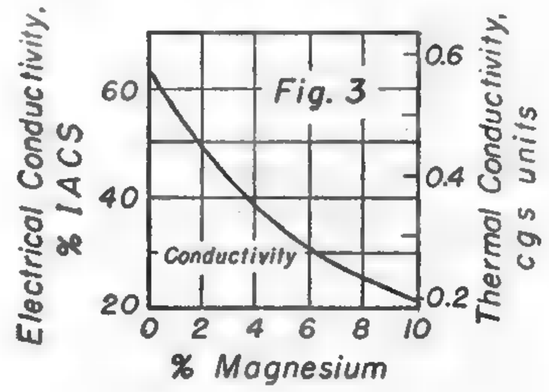

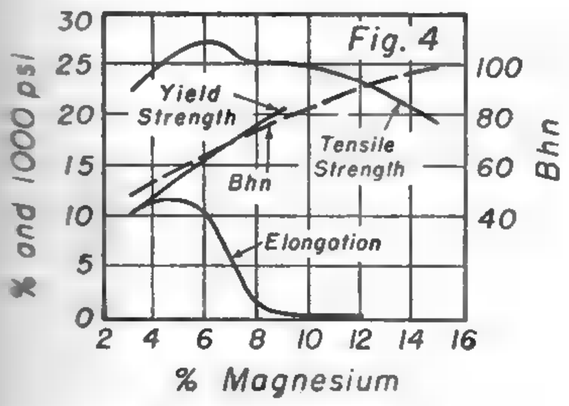

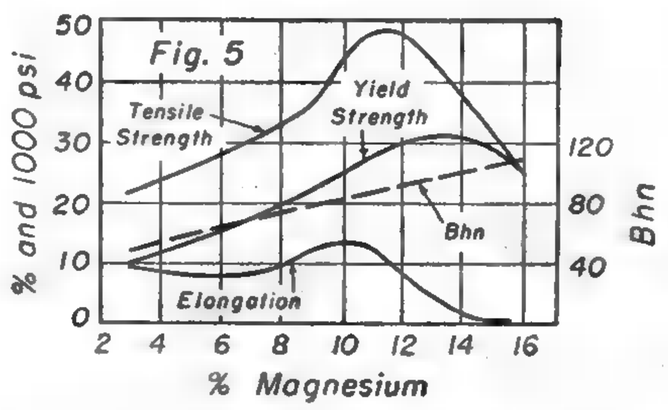

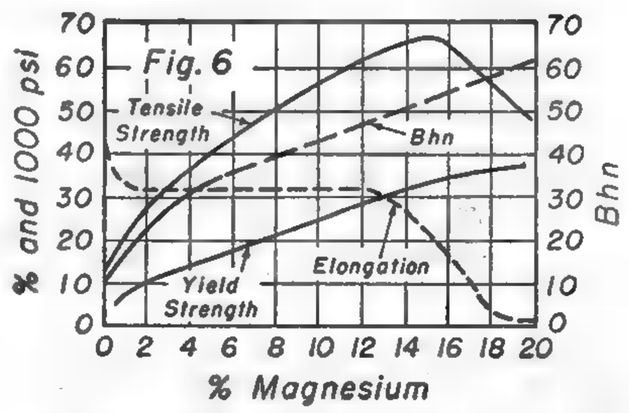

Fig. 1 to 6 Some physical and mechanical properties of aluminum-magnesium alloys

Fatigue Resistance. In wrought aluminum the endurance limit, based on 500,000,000 reversals of stress, is increased with magnesium content from about 5000 psi at 0 Mg to about 20,000 psi at 6% Mg. With greater concentrations of magnesium the rate of increase is much slower; the 10% Mg alloy has an endurance limit of about 21,000 psi. The aluminum-magnesium alloys have a higher ratio of endurance limit to tensile strength than the aluminum-silicon, aluminum-copper or aluminum-zinc alloys.

Properties at Elevated Temperatures. As indicated in Fig. 7 and 8 for sand castings of a 4% and a 10% Mg alloy respectively, tensile properties of these alloys at elevated temperatures are higher than those of alloys of the aluminum-silicon or aluminum-zinc systems but generally not so high as the corresponding aluminum-copper alloys. The data on which these curves are based were determined by testing specimens cast to size in green sand and heated at the temperature of testing, long enough to bring about complete stabilization.

Resistance to Corrosion. The cast aluminum-magnesium alloys display excellent resistance to corrosion, both in the atmosphere and in salt spray. This resistance to corrosion is of a different order of magnitude from that of casting alloys of the aluminum-silicon, aluminum-copper, or aluminum-zinc systems. The aluminum-magnesium alloys generally preserve a better appearance and suffer less loss in mechanical properties than the more common casting alloys. As in most aluminum alloys, the presence of impurities markedly reduces resistance to corrosion.

The wrought alloys also, in the compositions being produced commercially in this country, have excellent resistance to corrosion.

The aluminum-magnesium alloys are the most resistant to alkaline corrosion of any of the aluminum alloys; resistance increases with magnesium content.

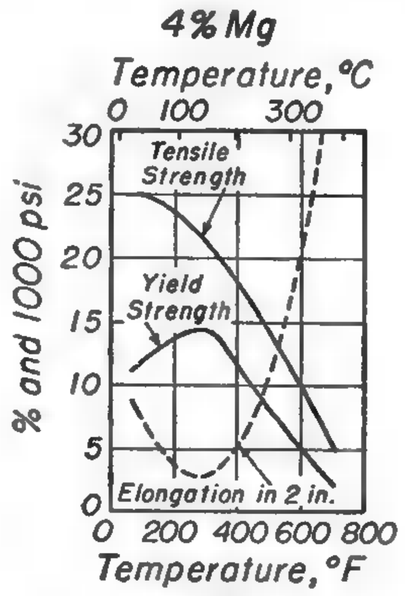

Fig. 7

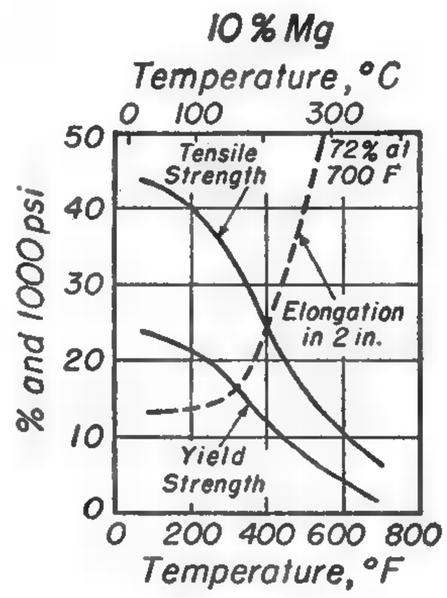

Fig. 8

Fig. 7 and 8 Tensile properties at elevated temperatures of Al – 4% Mg and Al – 10% Mg alloy sand-cast test specimens

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Temper Designations for Aluminum Alloys

For a generation the various tempers of commercial wrought aluminum alloys have been designated by a system of numbers and letters (-1/2H, -W, -T, -RT, and others).* More recently a comprehensive system, applicable to both cast and wrought products, was developed and applied to all tempers of cast products and to some tempers of certain new wrought products.

Metallurgical advances during the past several years have revealed inadequacies in the temper designations that have been used for wrought alloys. Consequently, beginning in October 1947, the more comprehensive system of nomenclature, recently revised, is being applied to both cast and wrought products. In this system, provision is made for developments that may come in the future. This revised system has been used fully in the ALUMINUM SECTION of the present edition of this Handbook.

The principle of the system of nomenclature for cast and wrought products remains the same; that is, the temper designation, where required, follows the alloy designation and is separated from it by a hyphen. The temper designation consists of a letter indicating the basic temper, which may be defined more specifically by the addition of one or more digits. No changes have been made in the temper designations for cast products.

The general scheme of the system of nomenclature is:

- **-F** As fabricated
- **-O** Annealed, recrystallized (wrought products only)
- **-H** Strain hardened
  - -H1, plus one or more digits — Strain hardened only
  - -H2, plus one or more digits — Strain hardened and then partial annealed
  - -H3, plus one or more digits — Strain hardened and then stabilized
- **-W** Solution heat treated—unstable temper
- **-T** Treated to produce stable tempers other than -F, -O, or -H
  - -T2 Annealed (cast products only)
  - -T3 Solution heat treated and then cold worked
  - -T4 Solution heat treated
  - -T5 Artificially aged only
  - -T6 Solution heat treated, then artificially aged
  - -T7 Solution heat treated, then stabilized
  - -T8 Solution heat treated, cold worked, and then artificially aged
  - -T9 Solution heat treated, artificially aged, and then cold worked
  - -T10 Artificially aged and then cold worked

More detailed information concerning the designations is given in the Explanatory Notes that follow the Conversion Tables I and II.

* EDITOR'S NOTE. These temper designations for aluminum alloys were developed by the Aluminum Company of America. The revised system of nomenclature described here has also been developed by the Aluminum Company of America, and is used in this section of Metals Handbook to designate the various tempers of the alloys for which this company has compiled data.

Table I. Temper Designations for Strain Hardened Wrought Aluminum Alloys That Are Not Heat Treatable[a]

Old Temper Designation	New Temper Designation[b]: Strain Hardened Only	Strain Hardened and Then Partial Annealed	Strain Hardened and Then Stabilized
	Alloys 2S and 3S		
¼H	-H12	-H22	
½H	-H14	-H24	
¾H	-H16	-H26	
H	-H18	-H28	
Extra Hard (Not Standard)	-H19		
	Alloys 4S, 52S and 56S[c]		
¼H			-H32
½H			-H34
¾H			-H36
H			-H38
Extra Hard (Not Standard)			-H39

(a) Alloys listed are also available in -O and -F tempers.
(b) The tempers shown are standard for the alloys listed.
(c) The alloys 4S, 52S and 56S may also be obtained in the -H1 and -H2 type conditions.

Table II. Temper Designations for Heat Treated Wrought Aluminum Alloys

Alloy	Old Temper Designation	New Temper Designation											
		Sheet and Plate[a]				Extrusions[a]		Wire Rod and Bar[a]	Tubing[a][c]		Forgings[b]	Rivets	
		Flat Sheet	Coiled Sheet	Plate									
		A	A	A	C	A	C	A	A	C	A	A	D
11S	-W -T3 -T8							-T4 -T3 -T8					
14S and Alclad 14S[i]	-W -T -T	-T3 -T6	-T4 -T6	-T4 -T6	-T4 -T6	-T4 -T6	-T42 -T62	-T4 -T6			-T4 -T6 -T61[d]		
17S	-T -T Any Temper							-T4				-T4	-T3[e] -T31[f] -T41[g]
A 17S	-T											-T4	-T3[e]
18S	-T										-T61[d]		
24S and Alclad 24S[i]	-T -RT -T80 -T81 -T86	-T3 -T36 -T81 -T86	-T4 -T6 	-T4 -T36 -T86	-T4 -T6 	-T4	-T42	-T4 -T36	-T3	-T4		-T4	-T31[f]
25S and 32S	-T										-T6		
A 51S	-W -T										-T4 -T6		
53S	-W Any temper -T -T5 -T61					-T4 -T6 -T5	-T4 -T6				-T4 -T6	-T4 -T6 -T61	-T4 -T41[g] -T6 -T61
61S	-W -T -T5 -T62 -T81	-T4 -T6	-T4 -T6	-T4 -T6	-T4 -T6	-T4 -T6 -T5 -T62	-T4 -T6	-T4 -T6 -T81	-T4 -T6	-T4 -T6		-T6	-T6
63S	-T -T5					-T6 -T5	-T6 -T5						
75S and Alclad 75S[i]	-W -T	-W[h] -T6	-W[h] -T6	-W[h] -T6	-W[h] -T6	-W[h] -T6	-W[h] -T6	-T6					

A, heat treated by the producer. C, heat treated by the manufacturer of the finished product. D, driven rivets.

(a) Products listed are available also in -O and -F tempers. (b) Forgings are available also in -F temper. (c) For extruded tubing see columns for extrusions. (d) Boiling water quench. (e) Driven cold after full natural aging. (f) Driven cold immediately after solution heat treament, or when refrigerated to defer natural aging. (g) Driven hot, at the solution heat treating temperature. (h) To be specific, the time of natural aging must be stated—for example, 75 S-W (2 hr), 75 S-W (2 months). (i) Available only in sheet and plate.

Explanatory Notes

-F **As Fabricated.** This designation applies to products that acquire some temper qualities in the shaping processes but are not subsequently thermally treated or intentionally strain hardened.

-O **Annealed, Recrystallized.** This designation applies to the softest temper of wrought alloy products.

-H **Strain Hardened.** This designation applies to products that have their strength increased by strain hardening, with or without supplementary thermal treatments to produce partial softening. The -H is always followed by two or more digits. The first digit indicates the specific combination of basic operations, and the final digit or digits, the final degree of strain hardening.

Subdivisions of the -H Temper

-H1 *Strain Hardened Only.* The number following this designation indicates the degree of strain hardening. Thus, 2S-¼H (strain hardened only) becomes 2S-H12, and a temper intermediate between -¼H and -½H would be designated -H13.

-H2 *Strain Hardened and Then Partial Annealed.* The number following this designation indicates the degree of strain hardening remaining after the product has been partial annealed. Thus, 2S-½H (strain hardened and partial annealed) becomes 2S-H24.

-H3 *Strain Hardened and Then Stabilized.* The number following this designation indicates the degree of strain hardening remaining after the product has been strain hardened a specific amount and then stabilized. Thus 52S-½H (strain hardened and stabilized) becomes 52S-H34.

-W **The Unstable Condition Following Solution Heat Treatment.** This designation, because of natural aging, is specific only when the period of aging is indicated, for example 24S-W (½ hr), 75S-W (2 months).

-T **Treated to Produce Stable Tempers Other Than -F, -O, or -H.** This designation applies to products treated thermally to produce stable tempers with or without supplementary strain hardening. The -T followed by the numerals 2 to 19 inclusive designates one specific combination of basic operations (61S-T6). Should some other variation of the same basic operations be applied to the same alloy, *resulting in different characteristics,* then other digits are added to the basic designation (61S-T61 or 61S-T62). A period of natural aging at room temperature may occur between or after the operations listed. This period is controlled when it is metallurgically important.

Subdivisions of the -T Temper

-T2 *Annealed.* (Cast products only.) This designation applies to castings annealed for such purposes as improving ductility and increasing dimensional stability (142-T21).

-T3 *Solution Heat Treated and Then Cold Worked.* This designation applies to products that are cold worked chiefly to increase the strength (24S-RT becomes 24S-T36), and also applies to products in which the effect of cold work, such as flattening, is recognized in specifications. (Mill heat treated 24S-T flat sheet becomes 24S-T3.)

-T4 *Solution Heat Treated and Naturally Aged to a Substantially Stable Condition.* This designation applies when the product is not cold worked after heat treatment (24S-T sheet, heat treated by the customer, becomes 24S-T4), and also when applicable specifications do not recognize the effect of cold work in flattening and straightening operations. (Mill heat treated 61S-W flat sheet becomes 61S-T4.)

-T5 *Artificially Aged Only.* This designation applies to products that are artificially aged without prior solution heat treatment. The artificial aging of these products improves mechanical properties (53S-T5 extrusions), and dimensional stability (A132-T551 cast pistons).

-T6 *Solution Heat Treated and Then Artificially Aged.* This designation applies to products that are not cold worked after solution heat treatment and in which the effect, if any, of flattening or straightening is not recognized in applicable specifications. (Whether flattened or not, 61S-T becomes 61S-T6, and 14S-T becomes 14S-T6.)

-T7 *Solution Heat Treated and Then Stabilized.* This designation applies to products in which the temperature and time conditions for stabilizing are such that the alloy is carried beyond the point of maximum hardness, providing control of growth or residual stress or both (355-T71).

-T8 *Solution Heat Treated, Cold Worked, and Then Artificially Aged.* This designation applies when the cold working is done for improving strength (11S-T8, Alclad 24S-T86), and also when the cold working effect of flattening is recognized in specifications (Alclad 24S-T81 flat sheet).

-T9 *Solution Heat Treated, Artificially Aged, and Then Cold Worked.* (The cast bearing formerly designated "XA750-T6 cold worked approximately 4%" becomes XA750-T91.)

-T10 *Artificially Aged and Then Cold Worked.* (The cast bearing formerly "750-T5 cold worked 4%" becomes 750-T101.)

PROPERTIES OF ALUMINUM AND ALUMINUM ALLOYS

Aluminum (99.996 Al)*

C *1 Density*
at 20 C (68 F). 2.6989 g per cu cm (0.09751 lb per cu in.)
at 25 C (77 F). 2.6978 g per cu cm (0.09747 lb per cu in.)
D *2 Melting point.* 660.2 C (1220.4 F)
4 Boiling point. 2060 C (3740 F)
6 Thermal expansion.
20 to 100 C (68 to 212 F). 0.00002386 per °C
20 to 200 C (68 to 392 F). 0.00002458 per °C
20 to 300 C (68 to 572 F). 0.00002545 per °C
20 to 400 C (68 to 752 F). 0.00002649 per °C
20 to 500 C (68 to 932 F). 0.00002768 per °C
11 Specific heat at 100 C (212 F). 0.2226 cal per g
13 Latent heat of fusion. 94.6 cal per ■
18 Heat of combustion. 7389 cal per g
E *1 Volume conductivity* referred to standard copper. 64.94%
2 Electrical resistivity at 20 C (68 F). 2.6548 microhm-cm
5 Temperature coefficient of electrical resistivity at 20 C (68 F). 0.00429 per °C
F *1 Reflectivity.* 90%, for light from tungsten filament; 85%, at $\lambda = 2500$ A; 95%, at $\lambda = 10{,}000$ A
5 Emissivity at 25 C (77 F). 0.030 in air
G *2 Mass magnetic susceptibility.* 0.6×10^{-6} cgs
J *1 Crystal structure.* Face-centered cubic; $a = 4.0413$ kX
K *Mechanical Properties.*

Condition	Tensile Strength, psi	Yield Strength, psi	Elongation,(a) percentage	Brinell Hardness Number(b)
Annealed	6,875	1,775	48.8	17
Cold rolled 75%	16,300	15,425	5.5	27

(a) Sheet specimens, $\frac{1}{16}$ in. thick (b) 500-kg load, 10-mm ball

Reference

C. S. Taylor, L. A. Willey, D. W. Smith and J. D. Edwards, The Properties of High Purity Aluminum, Metals & Alloys, 9, 189 (1938)

Aluminum (99.0+ Al)*

A *1 Common name.* Commercially pure aluminum
2 Trade name. 2S alloy
3 ASTM number. B 209–46T, Alloy A2 (sheet and plate); B 211–46T, Alloy A2 (bar, rod and wire)
4 Government number. QQ-A-561 (sheet and plate); QQ-A-411 (bar, rod, shapes and wire); WW-T-783 (tubing)
6 Foreign equivalents. British BS 2L4 (hard); BS 2L16 (half hard); BS 2L17 (soft) (sheet and plate); BS L34 (bar, rod and shapes); BS L36 (wire)
B *1 Typical uses.* Applications where very good formability or very good resistance to corrosion, or both, are required, and where high strength is not necessary. Cooking utensils, food- and chemical-handling and -storage equipment, bottle and jar closures, and various architectural components are typical.
C *1 Density* at 20 C (68 F). 2.71 g per cu cm (0.098 lb per cu in.)
5 Solidification shrinkage. 6.6%
D *1 Liquidus temperature.* 657 C (1215 F)
2 Solidus temperature. 643 C (1190 F)
6 Thermal expansion (condition O).
−60 to + 20 C (−76 to + 68 F). 0.0000217 per °C
20 to 100 C (68 to 212 F). 0.0000235 per °C
20 to 200 C (68 to 392 F). 0.0000246 per °C
20 to 300 C (68 to 572 F). 0.0000256 per °C
11 Specific heat at 100 C (212 F). 0.2297 cal per g
12 Heat content and specific heat versus temperature.

Temperature, deg Cent	Temperature, deg Fahr	Heat Content, Btu per lb	Heat Content, cal per g	Specific Heat, mean, 0° to T°	Specific Heat, at T°
Arranged from data of Wuest, Meuthen, and Duerrer(a)					
■	32	.....	.....	.....	0.2220
100	212	40.66	22.59	0.2259	0.2297
200	392	82.69	45.94	0.2297	0.2374
300	572	126.12	70.07	0.2336	0.2451
400	752	170.95	94.97	0.2374	0.2529
500	932	217.15	120.64	0.2413	0.2606
600	1112	264.76	147.09	0.2452	0.2683
657(s)	1214.6	292.50	162.50	0.2473	0.2727
657(l)	1214.6	461.63	256.46	0.3904	0.2502
700	1292	481.09	267.27	0.3818	0.2523
800	1472	526.93	292.74	0.3659	0.2571
900	1652	573.66	318.70	0.3541	0.2619
1000	1832	621.26	345.14	0.3451	0.2667

(a) J. F. Shadigen, Heat-Temperature Curves of Metals, Iron Age, 110, 218 (1922)

13 Latent heat of fusion. 93.0 cal per ■
16 Thermal conductivity at 25 C (77 F). 0.53 cal/sq cm/cm/°C/sec, condition O; 0.52 cal/sq cm/cm/°C/sec, condition H18
18 Heat of combustion. 7400 cal per g
19 Recrystallization temperature. 290 C (550 F) approx, 75% reduction
E *1 Volume conductivity* referred to standard copper. 59%, condition O; 57%, condition H18
2 Electrical resistivity at 20 C (68 F). 2.922 microhm-cm, condition O; 3.025 microhm-cm, condition H18
4 Electrical resistivity (liquid) at 657 C (1215 F). 20.1 microhm-cm
5 Temperature coefficient of electrical resistivity between 10 and 30 C (50 to 86 F). 0.0115 per °C
10 Electrochemical equivalent. 0.09316 mg per coulomb
11 Electrolytic solution potential versus N/10 calomel electrode is 0.83 volts, all tempers (53 g NaCl + 3 ■ H_2O_2 solution).
F *1 Reflectivity.*
As much as 90%, at $\lambda = 5{,}000$ A } depending on surface finish and purity of metal
As much at 87%, at $\lambda = 2{,}500$ A
As much as 97%, at $\lambda = 20{,}000$ A
2 Refractive index. 0.78 to 1.48 in white light
3 Absorptive index. 2.85 to 3.92 in white light
5 Emissivity at 25 C (77 F). 0.035 to 0.06 in air
H *1 Velocity of sound* at 20 C (68 F). 16,300 ft per sec
J *1 Crystal structure.* Face-centered cubic; $a = 4.04$ kX
K *Mechanical Properties. See* Table I.
Strength and elongation at elevated temperatures after prolonged heating at testing temperatures.

Property	Temperature, deg Fahr: 75	300	400	500	600	700
Annealed O						
Tensile strength, psi	13,000	7,500	6000	3500	2500	1500
Yield strength, psi	5,000	3,500	3000	2000	1500	1000
Elongation, %	45	65	70	85	90	95
Condition H14						
Tensile strength, psi	17,000	13,000	9500	3500	2500	1500
Yield strength, psi	14,000	10,000	6500	2000	1500	1000
Elongation, %	20	22	25	85	90	95
Condition H18						
Tensile strength, psi	24,000	17,500	6000	3500	2500	1500
Yield strength, psi	21,000	14,000	3000	2000	1500	1000
Elongation, %	15	16	70	85	90	95

2 Directional properties. Tensile strength and elongation are slightly lower in transverse direction than in longitudinal direction.

* Compiled by Aluminum Company of America

Table I. Mechanical Properties of Commercially Pure Aluminum

Condition	Tensile Strength,[a] psi	Yield Strength,[b] psi	Elongation, (c) percentage	Elongation, (d) percentage	Brinell Hardness Number[e]	Modulus of Elasticity, psi	Shear Strength, psi	Endurance Limit,[f] psi	Modulus of Rigidity, psi	Poisson's Ratio
Annealed O	13,000	5,000	35	45	23	10,000,000	9,500	5,000	3,850,000	0.33
H12	15,000	13,000	12	25	28	10,000,000	10,000	6,000	3,850,000	0.33
H14	17,000	14,000	9	20	32	10,000,000	11,000	7,000	3,850,000	0.33
H16	20,000	17,000	6	17	38	10,000,000	12,000	8,500	3,850,000	0.33
H18	24,000	21,000	5	15	44	10,000,000	13,000	8,500	3,850,000	0.33

(a) In general, strengths and elongations are unchanged or improved at low temperatures.
(b) The compressive yield strength is approximately the same as the tensile yield strength. The torsional yield strength is approximately 0.55 times the tensile yield strength. The torsional ultimate strength is approximately 0.65 times the tensile strength.
(c) Sheet specimens, $\frac{1}{16}$ in. thick. (d) Round specimens, ½ in. in diam. (e) 500-kg load, 10-mm ball.
(f) Based on 500,000,000 cycles using R. R. Moore type rotating-beam machine

6 Modulus of elasticity versus temperature.

Temperature, deg Fahr	75	300	400	500	600	700
Approx % of E at 75 F	100	95	90	85	65	40

L *2 Radiography.* Type A or 506 film with no intensifying screen, cardboard exposure holder, 36-in. focal distance, General Electric OX-10 unit, 2.1 H&D film density

Section, in.	Volts	Milliamperes	Time, min
½	65,000	10.0	1.0
1	95,000	6.7	1.0
1½	125,000	5.0	1.0
2	140,000	5.0	1.6

M *Composition Limits. See* Table II.
2 Consequences of exceeding impurity limits. High copper reduces resistance to corrosion.
High iron plus silicon plus manganese reduces formability.
N *1 Melting temperature range.* 675 to 745 C (1250 to 1375 F)
7 Hot working temperature range. 260 to 510 C (500 to 950 F)
10 Maximum reduction between anneals. 70% or more, depending on product
15 Heat treatment. Annealing, 345 C (650 F); holding at temperature is not required.
17 Joining.
Rivet compositions. 2S
Soft solder with Alcoa No. 800; Alcoa No. 61 flux.
Braze with Alcoa No. 717, 43 alloy; Alcoa No. 33 flux; flame either reducing oxyacetylene or reducing oxy-hydrogen.
Atomic-hydrogen weld with 2S alloy; Alcoa No. 22 flux.
Oxyacetylene weld with 2S alloy; Alcoa No. 22 flux; flame neutral.
Metal-arc weld with 2S alloy; Alcoa No. 27 flux.
Carbon-arc weld with 2S alloy; Alcoa No. 24 flux (automatic), Alcoa No. 27 flux (manual).
Tungsten-arc, argon atmosphere weld with 2S alloy; no flux.
Resistance welding. Spot, seam, and flash methods

References

Edwards, Frary and Jeffries, "The Aluminum Industry", McGraw-Hill Book Co., 1930
Mondolfo, "Metallography of Aluminum Alloys", John Wiley and Sons, 1943
Alcoa Aluminum and Its Alloys, Machining Alcoa Aluminum, Forming Aluminum, Welding and Brazing Alcoa Aluminum, Riveting Alcoa Aluminum, Aluminum in the Chemical Industry, Aluminum in Aircraft, all publications of Aluminum Company of America

Table II. Composition Limits of Commercially Pure Aluminum

Form	Designation	Al min	Impurities: Fe + Si max	Impurities: Cu max	Impurities: Mn max	Impurities: Zn max	Impurities: Others each max	Impurities: Others total max
Sheet and plate	QQ-A-561	99.0	...	...	...	...	...	...
Bar, rod, shapes and wire	QQ-A-411	99.0	1.00	0.20	0.05	0.10	0.05	0.15
Tubing	WW-T-783	99.0	1.00	0.20	0.10	0.03	0.03	0.10

WROUGHT ALLOYS

Al – 1.2 Mn*

A *2 Trade name.* 3S alloy
3 ASTM number. B 209–46T, Alloy M1 (sheet and plate); B 210–46T, Alloy M1 (tubing)
4 Government number. QQ-A-359 (sheet and plate); QQ-A-356 (bar, rod, shapes and wire); WW-T-788 (tubing)
B *1 Typical uses.* Applications where good formability or very good resistance to corrosion or good weldability, or all three, are required, and where more strength is desired than is provided by commercially pure aluminum. Cooking utensils, food– and chemical-handling and –storage equipment, gasoline and oil tanks, trim in transportation equipment, are typical.
C *1 Density* at 20 C (68 F). 2.73 g per cu cm (0.099 lb per cu in.)
D *1 Liquidus temperature.* 654 C (1210 F)
2 Solidus temperature. 643 C (1190 F)
6 Thermal expansion (condition O).
−60 to +20 C (−76 to +68 F). 0.0000214 per °C
20 to 100 C (68 to 212 F). 0.0000232 per °C
20 to 200 C (68 to 392 F). 0.0000242 per °C
20 to 300 C (68 to 572 F). 0.0000251 per °C
11 Specific heat at 100 C (212 F). Approx 0.23 cal per g
16 Thermal conductivity at 25 C (77 F).
0.46 cal/sq cm/cm/°C/sec, condition O
0.39 cal/sq cm/cm/°C/sec, H12
0.38 cal/sq cm/cm/°C/sec, H14
0.37 cal/sq cm/cm/°C/sec, H18
19 Recrystallization temperature. 315 C (600 F) approx, 75% reduction
E *1 Volume conductivity* referred to standard copper. 50%, condition O; 42%, H12; 41%, H14; 40%, H18
2 Electrical resistivity at 20 C (68 F). 3.448 microhm-cm, condition O; 4.105 microhm-cm, H12; 4.205 microhm-

* Compiled by Aluminum Company of America

cm, H14; 4.310 microhm-cm, H18
11 Electrolytic solution potential versus N/10 calomel electrode is 0.83 volts (53 g NaCl + 3 g H_2O_2 solution).
F *5 Emissivity* at 25 C (77 F). 0.035 to 0.07 in air
K *Mechanical Properties.*

Condition	Tensile Strength, (a) psi	Yield Strength, (b) psi	Elongation, (c) %	Elongation, (d) %	Bhn (e)	Shear Strength, psi	Endurance Limit, (f) psi
Annealed O..	16,000	6,000	30	40	28	11,000	7,000
H12	18,000	15,000	10	20	35	12,000	8,000
H14	21,000	18,000	8	16	40	14,000	9,000
H16	25,000	21,000	5	14	47	15,000	9,500
H18	29,000	25,000	4	10	55	16,000	10,000

(a) In general, strengths and elongation are unchanged or improved at low temperatures.
(b) The compressive yield strength is approximately the same as the tensile yield strength. The torsional yield strength is approximately 0.55 times the tensile yield strength. The torsional ultimate strength is approximately 0.65 times the tensile ultimate strength.
(c) Sheet specimens $\frac{1}{16}$ in. thick
(d) Round specimens ½ in. diam
(e) 500-kg load, 10-mm ball
(f) Based on 500,000,000 cycles using R. R. Moore type rotating-beam machine

Modulus of elasticity 10,000,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.
Strength and elongation at elevated temperatures after prolonged heating at testing temperatures. See Table I.
2 Directional properties (various hard tempers of sheet). Tensile strength and elongation are slightly lower in transverse direction than in longitudinal direction.
L *2 Radiography.* Same as for 2S alloy (commercially pure aluminum)
M *Composition Limits.* See Table II.
2 Consequences of exceeding impurity limits. High copper reduces resistance to corrosion. High iron plus silicon decreases formability.

Table I. Strength and Elongation of Al–1.2 Mn

Property	Temperature, deg Fahr: 75	300	400	500	600	700
Annealed O						
Tensile strength, psi.....	16,000	11,000	8000	5500	4000	3000
Yield strength, psi.....	6,000	5,000	4500	3500	2500	2000
Elongation, %	40	47	50	60	60	60
Condition H14						
Tensile strength, psi.....	21,000	18,000	14,000	10,500	6000	3000
Yield strength, psi.....	18,000	15,000	9,000	5,000	3000	2000
Elongation, %	16	17	22	25	40	60
Condition H18						
Tensile strength, psi.....	29,000	23,000	17,000	10,500	4500	3000
Yield strength, psi.....	25,000	16,000	8,000	5,000	3000	2000
Elongation, %	10	12	15	25	55	60

N *1 Melting temperature range.* 675 C to 745 C (1250 F to 1375 F)
3 Alloying. Add manganese as aluminum-rich alloy to melt-down or molten base metal (pure).
7 Hot working temperature range. 260 C to 510 C (500 F to 950 F)
10 Maximum reduction between anneals. 70% or more depending on product
15 Heat treatment. Annealing at 400 C (750 F); holding at temperature is not required.
17 Joining.
Rivet compositions. Condition O: 2S; all H tempers: A17S-T4, 53S-T61, 53S-T4
Other joining methods. Same as for 2S, except that alloy may be welded with either 2S or 3S alloy

Table II. Composition Limits of Al–1.2 Mn

Form	Designation	Components: Mn min	Mn max	Impurities: Cu max	Fe max	Si max	Zn max	Others each max	Others total max
Sheet and plate.....	QQ-A-359	1.00	1.50	0.20	0.70	0.60	0.10	0.05	0.15
Bar, rod, shapes and wire.....	QQ-A-356	1.00	1.50	0.20	0.70	0.60	0.10	0.05	0.15
Tubing	WW-T-788	1.00	1.50	0.20	0.70	0.60	....	0.03	0.10

Al–5.5 Cu–0.5 Pb–0.5 Bi*

A *2 Trade name.* 11S alloy
3 ASTM number. B 211-46T, Alloy CP21 (bar and rod)
4 Government number. Army Air Forces Specification 11330 (bar and rod); Army Ordnance Specification AXS-1318 (bar and rod)
6 Foreign equivalents. British BS 6L1 (bar and rod)
B *1 Typical uses.* Applications where good machinability and good strength are required. Screw-machine parts and miscellaneous forgings that require considerable machining, are typical.
C *1 Density* at 20 C (68 F). 2.82 ■ per cu cm (0.102 lb per cu in.)
D *1 Liquidus temperature.* 643 C (1190 F)
2 Solidus temperature. 535 C (995 F)
6 Thermal expansion (condition T3).
−60 to +20 C (−76 to +68 F). 0.0000212 per °C
20 to 100 C (68 to 212 F). 0.0000229 per °C
11 Specific heat at 100 C (212 F). Approx 0.23 cal per ■
16 Thermal conductivity at 25 C (77 F). 0.37 cal/sq cm/cm/°C/sec, condition T3
E *1 Volume conductivity* referred to standard copper. 40%, condition T3
2 Electrical resistivity at 20 C (68 F). 4.310 microhm-cm, condition T3
11 Electrolytic solution potential versus N/10 calomel electrode is 0.69 volts, condition T3; 0.83 volts, condition T8 (53 g NaCl + 3 g H_2O_2 solution)
F *5 Emissivity* at 25 C (77 F). 0.035 to 0.07 in air
K *Mechanical Properties.*

Condition(e)	Tensile Strength,(a) psi	Yield Strength,(b) psi	Elongation(c)	Brinell Hardness Number,(d)	Shear Strength, psi
T3	53,000	47,000	15	95	30,000
T8	57,000	44,000	14	100	33,000

(a) In general, strengths and elongation are unchanged or improved at low temperatures.
(b) The compressive yield strength is approximately the same as the tensile yield strength.
(c) Round specimens ½ in. diam
(d) 500-kg load, 10-mm ball
(e) Conditions T3 and T8 are produced by a combination of heat treatment and cold work.

Endurance limit (condition T3, 500,000,000 cycles) 12,500 psi; modulus of elasticity 10,300,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33; torsional ultimate strength approximately 0.65 times tensile strength; torsional yield strength approximately 0.55 times tensile yield strength.
Strength and elongation at elevated temperatures after prolonged heating at testing temperatures.

Property	Temperature, deg Fahr: 75	300	400	500	600	700
Condition T3						
Tensile strength, psi.....	53,000	27,000	19,000	8500	4000	2500
Yield strength, psi.....	47,000	18,000	13,000	4500	2000	1000
Elongation, %	15	25	34	44	90	125

L *2 Radiography.* Type A or 506 film with no intensifying screen, cardboard exposure holder, 36-in. focal distance, General Electric OX-250 unit, 2.1 H&D film density

* Compiled by Aluminum Company of America

Section, in.	Volts	Milliamperes	Time, min
½	110,000	7.0	1.0
1	140,000	7.0	1.0
1½	160,000	5.0	1.0
2	170,000	5.0	1.0

M *Composition Limits.* Bar and rod (Army Air Force Specification 11330), *components:* 3.5 to 6.0% Cu; 0.20 to 0.70% Bi; 0.20 to 0.70% Pb; *impurities:* 1.0% max Mn; 0.80% max Mg; 1.00% max Fe; 0.80% max Si; 0.25% max Cr; 0.30% max Zn; others (each) 0.05% max; others (total) 0.20% max.

2 *Consequences of exceeding impurity limits.* High iron reduces mechanical properties. High iron or magnesium impairs free-cutting characteristics. High silicon increases tool wear.

N 1 *Melting temperature.* 675 C to 745 C (1250 F to 1375 F)

3 *Alloying.* Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add bismuth as pure metal to molten base metal (pure). Add lead as pure metal to molten base metal (pure).

7 *Hot working temperature range.* 260 C to 480 C (500 to 900 F)

10 *Maximum reduction between anneals.* 50% or more depending on product

11 *Suited to forming by* machining or automatic screw-machining operations

15 *Heat treatment.*

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Cooling
Complete annealing O	399 to 427	750 to 800	2	Furnace-cool to 500 F (50 °F per hr max)
Removal of cold work	343	650	No holding time required	Not critical
Solution heat treatment T4	499 to 527	930 to 980	10 min to 1 hr (salt bath) Longer time in air	Cold water quench Heavy or complicated forgings, water 150 to 212 F.
Precipitation T8 (Start with T4 material)	160 to 171	320 to 340	12 to 18	Not critical

17 *Joining. Resistance welding.* Flash methods

Al – 4 Cu – 0.6 Mn – 0.6 Mg – 0.5 Pb – 0.5 Bi

COMPILED BY L. E. HOUSEHOLDER*

A 2 *Trade name.* R 317

4 *Government number.* Army Air Force Spec. No. 11330-B (bar and rod); U. S. Army Ordnance No. AXS-1651 (bar and rod)

B 1 *Typical uses.* Forgings and free-machining stock for screw-machine products

C 1 *Density* at 20 C (68 F). 2.81 g per cu cm (0.101 lb per cu in.)

E 1 *Volume conductivity* referred to standard copper. 30%

11 *Electrolytic solution potential* of T temper versus saturated calomel electrode is minus 0.59 volt.

I 1 *General resistance to corrosion.* The corrosion resistance is best in the T temper. A rapid transfer from the furnace to the cold water quenching medium is necessary to obtain best resistance to corrosion.

K *Mechanical Properties. Quenched T*: tensile strength 61,000 psi; yield strength 35,000 psi; elongation 22% in 2 in.; Bhn 100; Rockwell B 73; modulus of elasticity 10,500,000 psi.

L 1 *Metallography.* Etching, grain size, Keller's etch; etching, microstructure, Keller's etch and other for aluminum alloy constituents. Lead and bismuth constituents easily seen in as-polished metallographic specimens.

3 *Corrosion test commonly used.* $NaCl + H_2O_2$; *see* Spec. AN-QQ-H-186a for detail.

* Chief Plant Metallurgist, Reynolds Metals Company, Grand Rapids, Mich.

M *Composition Limits* (Spec. AXS-1651 U. S. Army Ordnance). *Components*: 3.5 to 4.5% Cu; 0.4 to 1.0% Mn; 0.2 to 0.8% Mg; 0.3 to 0.7% Bi; 0.3 to 0.7% Pb; *impurities*: 1.0% max Fe; 1.0% max Si; 0.25% max Cr; 0.2% max Zn; other elements (each), 0.05% max; other elements (total), 0.20% max.

N 7 *Hot working temperature range.* 355 to 400 C (675 to 750 F)

9 *Annealing temperature.* 400 to 425 C (750 to 800 F), soak for one hour and cool at a rate not greater than 50 °F per hr to 500 F.

11 *Suited to forming* by forging or machining.

15 *Heat treatment.*

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Atmosphere	Cooling
Solution heat treatment	499 to 510	930 to 950	Depends on thickness	Air or nitrate bath	Cold water quench
Aging (natural)	Room temperature		4 days minimum	.....	.....

17 *Joining.*
Rivet composition. 24 S-T4 or 17 S-T4.
Soldering, brazing and welding are not recommended.

Reference

Reynolds Metals Company Bulletin 55 A

Al – 4.4 Cu – 0.8 Si – 0.8 Mn – 0.4 Mg*

A 2 *Trade name.* 14 S alloy

3 *ASTM number.* B 209-46T, Alloy clad CS41 (sheet and plate, clad)

4 *Government number* AN-A-22 (sheet and plate, clad); AN-A-8 (shapes); QQ-A-367 (forgings)

6 *Foreign equivalents.* British DTD 364 (bar, extruded sections, and forgings)

B 1 *Typical uses.* Applications where high strength, relatively good formability and high hardness are required. Heavy-duty forgings, power-shovel bails, aircraft fittings and structures are typical.

C 1 *Density* at 20 C (68 F). 2.80 g per cu cm (0.101 lb per cu in.)

D 1 *Liquidus temperature.* 638 C (1180 F)

* Compiled by Aluminum Company of America

2 *Solidus temperature.* 510 C (950 F)

6 *Thermal expansion.*

	Condition O	*Condition T6*
−60 to +20 C (−76 to +68 F).	.....	0.0000214 per °C
20 to 100 C (68 to 212 F).	0.0000225	0.0000230 per °C
20 to 200 C (68 to 392 F).	0.0000236	..... per °C
20 to 300 C (68 to 572 F).	0.0000245	..... per °C

11 *Specific heat* at 100 C (212 F). Approx 0.23 cal per g

16 *Thermal conductivity* at 25 C (77 F). 0.46 cal/sq cm/cm/°C/sec, condition O; 0.37 cal/sq cm/cm/°C/sec, condition T6

19 *Recrystallization temperature.* 345 C (650 F) approx, 50% reduction

E 1 *Volume conductivity* referred to standard copper. 50%, condition O; 40%, condition T6

2 *Electrical resistivity* at 20 C (68 F). 3.448 microhm-cm,

Table I. Composition Limits of Al–4.4 Cu–0.8 Si–0.8 Mn–0.4 Mg

Form	Designation	Components: Cu min	Cu max	Si min	Si max	Mn min	Mn max	Mg min	Mg max	Impurities: Fe max	Cr max	Zn max	Ti max	Others each max	Others total max
Clad Sheet	AN-A-22														
Core		3.9	5.0	0.50	1.2	0.40	1.2	0.20	0.80	1.00	0.25	0.25	....	0.05	0.15
Cladding		...	0.10	0.35	1.0	....	0.75	0.80	1.50	0.60	0.35	0.20	0.10	0.05	0.15
Extrusions	AN-A-8	3.9	5.0	0.50	1.2	0.40	1.2	0.20	0.80	1.00	0.10	0.25	....	0.05	0.15
Forgings	QQ-A-367	3.9	5.0	0.50	1.2	0.40	1.2	0.20	0.75	1.00	0.10	0.25	0.15	0.05	0.15

condition O; 4.310 microhm, condition T6

11 Electrolytic solution potential versus N/10 calomel electrode is 0.68 volt, condition T4; 0.78 volt, condition T6 (53 g NaCl + 3 g H_2O_2 solution).

F *5 Emissivity* at 25 C (77 F). 0.035 to 0.07 in air

K *Mechanical Properties.*

Condition	Tensile Strength,(a) psi	Yield Strength,(b) psi	Elongation (c) percentage	Elongation (d) percentage	Bhn(e)	Shear Strength, psi
Bare Products						
O	27,000	14,000	..	18	45	18,000
T4	56,000	40,000	..	25	100	34,000
T6	70,000	60,000	..	13	135	42,000
Clad Sheet						
O	25,000	10,000	21	..	...	18,000
T4	59,000	38,000	18	..	...	39,000
T6	65,000	58,000	9	..	...	41,000

(a) In general, strengths and elongations are unchanged or improved at low temperatures.

(b) The compressive yield strength is approximately the same as the tensile yield strength. (c) Sheet specimens $\frac{1}{16}$ in. thick. (d) Round specimens ½ in. diam. (e) 500-kg load, 10-mm ball.

Endurance limit (bare products, conditions T4 and T6, 500,000,000 cycles) 18,000 psi, (condition O) 11,000 psi; modulus of elasticity (bare products) 10,600,000 psi, (clad sheet) 10,500,000 psi; modulus of rigidity 3,850,000 psi; torsional yield strength approximately 0.55 times the tensile yield strength; torsional ultimate strength approximately 0.65 times the tensile strength.

Strength and elongation at elevated temperatures after prolonged heating at testing temperatures:

Property	Temperature, deg Fahr: 75	300	400	500	600	700
Condition T6 (bare products)						
Tensile strength, psi	70,000	43,000	17,000	10,000	6000	4000
Yield strength, psi	60,000	39,000	13,000	8,000	4500	3500
Elongation, %	13	16	33	50	65	75

2 Directional properties (all tempers of sheet). Tensile strength and elongation are approximately equal in longitudinal and transverse directions. In forgings, transverse tensile strength approximately same as longitudinal. Transverse elongation approximately 70% of longitudinal.

L *2 Radiography.* Type A or 506 film with no intensifying screen, cardboard exposure holder, 36-in. focal distance, General Electric OX-250 unit, 2.1 H&D film density

Section, in.	Volts	Milliamperes	Time, min
½	75,000	9.0	1.0
1	105,000	7.0	1.0
1½	140,000	5.0	1.0
2	145,000	9.0	1.0

M *Composition Limits.* See Table I.

2 Consequences of exceeding impurity limits.
Core. High iron reduces tensile properties and formability. High chromium plus iron plus titanium may cause segregation.
Cladding. High copper lowers inherent resistance to corrosion of cladding and reduces potential difference between core and cladding.

N *1 Melting temperature.* 675 C to 745 C (1250 to 1375 F)

3 Alloying. Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add silicon as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add manganese as aluminum-rich alloy to melt-down or to molten base metal (pure). Add magnesium as pure metal to molten base metal.

7 Hot working temperature. 260 to 480 C (500 to 900 F)

10 Maximum reduction between anneals. 50% or more depending on product

15 Heat treatment.

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Cooling
Complete annealing O	399 to 427	750 to 800	2	Furnace-cool to 500 F (50 °F per hr max)
Removal of cold work	343	650	No holding time required	Not critical
Solution heat treatment T4	496 to 513	925 to 950	10 min to 1 hr (salt bath)	Cold water quench
			Longer time in air	Heavy or complicated forgings, water 150 to 212 F
Precipitation T6 (Start with T4 material)	168 to 174	335 to 345	8 to 12	Not critical
	157 to 163	315 to 325	or 16 to 20	Not critical

17 Joining. Rivet compositions. Condition T6: A 17 S-T4, 17 S-T4, 24 S-T4, or steel. *Metal-arc weld* with 43 alloy; Alcoa No. 27 flux. *Carbon-arc weld* with 43 alloy; Alcoa No. 24 flux (automatic), Alcoa No. 27 flux (manual). *Tungsten-arc, argon atmosphere weld* with 43 alloy; no flux. *Resistance welding.* Spot, seam, and flash methods

References

See references for commercially pure aluminum
Waldemar Naujoks, "Forging Handbook", American Society for Metals, 1942

Al–4.5 Cu–1.0 Si–0.8 Mn–0.4 Mg Clad With Al–1.0 Mg–0.7 Si–0.5 Mn

COMPILED BY L. F. MONDOLFO* AND T. L. FRITZLEN*

A *2 Trade name.* R 301
4 Government number. AN-A-22 (sheet and plate)
5 Other designations. Alclad 14 S

B *1 Typical uses.* Parts that require high strength, good formability, and good resistance to corrosion

C *1 Density* at 20 C (68 F). 2.78 ▮ per cu cm (0.101 lb per cu in.)

D *1 Liquidus temperature.* 637 C (1180 F)
2 Solidus temperature. 525 C (977 F)

* Illinois Institute of Technology, Chicago
• Reynolds Metals Company, McCook, Ill.

E *11 Electrolytic solution potential* versus saturated calomel electrode.

Condition	Core	Cladding
W temper	0.65 volt	0.83 volt
T temper	0.72 volt	0.82 volt

I *1 General resistance to corrosion.* Very good in W temper, good in O and T tempers. In W temper, comparable to 99% Al, slightly lower in T or O temper.

K *Mechanical Properties.* See Table I.

M *Composition Limits* (Spec AN-A-22). See Table II.

Table I. Mechanical Properties of R 301

Condition	Section	Tensile Strength, psi	Yield Strength, psi	Elongation, percentage	Rockwell Hardness
O	Sheet	25,000	10,000	22.0	E 45 to 50
W	Up to 0.039 in.	59,000	39,000	19	E 95 to 100
	0.040 in. and above	61,000	41,000	20	
T[a]	Up to 0.039 in.	66,000	60,000	9	E 100 to 105
	0.040 in. and above	69,000	61,000	9	....

(a) Aged T. Modulus of elasticity 10,300,000 psi; shear strength 43,000 psi; endurance limit (10^6 cycles) 12,500 psi.

N *9 Annealing temperature.* 650 F for one hour for cold worked material; 750 F for two hours and slow cool (50 °F per hr max) to 600 F for heat treated material.
11 Suited to forming in O temper, all methods; W temper, forming operations not requiring deep drawing or very small bend radii; T temper, only slight forming.
15 Heat treatment.
Solution Heat Treatment.

Section, in.	Time at 940 F, minutes	Allowable reheat treatments
Up to 0.032	10	none
0.033 to 0.063	15	1
0.064 to 0.101	20	2
0.102 to 0.250	30	2
0.251 to 1.000	60	3
Over 1.000	60 per inch	3

Aging Treatments After Quenching in Cold Water

Temperature, deg Fahr	320	330	340	350	360	375
Time, hours	17–19	11–13	7–9	5.5–6.5	4.5–5.5	3.75–4.25

References

Metals and Alloys, 20, 926 (1943)
Metal Progress, 48, 1128 (1945)
Product Eng, 16 (1945)
Reynolds Metals Company, Bulletin 50 B

Table II. Composition Limits from Specifications AN-A-22

	Components								Impurities					
	Cu min	Cu max	Si min	Si max	Mg min	Mg max	Mn min	Mn max	Fe max	Cr max	Zn max	Ti max	Other each max	Other total max
Core	3.9	5.0	0.5	1.2	0.2	0.8	0.4	1.2	1.0	0.25	0.25	...	0.05	0.15
Cladding	..	0.10	0.35	1.0	0.8	1.5	..	0.75	0.6	0.35	0.20	0.10	0.05	0.15

Al – 4 Cu – 0.5 Mg – 0.5 Mn*

A *2 Trade name.* 17S alloy
3 ASTM number. B 211-46T, Alloy CM21 (bar, rod, and wire)
4 Government number QQ-A-351 (bar, rod, shapes and wire); QQ-A-367, Class 1 (forgings)
6 Foreign equivalents. British BS 6L1 (bar, rod, shapes and wire); BS 6L1 (forgings)
B *1 Typical uses.* Applications where relatively high strength, good formability and good resistance to corrosion are required. Rivets, hardware, screw-machine parts, aircraft fittings, structural applications in the construction and transportation fields are typical.
C *1 Density* at 20 C (68 F). 2.79 g per cu cm (0.101 lb per cu in.)
D *1 Liquidus temperature.* 641 C (1185 F)
2 Solidus temperature. 513 C (955 F)
6 Thermal expansion.

	Condition O	*Condition T4*
−60 to +20 C (−76 to +68 F).	.....	0.0000216 per °C
20 to 100 C (68 to 212 F).	0.0000230	0.0000235 per °C
20 to 200 C (68 to 392 F).	0.0000240	.....per °C
20 to 300 C (68 to 572 F).	0.0000250	.....per °C

11 Specific heat at 100 C (212 F). Approx 0.23 cal per g
16 Thermal conductivity at 25 C (77 F). 0.41 cal/sq cm/cm/°C/sec, condition O; 0.29 cal/sq cm/cm/°C/sec, condition T4
19 Recrystallization temperature. 345 C (650 F) approx, 50% reduction
E *1 Volume conductivity* referred to standard copper. 45%, condition O; 30%, condition T4
2 Electrical resistivity at 20 C (68 F). 3.831 microhm-cm, condition O; 5.747 microhm-cm, condition T4
11 Electrolytic solution potential versus N/10 calomel electrode is 0.68 volt, condition T4 (53 g NaCl + 3 g H_2O_2 solution).
F *5 Emissivity* at 25 C (77 F). 0.035 to 0.07 in air
K *Mechanical Properties.* See Table I.
Elongation in tension test 22%; modulus of elasticity 10,400,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33; torsional yield strength approximately 0.55 times the tensile yield strength; torsional ultimate strength approximately 0.65 times the tensile strength.

* Compiled by Aluminum Company of America

Table I. Mechanical Properties of Al – 4 Cu – 0.5 Mg – 0.5 Mn

Condition	Tensile Strength,[a] psi	Yield Strength,[b] psi	Bhn[c]	Shear Strength, psi	Endurance Limit,[d] psi
O	26,000	10,000	45	18,000	11,000
T4	62,000	40,000	105	38,000	18,000

(a) In general, strengths and elongations are unchanged or improved at low temperatures.
(b) The compressive yield strength is approximately the same as the tensile yield strength.
(c) 500-kg load, 10-mm ball
(d) Based on 500,000,000 cycles using R. R. Moore type rotating-beam machine.

Strength and elongation at elevated temperatures after prolonged heating at testing temperatures.

Property	Temperature, deg Fahr: 75	300	400	500	600	700
	Condition T4					
Tensile strength, psi	62,000	41,000	17,000	10,000	6000	4000
Yield strength, psi	40,000	35,000	11,000	7,000	4000	3000
Elongation, %	22	18	33	50	80	100

2 Directional properties. Tensile strength and elongation are approximately equal in longitudinal and transverse directions.
L *2 Radiography.* Type A or 506 film with no intensifying screen, cardboard exposure holder, 36-in. focal distance, General Electric OX-10 unit, 2.1 H&D film density

Section, in.	Volts	Milliamperes	Time, min
½	70,000	9.0	1.0
1	100,000	7.0	1.0
1½	135,000	5.0	1.0
2	140,000	5.0	1.8

M *Composition Limits.* See Table I.
2 Consequences of exceeding impurity limits. High iron reduces tensile properties and formability. High iron plus titanium plus chromium may cause segregation.
N *1 Melting temperature range.* 675 to 745 C (1250 to 1375 F)
3 Alloying. Add copper as pure metal or aluminum-rich

alloy to base metal (pure), either in melt-down or molten alloy. Add magnesium as pure metal to molten base metal (pure). Add manganese as aluminum-rich alloy to melt-down or molten base metal (pure).

7 *Hot working temperature range.* 260 to 480 C (500 to 900 F)

10 *Maximum reduction between anneals.* 50% or more depending on product

15 *Heat treatment.* See table in right-hand column.

17 *Joining.*
Rivet compositions. Condition T4: A 17 S-T4, 17 S-T4, 24 S-T4, or steel
Resistance welding. Spot, seam, and flash methods

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Cooling
Complete annealing O	399 to 427	750 to 800	2	Furnace-cool to 500 F (50 °F per hr max)
Removal of cold work	343	650	No holding time required	Not critical
T4 Solution heat treatment	496 to 510	925 to 950	10 min to 1 hr (salt bath)	Cold water quench
T4 followed by			Longer time in air	Heavy or complicated forgings, water 150 to 212 F
T4 Precipitation	Room		48 to 96	.....

Table I. Composition Limits of Al – 4 Cu – 0.5 Mg – 0.5 Mn

Form	Designation	Components: Cu min	Cu max	Mn min	Mn max	Mg min	Mg max	Impurities: Fe max	Si max	Cr max	Zn max	Ti max	Others each max	Others total max
Bar, rod, shapes and wire..	QQ-A-351	3.5	4.5	0.40	1.00	0.20	0.80	1.00	0.80	0.25	0.10	....	0.05	0.15
Forgings	QQ-A-367 (Cl 1)	3.5	4.7	0.40	1.00	0.20	0.75	1.00	0.75	0.25	0.25	0.15	0.05	0.15

Al – 4 Cu – 2 Ni – 0.5 Mg*

A 2 *Trade name.* 18 S alloy

4 *Government number.* QQ-A-367, Class 7 (forgings)

6 *Foreign equivalents.* British BS 4L25 and BS 2L42

B 1 *Typical uses.* Applications where high strength is required at elevated temperatures. Forged cylinder heads and pistons are typical.

C 1 *Density* at 20 C (68 F). 2.80 g per cu cm (0.101 lb per cu in.)

D 1 *Liquidus temperature.* 638 C (1180 F)

2 *Solidus temperature.* 507 C (945 F)

6 *Thermal expansion.*

	Condition O	Condition T61
−60 to +20 C (−76 to +68 F).	.....	0.0000209 per °C
20 to 100 C (68 to 212 F).	0.0000224	0.0000226 per °C
20 to 200 C (68 to 392 F).	0.0000233	..... per °C
20 to 300 C (68 to 572 F).	0.0000242	..... per °C

11 *Specific heat* at 100 C (212 F). Approx 0.23 cal per g

16 *Thermal conductivity* at 25 C (77 F). 0.46 cal/sq cm/cm/°C/sec, condition O; 0.37 cal/sq cm/cm/°C/sec, condition T61

E 1 *Volume conductivity* referred to standard copper. 50%, condition O; 40%, condition T61

2 *Electrical resistivity* at 20 C (68 F). 3.448 microhm-cm, condition O; 4.310 microhm-cm, condition T61

F 5 *Emissivity* at 25 C (77 F). 0.035 to 0.07 in air

K *Mechanical Properties.* Condition T61: tensile strength 63,000 psi; yield strength 47,000 psi; elongation (round specimen, ½-in. diam) 17%; Bhn (500-kg load, 10-mm ball) 130; modulus of elasticity 10,600,000 psi; shear strength 39,000 psi; endurance limit (based on 500,000,000 cycles using R. R. Moore type rotating-beam machine) 17,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33; in general, strength and elongation remain unchanged or improve at low temperatures; compressive yield strength approximately the same as tensile yield strength; torsional yield strength approximately 0.55 times the tensile yield strength; ultimate torsional strength approximately 0.65 times the tensile strength.
Strength and elongation at elevated temperatures after prolonged heating at testing temperatures. See Table I.

2 *Directional properties* (forgings). Transverse tensile strength approximately same as longitudinal. Transverse elongation approximately 70% of longitudinal.

Table I. Strength and Elongation of Al – 4 Cu – 2 Ni – 0.5 Mg at Elevated Temperature

Property	Temperature, deg Fahr: 75	300	400	500	600	700
	Condition T61					
Tensile strength, psi....	63,000	49,000	22,000	11,000	6000	4000
Yield strength, psi.....	47,000	44,000	17,000	7,000	4000	2500
Elongation, %	17	10	15	32	55	85
Endurance limit, psi.... (100,000,000 cycles)	.....	15,000	9,500	6,500	....	....

L 2 *Radiography.* Same as for 14 S alloy (Al – 4.4 Cu – 0.8 Si – 0.8 Mn – 0.4 Mg)

M *Composition Limits.* Forgings (QQ-A-367, Class 7), *components:* 3.5 to 4.5% Cu; 1.7 to 2.3% Ni; 0.45 to 0.90% Mg; *impurities*: 0.90% max Si; 1.00% max Fe; 0.20% max Mn; 0.25% max Zn; 0.10% max Cr; 0.15% max Ti; others (each) 0.05% max; others (total) 0.15% max.

2 *Consequences of exceeding impurity limits.* Lead, cadmium or bismuth impairs forgeability.

N 1 *Melting temperature range.* 675 to 745 C (1250 to 1375 F)

3 *Alloying.* Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add nickel as aluminum-rich alloy to melt-down or molten base metal (pure). Add magnesium as pure metal to molten base metal (pure).

7 *Hot working temperature range.* 260 to 480 C (500 to 900 F)

15 *Heat treatment.*

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Cooling
Complete annealing O	399 to 427	750 to 800	2	Furnace-cool to 500 F (50 °F per hr max)
T61 Solution heat treatment	510 to 521	950 to 970	4 minimum	Cold water quench
T61 followed by				Heavy or complicated forgings, water 150 to 212 F
T61 Precipitation	168 to 174	335 to 345	8 to 12	Not critical

References

See references for commercially pure aluminum.

Waldemar Naujoks, "Forging Handbook", American Society for Metals, 1942

* Compiled by Aluminum Company of America

Al – 4.5 Cu – 1.5 Mg – 0.6 Mn*

A *2 Trade name.* 24 S alloy
3 ASTM number. B 209-46T, Alloy CG21 and clad CG21 (sheet and plate, bare and clad); B 211-46T, Alloy CG21 (bar, rod and wire); B 210-46T, Alloy CG21 (tubing)
4 Government number. QQ-A-355 (sheet and plate, bare); QQ-A-362 (sheet and plate, clad); QQ-A-354 (bar, rod, shapes and wire); WW-T-785 (tubing)
6 Foreign equivalents. British BS 2L40 (bar, rod, shapes and wire); DTD 273 (tubing)
B *1 Typical uses.* Applications where higher strengths are desired than are provided by 17 S alloy. Aircraft structures, rivets, hardware and other miscellaneous structural applications are typical.
C *1 Density* at 20 C (68 F). 2.77 g per cu cm (0.100 lb per cu in.)
D *1 Liquidus temperature.* 638 C (1180 F)
2 Solidus temperature. 502 C (935 F)
6 Thermal expansion.

	Condition O	*Condition T4*
−60 to +20 C (−76 to +68 F).	.....	0.0000215 per °C
20 to 100 C (68 to 212 F).	0.0000228	0.0000232 per °C
20 to 200 C (68 to 392 F).	0.0000239	..... per °C
20 to 300 C (68 to 572 F).	0.0000247	..... per °C

11 Specific heat at 100 C (212 F). Approx 0.23 cal per g
16 Thermal conductivity at 25 C (77 F). 0.45 cgs, condition O; 0.29 cgs, condition T4
19 Recrystallization temperature. 345 C (650 F) approx, 50% reduction
E *1 Volume conductivity* referred to standard copper. 50%, condition O; 30%, condition T4
2 Electrical resistivity at 20 C (68 F). 3.448 microhm-cm, condition O; 5.747 microhm-cm, condition T4
11 Electrolytic solution potential versus N/10 calomel electrode is 0.68 volt, condition T4 (53 g NaCl + 3 ▮ H_2O_2 solution).
F *5 Emissivity* at 25 C (77 F). 0.035 to 0.07 in air
K *Mechanical Properties.*

Condition	Tensile Strength,(a) psi	Yield Strength,(b) psi	Elongation, (c) percentage	Elongation, (d) percentage	Bhn(e)	Shear Strength, psi
Bare Products						
O	27,000	11,000	19	22	42	18,000
T4	68,000	46,000	19	22	120	41,000
T36(f)	73,000	57,000	13	..	130	42,000
Clad Sheet						
T4	64,000	43,000	18	..	...	40,000
T36(f)	67,000	53,000	11	..	...	41,000
T81.....	66,000	60,000	7	..	...	.....
T86.....	70,000	66,000	6	..	...	.....

(a) In general, strengths and elongations are unchanged or improved at low temperatures.
(b) The compressive yield strength is approximately the same as the tensile yield strength.
(c) Sheet specimens $\frac{1}{16}$ in. thick
(d) Round specimens ½ in. diam
(e) 500-kg load, 10-mm ball
(f) Condition T36 is produced by a combination of heat treatment and cold work.

Modulus of elasticity for both bare and clad sheet is 10,600,000 psi, with two exceptions, namely: clad sheet (secondary) where the modulus value is more dependent on the thickness than on condition: 10,000,000 psi for sheet 0.064 in. and thicker, and 9,600,000 psi for sheet less than 0.064 in. thick. Secondary values for conditions T36, T81 and T86 are the same as for condition T4.
Endurance limit (bare products, condition T4, 500-000,000 cycles) 18,000 psi, (condition O) 12,000 psi; modulus of rigidity (bare products only) 3,850,000 psi; Poisson's ratio (all conditions, bare and clad products) 0.33; torsional yield strength approximately 0.55 times the tensile yield strength; torsional ultimate strength approximately 0.65 times the tensile strength.
Strength and elongation at elevated temperature after prolonged heating at testing temperature.

Property	Temperature, deg Fahr: 75	300	400	500	600	700
Condition T4 (bare products)						
Tensile strength, psi....	68,000	42,000	20,000	12,000	7000	5000
Yield strength, psi.....	46,000	37,000	16,000	10,000	5500	3500
Elongation, %	22	20	26	40	70	100

2 Directional properties (all tempers of sheet). Tensile strength and elongation are approximately equal in the longitudinal and transverse directions.
L *2 Radiography.* Same as for 17 S alloy (Al – 4 Cu – 0.5 Mg – 0.5 Mn)
M *Composition Limits.* See Table I.
2 Consequences of exceeding impurity limits.
Core. High iron reduces tensile properties and formability. High silicon reduces tensile properties. High chromium interferes with annealing. This effect is more noticeable when nickel is also present. Lead produces hot shortness. Cadmium produces hot shortness.
Cladding. High copper lowers inherent resistance to corrosion of cladding and reduces potential difference between core and cladding. The latter is particularly significant for artificially aged conditions.
N *1 Melting temperature range.* 675 C to 745 C (1250 to 1375 F)
3 Alloying. Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add magnesium as pure metal to molten base metal (pure).
7 Hot working temperature range. 260 C to 480 C (500 to 900 F)
10 Maximum reduction between anneals. 50% or more depending on product
15 Heat treatment.

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Cooling
Complete annealing O	399 to 427	750 to 800	2	Furnace-cool to 500 F (50 °F per hr max)
Removal of cold work	343	650	No holding time required	Not critical
T4 Solution heat treatment	488 to 499	910 to 930	10 min to 1 hr (salt bath)	Cold water quench
T4 followed by Precipitation	Room		Longer time in air	
Precipitation T81	188 to 193	370 to 380	48 to 96 11 to 13	Not critical
	(Start with T4 material)			
Precipitation T84	188 to 193	370 to 380	8 to 10	Not critical
	(Start with T4 material stretched 3%)			
Precipitation T86	188 to 193	370 to 380	8 to 10	Not critical
	(Start with T36 material)			

17 Joining. Same as for 17 S alloy (Al – 4 Cu – 0.5 Mg – 0.5 Mn)

* Compiled by Aluminum Company of America

Table I. Composition Limits of Al – 4.5 Cu – 1.5 Mg – 0.6 Mn

Form	Designation	Components: Cu min	Cu max	Mg min	Mg max	Mn min	Mn max	Impurities: Fe max	Si max	Cr max	Zn max	Others each max	Others total max
Bare Products													
Sheet	QQ-A-355	3.8	4.9	1.2	1.8	0.30	0.90	0.50	0.50	0.25	0.10	0.03	0.10
Bar, rod, shapes and wire.....	QQ-A-354	3.8	4.9	1.2	1.8	0.30	0.90	0.50	0.50	0.25	0.10	0.05	0.15
Tubing	WW-T-785	3.8	4.9	1.2	1.8	0.30	0.90	0.50	0.50	0.25	0.10	0.05	0.15
Clad Sheet	QQ-A-362												
Core	.....	3.8	4.9	1.2	1.8	0.30	0.90	0.50	0.50	0.25	0.03	0.03	0.10
Cladding	.....	...	0.20	...	...	....	0.05	Fe + Si 0.70		....	0.20	Al, 99.3 min.	

Al – 4.5 Cu – 0.8 Mn – 0.8 Si*

A *2 Trade name.* 25 S alloy
4 Government number. QQ-A-367, Class 2 (forgings)
B *1 Typical uses.* Applications where good forgeability and fairly high strength are required. Airplane propellers, link rods, and radial-engine crankcases.
C *1 Density* at 20 C (68 F). 2.79 g per cu cm (0.101 lb per cu in.)
D *1 Liquidus temperature.* 641 C (1185 F)
2 Solidus temperature. 521 C (970 F)
6 Thermal expansion.

	Condition O	Condition T6
−60 to +20 C (−76 to +68 F).	.....	0.0000216 per °C
20 to 100 C (68 to 212 F).	0.0000228	0.0000233 per °C
20 to 200 C (68 to 392 F).	0.0000237	..... per °C
20 to 300 C (68 to 572 F).	0.0000245	..... per °C

11 Specific heat at 100 C (212 F). Approx 0.23 cal per
16 Thermal conductivity at 25 C (77 F). 0.37 cal/sq cm/cm/°C/sec, condition T6
E *1 Volume conductivity* referred to standard copper. 40%, condition T6
2 Electrical resistivity at 20 C (68 F). 4.310 microhm-cm, condition T6
11 Electrolytic solution potential versus N/10 calomel electrode is 0.80 volt, condition T6 (53 g NaCl + 3 g H_2O_2 solution).
F *5 Emissivity* at 25 C (77 F). 0.035 to 0.07 in air
K *Mechanical Properties.* Condition T6: tensile strength 57,000 psi; yield strength 35,000 psi; compressive yield strength approximately the same as tensile yield strength; torsional yield strength approximately 0.55 times the tensile yield strength; ultimate torsional strength approximately 0.65 times the tensile strength; elongation (round specimens ½-in. in diam) 18%; Bhn (500-kg load, 10-mm ball) 110; modulus of elasticity 10,400,000 psi; shear strength 35,000 psi; endurance limit (based on 500,000,000 cycles using R. R. Moore type rotating-beam machine) 18,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.
Strength and elongation at elevated temperatures after prolonged heating at testing temperatures. See Table I.
2 Directional properties (forgings). Transverse tensile strength approximately same as longitudinal. Transverse elongation approximately 70% of longitudinal.
L *2 Radiography.* Same as for 17 S alloy (Al – 4 Cu – 0.5 Mg – 0.5 Mn).
M *Composition Limits.* Forgings (QQ-A-367, Class 2), *components*: 3.9 to 5.0% Cu; 0.40 to 1.2% Mn; 0.50 to 1.2% Si; *impurities*: 1.00% max Fe; 0.05% max Mg; 0.10% max Cr; 0.25% max Zn; 0.15% max Ti; others (each) 0.05% max; others (total) 0.15% max.
2 Consequences of exceeding impurity limits. High iron or nickel reduces mechanical properties. Tin causes hot shortness which impairs forgeability. Bismuth decreases resistance to corrosion.

Table I. Mechanical Properties of Al – 4.5 Cu – 0.8 Mn – 0.8 Si

Property	Temperature, deg Fahr: 75	300	400	500	600	700
	Condition T6					
Tensile strength, psi.....	57,000	35,000	19,000	9000	4500	3500
Yield strength, psi.....	35,000	28,000	13,500	6000	4000	3000
Elongation, %	18	20	35	45	50	55
Endurance limit, psi..... (100,000,000 cycles)	....	9,500	6,500	3500	....	....

N *1 Melting temperature.* 675 to 745 C (1250 to 1375 F)
3 Alloying. Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add silicon as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add manganese as aluminum-rich alloy to melt-down or molten base metal (pure).
7 Hot working temperature range. 260 to 480 C (500 to 900 F)
15 Heat treatment.

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Cooling
Complete annealing O	399 to 427	750 to 800	2	Furnace cool to 500 F (50 °F per hr max)
T6: Solution heat treatment	510 to 521	950 to 970	4 (minimum)	Cold water quench Heavy or complicated forgings, water 150 to 212 F
T6: followed by Precipitation	168 to 174	335 to 345	8 to 12	Not critical

17 Joining. Rivet compositions. A 17 S-T4, 17 S-T4, 24 S-T4

References

See references for commercially pure aluminum.
Waldemar Naujoks, "Forging Handbook", American Society for Metals, 1942

Al – 12.5 Si – 1.0 Mg – 0.9 Cu – 0.9 Ni*

A *2 Trade name.* 32 S alloy
4 Government number. QQ-A-367, Class 6 (forgings)
B *1 Typical uses.* Applications where good forgeability and low coefficient of thermal expansion are required. Forged pistons are typical.
C *1 Density* at 20 C (68 F). 2.69 g per cu cm (0.097 lb per cu in.)
D *1 Liquidus temperature.* 571 C (1060 F)
2 Solidus temperature. 532 C (990 F)
6 Thermal expansion.

	Condition O	Condition T6
−60 to +20 C (−76 to +68 F).	.....	0.0000184 per °C
20 to 100 C (68 to 212 F).	0.0000194	0.0000199 per °C
20 to 200 C (68 to 392 F).	0.0000203	..... per °C
20 to 300 C (68 to 572 F).	0.0000211	..... per °C

11 Specific heat at 100 C (212 F). Approx 0.23 cal per
16 Thermal conductivity at 25 C (77 F). 0.37 cal/sq cm/cm/°C/sec, condition O; 0.33 cal/sq cm/cm/°C/sec, condition T6
E *1 Volume conductivity* referred to standard copper. 40%, condition O; 35%, condition T6
2 Electrical resistivity at 20 C (68 F). 4.310 microhm-cm, condition O; 4.926 microhm-cm, condition T6
F *5 Emissivity* at 25 C (77 F). 0.035 to 0.07 in air
K *Mechanical Properties.* Condition T6: tensile strength 56,000 psi; yield strength 46,000 psi; elongation (round specimens ½ in. in diam) 8%; Bhn (500-kg load, 10-mm ball) 125; modulus of elasticity 10,300,000 psi; shear strength 38,000 psi; endurance limit (based on 500,000,000 cycles using R. R. Moore type rotating-beam machine) 16,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33; in general, strengths and elongations remain unchanged or improve at low temperatures; compressive yield strength approximately the same as tensile yield strength; torsional yield strength approximately 0.55 times the tensile yield strength, and torsional ultimate strength approximately 0.65 times the tensile strength.
Strength and elongation at elevated temperatures after prolonged heating at testing temperatures.

Property	Temperature, deg Fahr: 75	300	400	500	600	700
	Condition T6					
Tensile strength, psi.....	56,000	39,000	16,000	8500	6000	3500
Yield strength, psi.....	46,000	33,000	11,000	6500	3500	2000
Elongation, %	8	9	30	50	60	120

2 Directional properties (forgings). Transverse tensile

* Compiled by Aluminum Company of America

strength approximately same as longitudinal. Transverse elongation approximately 70% of longitudinal.

L 2 *Radiography.* Same as for 2S alloy (commercially pure aluminum)

M *Composition Limits.* Forgings (QQ-A-367, Class 6), *components:* 11.5 to 13.5% Si; 0.50 to 1.3% Cu; 0.80 to 1.3% Mg; 0.50 to 1.3% Ni; *impurities:* 1.00% max Fe; 0.20% max Mn; 0.10% max Cr; 0.25% max Zn; 0.15% max Ti; others (each) 0.05% max; and others (total) 0.15% max.

2 *Consequences of exceeding impurity limits.* High iron reduces mechanical properties. Lead, cadmium, or bismuth impairs forgeability.

N 1 *Melting temperature range.* 675 C to 745 C (1250 to 1375 F)

3 *Alloying.* Add silicon as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add magnesium as pure metal to molten base metal (pure). Add nickel as aluminum-rich alloy to melt-down or molten base metal (pure).

7 *Hot working temperature range.* 260 to 480 C (500 to 900 F)

15 *Heat treatment.*

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Cooling
Complete annealing O	399 to 427	750 to 800	2	Furnace cool to 500 F (50 °F per hr max)
T6 Solution heat treatment	510 to 521	950 to 970	4 (minimum)	Cold water quench Heavy or complicated forgings, water 150 to 212 F
T6 followed by Precipitation	168 to 174	335 to 345	6 to 10	Not critical

Al – 1.0 Si – 0.6 Mg – 0.25 Cr*

A 2 *Trade name.* A 51 S alloy

4 *Government number.* QQ-A-367, Class 3 (forgings)

B 1 *Typical uses.* Applications where very good forgeability, good strength and good resistance to corrosion are required. Crankcases, fuse parts, machine and automotive parts are typical.

C 1 *Density* at 20 C (68 F). 2.69 g per cu cm (0.097 lb per cu in.)

D 1 *Liquidus temperature.* 649 C (1200 F)

2 *Solidus temperature.* 552 C (1025 F)

6 *Thermal expansion.*

	Condition O	Condition T6
−60 to +20 C (−76 to +68 F).	.....	0.0000216 per °C
20 to 100 C (68 to 212 F).	0.0000231	0.0000233 per °C
20 to 200 C (68 to 392 F).	0.0000242	..... per °C
20 to 300 C (68 to 572 F).	0.0000250	..... per °C

11 *Specific heat* at 100 C (212 F). Approx 0.23 cal per

16 *Thermal conductivity* at 25 C (77 F). 0.50 cal/sq cm/cm/°C/sec, condition O; 0.41 cal/sq cm/cm/°C/sec, conditions T4 and T6

E 1 *Volume conductivity* referred to standard copper. 55%, condition O; 45%, conditions T4 and T6

2 *Electrical resistivity* at 20 C (68 F). 3.135 microhm-cm, condition O; 3.831 microhm-cm, conditions T4 and T6

F 5 *Emissivity* at 25 C (77 F). 0.035 to 0.07 in air

K *Mechanical Properties.* Condition T6: tensile strength 47,000 psi; yield strength 40,000 psi; elongation (round specimen ½ in. in diam) 20%; Bhn (500-kg load, 10-mm ball) 100; modulus of elasticity 10,200,000 psi; shear strength 32,000 psi; endurance limit (based on 500,000,000 cycles using R. R. Moore type rotating-beam machine) 11,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33; in general, strengths and elongations remain unchanged or improve at low temperatures; compressive yield strength approximately the same as tensile yield strength; torsional yield strength approximately 0.55 times the tensile yield strength; torsional ultimate strength approximately 0.65 times the tensile strength.

Strength and elongation at elevated temperatures after prolonged heating at testing temperatures.

Property	Temperature, deg Fahr: 75	300	400	500	600	700
	Condition T6					
Tensile strength, psi.....	47,000	19,000	7500	5500	4500	3500
Yield strength, psi.....	40,000	15,000	5500	4500	3500	3000
Elongation, %	20	28	58	59	60	65
Endurance limit, psi..... (100,000,000 cycles)	....	....	3500	3500	....	....

2 *Directional properties* (forgings). Transverse tensile strength approximately same as longitudinal. Transverse elongation approximately 70% of longitudinal.

L 2 *Radiography.* Same as for 2S alloy (commercially pure aluminum)

M *Composition Limits.* Forgings (QQ-A-367, Class 3), *components:* 0.60 to 1.20% Si; 0.45 to 0.80% Mg; 0.15 to 0.35% Cr; *impurities:* 1.00% max Fe; 0.35% max Cu; 0.20% max Mn; 0.25% max Zn; 0.15% max Ti; others (each) 0.05% max, and others (total) 0.15% max.

2 *Consequences of exceeding impurity limits.* Tin or cadmium impairs forgeability. Lead impairs mechanical properties and forgeability.

N 1 *Melting temperature range.* 675 C to 745 C (1250 to 1375 F)

3 *Alloying.* Add silicon as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add magnesium as pure metal to molten base metal (pure). Add chromium as aluminum-rich alloy to melt-down or molten base metal (pure).

7 *Hot working temperature range.* 260 C to 480 C (500 to 900 F)

15 *Heat treatment.*

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Cooling
Complete annealing O	399 to 427	750 to 800	2	Furnace-cool to 500 F (50 °F per hr max)
Solution heat treatment T4	516 to 527	960 to 980	4 (minimum)	Cold water quench Heavy or complicated forgings, water 150 to 212 F
Precipitation T6 (Start with T4 material)	168 to 174	335 to 345	6 to 10	Not critical

17 *Joining.*

Rivet compositions. 53 S-T61, 53 S-T4, 53 S-T6

Soft solder with Alcoa No. 800; Alcoa No. 61 flux.

Braze with Alcoa No. 717; Alcoa No. 33 flux; flame either reducing oxyacetylene or reducing oxyhydrogen.

Atomic-hydrogen weld with 43 alloy; Alcoa No. 22 flux.

Oxyacetylene weld with 43 alloy; Alcoa No. 22 flux; flame neutral.

Metal-arc weld with 43 alloy; Alcoa No. 27 flux.

Carbon-arc weld with 43 alloy; Alcoa No. 24 flux (automatic), Alcoa No. 27 flux (manual).

Tungsten-arc, argon atmosphere weld with 43 alloy; no flux.

Resistance welding. Spot, seam, and flash methods

References

See references for commercially pure aluminum.

Waldemar Naujoks, "Forging Handbook", American Society for Metals, 1942

* Compiled by Aluminum Company of America

Al – 2.5 Mg – 0.25 Cr*

A *2 Trade name.* 52 S alloy
3 ASTM number. B 209-46T, Alloy GR1 (sheet and plate); B 210-46T, Alloy GR1 (tubing)
4 Government number. QQ-A-318 (sheet and plate); QQ-A-315 (bar, rod, shapes, and wire); WW-T-787 (tubing)
6 Foreign equivalents. British DTD 440 (tubing)
B *1 Typical uses.* Applications where good workability, very good resistance to corrosion, high fatigue strength and moderate static strength are desired. Aircraft fuel and oil lines, fuel tanks, miscellaneous marine and transportation applications are typical.
C *1 Density* at 20 C (68 F). 2.68 g per cu cm (0.097 lb per cu in.)
D *1 Liquidus temperature.* 649 C (1200 F)
2 Solidus temperature. 593 C (1100 F)
6 Thermal expansion (condition O).

−60 to +20 C	(−76 to +68 F).	0.0000220 per °C
20 to 100 C	(68 to 212 F).	0.0000238 per °C
20 to 200 C	(68 to 392 F).	0.0000249 per °C
20 to 300 C	(68 to 572 F).	0.0000258 per °C

11 Specific heat at 100 C (212 F). Approx 0.23 cal per g
16 Thermal conductivity at 25 C (77 F). 0.33 cal/sq cm/cm/°C/sec, condition O; 0.33 cal/sq cm/cm/°C/sec, condition H38
19 Recrystallization temperature. 290 C (550 F) approx, 50% reduction
E *1 Volume conductivity* referred to standard copper. 35%, condition O; 35%, condition H38
2 Electrical resistivity at 20 C (68 F). 4.926 microhm-cm, condition O; 4.926 microhm-cm, condition H38
11 Electrolytic solution potential versus N/10 calomel electrode is 0.85 volt (53 g NaCl + 3 g H_2O_2 solution).
F *5 Emissivity* at 25 C (77 F). 0.035 to 0.07 in air
K *Mechanical Properties.* See Table I.
Modulus of elasticity 10,200,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33; torsional yield strength approximately 0.55 times the tensile yield strength; torsional ultimate strength approximately 0.65 times the tensile strength.
Strength and elongation at elevated temperatures after prolonged heating at the testing temperatures. See Table II.
2 Directional properties (various hard tempers of sheet). Tensile strength and elongation are slightly lower in transverse than in longitudinal direction.
L *2 Radiography.* Same as for 2 S alloy (commercially pure aluminum)
M *Composition Limits.* See Table III.
2 Consequences of exceeding impurity limits. High copper lowers resistance to corrosion. High iron plus silicon reduces formability. High silicon may reduce tensile properties.

Table I. Mechanical Properties of Al – 2.5 Mg – 0.25 Cr

Condition	Tensile Strength, (a) psi	Yield Strength, (b) psi	Elongation, (c) (d) %	Bhn (e)	Shear Strength, psi	Endurance Limit, (f) psi
Annealed O	29,000	14,000	25 30	45	18,000	17,000
H32	34,000	26,000	12 18	62	20,000	17,500
H34	37,000	29,000	10 14	67	21,000	18,000
H36	39,000	34,000	8 10	74	23,000	18,500
H38	41,000	36,000	7 8	85	24,000	19,000

(a) In general, strength and elongation are unchanged or improved at low temperatures.
(b) The compressive yield strength is approximately the same as the tensile yield strength.
(c) Sheet specimens $\frac{1}{16}$ in. thick
(d) Round specimens ½ in. in diam
(e) 500-kg load, 10-mm ball
(f) Based on 500,000,000 cycles using R. R. Moore type rotating-beam machine.

N *1 Melting temperature range.* 675 to 745 C (1250 to 1375 F).
3 Alloying. Add magnesium as pure metal to molten base metal (pure). Add chromium as pure aluminum-rich alloy to melt-down or molten base metal (pure).
7 Hot working temperature range. 260 to 510 C (500 to 950 F).
10 Maximum reduction between anneals. 50% or more depending on product
15 Heat Treatment. Annealing at 345 C (650 F); holding at temperature not required.

Table II. Strength and Elongation of Al – 2.5 Mg – 0.25 Cr

Property	Temperature, deg Fahr 75	300	400	500	600	700
Annealed O						
Tensile strength, psi....	29,000	23,000	18,000	12,000	7500	5000
Yield strength, psi.....	14,000	13,500	11,000	8,000	4000	2500
Elongation, %	30	55	65	100	105	120
Condition H36						
Tensile strength, psi....	39,000	32,000	25,000	12,000	8000	5000
Yield strength, psi.....	34,000	27,000	11,000	8,000	4500	2500
Elongation, %	10	16	35	80	100	120

17 Joining. Rivet compositions. Condition O: 2 S; all H tempers: A17 S-T4, 53 S-T61, 53 S-T4. *Other joining methods* same as for A 51 S (Al – 1.0 Si – 0.6 Mg – 0.25 Cr)

Table III. Composition Limits of Al – 2.5 Mg – 0.25 Cr

Form	Designation	Components: Mg min	Mg max	Cr min	Cr max	Impurities: Fe + Si max	Mn max	Cu max	Zn max	Others each max	Others total max
Sheet	QQ-A-318	2.20	2.80	0.15	0.35	0.45	0.10	0.10	0.03	0.03	0.10
Bar, rod, shapes and wire.....	QQ-A-315	2.20	2.80	0.15	0.35	0.45	0.10	0.10	0.10	0.05	0.15
Tubing	WW-T-787	2.20	2.80	0.15	0.35	0.45	0.10	0.10	0.03	0.03	0.10

Al – 1.3 Mg – 0.7 Si – 0.25 Cr*

A *2 Trade name.* 53 S alloy
4 Government number QQ-A-331 (bar, rod, shapes, and wire); QQ-A-367 Class 8 (forgings)
B *1 Typical uses.* Applications where good workability, very good resistance to corrosion, and moderate strength are required. Petroleum refining equipment, beer barrels, miscellaneous naval construction and architectural applications are typical.
C *1 Density* at 20 C (68 F). 2.69 g per cu cm (0.097 lb per cu in.)
D *1 Liquidus temperature.* 652 C (1205 F)
2 Solidus temperature. 579 C (1075 F)
6 Thermal expansion.

		Condition O	*Condition T6*
−60 to +20 C	(−76 to +68 F).	.....	0.0000217 per °C
20 to 100 C	(68 to 212 F).	0.0000229	0.0000235 per °C
20 to 200 C	(68 to 392 F).	0.0000241	..... per °C
20 to 300 C	(68 to 572 F).	0.0000251	..... per °C

11 Specific heat at 100 C (212 F). Approx 0.23 cal per g
16 Thermal conductivity at 25 C (77 F). 0.41 cal/sq cm/cm/°C/sec, condition O; 0.37 cal/sq cm/cm/°C/sec, conditions T4 and T6
19 Recrystallization temperature. 345 C (650 F) approx, 75% reduction
E *1 Volume conductivity* referred to standard copper. 45%, condition O; 40%, conditions T4 and T6

* Compiled by Aluminum Company of America

2 *Electrical resistivity* at 20 C (68 F). 3.831 microhm-cm, condition O; 4.310 microhm-cm, conditions T4 and T6
11 *Electrolytic solution potential* versus N/10 calomel electrode is 0.83 volt, condition T6 (53 g NaCl + 3 ■ H_2O_2 solution).
F 5 *Emissivity* at 25 C (77 F). 0.035 to 0.07 in air
K *Mechanical Properties.*

Condition	Tensile Strength, (a) psi	Yield Strength, (b) psi	Elongation, (c) %	Bhn (d)	Shear Strength, psi	Endurance Limit, (e) psi
O	16,000	7,000	35	26	11,000	8,000
T4	33,000	20,000	30	65	20,000	13,000
T6	39,000	33,000	20	80	24,000	13,000

(a) In general, strengths and elongation are unchanged or improved at low temperatures.
(b) The compressive yield strength is approximately the same as the tensile yield strength.
(c) Round specimens ½ in. diam
(d) 500-kg load, 10-mm ball
(e) Based on 500,000,000 cycles using R. R. Moore type rotating-beam machine

Modulus of elasticity 10,000,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33; torsional yield strength approximately 0.55 times the tensile yield strength; torsional ultimate strength approximately 0.65 times the tensile strength.
Strength and elongation at elevated temperatures after prolonged heating at testing temperatures.

Property	Temperature, deg Fahr: 75	300	400	500	600	700
Condition T6						
Tensile strength, psi....	39,000	25,000	13,000	6,000	3,500	2,500
Yield strength, psi.....	33,000	22,000	10,000	3,500	2,500	2,000
Elongation, %	20	17	30	70	75	90

2 *Directional properties* (all tempers of sheet). Tensile strength and elongation are approximately equal in longitudinal and transverse directions.

L 2 *Radiography.* Same as for 2S alloy (commercially pure aluminum)
M *Composition Limits.* See Table I.
2 *Consequences of exceeding impurity limits.* High copper lowers resistance to corrosion.
N 1 *Melting temperature range.* 675 to 745 C (1250 to 1375 F)
3 *Alloying.* Add magnesium as pure metal to molten base metal (pure). Add chromium as aluminum-rich alloy to melt-down or molten base metal (pure). Add silicon as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy.
7 *Hot working temperature range.* 260 to 510 C (500 to 950 F).
10 *Maximum reduction between anneals.* 70% or more depending on product
15 *Heat treatment.*

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hr	Cooling
Complete annealing O	399 to 427	750 to 800	2	Furnace-cool to 500 F (50° F per hr max)
Removal of cold work	343	650	No holding time required	Not critical
Solution heat treatment T4	516 to 527	960 to 980	10 min to 1 hr (salt bath) Longer time in air	Cold water quench Heavy or complicated forgings, water 150 to 212 F
Precipitation T6 (Start with T4 material)	157 to 163	315 to 325	16 to 20	Not critical
	174 to 179	345 to 355	or 6 to 10	Not critical

17 *Joining.*
Rivet compositions. Conditions T4 and T6; 53S-T61, 53S-T4, 53S-T6, steel
Other joining methods same as for A 51S (Al – 1.0 Si – 0.6 Mg – 0.25 Cr)

Table I. Composition Limits of Al – 1.3 Mg – 0.7 Si – 0.25 Cr

	Designation	Components: Mg min	Mg max	Cr min	Cr max	Si min	Si max	Impurities: Fe max	Cu max	Zn max	Ti max	Others each max	Others total max
Bar, rod, shapes and wire.....	QQ-A-331	1.10	1.40	0.15	0.35	not <0.45 of Mg	not >0.65 of Mg	0.35	0.10	0.10	0.15	0.05	0.15
Forgings	QQ-A-367 Class 8	1.10	1.40	0.15	0.35	not <0.45 of Mg	not >0.65 of Mg	0.35	0.10	0.25	0.15	0.05	0.15

Al – 5.2 Mg – 0.1 Mn – 0.1 Cr*

A 2 *Trade name.* 56S alloy
4 *Government number.* AN-QQ-W-298 (wire)
6 *Foreign equivalents.* British DTD-303 (bar, rod, shapes and wire)
B 1 *Typical uses.* Applications where wire products of good resistance to corrosion are required. Rivets for use with magnesium alloy and cable sheathing are typical.
C 1 *Density* at 20 C (68 F). 2.64 g per cu cm (0.095 lb per cu in.)
D 1 *Liquidus temperature.* 638 C (1180 F)
2 *Solidus temperature.* 568 C (1055 F)
6 *Thermal expansion* (condition O).

–60 to +20 C (–76 to +68 F).	0.0000223 per °C
20 to 100 C (68 to 212 F).	0.0000243 per °C
20 to 200 C (68 to 392 F).	0.0000254 per °C
20 to 300 C (68 to 572 F).	0.0000263 per °C

11 *Specific heat* at 100 C (212 F). Approx 0.23 cal per g
16 *Thermal conductivity* at 25 C (77 F). 0.28 cgs, condition O; 0.26 cgs, condition H38
E 1 *Volume conductivity* referred to standard copper. 29%, condition O; 27%, condition H38
2 *Electrical resistivity* at 20 C (68 F). 5.945 microhm-cm, condition O; 6.386 microhm-cm, condition H38

*Compiled by Aluminum Company of America

11 *Electrolytic solution potential* versus N/10 calomel electrode is 0.87 volts (53 g NaCl + 3 ■ H_2O_2 solution).
F 5 *Emissivity* at 25 C (77 F). 0.035 to 0.07 in air
K *Mechanical Properties.*

Condition	Tensile Strength, (a) psi	Yield Strength, (b) psi	Elongation, (c) percentage	Endurance Limit, (d) psi
O	42,000	20,000	35	20,000
H38	58,000	48,000	7	22,000

(a) In general, strengths and elongation are unchanged or improved at low temperatures.
(b) The compressive yield strength is approximately the same as the tensile yield strength.
(c) Round specimens ½ in. diam
(d) Based on 500,000,000 cycles using R. R. Moore type rotating-beam machine

Modulus of elasticity 10,300,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33; torsional yield strength approximately 0.55 times the tensile yield strength; torsional ultimate strength approximately 0.65 times the tensile strength.
L 2 *Radiography.* Type A or 506 film with no intensifying screen, cardboard exposure holder, 36-in. focal distance. General Electric OX-10 unit, 2.1 H&D film density. For data, see Table I on the next page.

Table I. Radiography of Al – 5.2 Mg – 0.1 Mn – 0.1 Cr

Section, in.	Volts	Milliamperes	Time, min
½	60,000	10.0	1.0
1	90,000	6.7	1.0
1½	120,000	5.0	1.0
2	140,000	5.0	1.0

M *Composition Limits.* Wire (AN-QQ-W-298), *components:* 4.5 to 5.6% Mg; 0.05 to 0.20% Mn; 0.05 to 0.20% Cr; *impurities:* 0.10% max Cu; 0.30% max Si; 0.30% max Fe; others (each) 0.05% max; others (total) 0.15% max.

2 Consequences of exceeding impurity limits. High copper lowers resistance to corrosion. High silicon may reduce tensile properties.

N *1 Melting temperature.* 675 to 745 C (1250 to 1375 F)

3 Alloying. Add magnesium as pure metal to molten base metal (pure). Add manganese as aluminum-rich alloy to melt-down or molten base metal (pure). Add chromium as aluminum-rich alloy to melt-down or molten base metal (pure).

7 Hot working temperature. 260 to 510 C (500 to 950 F)

10 Maximum reduction between anneals 50% or more depending on product

15 Heat treatment. Annealing at 345 C (650 F); holding at temperature not required.

17 Joining.
Rivet compositions. 56 S (if any applications)
Metal-arc weld with 56 S alloy; Alcoa No. 27 flux.
Carbon-arc weld with 56 S alloy; Alcoa No. 24 flux (automatic), Alcoa No. 27 flux (manual).
Tungsten-arc, argon atmosphere weld with 56 S alloy; no flux.
Resistance welding. Spot, seam, and flash methods

Al – 1.0 Mg – 0.6 Si – 0.25 Cu – 0.25 Cr*

A *2 Trade name.* 61 S alloy

3 ASTM number. B 209-46T, Alloy GS21 (sheet and plate); B 211-46T, Alloy GS21 (bar, rod and wire); B 210-46T, Alloy GS21 (tubing)

4 Government number. QQ-A-327 (sheet and plate); QQ-A-325 (bar, rod, shapes, and wire); WW-T-789 (tubing)

B *1 Typical uses.* Applications where good strength, workability and very good resistance to corrosion are required. Aircraft landing mats, pontoon boats, canoes, furniture, vacuum cleaner tubing and transportation equipment are typical.

C *1 Density* at 20 C (68 F). 2.70 g per cu cm (0.098 lb per cu in.)

D *1 Liquidus temperature.* 652 C (1205 F)

2 Solidus temperature. 582 C (1080 F)

6 Thermal expansion.

	Condition O	*Condition T6*
−60 to +20 C (−76 to +68 F).	.....	0.0000216 per °C
20 to 100 C (68 to 212 F).	0.0000235	0.0000235 per °C
20 to 200 C (68 to 392 F).	0.0000243	..... per °C
20 to 300 C (68 to 572 F).	0.0000254	..... per °C

11 Specific heat at 100 C (212 F). Approx 0.23 cal per g

16 Thermal conductivity at 25 C (77 F). 0.41 cal/sq cm/cm/°C/sec, condition O; 0.37 cal/sq cm/cm/°C/sec, conditions T4 and T6

19 Recrystallization temperature. 345 C (650 F) approx, 75% reduction

E *1 Volume conductivity* referred to standard copper. 45%, condition O; 40%, conditions T4 and T6

2 Electrical resistivity at 20 C (68 F). 3.831 microhm-cm, condition O; 4.310 microhm-cm, conditions T4 and T6

11 Electrolytic solution potential versus N/10 calomel electrode is 0.80 volt, condition T4; 0.83 volt, condition T6 (53 g NaCl + 3 g H_2O_2 solution).

F *5 Emissivity* at 25 C (77 F). 0.035 to 0.07 in air

K *Mechanical Properties.*

Condition	Tensile Strength, (a) psi	Yield Strength, (b) psi	Elongation, (c) %	Elongation, (d) %	Bhn (e)	Shear Strength, psi	Endurance Limit, (f) psi
O	18,000	8,000	22	30	30	12,500	9,000
T4	35,000	21,000	22	28	65	24,000	13,500
T6	45,000	40,000	12	15	95	30,000	13,500

(a) In general, strengths and elongation are unchanged or improved at low temperatures.
(b) The compressive yield strength is approximately the same as the tensile yield strength.
(c) Sheet specimens $\frac{1}{16}$ in. thick
(d) Round specimens ½ in. in diam
(e) 500-kg load, 10-mm ball
(f) Based on 500,000,000 cycles using R. R. Moore type rotating-beam machine

Modulus of elasticity 10,000,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33; torsional yield strength approximately 0.55 times the tensile yield strength; torsional ultimate strength approximately 0.65 times the tensile strength.
Strength and elongation at elevated temperatures after prolonged heating at testing temperatures.

Property	Temperature, deg Fahr: 75	300	400	500	600	700
	Condition T6					
Tensile strength, psi.....	45,000	31,000	19,000	7500	3500	3000
Yield strength, psi.....	40,000	29,000	15,000	5000	2500	2000
Elongation, %	15	■	29	55	90	105

2 Directional properties (all tempers of sheet). Tensile strength and elongation are approximately equal in the longitudinal and transverse directions.

L *2 Radiography.* Same as for 2 S alloy (commercially pure aluminum)

M *Composition Limits.* See Table I (next page).

2 Consequences of exceeding impurity limits. High iron will reduce formability and may reduce resistance to corrosion.

N *1 Melting temperature range.* 675 to 745 C (1250 to 1375 F)

3 Alloying. Add magnesium as pure metal to molten base metal (pure). Add silicon as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add chromium as aluminum-rich alloy to melt-down or molten base metal (pure).

7 Hot working temperature range. 260 to 510 C (500 to 950 F)

10 Maximum reduction between anneals. 70% or more depending on product

15 Heat treatment.

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Cooling
Complete annealing O	399 to 427	750 to 800	2	Furnace-cool to 500 F (50 °F per hr max)
Removal of cold work	343	650	No holding time required	Not critical
Solution heat treatment T4.	516 to 527	960 to 980	10 min to 1 hr (salt bath) Longer time in air	Cold water quench
Precipitation T6 (Start with T4 material)	157 to 163	315 to 325	16 to 20 or	Not critical
..	174 to 179	345 to 355	6 to 10	Not critical

17 Joining.
Rivet compositions. Conditions T4 and T6; 53 S-T61, 53 S-T4, 53 S-T6, or steel.
Other joining methods same as for A 51 S (Al-1.0 Si-0.6 Mg – 0.25 Cr)

* Compiled by Aluminum Company of America

Table I. Composition Limits of Al–1.0 Mg–0.6 Si–0.25 Cu–0.25 Cr

Form	Designation	Components: Mg min	Mg max	Si min	Si max	Cu min	Cu max	Cr min max	Impurities: Fe max	Ti max	Mn max	Zn max	Others each max	Others total max
Sheet	QQ-A-327	0.80	1.2	0.40	0.80	0.15	0.40	0.35 max	0.70	0.15	0.15	0.20	0.03	0.10
Bar, rod, shapes and wire	QQ-A-325	0.80	1.2	0.40	0.80	0.15	0.40	0.15–0.35	0.70	0.15	0.15	0.20	0.05	0.15
Tubing	WW-T-789	0.80	1.2	0.40	0.80	0.15	0.40	0.35 max	0.70	0.15	0.15	0.20	0.03	0.10

Al–5.5 Zn–2.5 Mg–1.5 Cu–0.3 Cr–0.2 Mn*

A 2 *Trade name.* 75S alloy

3 *ASTM number.* B 209–46T, Alloy ZG42 and clad ZG42 (sheet and plate, bare and clad)

4 *Government number.* AN–A–9 (sheet and plate, bare); AN–A–10 (sheet and plate, clad); AN–A–11 (shapes)

B 1 *Typical uses.* Applications where very good strength and good resistance to corrosion are required. Aircraft structural parts are the most typical application. Other structural applications are becoming important.

C 1 *Density* at 20 C (68 F). 2.80 g per cu cm (0.101 lb per cu in.)

D 1 *Liquidus temperature.* 638 C (1180 F)

2 *Solidus temperature.* 476 C (890 F)

6 *Thermal expansion.*

	Condition O	Condition T6
−60 to +20 C (−76 to +68 F)	.....	0.0000216 per °C
20 to 100 C (68 to 212 F)	0.0000232	0.0000236 per °C
20 to 200 C (68 to 392 F)	0.0000242	..... per °C
20 to 300 C (68 to 572 F)	0.0000260	..... per °C

11 *Specific heat* at 100 C (212 F). Approx 0.23 cal per g

16 *Thermal conductivity* at 25 C (77 F). 0.29 cal/sq cm/cm/°C/sec, condition T6

19 *Recrystallization temperature.* 415 C (775 F) approx, 50% reduction

E 1 *Volume conductivity* referred to standard copper. 30%, condition T6

2 *Electrical resistivity* at 20 C (68 F). 5.747 microhm-cm, condition T6

11 *Electrolytic solution potential* versus N/10 calomel electrode is 0.88 volt, condition W; 0.81 volt, condition T6 (53 g NaCl + 3g H_2O_2 solution).

F 5 *Emissivity* at 25 C (77 F). 0.035 to 0.07 in air

K *Mechanical Properties.*

Condition	Tensile Strength, (a) psi	Yield Strength, (b) psi	Elongation (c) %	Elongation (d) %	Bhn (e)	Modulus of Elasticity,	Shear Strength, psi
Extrusions							
O	40,000	20,000	..	■	...	10,400,000	.....
T6	88,000	80,000	..	10	150	10,400,000	47,000
Other Bare Products							
O	33,000	15,000	17	12	...	.....	.....
T6	82,000	72,000	11	10	150	.....	.....
Clad Sheet							
O	32,000	14,000	16	..	...	10,400,000 (primary) 9,600,000 (secondary)	.....
T6	76,000	66,000	11	..	...	10,400,000 (primary) 9,600,000 (secondary)	46,000

(a) In general, strengths and elongation are unchanged or improved at low temperatures.
(b) The compressive yield strength is approximately the same as the tensile yield strength
(c) Sheet specimens $\frac{1}{16}$ in. thick
(d) Round specimens ½ in. in diam
(e) 500-kg load, 10-mm ball

Endurance limit (500,000,000 cycles) extrusions, condition T6, 22,500 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33; torsional yield strength approximately 0.55 times the tensile yield strength; torsional ultimate strength approximately 0.65 times the tensile strength.

Strength and elongation at elevated temperatures after prolonged heating at the testing temperatures.

Property	Temperature, deg Fahr: 75	300	400	500	600	700
Condition T6 (extrusions)						
Tensile strength, psi	88,000	25,000	15,000	12,000	8500	6500
Yield strength, psi	80,000	22,000	12,000	8,000	6000	5000
Elongation, %	10	32	55	60	68	75

2 *Directional properties* (all tempers of sheet). Tensile strength and elongation are approximately equal in the longitudinal and transverse directions.

L 2 *Radiography.* Same as for 14S alloy (Al–4.4 Cu–0.8 Si–0.8 Mn–0.4 Mg)

M *Composition Limits.* See Table I (next page).

2 *Consequences of exceeding impurity limits.*
Core. High iron increases segregation difficulties, adversely affects formability and may reduce resistance to corrosion. High silicon will reduce mechanical properties. Nickel reduces resistance to corrosion. Lead produces hot shortness.
Cladding. High copper lowers potential difference between cladding and core.

N 1 *Melting temperature.* 675 to 745 C (1250 to 1375 F)

3 *Alloying.* Add zinc as pure metal to molten base metal (pure). Add magnesium as pure metal to molten base metal (pure). Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add manganese as aluminum-rich alloy to melt-down or molten base metal (pure). Add chromium as aluminum-rich alloy to melt-down or molten base metal (pure).

7 *Hot working temperature.* 260 to 455 C (500 to 850 F)

10 *Maximum reduction between anneals.* 40% or more depending on product.

15 *Heat treatment.*

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Cooling
Complete annealing O	413 to 454	775 to 850	2	Air cool
followed by	232	450	4	Not critical
Removal of cold work	413	775	No holding time required	Not critical
Solution heat treatment W.	460 to 499	860 to 930(a)	10 min to 1 hr (salt bath) Longer time in air	Cold water quench
Precipitation T6 (Start with W material)	118 to 124	245 to 255	22 to 26	Not critical
or heat to	96 to 102	205 to 215	4 to 6 (b)	
and then cool to room temp and reheat to	154 to 160	310 to 320	8 to 10	Not critical

(a) Extrusions must be heated between 860 and 880 F
(b) U. S. Patent 1,858,092

17 *Joining.* Same as for 17S (Al–4 Cu–0.5 Mg–0.5 Mn)

* Compiled by Aluminum Company of America

Table I. Composition Limits of Al – 5.5 Zn – 2.5 Mg – 1.5 Cu – 0.3 Cr – 0.2 Mn

Form	Designation	Components										Impurities				
		Zn min	Zn max	Mg min	Mg max	Cu min	Cu max	Mn min	Mn max	Cr min	Cr max	Fe max	Si max	Ti max	Others each max	Others total max
Bare Products																
Sheet	AN-A-9	5.10	6.10	2.1	2.9	1.2	2.0	0.10	0.30	0.15	0.40	0.70	0.50	0.20	0.05	0.15
Clad Sheet	AN-A-10															
Core		5.10	6.10	2.1	2.9	1.2	2.0	0.10	0.30	0.15	0.40	0.70	0.50	0.20	0.05	0.15
Cladding		0.75	1.25	..	0.10	..	0.10	...	0.10	...	...	Fe + Si 0.70		...	0.05	0.15

Al – 6.4 Zn – 2.5 Mg – 1.2 Cu

COMPILED BY L. E. HOUSEHOLDER*

A *2 Trade name.* R 303

B *1 Typical uses.* Aircraft and other transportation

2 Precautions in use. To ensure meeting the specified mechanical properties and to obtain maximum resistance to stress-corrosion cracking, the prescribed heat treating practices should be followed carefully.

C *1 Density* at 20 C (68 F). 2.82 g per cu cm (0.102 lb per cu in.)

E *11 Electrolytic solution potential* of T temper versus saturated calomel electrode is minus 0.77 volt.

I *1 General resistance to corrosion.* The corrosion resistance is best if the heat treating practices are followed carefully. The T315 temper is somewhat more resistant than other tempers to both general corrosion and stress-corrosion cracking. For maximum resistance to corrosion the clad sheet is recommended.

K *Mechanical Properties.*

Condition	Section, in.	Tensile Strength, psi	Yield Strength, psi	Elongation in 2 in., percentage	Rockwell Hardness
Annealed	0.064 sheet	30,000	15,000	18	E 57 to 62
Quenched T275 and aged T315	0.064 sheet	79,000	73,000	9	B 89 to 93
		75,000	69,000	9	B 87 to 91
Quenched T275 and aged T315	extrusions	85,000	80,000	9	.....
	extrusions	79,000	73,000	9	.....

Shear strength (T275) 48,000 psi, (T315) 47,000 psi
Other mechanical properties (same for both T275 and T315)
Modulus of elasticity. 10,400,000 psi.
Endurance limit (500,000,000 cycles). 23,000 psi
Shear modulus. 3,900,000 psi
Compressive yield strength. Same as tensile yield strength
Bearing yield strength. Edge distance 1.50*D*, 1.4 times tensile yield. Edge distance 2.00*D*, 1.6 times tensile yield
Bearing ultimate strength. Edge distance 1.50*D*, 1.5 times tensile strength
Edge distance 2.00*D*, 1.9 times tensile strength

L *1 Metallography.* Etching, grain size (T condition) HNO_3-CH_3COOH (*see reference*); etching, microstructure (*see reference*).

3 Corrosion test commonly used. NaCl + H_2O_2, *see* Spec. AN-QQ-H-186a for detail.

N *7 Hot working temperature range.* 370 to 425 C (700 to 800 F)

9 Annealing temperature. 355 to 370 C (675 to 700 F), cool to 450 F and soak for 4 hr.

11 Suited to forming by drawing, drop-hammer forging, stretcher forming, coining or machining. Very little forming can be done in the T condition, but the alloy has good formability in the annealed temper or in the freshly quenched condition.

12 Precautions in forming. When forming in the freshly quenched condition, the forming should be done within one hour after quenching, or the alloy should be stored in dry ice until ready.

15 Heat treatment.

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Atmosphere	Cooling
Solution heat treatment	432 to 449	810 to 840	Depends on thickness	Air or nitrate bath	Cold water
Age harden T275	132 to 138	270 to 280	24	Air	Air
Age harden T315	154 to 160	310 to 320	8	Air	Air
Incubation period	Room temperature		24		

17 Joining. Rivet compositions. 24 S-T4 or 17 S-T4. *Soldering, brazing, gas welding and carbon-arc welding* are not recommended. *Spot welding* of bare sheet is not recommended. Clad sheet can be spot welded satisfactorily.

* Chief Plant Metallurgist, Reynolds Metals Company, Grand Rapids, Mich.

Reference. Paul P. Zeigler, L. E. Householder and H. N. Logsdon, Aluminum Alloy R 303, Iron Age, Oct. 4, 1945

CASTING ALLOYS

Al – 12 Si*

A *2 Trade name.* 13 alloy (die casting)
3 ASTM number. B 85–46T, Alloy S5
4 Government number. QQ–A–591, Class 1 (die casting)

B *1 Typical uses.* Applications where excellent castability and resistance to corrosion are required. Miscellaneous thin-walled and intricately designed castings are typical.

C *1 Density* at 20 C (68 F). 2.66 g per cu cm (0.096 lb per cu in.)

D *1 Liquidus temperature.* 585 C (1085 F)
2 Solidus temperature. 574 C (1065 F)
6 Thermal expansion

20 to 100 C (68 to 212 F). 0.0000200 per °C
20 to 200 C (68 to 392 F). 0.0000205 per °C
20 to 300 C (68 to 572 F). 0.0000215 per °C

11 Specific heat at 100 C (212 F). Approx 0.23 cal per g
13 Latent heat of fusion. Approx 93 cal per g
16 Thermal conductivity at 25 C (77 F). 0.37 cal/sq cm/cm/°C/sec

E *1 Volume conductivity* referred to standard copper. 39%
2 Electrical resistivity at 20 C (68 F). 4.421 microhm-cm

F *5 Emissivity.* 0.035 to 0.07 at 25 C (77 F) in air

K *Mechanical Properties. Die cast:* Tensile strength 37,000 psi; yield strength 18,000 psi; elongation (round specimens, ¼-in. diam) 1.8%; modulus of elasticity 10,300,000 psi; endurance limit (based on 500,000,000 cycles using R. R. Moore type of rotating-beam machine) 15,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.

L *2 Radiography.* Type A or 506 film using no intensifying screen, cardboard exposure holder, 36-in. focal distance, General Electric OX–10 unit, 2.1 H&D film density.

* Compiled by Aluminum Company of America

Section, in.	Volts	Milliamperes	Time, min
½	60,000	10.0	1.0
1	90,000	6.7	1.0
1½	120,000	5.0	1.0
2	140,000	5.0	1.0

M *Composition Limits. Die cast* (QQ–A–591, Class 1), *components:* 11.0 to 13.0% Si; *impurities:* 2.0% max Fe; 0.60% max Cu; 0.10% max Mg; 0.30% max Mn; 0.50% max Zn; 0.50% max Ni; 0.10% max Sn; others (total) 0.20% max.

2 *Consequences of exceeding impurity limits.* Relatively large quantities of impurities may be present before serious effects are detected. In general, increasing copper will lower resistance to corrosion and increasing iron and magnesium will lower ductility.

N 1 *Melting temperature range.* 649 to 760 C (1200 to 1400 F)

2 *Die-casting temperature range.* 635 to 704 C (1175 to 1300 F)

3 *Alloying.* Add silicon as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy.

5 *Type of flux* for remelting for casting. Gaseous type, nitrogen or chlorine; or solid, aluminum chloride base

17 *Joining.*
Rivet compositions. 53 S-T4, 53 S-T6, 53 S-T61
Soft solder after copper plating, then use methods applicable to copper-base alloys.
Resistance welding. Flash method

Al – 5 Si*

A 2 *Trade name.* 43 alloy (sand casting, permanent mold casting and die casting)

3 *ASTM number.* B 85-46T, Alloy S4 (die casting); B 26-46T, Alloy S1 and S2 (sand); B 108–46T, Alloy S1 and S2 (permanent mold)

4 *Government number.* QQ-A-591, Class 3 (die casting); QQ–A-601, Class 2 (sand); QQ–A-596, Class 7 (permanent mold)

B 1 *Typical uses. Die casting:* applications where above-average ductility and excellent resistance to corrosion are required.
Sand and permanent mold casting: applications where very good castability and resistance to corrosion with moderate strength are required. Cooking utensils, food-handling equipment, marine fittings and miscellaneous thin-section castings are typical.

C 1 *Density* at 20 C (68 F). 2.69 g per cu cm (0.097 lb per cu in.)

D 1 *Liquidus temperature.* 629 C (1165 F)

2 *Solidus temperature.* 577 C (1070 F)

6 *Thermal expansion*

20 to 100 C (68 to 212 F). 0.0000220 per °C
20 to 200 C (68 to 392 F). 0.0000230 per °C
20 to 300 C (68 to 572 F). 0.0000240 per °C

11 *Specific heat* at 100 C (212 F). Approx 0.23 cal per g

13 *Latent heat of fusion.* Approx 93 cal per g

16 *Thermal conductivity* at 25 C (77 F). 0.35 cal/sq cm/cm/°C/sec, as cast; 0.39 cal/sq cm/cm/°C/sec, annealed*

E 1 *Volume conductivity* referred to standard copper.
37%, as cast (sand, permanent mold and die castings)
42%, annealed (sand and permanent mold)*

2 *Electrical resistivity* at 20 C (68 F)
4.660 microhm-cm, as cast (sand, permanent mold and die castings)
4.105 microhm-cm, annealed (sand and permanent mold)*

11 *Electrolytic solution potential* versus N/10 calomel electrode is 0.83 volt, sand cast; 0.82 volt, permanent mold cast (53 g NaCl + 3 g H_2O_2 solution)

F 5 *Emissivity.* 0.035 to 0.07 at 25 C (77 F) in air

K *Mechanical Properties.* See Table I.
Modulus of elasticity 10,300,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.

L 2 *Radiography.* Same as for 13 alloy (Al – 12 Si)

M *Composition Limits.* See Table II.

2 *Consequences of exceeding impurity limits.* For die-cast alloy, relatively large quantities of impurities may be present before serious effects are detected. In general, increasing copper will tend to lower resistance to corrosion and increasing iron and magnesium will tend to lower ductility.
For the sand and permanent mold cast alloys, high copper, iron, or nickel decrease ductility and resistance to corrosion. Increasing magnesium reduces ductility.

N 1 *Melting temperature range.*
649 to 760 C (1200 to 1400 F) (die casting)
677 to 816 C (1250 to 1500 F) (sand and permanent mold casting)

2 *Casting temperature range.*
635 to 704 C (1175 to 1300 F) (die casting)
677 to 788 C (1250 to 1450 F) (sand and permanent mold casting)

3 *Alloying.* Add silicon as pure metal or aluminum-rich alloy to molten base metal (pure), either in melt-down or molten alloy.

5 *Type of flux* for remelting for casting. Gaseous type,

* Compiled by Aluminum Company of America
* Sand and permanent mold castings are not usually annealed

Table I. Mechanical Properties of Al – 5 Si

Form	Tensile Strength,[a] psi	Yield Strength, psi	Elongation,[b] percentage	Elongation,[c] percentage	Brinell Hardness Number[d]	Shear Strength, psi	Endurance Limit,[e] psi	Compressive Yield Strength, psi
Die cast	30,000	14,000	7.0	..	..	.....	....	.....
Sand cast	19,000	9,000	..	6.0	40	14,000	6,500	10,000
Permanent mold cast	24,000	9,000	..	9.0	45	18,000	....	9,000

(a) In general, strengths and elongations remain unchanged or improve at low temperatures.
(b) Round specimens, ¼-in. diam
(c) Round specimens, ½-in. diam
(d) 500-kg, 10-mm ball
(e) Based on 500,000,000 cycles using R. R. Moore type of rotating-beam machine.

Table II. Composition Limits of Al – 5 Si

Form	Designation	Components: Si min	Components: Si max	Impurities: Fe max	Cu max	Mg max	Mn max	Zn max	Ti max	Others total max
Die cast	QQ-A-591, Class 3	4.5	6.0	2.00	0.60	0.10	0.30	0.50	...	0.20
Sand cast	QQ-A-601, Class 2	4.5	6.0	0.80	0.10	0.05	0.10	0.20	0.20	0.10
Permanent mold cast	QQ-A-596, Class 7	4.5	6.0	0.80	0.10	0.05	0.10	0.10	0.20	0.10

nitrogen or chlorine; or solid type, aluminum chloride base.

17 *Joining.*
Rivet compositions. 53 S-T4, 53 S-T6, 53 S-T61
Soft solder with copper plate and use methods applicable to copper-base alloys, for die-cast alloy. Use Alcoa No. 802, no flux, or rub-tin with Alcoa No. 802 for sand and permanent mold castings.
The following details apply only to the sand and permanent mold casting alloys, unless otherwise noted.
Braze with Alcoa No. 717; Alcoa No. 33 flux; flame either reducing oxyacetylene or reducing oxyhydrogen.
Atomic-hydrogen weld with 43 alloy; Alcoa No. 22 flux.
Oxyacetylene weld with 43 alloy; Alcoa No. 22 flux; neutral flame.
Metal-arc weld with 43 alloy; Alcoa No. 27 flux.
Carbon-arc weld with 43 alloy; Alcoa No. 24 flux (automatic), Alcoa No. 27 (manual).
Tungsten-arc, argon atmosphere weld with 43 alloy; no flux.
Resistance weld. Flash method for die-cast alloys. Spot, seam and flash methods for sand and permanent mold cast alloys.

Al – 5 Si – 4 Cu*

A 2 *Trade name.* 85 alloy (die casting)
3 *ASTM number.* B 85-46T, Alloy SC2
4 *Government number.* QQ-A-591, Class 5
B 1 *Typical uses.* General-purpose applications
C 1 *Density* at 20 C (68 F). 2.78 ■ per cu cm (0.101 lb per cu in)
D 1 *Liquidus temperature.* 613 C (1135 F)
2 *Solidus temperature.* 521 C (970 F)
6 *Thermal expansion*
20 to 100 C (68 to 212 F). 0.0000210 per °C
20 to 200 C (68 to 392 F). 0.0000220 per °C
20 to 300 C (68 to 572 F). 0.0000230 per °C
11 *Specific heat* at 100 C (212 F). Approx 0.23 cal per ■
13 *Latent heat of fusion.* Approx 93 cal per ■
16 *Thermal conductivity* at 25 C (77 F). 0.27 cal/sq cm/cm/°C/sec
E 1 *Volume conductivity* referred to standard copper. 28%
2 *Electrical resistivity* at 20 C (68 F). 6.158 microhm-cm
F 5 *Emissivity.* 0.035 to 0.07 at 25 C (77 F) in air
K *Mechanical Properties. Die cast:* Tensile strength 40,000 psi; yield strength 22,000 psi; elongation (round specimens, ¼-in. diam) 3.5%; modulus of elasticity 10,300,000 psi; endurance limit (based on 500,000,000 cycles using R. R. Moore type of rotating-beam machine) 17,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.
L 2 *Radiography.* Type A or 506 film using no intensifying screen, cardboard exposure holder, 36-in. focal distance, General Electric OX-10 unit, 2.1 H&D film density.

Section, in.	Volts	Milliamperes	Time, min
½	70,000	9.0	1.0
1	100,000	7.0	1.0
1½	135,000	5.0	1.0
2	140,000	5.0	1.8

M *Composition Limits.* Die cast (QQ-A-591, Class 5), *components:* 3.5 to 4.5% Cu; 4.5 to 5.5% Si; *impurities*: 2.3% max Fe; 0.10% max Mg; 0.30% max Mn; 1.00% max Zn; 0.50% max Ni; 0.30% max Sn; others (total) 0.20% max.
2 *Consequences of exceeding impurity limits.* Relatively large quantities of impurities may be present before serious effects are detected. In general, increasing iron will tend to lower ductility.
N 1 *Melting temperature.* 649 to 760 C (1200 to 1400 F)
2 *Die-casting temperature.* 635 to 704 C (1175 to 1300 F)
3 *Alloying.* Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add silicon as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy.
5 *Type of flux* for remelting for casting. Gaseous type, nitrogen or chlorine; or solid, aluminum chloride base
17 *Joining.* Same as for 13 alloy (Al-12 Si)

Al – 4 Cu – 3 Si*

A 2 *Trade name.* 108 alloy (sand casting)
4 *Government number.* QQ-A-601, Class 8
B 1 *Typical uses.* Applications where good casting characteristics, good weldability, pressure tightness, and moderate strength are required. Manifolds, valve bodies, and similar castings requiring pressure tightness are typical.
C 1 *Density* at 20 C (68 F). 2.79 g per cu cm (0.101 lb per cu in.)
D 1 *Liquidus temperature.* 632 C (1170 F)
2 *Solidus temperature.* 521 C (970 F)
6 *Thermal expansion*
20 to 100 C (68 to 212 F). 0.0000220 per °C
20 to 200 C (68 to 392 F). 0.0000230 per °C
20 to 300 C (68 to 572 F). 0.0000240 per °C
11 *Specific heat* at 100 C (212 F). Approx 0.23 cal per g
13 *Latent heat of fusion.* Approx 93 cal per g
16 *Thermal conductivity* at 25 C (77 F). 0.29 cal/sq cm/cm/°C/sec
E 1 *Volume conductivity* referred to standard copper. 31%
2 *Electrical resistivity* at 20 C (68 F). 5.562 microhm-cm
11 *Electrolytic solution potential* versus N/10 calomel electrode is 0.77 volts (53 g NaCl + 3 g H_2O_2 solution)
F 5 *Emissivity.* 0.035 to 0.07 at 25 C (77 F) in air
K *Mechanical Properties. Sand cast:* Tensile strength 21,000 psi; yield strength 14,000 psi; compressive yield strength 14,000 psi; elongation (round specimen, ½-in. diam) 2.5%; Bhn (500-kg load, 10-mm ball) 55; modulus of elasticity 10,300,000 psi; shear strength 20,000 psi; endurance limit (based on 500,000,000 cycles using R. R. Moore type of rotating-beam machine) 8000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.
L 2 *Radiography.* Same as for 85 alloy (Al – 5 Si – 4 Cu)
M *Composition Limits. Sand cast* (QQ-A-601, Class 8), *components*: 3.5 to 4.5% Cu; 2.5 to 3.5% Si; *impurities:* 1.00% max Fe; 0.03% max Mg; 0.30% max Mn; 0.20% max Zn; 0.20% max Ti; others (total) 0.30% max.
2 *Consequences of exceeding impurity limits.* High iron decreases mechanical properties, especially ductility. Zinc or tin decreases mechanical properties. Magnesium reduces ductility.
N 1 *Melting temperature range.* 677 to 816 C (1250 to 1500 F)
2 *Casting temperature range.* (sand) 677 to 788 C (1250 to 1450 F)
3 *Alloying.* Add silicon as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy.
5 *Type of flux* for remelting for casting. Gaseous type, nitrogen or chlorine; or solid, aluminum chloride base

* Compiled by Aluminum Company of America

17 *Joining.*
Rivet compositions. A 17 S-T4, 17 S-T4
Soft solder with Alcoa No. 802; no flux. Rub-tin with Alcoa No. 802.
Braze with Alcoa No. 717; Alcoa No. 33 flux; flame either reducing oxyacetylene or reducing oxyhydrogen.
Metal-arc weld with 43 alloy; Alcoa No. 27 flux.
Carbon-arc weld with 43 alloy; Alcoa No. 24 flux (automatic), Alcoa No. 27 flux (manual).
Tungsten-arc, argon atmosphere weld with 43 alloy; no flux.
Resistance welding. Spot, seam, and flash methods

Al – 5 Si – 3 Cu

COMPILED BY O. TICHY*

A 2 *Trade name.* Allcast (sand and permanent mold casting)
3 *ASTM number.* B 26-46T; B 108-46T, Alloy SC8
B 1 *Typical uses.* A general-purpose aluminum alloy for sand and permanent mold castings, which can be used without heat treatment to develop better mechanical properties than common aluminum alloys that are not heat treated; or can be solution heat treated to provide mechanical properties required by most current specifications for heat treatable aluminum alloys.
2 *Precautions in use.* Because this alloy contains 5.5% Si, it is subject to about 0.001 in. per in. growth if heated to approximately 400 F in use or fabrication. A heat treatment of 5 hr at 450 F applied to rough castings will prevent further dimensional change.
C 1 *Density* at 20 C (68 F). 2.76 g per cu cm (0.100 lb per cu in.)
D 6 *Thermal expansion* 20 to 100 C (68 to 212 F). 0.0000219 per °C
16 *Thermal conductivity* at 20 C (68 F). 0.25 cal/sq cm/cm/°C/sec, as cast; 0.28, stress relieved; 0.27, solution heat treated and aged; 0.33, solution heat treated and stress relieved
E 1 *Volume conductivity* referred to standard copper.
27%, as cast
30%, stress relieved
30%, solution heat treated and aged
36%, solution heat treated and stress relieved
K *Mechanical Properties.* See Table I.
M *Composition Limits. Sand and permanent mold cast, components:* 2.5 to 3.5% Cu; 4.5 to 6.0% Si; *impurities:* 0.2% max Ti; 1.2% max Fe; 0.15% max Mg; 0.8% max Mn; 0.5% max Ni; 1.0% max Zn; others (total) 1.0% max.
N 6 *Precautions in melting.* If the metal is heated to more than 1375 F some pinhole porosity may result. For the production of castings free from pinhole porosity, made with pouring temperatures of over 1375 F, the melt should be degassed with chlorine, nitrogen, or boron trichloride.

* Research Laboratory, National Smelting Company, Cleveland

Table I. Mechanical Properties of Al – 5 Si – 3 Cu

Condition	Tensile Strength, psi	Yield Strength,(a) psi	Elongation,(b) percentage	Rockwell E Hardness	Endurance Limit,(c) psi	Compressive Yield Strength, psi	Charpy Impact Value, ft-lb
Sand Cast							
As cast	27,000	14,000	2.5	E 65	....	....	1.0
Stress relieved	29,000	18,000	2.0	E 67	....	19,000	0.8
Solution heat treated and aged	35,000	20,000	4.0	E 80	10,500	25,000	1.6
Solution heat treated and stress relieved	37,000	23,000	2.5	E 81	....	30,000	1.0
Permanent Mold Cast							
As cast	35,000	18,000	3.0	E 80	....	....	1.0
Stress relieved	37,000	22,000	2.0	E 82	....	24,000	0.8
Solution heat treated and aged	42,000	22,000	5.0	E 85	....	24,000	2.0
Solution heat treated and stress relieved	42,000	23,000	3.0	E 86	....	24,000	1.0

(a) 0.2% offset
(b) Round specimens, ½-in. diam
(c) Based on 500,000,000 cycles using R. R. Moore type of rotating-beam machine.

Al – 5.5 Si – 4.5 Cu*

A 2 *Trade name.* A 108 alloy (permanent mold casting)
3 *ASTM number.* B 108-46T, Alloy SC1
4 *Government number.* QQ-A-596, Class 5
B 1 *Typical uses.* Applications where good casting characteristics, good weldability, pressure tightness, and moderate strength are required. Ornamental grilles, reflectors, general-purpose castings are typical.
C 1 *Density* at 20 C (68 F). 2.79 g per cu cm (0.101 lb per cu in.)
D 1 *Liquidus temperature.* 616 C (1140 F)
2 *Solidus temperature.* 516 C (960 F)
6 *Thermal expansion*
20 to 100 C (68 to 212 F). 0.0000215 per °C
20 to 200 C (68 to 392 F). 0.0000225 per °C
20 to 300 C (68 to 572 F). 0.0000230 per °C
11 *Specific heat* at 100 C (212 F). Approx 0.23 cal per g
13 *Latent heat of fusion.* Approx 93 cal per g
16 *Thermal conductivity* at 25 C (77 F). 0.34 cal/sq cm/cm/°C/sec
E 1 *Volume conductivity* referred to standard copper. 37%
2 *Electrical resistivity* at 20 C (68 F). 4.660 microhm-cm
11 *Electrolytic solution potential* versus N/10 calomel electrode is 0.75 volts (53 g NaCl + 3 g H_2O_2 solution).
F 5 *Emissivity.* 0.035 to 0.07 at 25 C (77 F) in air
K *Mechanical Properties. Permanent mold cast:* Tensile strength 28,000 psi; yield strength 16,000 psi; compressive yield strength 16,000 psi; elongation (round specimen, ½-in. diam) 2.0%; Bhn (500-kg load, 10-mm ball) 70; modulus of elasticity 10,300,000 psi; shear strength 25,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.
L 2 *Radiography.* Same as for 85 alloy (Al – 5 Cu – 4 Si)
M *Composition Limits. Permanent mold cast* (QQ-A-596, Class 5), *components*: 5.0 to 6.0% Si; 4.0 to 5.0% Cu; *impurities*: 1.00% max Fe; 0.30% max Mn; 0.10% max Mg; 0.50% max Zn; 0.20% max Ti; others (total) 0.50% max.
2 *Consequences of exceeding impurity limits.* High iron, zinc, or tin decreases mechanical properties. Magnesium decreases ductility.

* Compiled by Aluminum Company of America

N *1 Melting temperature range.* 677 to 816 C (1250 to 1500 F)
2 Casting temperature range. 677 to 788 C (1250 to 1450 F)
3 Alloying. Add silicon as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy.
5 Type of flux for remelting for casting. Gaseous type, nitrogen or chlorine; or solid, aluminum chloride base.
17 Joining. Same as for 108 alloy (Al – 4 Cu – 3 Si)

Al – 7 Cu – 2 Si – 1.7 Zn*

A *2 Trade name.* 113 alloy (sand casting)
3 ASTM number. B 26-46T, Alloy CS22
4 Government number. AN-A-28
B *1 Typical uses.* Applications where good casting characteristics, very good machinability, and pressure tightness are required. Miscellaneous general-purpose castings requiring pressure tightness are typical.
C *1 Density* at 20 C (68 F). 2.91 g per cu cm (0.105 lb per cu in.)
D *1 Liquidus temperature.* 629 C (1165 F)
2 Solidus temperature. 524 C (975 F)
6 Thermal expansion

20 to 100 C (68 to 212 F). 0.0000220 per °C
20 to 200 C (68 to 392 F). 0.0000230 per °C
20 to 300 C (68 to 572 F). 0.0000240 per °C

11 Specific heat at 100 C (212 F). Approx 0.23 cal per g
13 Latent heat of fusion. Approx 93 cal per g
16 Thermal conductivity at 25 C (77 F). 0.28 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 30%
2 Electrical resistivity at 20 C (68 F). 5.747 microhm-cm
F *5 Emissivity.* 0.035 to 0.07 at 25 C (77 F) in air
K *Mechanical Properties. Sand cast:* Tensile strength 24,000 psi; yield strength 15,000 psi; compressive yield strength 17,000 psi; elongation (round specimens, ½-in. diam) 1.5%; Bhn (500-kg load, 10-mm ball) 70; modulus of elasticity 10,300,000 psi; sheer strength 20,000 psi; endurance limit (based on 500,000,000 cycles using R. R. Moore type of rotating-beam machine) 9,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.
L *2 Radiography.* Type A or 506 film using no intensifying screen, cardboard exposure holder, 36-in. focal distance, General Electric OX-250 unit, 2.1 H&D film density.

Section, in.	Volts	Milliamperes	Time, min
½	110,000	7.0	1.0
1	140,000	7.0	1.0
1½	160,000	5.0	1.0
2	170,000	5.0	1.0

M *Composition Limits. Sand cast* (AN-A-28), *components*: 6.0 to 8.0% Cu; 1.0 to 3.0% Si; 2.5% max Zn; *impurities*: 1.4% max Fe; 0.50% max Mn; 0.30% max Ni; 0.20% max Ti; 0.07% max Mg; others (total) 0.50% max.
2 Consequences of exceeding impurity limits. High iron decreases mechanical properties and may cause shrinkage difficulties. Magnesium or nickel decreases ductility.
N *1 Melting temperature range.* 677 to 816 C (1250 to 1500 F)
2 Casting temperature range. 677 to 788 C (1250 to 1450 F)
3 Alloying. Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add silicon as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy.
5 Type of flux for remelting for casting. Gaseous type, nitrogen or chlorine; or solid. aluminum chloride base.
17 Joining. Same as for 108 alloy (Al – 4 Cu – 3 Si)

Al – 7 Cu – 3.5 Si*

A *2 Trade name.* C 113 alloy (permanent mold casting)
3 ASTM number. B 108-46T, Alloy CS22
4 Government number. QQ-A-596, Class 1
B *1 Typical uses.* Applications where good casting characteristics, very good machinability, and pressure tightness are required. Washing-machine agitators, automotive cylinder heads and miscellaneous general-purpose castings having pressure requirements are typical.
C *1 Density* at 20 C (68 F). 2.91 g per cu cm (0.105 lb per cu in.)
D *1 Liquidus temperature.* 629 C (1165 F)
2 Solidus temperature. 524 C (975 F)
6 Thermal expansion

20 to 100 C (68 to 212 F). 0.0000220 per °C
20 to 200 C (68 to 392 F). 0.0000230 per °C
20 to 300 C (68 to 572 F). 0.0000240 per °C

11 Specific heat at 100 C (212 F). Approx 0.23 cal per g
13 Latent heat of fusion. Approx 93 cal per g
16 Thermal conductivity at 25 C (77 F). 0.26 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 27%
2 Electrical resistivity at 20 C (68 F). 6.386 microhm-cm
F *5 Emissivity.* 0.035 to 0.07 at 25 C (77 F) in air
K *Mechanical Properties. Permanent mold cast*: Tensile strength 30,000 psi; yield strength 24,000 psi; compressive yield strength 24,000 psi; elongation (round specimens, ½-in. diam) 1%; Bhn (500-kg load, 10-mm ball) 80; modulus of elasticity 10,300,000 psi; sheer strength 22,000 psi; endurance limit (based on 500,000,000 cycles using R. R. Moore type of rotating-beam machine) 9,500 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.
L *2 Radiography.* Same as for 113 alloy (Al – 7 Cu – 2 Si – 1.7 Zn)
M *Composition Limits. Permanent mold cast* (QQ-A-596, Class 1), *components:* 6.0 to 8.0% Cu; 4.0% max Si; *impurities*: 1.4% max Fe; 0.30% max Mn; 0.10% max Mg; 2.5% max Zn; 0.20% max Ti; others (total) 1.00% max.
2 Consequences of exceeding impurity limits. High iron decreases mechanical properties. Magnesium or nickel decreases ductility.
N *1 Melting temperature range.* 677 to 816 C (1250 to 1500 F)
2 Casting temperature range. 677 to 788 C (1250 to 1450 F)
3 Alloying. Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add silicon as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy.
5 Type of flux for remelting for casting. Gaseous type, nitrogen or chlorine; or solid type, aluminum chloride base.
17 Joining. Same as for 108 alloy (Al – 4 Cu – 3 Si)

* Compiled by Aluminum Company of America

Al–10 Cu–0.2 Mg*

A *2 Trade name.* 122 alloy (sand and permanent mold casting)
3 ASTM number. B 26-46T, Alloy CG1 (sand); B 108-46T, Alloy CG1 (permanent mold)
4 Government number. QQ-A-601, Class 7 (sand); QQ-A-596, Class 2 (permanent mold)

B *1 Typical uses.* Applications where good high-temperature strength, high hardness, resistance to wear and good machinability are required. Air-cooled cylinder heads, automotive pistons, bushings, tappet guide clusters are typical.

C *1 Density* at 20 C (68 F). 2.95 ■ per cu cm (0.106 lb per cu in.)

D *1 Liquidus temperature.* 627 C (1160 F)
2 Solidus temperature. 541 C (1005 F)
6 Thermal expansion
20 to 100 C (68 to 212 F). 0.0000220 per °C
20 to 200 C (68 to 392 F). 0.0000230 per °C
20 to 300 C (68 to 572 F). 0.0000235 per °C
11 Specific heat at 100 C (212 F). Approx 0.23 cal per ■
13 Latent heat of fusion. Approx 93 cal per g
16 Thermal conductivity at 25 C (77 F).
0.38 cal/sq cm/cm/°C/sec, sand, condition T2
0.31 cal/sq cm/cm/°C/sec, sand, condition T61
0.32 cal/sq cm/cm/°C/sec, permanent mold, as cast

E *1 Volume conductivity* referred to standard copper.
41%, sand, condition T2
33%, sand, condition T61
34%, permanent mold, as cast
2 Electrical resistivity at 20 C (68 F)
4.205 microhm-cm, sand, condition T2
5.225 microhm-cm, sand, condition T61
5.071 microhm-cm, permanent mold, as cast

F *5 Emissivity.* 0.035 to 0.07 at 25 C (77 F) in air

K *Mechanical Properties.* See Tables I and II.
Modulus of elasticity 10,300,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.

L *2 Radiography.* Type A or 506 film using no intensifying screen, cardboard exposure holder, 36-in. focal distance, General Electric OX-250 unit, 2.1 H&D film density.

Section, in.	Volts	Milliamperes	Time, min
½	120,000	6.0	1.0
1	160,000	5.0	1.0
1½	170,000	5.0	1.0
2	180,000	5.0	1.0

M *Composition Limits.* See Table III (next page).
2 Consequences of exceeding impurity limits. High iron may cause shrinkage difficulties.

N *1 Melting temperature.* 677 to 816 C (1250 to 1500 F)
2 Casting temperature range. (sand) 677 to 788 C (1250 to 1450 F), (permanent mold) 677 to 788 C (1250 to 1450 F)
3 Alloying. Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add magnesium as pure metal to molten base metal (pure).
5 Type of flux for remelting for casting. Gaseous type nitrogen or chlorine; or solid type, aluminum chloride base.
15 Heat treatment.

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Cooling
Sand Castings				
Annealing T2	313 to 318	595 to 605	2 to 4	Not critical
Solution heat treatment	507 to 513	945 to 955	12(a)	Water at 150 to 212 F
Precipitation T61(c)	152 to 157	305 to 315	10 to 14	Not critical
Permanent Mold Castings				
Precipitation T52(b)	152 to 157	305 to 315	5 to 7	Not critical
Precipitation T551(b)	168 to 174	335 to 345	18 to 22	Not critical
Solution heat treatment	507 to 513	945 to 955	12(a)	Water at 150 to 212 F
Precipitation T65(c)	168 to 174	335 to 345	7 to 9	Not critical

(a) Soaking time periods required for average castings after load has reached specified temperature. Time can be decreased or may have to be increased, depending on experience with particular castings.
(b) No solution heat treatment.
(c) Start with solution heat treated material.

17 Joining. Rivet compositions. A 17 S-T4, 17 S-T4. *Soft solder* with Alcoa No. 802; no flux. Rub-tin with Alcoa No. 802. *Metal-arc weld* with 43 alloy; Alcoa No. 27 flux. *Carbon-arc weld* with 43 alloy; Alcoa No. 24 flux (automatic), Alcoa No. 27 flux (manual). *Tungsten-arc, argon atmosphere weld* with 43 alloy; no flux. *Resistance welding.* Spot, seam and flash methods.

* Compiled by Aluminum Company of America

Table I. Mechanical Properties of Al–10 Cu–0.2 Mg

Condition	Tensile Strength,(a) psi	Yield Strength, psi	Elongation,(b) percentage	Brinell Hardness Number(c)	Shear Strength, psi	Endurance Limit,(d) psi	Compressive Yield Strength, psi
Sand Cast							
T2	27,000	20,000	1.0	80	21,000	9,500	20,000
T61	40,000	30,000	<0.5	115	29,000	8,500	43,000
Permanent Mold Cast							
T52	35,000	31,000	1.0	100	25,000	....	31,000
T551	37,000	35,000	<0.5	115	27,000	8,500	40,000
T65	48,000	36,000	<0.5	140	30,000	9,000	36,000

(a) In general, strengths and elongation are unchanged or improve at low temperatures.
(b) Round specimens, ½-in. diam.
(c) 500-kg load, 10-mm ball.
(d) Based on 500,000,000 cycles using R. R. Moore type of rotating-beam machine.

Table II. Strength and Elongation of Al–10 Cu–0.2 Mg at Elevated Temperatures

After prolonged heating at testing temperatures

Property	Temperature, deg Fahr: 75 F	300 F	400 F	500 F	600 F
Sand Cast, Condition T2					
Tensile strength, psi	27,000	25,000	22,000	17,000	8,000
Yield strength, psi	20,000	17,000	14,000	11,000	4,500
Elongation, %	1.0	1.0	1.5	3.0	14.0
Sand Cast, Condition T61					
Tensile strength, psi	40,000	35,000	22,000	10,000	8,000
Yield strength, psi	30,000	30,000	16,000	5,000	4,500
Elongation, %	0.5	1.0	2.0	6.0	14.0
Permanent Mold Cast, Condition T551					
Tensile strength, psi	37,000	33,000	26,000	18,000	10,000
Yield strength, psi	35,000	29,000	20,000	12,500	6,000
Elongation, %	0.5	0.5	1.0	3.0	10.0

Table III. Composition Limits of Al–10 Cu–0.2 Mg

Form	Designation	Components: Cu min	Cu max	Mg min	Mg max	Impurities: Fe max	Fe + Si max	Mn max	Zn max	Ni max	Ti max	Others total max
Sand cast	QQ-A-601, Class 7	9.2	10.8	0.15	0.35	1.5	2.0	0.10	0.10	...	0.20	0.10
Permanent mold cast	QQ-A-596, Class 2	9.2	10.7	0.15	0.35	1.5	Si max 1.00	0.30	0.40	0.30	0.20	0.30

Al–12 Si–2.5 Ni–1.2 Mg–0.8 Cu*

A *2 Trade name.* A 132 alloy (permanent mold casting)
3 ASTM number. B 108-46T, Alloy SC41
4 Government number. QQ-A-596, Class 9

B *1 Typical uses.* Applications where good high-temperature strength, low coefficient of thermal expansion, and good resistance to wear are required. Automotive and diesel pistons, pulleys and sheaves are typical.

C *1 Density* at 20 C (68 F). 2.68 ■ per cu cm (0.097 lb per cu in.)

D *1 Liquidus temperature.* 591 C (1095 F)
2 Solidus temperature. 538 C (1000 F)
6 Thermal expansion

20 to 100 C (68 to 212 F). 0.0000190 per °C
20 to 200 C (68 to 392 F). 0.0000200 per °C
20 to 300 C (68 to 572 F). 0.0000210 per °C

11 Specific heat at 100 C (212 F). Approx 0.23 cal per g
13 Latent heat of fusion. Approx 93 cal per ■
16 Thermal conductivity at 25 C (77 F). 0.28 cal/sq cm/cm/°C/sec, condition T551

E *1 Volume conductivity* referred to standard copper. 29%, condition T551
2 Electrical resistivity at 20 C (68 F). 5.945 microhm-cm, condition T551

F *5 Emissivity.* 0.035 to 0.07 at 25 C (77 F) in air

K *Mechanical Properties.* See Tables I and II. Modulus of elasticity 10,300,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.

L *2 Radiography.* Type A or 506 film using no intensifying screen, cardboard exposure holder, 36-in. focal distance, General Electric OX-10 unit, 2.1 H&D film density.

Section, in.	Volts	Milliamperes	Time, min
½	65,000	10.0	1.0
1	95,000	6.7	1.0
1½	125,000	5.0	1.0
2	140,000	5.0	1.6

M *Composition Limits. Permanent mold cast* (QQ-A-596, Class 9), *components:* 11.0 to 13.0% Si; 0.5 to 1.5% Cu; 0.70 to 1.3% Mg; 2.0 to 3.0% Ni; *impurities:* 1.3% max Fe; 0.10% max Mn; 0.10% max Zn; 0.20% max Ti; others (total) 0.20% max.
2 Consequences of exceeding impurity limits. High iron or chromium promotes shrinkage difficulties.

N *1 Melting temperature.* 677 to 816 C (1250 to 1500 F)
2 Casting temperature. 677 to 788 C (1250 to 1450 F)

3 Alloying. Add silicon as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add copper as pure metal or aluminum-rich alloy to base metal (pure) either in melt-down or molten alloy. Add magnesium as pure metal to molten base metal (pure). Add nickel as aluminum-rich alloy to melt-down or molten base metal (pure).
5 Type of flux for remelting for casting. Gaseous type, nitrogen or chlorine; or solid type, aluminum chloride base.

15 Heat treatment.

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Cooling
Precipitation T551[b]	168 to 174	335 to 345	14 to 18	Not critical
Solution heat treatment	513 to 518	955 to 965	8[a]	Water at 150 to 212 F
Precipitation T65[c]	168 to 174	335 to 345	12 to 16	Not critical

(a) Soaking time periods required for average castings after load has reached specified temperature. Time can be decreased or may have to be increased, depending on experience with particular castings.
(b) No solution heat treatment.
(c) Start with solution heat treated material.

Table I
Mechanical Properties of Al–12 Si–2.5 Ni–1.2 Mg–0.8 Cu

Condition	Tensile Strength,[a] psi	Yield Strength, psi	Elongation,[b] percentage	Bhn[c]	Shear Strength, psi	Compressive Yield Strength, psi
Permanent Mold Cast						
T551	36,000	28,000	0.5	105	24,000	30,000
T65	47,000	.....	0.5	125	27,000	.....

(a) In general, strengths and elongations remain unchanged or improve at low temperatures.
(b) Round specimens, ½-in. diam
(c) 500-kg load, 10-mm ball

Table II. Strength and Elongation of Al–12 Si–2.5 Ni–1.2 Mg–0.8 Cu at Elevated Temperatures

After prolonged heating at testing temperatures

Property	Temperature, deg Fahr: 75 F	300 F	400 F	500 F	600 F
Condition T551					
Tensile strength, psi	36,000	31,000	23,000	17,500	11,000
Yield strength, psi	28,000	22,000	13,500	9,500	5,000
Elongation, %	0.5	1.0	2.0	2.0	8.0

17 Joining. Rivet compositions. 53 S-T4, 53 S-T6, 53 S-T61. Other joining methods same as for 122 alloy (Al – 10 Cu – 0.2 Mg)

* Compiled by Aluminum Company of America

Al–12 Si–1.5 Cu–0.7 Mn–0.7 Mg

COMPILED BY F. ROMANO*

A *2 Trade name.* Red X-13 (permanent mold casting)
3 ASTM number. B 108-46T, Alloy SC41
4 Government number. QQ-A-596; 46 A 15 (Interim)

B *1 Typical uses.* An aluminum alloy for pistons in internal combustion engines, which combines high strength at elevated temperatures with a low coefficient of expansion.

* Research Laboratory, National Smelting Company, Cleveland

2 Precautions in use: For use in pistons this alloy must be given a degrowthing heat treatment for about 8 hours at 400 F.

C *1 Density* at 20 C (68 F). 2.7 ■ per cu cm (0.098 lb per cu in.)

D *6 Thermal expansion*
20 to 100 C (68 to 212 F). 0.0000201 per °C
20 to 200 C (68 to 392 F). 0.0000208 per °C

20 to 300 C (68 to 572 F). 0.0000217 per °C
20 to 400 C (68 to 752 F). 0.0000223 per °C

K *Mechanical Properties.* See table at right.

M *Composition Limits. Permanent mold cast, components*: 1.0 to 2.0% Cu; 0.4 to 1.0% Mg; 0.5 to 0.9% Mn; 11.0 to 13.0% Si; *impurities:* 0.2% max Ti; 0.9% max Fe; 0.05% max Ni; 0.4% max Zn; others (total) 0.5% max.

N 5 *Type of flux.* None required.

6 *Precautions in melting.* Loss of magnesium should be controlled.

Condition	Tensile Strength, psi	Yield Strength,[a] psi	Elongation,[b] percentage	Rockwell E Hardness	Brinell Hardness Number[c]
		Permanent Mold Cast			
Stress relieved	36,000	....	0.5	E 92	100
400 F for 8 hr	40,000	....	..	E 97	115
Solution heat treated and aged	43,000	38,000	1.0	E 92	100

(a) 0.2% offset (b) Round specimen, ½-in. diam (c) 500-kg load, 10-mm ball

Al – 4 Cu – 2 Ni – 1.5 Mg*

A 2 *Trade name.* 142 alloy (sand and permnanent mold casting)

3 *ASTM number.* B 26-46T, Alloy CN21 (sand); B 108-46T, Alloy CN21 (permanent mold)

4 *Government number.* QQ-A-601, Class 6 (sand); QQ-A-596, Class 3 (permanent mold)

B 1 *Typical uses.* Applications where excellent high-temperature strength is required. Motorcycle, diesel and aircraft pistons, air-cooled cylinder heads, aircraft generator housings are typical.

C 1 *Density* at 20 C (68 F). 2.81 g per cu cm (0.101 lb per cu in.)

D 1 *Liquidus temperature.* 629 C (1165 F)

2 *Solidus temperature.* 535 C (995 F)

6 *Thermal expansion*

20 to 100 C (68 to 212 F). 0.0000225 per °C
20 to 200 C (68 to 392 F). 0.0000235 per °C
20 to 300 C (68 to 572 F). 0.0000245 per °C

11 *Specific heat* at 100 C (212 F). Approx 0.23 cal per g

13 *Latent heat of fusion.* Approx 93 cal per g

16 *Thermal conductivity* at 25 C (77 F).

0.40 cal/sq cm/cm/°C/sec, sand, condition T21
0.32 cal/sq cm/cm/°C/sec, sand, condition T571
0.36 cal/sq cm/cm/°C/sec, sand, condition T77
0.31 cal/sq cm/cm/°C/sec, permanent mold, condition T61

E 1 *Volume conductivity* referred to standard copper.
44%, sand, condition T21
34%, sand, condition T571
37%, sand, condition T77
32%, permanent mold, condition T61

2 *Electrical resistivity* at 20 C (68 F).
3.918 microhm-cm, sand, condition T21
5.071 microhm-cm, sand, condition T571
4.660 microhm-cm, sand, condition T77
5.388 microhm-cm, permanent mold, condition T61

F 5 *Emissivity.* 0.035 to 0.07 at 25 C (77 F) in air

K *Mechanical Properties.* See Tables I and II. Modulus of elasticity 10,300,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.

L 2 *Radiography.* Same as for 85 alloy (Al – 5 Cu – 4 Si)

M *Composition Limits.* See Table III.

2 *Consequences of exceeding impurity limits.* High iron may cause shrinkage difficulties. High silicon de-

* Compiled by Aluminum Company of America

Table I. Mechanical Properties of Al – 4 Cu – 2 Ni – 1.5 Mg

Condition	Tensile Strength,[a] psi	Yield Strength, psi	Elongation,[b] percentage	Brinell Hardness Number[c]	Shear Strength, psi	Endurance Limit,[d] psi	Compressive Yield Strength, psi
			Sand Cast				
T21	27,000	18,000	1.0	70	21,000	6,500	18,000
T571	32,000	28,000	0.5	85	27,000	8,000	34,000
T77	28,000	25,000	2.0	75	24,000	9,500	.....
			Permanent Mold Cast				
T571	40,000	34,000	1.0	105	26,000	10,500	34,000
T61	47,000	42,000	0.5	110	31,000	9,500	46,000

(a) In general, strengths and elongations remain unchanged or improve at low temperatures.
(b) Round specimens, ½-in. diam
(c) 500-kg load, 10-mm ball
(d) Based on 500,000,000 cycles using R. R. Moore type of rotating-beam machine.

Table II. Strength and Elongation of Al – 4 Cu – 2 Ni – 1.5 Mg at Elevated Temperatures
After prolonged heating at testing temperatures

Property	Temperature, deg Fahr 75 F	300 F	400 F	500 F	600 F
		Sand Cast, Condition T21			
Tensile strength, psi	27,000	27,000	21,000	16,000	8,000
Yield strength, psi	18,000	18,000	14,000	8,000	4,000
Elongation, %	1.0	1.0	1.5	3.0	9.0
		Permanent Mold Cast, Condition T571			
Tensile strength, psi	40,000	37,000	28,000	15,000	9,000
Yield strength, psi	34,000	33,000	22,000	9,000	5,000
Elongation, %	1.0	1.0	2.0	10.0	30.0

Table III. Composition Limits of Al – 4 Cu – 2 Ni – 1.5 Mg

Form	Designation	Components Cu min	Cu max	Mg min	Mg max	Ni min	Ni max	Impurities Fe max	Si max	Mn max	Zn max	Ti max	Others total max
Sand cast	QQ-A-601, Class 6	3.5	4.5	1.2	1.8	1.7	2.3	1.00	0.80	0.10	0.03	0.20	0.30
Permanent mold cast	QQ-A-596, Class 3	3.5	4.5	1.2	1.8	1.7	2.3	1.00	0.70	0.30	0.10	0.20	0.30

creases mechanical properties. Chromium decreases thermal conductivity.

N 1 *Melting temperature.* 677 to 816 C (1250 to 1500 F)
2 *Casting temperature range.* (sand) 677 to 788 C (1250 to 1450 F), (permanent mold) 677 to 788 C (1250 to 1450 F)
3 *Alloying.* Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add magnesium as pure metal to molten base metal (pure). Add nickel as aluminum-rich alloy to melt-down or molten base metal (pure).
5 *Type of flux* for remelting for casting. Gaseous type, nitrogen or chlorine; or solid type, aluminum chloride base.
15 *Heat treatment.* See right-hand column.
17 *Joining.* Same as for 122 alloy (Al – 10 Cu – 0.2 Mg)

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Cooling
Sand Castings				
Annealing T21	341 to 346	645 to 655	2 to 4	Not critical
Precipitation T571[b]	168 to 174	335 to 345	40 to 48	Not critical
Solution heat treatment	518 to 524	965 to 975	6[a]	Still air
Precipitation T77[c] [d]	341 to 346	645 to 655	1 to 3	Not critical
Permanent Mold Castings				
Precipitation T571[b]	168 to 174	335 to 345	40 to 48	Not critical
Solution heat treatment	513 to 518	955 to 965	4[a]	Water at 150 to 212 F
Precipitation T61[c]	202 to 207	395 to 405	3 to 5	Not critical

(a) Soaking time periods required for average castings after load has reached specified temperature. Time can be decreased or may have to be increased, depending on experience with particular castings. (b) No solution heat treatment. (c) Start with solution heat treated material. (d) U. S. Patent 1,822,877.

Al – 4.5 Cu*

A 2 *Trade name.* 195 alloy (sand casting)
3 *ASTM number.* B 26-46T, Alloy C1
4 *Government number.* QQ-A-601, Class 4
B 1 *Typical uses.* Applications where a combination of high tensile properties, and good machinability are required. Flywheel housings, rear-axle housings, bus wheels, aircraft wheels, fittings and crankcases are typical.
C 1 *Density* at 20 C (68 F). 2.81 g per cu cm (0.101 lb per cu in.)
D 1 *Liquidus temperature.* 646 C (1195 F)
2 *Solidus temperature.* 549 C (1020 F)
6 *Thermal expansion*

20 to 100 C (68 to 212 F).	0.0000230 per °C
20 to 200 C (68 to 392 F).	0.0000240 per °C
20 to 300 C (68 to 572 F).	0.0000250 per °C

Conditions T4, T6, T62

11 *Specific heat* at 100 C (212 F). Approx 0.23 cal per g
13 *Latent heat of fusion.* Approx 93 cal per g
16 *Thermal conductivity* at 25 C (77 F). 0.33 cal/ sq cm/ cm/°C/sec, condition T4; 0.35 cal/sq cm/cm/°C/sec. condition T62
E 1 *Volume conductivity* referred to standard copper. 35%, condition T4; 37%, condition T62.
2 *Electrical resistivity* at 20 C (68 F). 4.926 microhm-cm, condition T4; 4.660 microhm-cm, condition T62.
11 *Electrolytic solution potential* versus N/10 calomel electrode is 0.70 volts, condition T4; 0.71 volts, condition T6; 0.73 volts, condition TC2 (53 g NaCl + 3 g H_2O_2 solution)
F 5 *Emissivity.* 0.035 to 0.07 at 25 C (77 F) in air
K *Mechanical Properties.* See Tables I and II. Modulus of elasticity 10,300,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.
L 2 *Radiography.* Same as for 85 alloy (Al – 5 Cu – 4 Si)
M *Composition Limits. Sand cast* (QQ-A-601, Class 4), *components:* 4.0 to 5.0% Cu; *impurities:* 1.00% max Fe; 1.20% max Si; 0.03% max Mg; 0.10% max Zn; 0.20% max Ti; others (total) 0.10% max.
2 *Consequences of exceeding impurity limits.* High iron or silicon decreases tensile properties, especially ductility. Manganese or magnesium decreases ductility. Tin reduces strength, hardness, and resistance to corrosion.
N 1 *Melting temperature.* 677 to 816 C (1250 to 1500 F)
2 *Casting temperature.* 677 to 788 C (1250 to 1450 F)
3 *Alloying.* Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy.
5 *Type of flux* for remelting for casting. Gaseous type, nitrogen or chlorine; or solid type, aluminum chloride base.
15 *Heat treatment.* See top of next page.
17 *Joining.*
Rivet compositions. A 17 S-T4, 17 S-T4
Soft solder with Alcoa No. 802; no flux. Rub-tin with Alcoa No. 802.

* Compiled by Aluminum Company of America

Table I. Mechanical Properties of Al – 4.5 Cu

Condition	Tensile Strength,[a] psi	Yield Strength, psi	Elongation,[b] percentage	Brinell Hardness Number[c]	Shear Strength, psi	Endurance Limit,[d] psi	Compressive Yield Strength, psi
			Sand Cast				
T4	32,000	16,000	8.5	60	24,000	6,000	16,000
T6	36,000	24,000	5.0	75	30,000	6,500	25,000
T62	40,000	30,000	2.0	95	31,000	7,000	38,000

(a) In general, strengths and elongations remain unchanged or improve at low temperatures.
(b) Round specimens, ½-in. diam
(c) 500-kg load, 10-mm ball
(d) Based on 500,000,000 cycles using R. R. Moore type of rotating-beam machine.

Table II. Strength and Elongation of Al – 4.5 Cu at Elevated Temperatures

After prolonged heating at testing temperatures

Property	Temperature, deg Fahr: 75 F	300 F	400 F	500 F	600 F
		Condition T4			
Tensile strength, psi	32,000	24,000	15,000	9,500	4,000
Yield strength, psi	16,000	13,000	9,000	6,000	3,000
Elongation, %	8.5	9.0	20.0	25.0	80.0
		Condition T6			
Tensile strength, psi	36,000	24,000	15,000	9,500	4,000
Yield strength, psi	24,000	13,000	9,000	6,000	3,000
Elongation, %	5.0	9.0	20.0	25.0	80.0

Atomic-hydrogen weld with 43 alloy; Alcoa No. 22 flux.
Oxyacetylene weld with 43 alloy; Alcoa No. 22 flux; flame neutral.
Metal-arc weld with 43 alloy; Alcoa No. 27 flux.
Carbon-arc weld with 43 alloy; Alcoa No. 24 flux (automatic), Alcoa No. 27 flux (manual).
Tungsten-arc, argon atmosphere weld with 43 alloy; no flux.
Resistance welding. Spot, seam, and flash methods

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Cooling
Solution heat treatment T4	513 to 518	955 to 965	12[a]	Water at 150 to 212 F
Precipitation T6[b]	152 to 157	305 to 315	3 to 5	Not critical
Precipitation T62[b]	152 to 157	305 to 315	12 to 16	Not critical

(a) Soaking time periods required for average castings after load has reached specified temperature. Time can be decreased or may have to be increased, depending on experience with particular castings.
(b) Start with solution heat treated material.

Al – 4.5 Cu – 2.5 Si*

A 2 *Trade name.* B 195 alloy (permanent mold casting)
3 *ASTM number.* B 108-46T, Alloy CS4
4 *Government number.* QQ-A-596, Class 4

B 1 *Typical uses.* Applications requiring a combination of high tensile properties and good machinability. Aircraft fittings, aircraft gun control parts, aircraft wheels, railroad-car seat frames, compressor connecting rods, fuel-pump bodies are typical.

C 1 *Density* at 20 C (68 F). 2.78 g per cu cm (0.101 lb per cu in.)

D 1 *Liquidus temperature.* 627 C (1160 F)
2 *Solidus temperature.* 527 C (980 F)
6 *Thermal expansion*
20 to 100 C (68 to 212 F). 0.0000220 per °C
20 to 200 C (68 to 392 F). 0.0000230 per °C
20 to 300 C (68 to 572 F). 0.0000240 per °C
11 *Specific heat* at 100 C (212 F). Approx 0.23 cal per g
13 *Latent heat of fusion.* Approx 93 cal per g
16 *Thermal conductivity* at 25 C (77 F). 0.33 cal/sq cm/cm/°C/sec, condition T4; 0.34 cal/sq cm/cm/°C/sec, condition T6

E 1 *Volume conductivity* referred to standard copper. 35%, condition T4; 36%, condition T6
2 *Electrical resistivity* at 20 C (68 F). 4.926 microhm-cm, condition T4; 4.789 microhm-cm, condition T6
11 *Electrolytic solution potential* versus N/10 calomel electrode is 0.71 volts, condition T4 (53 g NaCl + 3 g H_2O_2 solution)

F 5 *Emissivity.* 0.035 to 0.07 at 25 C (77 F) in air

K *Mechanical Properties.* See Tables I and II.
Modulus of elasticity 10,300,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.

L 2 *Radiography.* Same as for 85 alloy (Al – 5 Cu – 4 Si)

M *Composition Limits. Permanent mold casting* (QQ-A-596, Class 4), *components:* 4.0 to 5.0% Cu; 2.0 to 3.0% Si; *impurities:* 1.0% max Fe; 0.30% max Mn; 0.05% max Mg; 0.20% max Zn; 0.20% max Ti; others (total) 0.30% max.
2 *Consequences of exceeding impurity limits.* High iron decreases tensile properties, especially ductility. Zinc or tin decreases tensile properties. Manganese or magnesium reduces ductility.

N 1 *Melting temperature range.* 677 to 816 C (1250 to 1500 F)
2 *Casting temperature range.* 677 to 788 C (1250 to 1450 F)
3 *Alloying.* Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add silicon as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy.
5 *Type of flux* for remelting for casting. Gaseous type, nitrogen or chlorine; or solid type, aluminum chloride base.
15 *Heat treatment.*

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Cooling
Solution heat treatment T4	507 to 513	945 to 955	8[a]	Water at 150 to 212 F
Precipitation T6[c]	152 to 157	305 to 315	5 to 7	Not critical
Precipitation T7[b][c]	257 to 263	495 to 505	4 to 6	Not critical

(a) Soaking time periods required for average castings after load has reached specified temperature. Time can be decreased or may have to be increased, depending on experience with particular castings.
(b) U. S. Patent No. 1,822,877
(c) Start with solution heat treated material.

17 *Joining.* Same as for 195 alloy (Al – 4.5 Cu)

* Compiled by Aluminum Company of America

Table I. Mechanical Properties of Al – 4.5 Cu – 2.5 Si

Condition	Tensile Strength,[a] psi	Yield Strength, psi	Elongation,[b] percentage	Brinell Hardness Number,[c]	Shear Strength, psi	Endurance Limit,[d] psi	Compressive Yield Strength, psi
			Permanent Mold Cast				
T4	40,000	22,000	10.0	75	30,000	9,500	22,000
T6	45,000	33,000	5.0	90	32,000	10,000	33,000
T7	39,000	20,000	4.5	80	.....	.....	.....

(a) In general, strengths and elongation remain unchanged or improve at low temperatures.
(b) Round specimens, ½-in. diam
(c) 500-kg load, 10-mm ball
(d) Based on 500,000,000 cycles using R. R. Moore type of rotating-beam machine

Table II. Strength and Elongation of Al – 4.5 Cu – 2.5 Si at Elevated Temperatures

After prolonged heating at testing temperatures

Property	Temperature, deg Fahr: 75 F	300 F	400 F	500 F	600 F
		Condition T4			
Tensile strength, psi	40,000	33,000	17,000	8,500	4,000
Yield strength, psi	22,000	20,000	9,000	5,000	2,500
Elongation, %	10.0	11.0	15.0	25.0	65.0
		Condition T6			
Tensile strength, psi	45,000	33,000	17,000	8,500	4,000
Yield strength, psi	33,000	20,000	9,000	5,000	2,500
Elongation, %	5.0	11.0	15.0	25.0	65.0

Al – 3.8 Mg*

A *2 Trade name.* 214 alloy (sand casting)
3 ASTM number. B 26-46T, Alloy G1
4 Government number. QQ-A-601, Class 5
6 Foreign equivalents. British DTD 165

B *1 Typical uses.* Applications where excellent resistance to corrosion and tarnish are required. Dairy and food-handling equipment, cooking utensils, fittings for chemical and sewage use are typical.

C *1 Density* at 20 C (68 F). 2.65 g per cu cm (0.096 lb per cu in.)

D *1 Liquidus temperature.* 641 C (1185 F)
2 Solidus temperature. 579 C (1075 F)
6 Thermal expansion
20 to 100 C (68 to 212 F). 0.0000240 per °C
20 to 200 C (68 to 392 F). 0.0000250 per °C
20 to 300 C (68 to 572 F). 0.0000260 per °C
11 Specific heat at 100 C (212 F). Approx 0.23 cal per g
13 Latent heat of fusion. Approx 93 cal per g
16 Thermal conductivity at 25 C (77 F). 0.33 cal/sq cm/cm/°C/sec

E *1 Volume conductivity* referred to standard copper. 35%.
2 Electrical resistivity at 20 C (68 F). 4.926 microhm-cm
11 Electrolytic solution potential versus N/10 calomel electrode is 0.87 volts (53 g NaCl + 3 g H_2O_2 solution).

F *5 Emissivity.* 0.035 to 0.07 at 25 C (77 F) in air

K *Mechanical Properties. Sand cast:* Tensile strength 25,000 psi; yield strength 12,000 psi; compressive yield strength 12,000 psi; elongation (round specimens, ½-in. diam) 9.0%; Bhn (500-kg load, 10-mm ball) 50; modulus of elasticity 10,300,00 psi; shear strength 20,000 psi; endurance limit (based on 500,000,000 cycles using R. R. Moore type of rotating-beam machine) 5,500 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33. See table at right.

Strength and Elongation at Elevated Temperatures
After prolonged heating at testing temperatures

Property	Temperature, deg Fahr				
	75 F	300 F	400 F	500 F	600 F
Tensile strength, psi	25,000	23,000	18,500	13,500	9,000
Yield strength, psi	12,000	15,000	12,500	8,000	4,000
Elongation, %	9	7	9	12	17

L *2 Radiography.* Same as for 13 alloy (Al – 12 Si)

M *Composition Limits. Sand cast* (QQ-A-601, Class 5), *components:* 3.2 to 4.3% Mg; *impurities* (*max*): 0.10% Cu, 0.60% Fe, 0.30% Si, 0.60% Mn, 0.10% Zn, 0.20% Ti, others (total) 0.10%.
2 Consequences of exceeding impurity limits. High copper or nickel greatly decreases resistance to corrosion and decreases ductility. High iron, silicon, or manganese decreases strength and ductility. Tin reduces resistance to corrosion.

N *1 Melting temperature.* 677 to 816 C (1250 to 1500 F)
2 Casting temperature. 677 to 788 C (1250 to 1450 F)
3 Alloying. Add magnesium as pure metal to molten base metal (pure).
5 Type of flux for remelting for casting. Gaseous, nitrogen or chlorine; or solid, aluminum chloride base.
17 Joining.

Rivet compositions. 53 S-T4, 53 S-T6, ■ S-T61. *Soft solder* with Alcoa No. 802; no flux. Rub-tin with Alcoa No. 802. *Braze* with Alcoa No. 717; Alcoa No. 33 flux; flame either reducing oxyacetylene or reducing oxyhydrogen. *Atomic-hydrogen weld* with 43 alloy; Alcoa No. 22 flux. *Oxyacetylene weld* with 43 alloy; Alcoa No. 22 flux; flame neutral. *Metal-arc weld* with 43 alloy; Alcoa No. 27 flux. *Carbon-arc weld* with 43 alloy; Alcoa No. 24 flux (automatic), Alcoa No. 27 flux (manual). *Tungsten-arc, argon atmosphere weld* with 43 alloy; no flux. *Resistance welding.* Spot, seam, and flash methods

Al – 3.8 Mg – 1.8 Zn*

A *2 Trade name.* A 214 alloy (permanent mold casting)

B *1 Typical uses.* Applications where good resistance to corrosion and tarnishing are required. Cooking utensils are the most typical application.

C *1 Density* at 20 C (68 F). 2.65 g per cu cm (0.096 lb per cu in.)

D *1 Liquidus temperature.* 638 C (1180 F)
2 Solidus temperature. 566 C (1050 F)
6 Thermal expansion
20 to 100 C (68 to 212 F). 0.0000240 per °C
20 to 200 C (68 to 392 F). 0.0000250 per °C
20 to 300 C (68 to 572 F). 0.0000260 per °C
11 Specific heat at 100 C (212 F). Approx 0.23 cal per g
13 Latent heat of fusion. Approx 93 cal per g
16 Thermal conductivity at 25 C (77 F). 0.31 cal/sq cm/cm/°C/sec

E *1 Volume conductivity* referred to standard copper. 33%
2 Electrical resistivity at 20 C (68 F). 5.225 microhm-cm

F *5 Emissivity.* 0.035 to 0.07 at 25 C (77 F) in air

K *Mechanical Properties. Permanent mold cast:* Tensile strength 27,000 psi; yield strength 16,000 psi; compressive yield strength 17,000 psi; elongation (round specimens, ½-in. diam) 7.0%; Bhn (500-kg load, 10-mm ball) 60; modulus of elasticity 10,300,000 psi; shear strength 22,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.

L *2 Radiography.* Same as for 13 alloy (Al – 12 Si)

M *Composition Limits. Permanent mold cast, components:* 3.5 to 4.3% Mg; 1.4 to 2.2% Zn; *impurities:* 0.10% max Cu; 0.30% max Si; 0.40% max Fe; 0.30% max Mn; others (each) 0.05% max.
2 Consequences of exceeding impurity limits. High copper, nickel, or tin impairs resistance to corrosion. High iron or silicon decreases strength and ductility. High silicon promotes hot cracking.

N *1 Melting temperature.* 677 to 816 C (1250 to 1500 F)
2 Casting temperature. 677 to 788 C (1250 to 1450 F)
3 Alloying. Add magnesium as pure metal to molten base metal (pure). Add zinc as pure metal to molten base metal (pure).
5 Type of flux for remelting for casting. Gaseous, nitrogen or chlorine; or solid, aluminum chloride base.
17 Joining. Rivet compositions. 53 S-T4, 53 S-T6, 53 S-T61. *Other joining methods.* Same as for 108 alloy (Al – 4 Cu – 3 Si).

Al – 8 Mg*

A *2 Trade name.* 218 alloy (die casting)
4 Government number. QQ-A-591, Class 7

B *1 Typical uses.* Applications where exceptional mechanical properties, resistance to corrosion and finishing characteristics are required.

C *1 Density* at 20 C (68 F). 2.53 ■ per cu cm (0.091 lb per cu in.)

D *1 Liquidus temperature.* 621 C (1150 F)
2 Solidus temperature. 541 C (1005 F)
11 Specific heat at 100 C (212 F). Approx 0.23 cal per g
13 Latent heat of fusion. Approx 93 cal per g
16 Thermal conductivity at 25 C (77 F). 0.24 cal/sq cm/cm/°C/sec

E *1 Volume conductivity* referred to standard copper. 24%.
2 Electrical resistivity at 20 C (68 F). 7.184 microhm-cm

F *5 Emissivity.* 0.035 to 0.07 at 25 C (77 F) in air

* Compiled by Aluminum Company of America

K *1 Mechanical Properties. Die cast*: Tensile strength 42,000 psi; yield strength 23,000 psi; elongation (round specimens, ¼-in. diam) 7.0%; modulus of elasticity 10,300,000 psi; endurance limit (based on 500,000,000 cycles using R. R. Moore type of rotating-beam machine) 18,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.

L *2 Radiography*. Type A or 506 film with no intensifying screen, cardboard exposure holder, 36-in. focal distance, General Electric OX-10 unit, 2.1 H&D film density.

Section, in.	Volts	Milliamperes	Time, min
½	60,000	9.0	1.0
1	90,000	6.0	1.0
1½	110,000	6.0	1.0
2	135,000	5.0	1.0

M *Composition Limits. Die cast.* (QQ-A-591, Class 7), *components:* 7.5 to 8.5% Mg; *impurities:* 1.8% max Fe; 0.20% max Cu; 0.30% max Si; 0.30% max Mn; 0.10% max Zn; 0.10% max Ni; 0.10% max Sn; others (total) 0.20% max.

2 Consequences of exceeding impurity limits. Relatively large quantities of impurities may be present before serious effects are detected. In general, increasing copper will lower resistance to corrosion and increasing iron will lower ductility.

N *1 Melting temperature*. 649 to 760 C (1200 to 1400 F)

2 Die-casting temperature. 635 to 704 C (1175 to 1300 F)

3 Alloying. Add magnesium as pure metal to molten base metal (pure).

5 Type of flux for remelting for casting. Gaseous, nitrogen or chlorine; or solid, aluminum chloride base.

17 Joining. Same as for 13 alloy (Al – 12 Si)

Al – 10 Mg*

A *2 Trade name*. 220 alloy (sand casting)

4 Government number. AN-A-33

B *1 Typical uses*. Applications where excellent machinability and resistance to corrosion with highest strength and elongation of any aluminum sand casting alloy are desired. Aircraft fittings, railroad passenger-car frames, miscellaneous castings requiring strength and shock resistance are typical.

C *1 Density* at 20 C (68 F). 2.58 ■ per cu cm (0.093 lb per cu in.)

D *1 Liquidus temperature*. 621 C (1150 F)

2 Solidus temperature. 499 C (840 F)

6 Thermal expansion
20 to 100 C (68 to 212 F). 0.0000245 per °C
20 to 200 C (68 to 392 F). 0.0000255 per °C
20 to 300 C (68 to 572 F). 0.0000265 per °C

11 Specific heat at 100 C (212 F). Approx 0.23 cal per ■

13 Latent heat of fusion. Approx 93 cal per g

16 Thermal conductivity at 25 C (77 F). 0.21 cal/sq cm/cm/°C/sec, condition T4

E *1 Volume conductivity* referred to standard copper. 21% condition T4

2 Electrical resistivity at 20 C (68 F). 8.210 microhm-cm, condition T4

11 Electrolytic solution potential versus N/10 calomel electrode is 0.89 volts, condition T4 (53 ■ NaCl + 3 g H_2O_2 solution)

F *5 Emissivity* 0.035 to 0.07 at 25 C (77 F) in air

K *Mechanical Properties. Sand cast, condition T4:* Tensile strength 46,000 psi; yield strength 25,000 psi; compressive yield strength 26,000 psi; elongation (round specimens, ½-in. diam) 14.0%; Bhn (500-kg load, 10-mm ball) 75; modulus of elasticity 10,300,000 psi; shear strength 33,000 psi; endurance limit (based on 500,000,000 cycles using R. R. Moore type of rotating-beam machine) 7,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.

Strength and Elongation at Elevated Temperatures

After prolonged heating at testing temperatures

Property	Temperature, deg Fahr				
	75 F	300 F	400 F	500 F	600 F
Tensile strength, psi	46,000	35,000	22,000	15,000	10,500
Yield strength, psi	25,000	19,000	11,500	7,500	3,500
Elongation, %	14	16	40	55	70

L *2 Radiography*. Same as for 218 alloy (Al – 8 Mg)

M *Composition Limits. Sand cast* (AN-A-33), *components:* 9.5 to 10.6% Mg; *impurities:* 0.20% max Cu; 0.30% max Fe; 0.20% max Si; 0.10% max Mn; 0.10% max Zn; others (each) 0.05% max; and others (total) 0.15% max.

2 Consequences of exceeding impurity limits. High copper or nickel greatly decreases resistance to corrosion. High iron, silicon or manganese decreases mechanical properties.

N *1 Melting temperature*. 677 to 816 C (1250 to 1500 F)

2 Casting temperature. 677 to 788 C (1250 to 1450 F)

3 Alloying. Add magnesium as pure metal to molten base metal (pure).

5 Type of flux for remelting for casting. Gaseous, nitrogen or chlorine; or solid, aluminum chloride base.

17 Joining.
Rivet compositions. 53 S-T4, 53 S-T6, 53 S-T61
Soft solder with Alcoa No. 802; no flux. Rub-tin with Alcoa No. 802.
Resistance welding. Spot, seam, and flash methods.

Al – 6 Si – 3.5 Cu*

A *2 Trade name*. 319 alloy (sand and permanent mold casting)

3 ASTM number. B 26-46T, alloy SC8 (sand); B 108-46T, alloy SC8 (permanent mold)

B *1 Typical uses*. Applications where good casting characteristics, good weldability, pressure tightness, and moderate strength are required. Automotive cylinder heads, internal combustion engine crankcases, typewriter frames and piano plates are typical.

C *1 Density* at 20 C (68 F). 2.77 g per cu cm (0.100 lb per cu in.)

D *1 Liquidus temperature*. 604 C (1120 F)

2 Solidus temperature. 510 C (950 F)

6 Thermal expansion
20 to 100 C (68 to 212 F). 0.0000215 per °C
20 to 200 C (68 to 392 F). 0.0000225 per °C
20 to 300 C (68 to 572 F). 0.0000235 per °C

11 Specific heat at 100 C (212 F). Approx 0.23 cal per g

13 Latent heat of fusion. Approx 93 cal per ■

16 Thermal conductivity at 25 C (77 F). 0.26 cal/sq cm/cm/°C/sec

E *1 Volume conductivity* referred to standard copper. 27%, sand; 28%, permanent mold

2 Electrical resistivity at 20 C (68 F).
6.386 microhm-cm, sand;
6.158 microhm-cm, permanent mold

11 Electrolytic solution potential versus N/10 calomel electrode is 0.81 volts, sand; 0.76 volts, permanent mold (53 ■ NaCl + 3 ■ H_2O_2 solution)

F *5 Emissivity*. 0.035 to 0.07 at 25 C (77 F) in air

K *Mechanical Properties*. See Table I. *Sand and permanent mold cast:* Modulus of elasticity 10,300,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.

L *2 Radiography*. Same as for 85 alloy (Al – 5 Si – 4 Cu)

* Compiled by Aluminum Company of America

Table I. Mechanical Properties of Al–6 Si–3.5 Cu

Condition	Tensile Strength,(a) psi	Yield Strength, psi	Elongation,(b) percentage	Brinell Hardness Number(c)	Shear Strength, psi	Endurance Limit,(d) psi	Compressive Yield Strength, psi
			Sand Cast				
As cast	27,000	18,000	2.0	70	24,000	10,000	18,000
T6	36,000	24,000	2.0	80	....	10,000	....
			Permanent Mold Cast				
As cast	34,000	19,000	2.5	85	24,000	....	19,000
T6	40,000	27,000	3.0	[illegible]	....	....	....

(a) In general, strengths and elongation are unchanged or improve at low temperatures.
(b) Round specimens, ½-in. diam.
(c) 500-kg load, 10-mm ball.
(d) Based on 500,000,000 cycles, using R. R. Moore type rotating-beam machine.

M *Composition Limits. Sand and permanent mold cast, components:* 2.5 to 4.5% Cu, 5.0 to 7.0% Si, *impurities (max):* 1.20% Fe, 0.50% Mg, 0.80% Mn, 1.00% Zn, 0.50% Ni, 0.20% Ti, others (total) 1.00%.

2 Consequences of exceeding impurity limits. High iron, manganese, nickel or magnesium decreases mechanical properties.

N *1 Melting temperature range.* 677 to 816 C (1250 to 1500 F)

2 Casting temperature. (sand) 677 to 788 C (1250 to 1450 F)

3 Alloying. Add silicon as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy.

5 Type of flux for remelting for casting. Gaseous type, nitrogen or chlorine; or solid, aluminum chloride base.

15 Heat Treatment.

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Cooling
		Sand Castings		
Solution heat treatment ..	501 to 507	935 to 945	12(a)	Water at 150 to 212 F
Precipitation T6(b)	152 to 157	305 to 315	2 to 5	Not critical
		Permanent Mold Castings		
Solution heat treatment ...	501 to 507	935 to 945	8(a)	Water at 150 to 212 F
Precipitation T6(b)	152 to 157	305 to 315	2 to 5	Not critical

(a) Soaking time periods required for average castings after load has reached specified temperature. Time can be decreased or may have to be increased, depending on experience with particular castings.
(b) Start with solution heat treated material.

17 Joining. Same as for 108 alloy (Al–4 Cu–3 Si)

Al–5 Si–1.3 Cu–0.5 Mg*

A *2 Trade name.* 355 alloy (sand and permanent mold casting)

3 ASTM number. B 26-46T, Alloy SC21 (sand); B 108-46T, Alloy SC21 (permanent mold)

4 Government number. QQ-A-601, Class 10 (sand); QQ-A-596, Class 6 (permanent mold)

B *1 Typical uses.* Applications where good castability, weldability and pressure tightness are required. Aircraft supercharger covers, fuel-pump bodies, air-compressor pistons, liquid-cooled cylinder heads, liquid-cooled aircraft engine crankcases, water jackets, and blower housings are typical.

C *1 Density* at 20 C (68 F). 2.70 g per cu cm (0.098 lb per cu in.)

D *1 Liquidus temperature.* 627 C (1160 F)

2 Solidus temperature. 579 C (1075 F)

6 Thermal expansion.
20 to 100 C (68 to 212 F). 0.0000220 per °C
20 to 200 C (68 to 392 F). 0.0000230 per °C
20 to 300 C (68 to 572 F). 0.0000240 per °C

11 Specific heat at 100 C (212 F). Approx 0.23 cal per g

16 Thermal conductivity at 25 C (77 F).
0.40 cal/sq cm/cm/°C/sec, sand, condition T51
0.34 cal/sq cm/cm/°C/sec, sand, condition T6
0.35 cal/sq cm/cm/°C/sec, sand, condition T61
0.39 cal/sq cm/cm/°C/sec, sand, condition T7
0.36 cal/sq cm/cm/°C/sec, permanent mold, condition T6

E *1 Volume conductivity* referred to standard copper.
43%, sand, condition T51
36%, sand, condition T6
37%, sand, condition T61
42%, sand, condition T7
39%, permanent mold, condition T6

* Compiled by Aluminum Company of America

Table I. Mechanical Properties of Al–5 Si–1.3 Cu–0.5 Mg

Condition	Tensile Strength,(a) psi	Yield Strength, psi	Elongation,(b) percentage	Brinell Hardness Number,(c)	Shear Strength, psi	Endurance Limit,(d) psi	Compressive Yield Strength, psi
			Sand Cast				
T51	28,000	23,000	1.5	65	22,000	7,000	24,000
T6	35,000	25,000	2.5	80	30,000	8,500	29,000
T61	39,000	35,000	1.0	90	32,000	....	37,000
T7	38,000	36,000	0.5	85	26,000	8,500	35,000
T71	35,000	29,000	1.5	75	.....	10,000	.....
			Permanent Mold Cast				
T51	30,000	24,000	2.0	75	24,000	....	24,000
T6	43,000	27,000	4.0	90	30,000	9,000	26,000
T62	45,000	40,000	1.5	105	36,000	....	.....
T7	40,000	30,000	2.0	85	30,000	....	.....
T71	36,000	31,000	3.0	85	26,000	....	.....

(a) In general, strengths and elongations remain unchanged or improve at low temperatures.
(b) Round specimens, ½-in. diam
(c) 500-kg load, 10-mm ball
(d) Based on 500,000,000 cycles using R. R. Moore type of rotating-beam machine

Table II. Strength and Elongation of Al – 5 Si – 1.3 Cu – 0.5 Mg at Elevated Temperatures
After prolonged heating at testing temperatures

Property	Temperature, deg Fahr: 75 F	300 F	400 F	500 F	600 F
Sand Cast, Condition T6					
Tensile strength, psi	35,000	30,000	13,000	8,000	6,000
Yield strength, psi	25,000	25,000	9,000	5,000	3,500
Elongation, %	2.5	1.5	12.0	22.0	30.0
Sand Cast, Condition T51					
Tensile strength, psi	28,000	22,000	13,000	8,000	6,000
Yield strength, psi	23,000	17,000	9,000	5,000	3,500
Elongation, %	1.5	2.5	12.0	22.0	30.0
Permanent Mold Cast, Condition T6					
Tensile strength, psi	43,000	33,000	12,000	8,000	4,500
Yield strength, psi	27,000	29,000	9,000	6,000	3,000
Elongation, %	4.0	2.0	20.0	25.0	50.0

Table III. Composition Limits of Al–5 Si–1.3 Cu–0.5 Mg

Form	Designation	Components: Si min	Si max	Cu min	Cu max	Mg min	Mg max	Impurities: Fe max	Mn max	Zn max	Ti max	Others total max
Sand cast	QQ-A-601, Class 10	4.5	5.5	1.00	1.5	0.40	0.60	0.60	0.10	0.10	0.20	0.10
Permanent mold cast	QQ-A-596, Class 6	4.5	5.5	1.00	1.5	0.40	0.60	0.60	0.10	0.10	0.20	0.10

2 Electrical resistivity at 20 C (68 F).
4.010 microhm-cm, sand, condition T51
4.789 microhm-cm, sand, condition T6
4.660 microhm-cm, sand, condition T61
4.105 microhm-cm, sand, condition T7
4.421 microhm-cm, permanent mold, condition T6

11 Electrolytic solution potential versus N/10 calomel electrode is 0.78 volts, condition T4; 0.79 volts, condition T6 (53 g NaCl + 3 g H_2O_2 solution)

F *5 Emissivity*. 0.035 to 0.07 at 25 C (77 F) in air

K *Mechanical Properties*. See Tables I and II. Modulus of elasticity 10,300,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.

L *2 Radiography*. Type A or 506 film with no intensifying screen, cardboard exposure holder, 36-in. focal distance, General Electric OX-10 unit, 2.1 H&D film density.

Section, in.	Volts	Milliamperes	Time, min
½	65,000	10.0	1.0
1	95,000	6.7	1.0
1½	125,000	5.0	1.0
2	140,000	5.0	1.2

M *Composition Limits*. See Table III.
2 Consequences of exceeding impurity limits. High iron decreases ductility. Nickel decreases resistance to corrosion. Tin reduces mechanical properties.

N *1 Melting temperature*. 677 to 816 C (1250 to 1500 F)
2 Casting temperature range. (sand) 677 to 788 C (1250 to 1450 F)
(permanent mold) 677 to 788 C (1250 to 1450 F)
3 Alloying. Add silicon as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add magnesium as pure metal to molten base metal (pure).
5 Type of flux for remelting for casting. Gaseous type, nitrogen or chlorine; or solid type, aluminum chloride base.
15 Heat treatment.

Purpose	Temperature: deg Cent	deg Fahr	Time, hours	Cooling
Sand Castings				
Precipitation T51[c]	224 to 230	435 to 445	7 to 9	Not critical
Solution heat treatment	524 to 529	975 to 985	12[a]	Water at 150 to 212 F
Precipitation T6[d]	152 to 157	305 to 315	3 to 5	Not critical
Precipitation T61[d]	152 to 157	305 to 315	8 to 10	Not critical
Precipitation T7[b][d]	224 to 230	435 to 445	7 to 9	Not critical
Precipitation T71[b][d]	243 to 249	470 to 480	4 to 6	Not critical
Permanent Mold Castings				
Precipitation T51[c]	224 to 230	435 to 445	7 to 9	Not critical
Solution heat treatment	524 to 529	975 to 985	8[a]	Water at 150 to 212 F
Precipitation T6[d]	152 to 157	305 to 315	3 to 5	Not critical
Precipitation T62[d]	168 to 174	335 to 345	14 to 18	Not critical
Precipitation T7[b][d]	224 to 230	435 to 445	7 to 9	Not critical
Precipitation T71[b][d]	243 to 249	470 to 480	4 to 6	Not critical

(a) Soaking time periods required for average castings after load has reached specified temperature. Time can be decreased or may have to be increased, depending on experience with particular castings.
(b) U. S. Patent 1,822,877
(c) No solution heat treatment
(d) Start with solution heat treated material.

17 Joining. Same as for 214 alloy (Al – 3.8 Mg)

Al – 7 Si – 0.3 Mg*

A *2 Trade name*. 356 alloy (sand and permanent mold casting)
3 ASTM number. B 26–46T, Alloy SG1 (sand); B 108-46T, Alloy SG1 (permanent mold)
4 Government number. QQ-A-601, Class 3 (sand); QQ-A-596, Class 8 (permanent mold)

B *1 Typical uses*. Applications where excellent castability and good weldability, pressure tightness and good resistance to corrosion are required. Aircraft pump parts, automotive transmission cases, aircraft fittings and control parts, water-cooled cylinder blocks are typical.

C *1 Density* at 20 C (68 F). 2.68 g per cu cm (0.097 lb per cu in.)

D *1 Liquidus temperature*. 610 C (1130 F)
2 Solidus temperature. 579 C (1075 F)
6 Thermal expansion
20 to 100 C (68 to 212 F). 0.0000215 per °C
20 to 200 C (68 to 392 F). 0.0000230 per °C
20 to 300 C (68 to 572 F). 0.0000235 per °C
11 Specific heat at 100 C (212 F). Approx 0.23 cal per
13 Latent heat of fusion. Approx 93 cal per g
16 Thermal conductivity at 25 C (77 F).
0.40 cal/sq cm/cm/°C/sec, sand, condition T51
0.36 cal/sq cm/cm/°C/sec, sand, condition T6
0.37 cal/sq cm/cm/°C/sec, sand, condition T7
0.38 cal/sq cm/cm/°C/sec, permanent mold, condition T6

E *1 Volume conductivity* referred to standard copper.
43%, sand, condition T51
39%, sand, condition T6

* Compiled by Aluminum Company of America

Table I. Mechanical Properties of Al–7 Si–0.3 Mg

Condition	Tensile Strength,[a] psi	Yield Strength, psi	Elongation,[b] percentage	Brinell Hardness Number[c]	Shear Strength, psi	Endurance Limit,[d] psi	Compressive Yield Strength, psi
Sand Cast							
T51	25,000	20,000	2.0	60	18,000	7,500	22,000
T6	33,000	24,000	4.0	70	27,000	8,000	22,000
T7	34,000	30,000	2.0	75	18,000	....	29,000
T71	28,000	21,000	4.5	60	16,000	....	.....
Permanent Mold Cast							
T6	40,000	27,000	5.0	90	.....	....	24,000
T7	33,000	.....	5.0	70	.....	....	.....

(a) In general, strengths and elongations remain unchanged or improve at low temperature.
(b) Round specimens, ½-in. diam
(c) 500-kg load, 10-mm ball
(d) Based on 500,000,000 cycles using R. R. Moore type of rotating-beam machine.

40%, sand, condition T7
41%, permanent mold, condition T6

2 Electrical resistivity at 20 C (68 F).
4.010 microhm-cm., sand, condition T51
4.421 microhm-cm., sand, condition T6
4.310 microhm-cm., sand, condition T7
4.205 microhm-cm., permanent mold, condition T6

11 Electrolytic solution potential versus N/10 calomel electrode is 0.82 volts, sand, condition T6 (53 g NaCl + 3 ▪ H_2O_2 solution)

F *5 Emissivity.* 0.035 to 0.07 at 25 C (77 F) in air

K *Mechanical Properties.* See Table I.
Modulus of elasticity 10,300,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.

Strength and Elongation at Elevated Temperatures
After prolonged heating at testing temperatures

Property	75 F	300 F	400 F	500 F	600 F
	Temperature, deg Fahr				
Sand Cast, Condition T6					
Tensile strength, psi	33,000	21,000	13,000	8,000	4,500
Yield strength, psi	24,000	16,000	9,000	5,500	3,000
Elongation, %	4	5	8	20	45

L *2 Radiography.* Same as for 13 alloy (Al–12 Si)

M *Composition Limits.* See Table II.
2 Consequences of exceeding impurity limits. High copper or nickel decreases ductility and resistance to corrosion. High iron decreases strength and ductility.

N *1 Melting temperature.* 677 to 816 C (1250 to 1500 F)
2 Casting temperature. (sand) 677 to 788 C (1250 to 1450 F); (permanent mold) 677 to 788 C (1250 to 1450 F)
3 Alloying. Add silicon as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add magnesium as pure metal to molten base metal (pure).
5 Type of flux for remelting for casting. Gaseous type, nitrogen or chlorine; or solid type, aluminum chloride base.

15 Heat treatment.

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Cooling
Sand Castings				
Precipitation T51[c]	224 to 230	435 to 445	7 to 9	Not critical
Solution heat treatment	535 to 541	995 to 1005	12[a]	Water at 150 to 212 F
Precipitation T6[d]	152 to 158	305 to 315	2 to 5	Not critical
Precipitation T7[b][d]	224 to 230	435 to 445	7 to 9	Not critical
Precipitation T71[d]	243 to 249	470 to 480	2 to 4	Not critical
Permanent Mold Castings				
Solution heat treatment	535 to 541	995 to 1005	8[a]	Water at 150 to 212 F
Precipitation T6[d]	152 to 157	305 to 315	3 to 5	Not critical
Precipitation T7[b][d]	224 to 230	435 to 445	7 to 9	Not critical

(a) Soaking time periods required for average casting after load has reached specified temperature. Time can be decreased or may have to be increased, depending on experience with particular castings.
(b) U. S. Patent No. 1,822,877
(c) No solution heat treatment.
(d) Start with solution heat treated material.

17 Joining. Same as for 214 alloy (Al–3.8 Mg)

Table II. Composition Limits of Al–7 Si–0.3 Mg

Form	Designation	Components: Si min	Si max	Mg min	Mg max	Impurities: Cu max	Fe max	Mn max	Zn max	Ti max	Others total max
Sand cast	QQ-A-601, Class 3	6.5	7.5	0.20	0.40	0.20	0.60	0.10	0.10	0.20	0.10
Permanent mold cast	QQ-A-596, Class 8	6.5	7.5	0.20	0.40	0.20	0.60	0.10	0.10	0.20	0.10

Al – 8 Si – 1.5 Cu – 0.3 Mg – 0.3 Mn

COMPILED BY F. ROMANO*

A *2 Trade name.* Red X-8 (sand and permanent mold casting)
3 ASTM number. B 26–46T, Alloy SC 42 (sand); B 108–46T, Alloy SC 42 (permanent mold).
4 Government number. 46 A 15 (Interim)

B *1 Typical uses.* A general-purpose aluminum alloy for sand and permanent mold castings, which has its properties improved by solution heat treatment. It is used in castings for internal combustion engines or other machine parts subjected to high stresses at elevated temperatures.
2 Precautions in use. Because this alloy contains 8% Si, it is subject to about 0.001 in. per in. growth if heated to approximately 400 F in use or fabrication. A heat treatment of 5 hr at 450 F applied to rough castings will prevent further dimensional change from this cause.

C *1 Density* at 20 C (68 F). 2.73 g per cu cm (0.099 lb per cu in.)

D *6 Thermal expansion* 20 to 100 C (68 to 212 F). 0.0000214 per °C
16 Thermal conductivity at 20 C (68 F). 0.24 cal/sq cm/cm/°C/sec, as cast; 0.27 cal/sq cm/cm/°C/sec, stress relieved

E *1 Volume conductivity* referred to standard copper. 26%, as cast; 29%, stress relieved

K *Mechanical Properties.* See Tables I and II.

M *Composition Limits. Sand and chill cast, components:* 1.0 to 2.0% Cu; 0.20 to 0.60% Mg; 0.20 to 0.60% Mn; 7.0 to 8.6% Si; 0.3% max Ti; *impurities:* 1.0% max Fe; 0.2% max Ni; 0.5% max Zn; 0.3% max Cr; others (total) 0.5% max.

* Research Laboratory, National Smelting Company, Cleveland.

Table I. Mechanical Properties of Al – 8 Si – 1.5 Cu – 0.3 Mg – 0.3 Mn

Condition	Tensile Strength, psi	Yield Strength,[a] psi	Elongation,[b] percentage	Rockwell E Hardness
Sand Cast				
Stress relieved	30,000	21,000	1.5	E 76
Solution heat treated and aged	39,000	30,000	1.5	E 88
Solution heat treated and stress relieved	36,000	28,000	2.0	E 82
Permanent Mold Cast				
Stress relieved	36,000	.....	1.0	E 88
Solution heat treated and aged	44,000	27,000	4.0	E 91
Solution heat treated and stress relieved	41,000	28,000	3.0	E 88

(a) 0.2% offset (b) Round specimen, ½-in. diam

Table II. Short-Time Tests at Elevated Temperature

Condition	Tensile Strength, psi	Elongation,[a] percentage	Rockwell E Hardness	Temperature, deg Fahr
Sand Cast				
Stress relieved	31,000	1.5	E 81	75
	30,000	1.5	E 84	200
	27,000	2.0	E 80	300
	23,000	3.0	E 80	400
	19,000	3.5	E 78	500
	13,000	7.0	E 71	600
Solution heat treated and aged	38,000	2.5	E 88	75
	36,000	2.5	E 89	200
	34,000	3.0	E 88	300
	31,000	3.5	E 92	400
	20,000	5.5	E 83	500
	11,000	12.8	E 68	600
Permanent Mold Cast				
Stress relieved	41,000	2.0	E 89	75
	39,000	2.5	E 89	200
	34,000	3.0	E 88	300
	28,000	4.5	E 88	400
	22,000	6.5	E 85	500
	14,000	14.0	E 75	600
Solution heat treated and aged	45,000	4.5	E 92	75
	43,000	5.0	E 92	200
	39,000	6.0	E 92	300
	33,000	6.5	E 95	400
	23,000	11.0	E 87	500
	11,000	23.0	E 71	600

(a) Round specimen, ½-in. diam

N 6 *Precautions in melting:* If the metal is heated to more than 1375 F some pinhole porosity may result. For the production of castings free from pinhole porosity, made with pouring temperatures over 1375 F, the melt should be degassed with chlorine, nitrogen, or boron trichloride. Loss of magnesium should be controlled.

Al – 9.5 Si – 0.5 Mg*

A 2 *Trade name.* 360 alloy (die casting)
5 *Other designations.* SAE AMS 4290
B 1 *Typical uses.* Applications where excellent castability and resistance to corrosion are required. Miscellaneous thin-walled and intricate castings are typical.
C 1 *Density* at 20 C (68 F). 2.68 g per cu cm (0.097 lb per cu in.)
D 1 *Liquidus temperature.* 591 C (1095 F)
2 *Solidus temperature.* 566 C (1050 F)
6 *Thermal expansion*
20 to 100 C (68 to 212 F). 0.0000195 per °C
20 to 200 C (68 to 392 F). 0.0000205 per °C
20 to 300 C (68 to 572 F). 0.0000215 per °C
11 *Specific heat* at 100 C (212 F). Approx 0.23 cal per g
13 *Latent heat of fusion.* Approx 93 cal per g
16 *Thermal conductivity* at 25 C (77 F). 0.35 cgs
E 1 *Volume conductivity* referred to standard copper. 37%
2 *Electrical resistivity* at 20 C (68 F). 4.660 microhm-cm
F 5 *Emissivity.* 0.035 to 0.07 at 25 C (77 F) in air
K *Mechanical Properties. Die cast:* Tensile strength 42,000 psi; yield strength 23,000 psi; elongation (round specimens, ¼-in. diam) 1.8%; modulus of elasticity 10,300,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.
L 2 *Radiography.* Same as for 355 alloy (Al – 5 Si – 1.3 Cu – 0.5 Mg)
M *Composition Limits. Die cast* (AMS 4290), *components:* 9.0 to 10.0% Si; 0.40 to 0.60% Mg; *impurities:* 2.0% max Fe; 0.60% max Cu; 0.30% max Mn; 0.50% max Zn; 0.50% max Ni; 0.10% max Sn; others (total) 0.20% max.
2 *Consequences of exceeding impurity limits.* Relatively large quantities of impurities may be present before serious effects are detected. In general, increasing copper will lower resistance to corrosion and increasing iron will lower ductility.
N 1 *Melting temperature range.* 649 to 760 C (1200 to 1400 F)
2 *Die-casting temperature range.* 635 to 704 C (1175 to 1300 F)
3 *Alloying.* Add silicon as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add magnesium as pure metal to molten base metal (pure).
5 *Type of flux* for remelting for casting. Gaseous type, nitrogen or chlorine; or solid type, aluminum chloride base.
17 *Joining.* Same as for 13 alloy (Al – 12 Si)

Al – 8.5 Si – 3.5 Cu*

A 2 *Trade name.* 380 alloy, 4–9 alloy (die casting)
3 *ASTM number.* B 85–46T, Alloy SC7
4 *Government number.* QQ–A–591, Class 11.
B 1 *Typical uses.* General-purpose applications where greater castability is required than that afforded by 85 alloy (Al – 5 Si – 4 Cu).
C 1 *Density* at 20 C (68 F). 2.76 g per cu cm (0.099 lb per cu in.)
D 1 *Liquidus temperature.* 588 C (1090 F)
2 *Solidus temperature.* 521 C (970 F)
11 *Specific heat* at 100 C (212 F). Approx 0.23 cal per g
13 *Latent heat of fusion.* Approx 93 cal per g
16 *Thermal conductivity* at 25 C (77 F). 0.26 cal/sq cm/cm/°C/sec
E 1 *Volume conductivity* referred to standard copper. 27%
2 *Electrical resistivity* at 20 C (68 F). 6.386 microhm-cm
F 5 *Emissivity.* 0.035 to 0.07 at 25 C (77 F) in air
K *Mechanical Properties. Die cast:* Tensile strength 45,000 psi; yield strength 25,000 psi; elongation (round specimens, ¼-in. diam) 2.0%; modulus of elasticity 10,300,000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.
L 2 *Radiography.* Same as for 85 alloy (Al – 5 Cu – 4 Si)
M *Composition Limits. Die cast* (QQ–A–591, Class 11), *components:* 7.5 to 9.5% Si; 3.0 to 4.0% Cu; *impurities:* 2.0% max Fe; 0.10% max Mg; 0.50% max Mn; 1.0% max Zn; 0.50% max Ni; others (each) 0.15% max, and others (total) 0.50% max.
2 *Consequences of exceeding impurity limits.* Relatively large quantities of impurities may be present before serious effects are detected. In general, increasing iron will lower ductility.
N 1 *Melting temperature.* 649 to 760 C (1200 to 1400 F)

* Compiled by Aluminum Company of America

2 *Die-casting temperature range.* 635 to 704 C (1175 to 1300 F)
3 *Alloying.* Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add silicon as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy.
5 *Type of flux* for remelting for casting. Gaseous, nitrogen or chlorine; or solid, aluminum chloride base
17 *Joining.* Same as for 13 alloy (Al – 12 Si)

Al – 6.5 Sn – 1 Cu – 1 Ni*

A 2 *Trade name.* 750 alloy (permanent mold casting)
B 1 *Typical uses.* Applications where excellent bearing qualities are required. Bearings and bushings.
C 1 *Density* at 20 C (68 F). 2.89 g per cu cm (0.104 lb per cu in.)
D 1 *Liquidus temperature.* 649 C (1200 F)
2 *Solidus temperature.* 232 C (450 F)
6 *Thermal expansion*
20 to 100 C (68 to 212 F). 0.0000231 per °C
20 to 200 C (68 to 392 F). 0.0000243 per °C
11 *Specific heat* at 100 C (212 F). Approx 0.23 cal per ■
13 *Latent heat of fusion.* Approx 93 per g
16 *Thermal conductivity* at 25 C (77 F). 0.42 cal/sq cm/cm/°C/sec
E 1 *Volume conductivity* referred to standard copper. 45%
2 *Electrical resistivity* at 20 C (68 F). 3.831 microhm-cm
F 5 *Emissivity.* 0.035 to 0.07 at 25 C (77 F) in air
K *Mechanical Properties. Permanent mold cast, condition T5:* Tensile strength 22,000 psi; yield strength 10,000 psi; compressive yield strength 10,000 psi; elongation (round specimens, ½-in. diam) 12%; Bhn (500-kg load, 10-mm ball) 45; modulus of elasticity 10,300,000 psi; shear strength 14,000 psi; endurance limit (based on 500,000,000 cycles using R. R. Moore type of rotating-beam machine) 9000 psi; modulus of rigidity 3,850,000 psi; Poisson's ratio 0.33.

* Compiled by Aluminum Company of America

L 2 *Radiography.* Type A or 506 film with no intensifying screen, cardboard exposure holder, 36-in. focal distance, General Electric OX-250 unit, 2.1 H&D film density.

Section, in.	Volts	Milliamperes	Time, min
½	140,000	5.0	1.0
1	180,000	5.0	1.0
1½	185,000	7.0	1.0
2	200,000	10.0	1.0

M *Composition Limits. Permanent mold cast, components:* 5.5 to 7.0% Sn; 0.70 to 1.3% Cu; 0.70 to 1.3% Ni; *impurities:* 0.70% max Si; 0.70% max Fe; 0.10% max Mn; 0.20% max Ti; others (total) 0.30% max.
2 *Consequences of exceeding impurity limits.* High iron, manganese, or magnesium decreases ductility and increases hardness. High silicon modifies bearing characteristics.
N 1 *Melting temperature.* 649 to 732 C (1200 to 1350 F)
2 *Casting temperature.* 649 to 704 C (1200 to 1300 F)
3 *Alloying.* Add tin as pure metal to molten base metal (pure). Add copper as pure metal or aluminum-rich alloy to base metal (pure), either in melt-down or molten alloy. Add nickel as aluminum-rich alloy to melt-down or molten base metal (pure).
5 *Type of flux* for remelting for casting. Gaseous type, nitrogen or chlorine; or solid type, aluminum chloride base.

Al – 5.5 Zn – 0.6 Mg – 0.5 Cr – 0.2 Ti*

A 2 *Trade name.* 40 E alloy (sand casting)
3 *ASTM number.* B 26–46T, Alloy ZG41
4 *Government number.* AN-A-17; 46A1 (Int), Class 1
5 *Other designations.* SAE 310, AFA B 81
B 1 *Typical uses.* Applications where a good combination of mechanical properties is required without heat treatment: shock and corrosion resistance, machinability, dimensional stability, and freedom from distortion caused by heat treatment. Airplane stressed parts, turret housings, air-compressor pistons, instrument parts, and machine parts subjected to shock.
C 1 *Density* at 20 C (68 F). 2.81 g per cu cm (0.101 lb per cu in.)
D 1 *Liquidus temperature.* 760 C (1140 F)
2 *Solidus temperature.* 572 C (1060 F)
6 *Thermal expansion* 21 to 93 C. 0.0000247 per °C
11 *Specific heat* at 100 C (212 F). Approx 0.23 cal per ■
13 *Latent heat of fusion.* Approx 93 cal per g
16 *Thermal conductivity* at 25 C (77 F). 0.33 cgs
E 1 *Volume conductivity* referred to standard copper. 35%
2 *Electrical resistivity* at 20 C (68 F). 4.926 microhm-cm
F 5 *Emissivity.* 0.035 to 0.07 at 25 C (77 F) in air
K *Mechanical Properties. Sand cast*: Tensile strength 35,000 psi; yield strength 25,000 psi; elongation (round specimens, ½-in. diam) 5%; Bhn (500-kg load, 10-mm ball) 80; modulus of elasticity 10,300,000 psi; impact value (Charpy) 2 to 3 ft-lb; shear strength 27,800 psi; endurance limit (based on 500,000,000 cycles using R. R. Moore type of rotating-beam machine) 9,000 psi; Poisson's ratio 0.33; compressive proportional limit 14,000 psi; low-temperature strength after 24 hr at minus 94 F, tensile strength 38,400 psi and elongation 5%. See table at right.

* Compiled by Frontier Bronze Corporation

Strength and Elongation at Elevated Temperatures
After 1000 hr at testing temperature

Property	Temperature, deg Fahr: 175 F	250 F	350 F
Tensile strength, psi	33,800	29,500	19,700
Yield strength, psi	30,700	25,200	17,000
Elongation, %	3	2	6

L 2 *Radiography.* Same as for 113 alloy (Al – 7 Cu – 2 Si – 1.7 Zn)
M *Composition Limits. Sand cast* (ASTM B 26–46T, Alloy ZG41), *components*: 5.0 to 6.0% Zn; 0.50 to 0.65% Mg; 0.40 to 0.60% Cr; 0.10 to 0.30 Ti; *impurities,* 0.30% max Cu; 1.00% max Fe; 0.25% max Si; 0.30% max Mn; others (each) 0.05% max.
N 1 *Melting temperature range.* 677 to 802 C (1250 to 1475 F)
2 *Casting temperature range.* 677 to 802 C (1250 to 1475 F)
3 *Alloying.* Add magnesium as pure metal to base metal (pure) to compensate for furnace loss.
5 *Type of flux* for remelting for casting. Gaseous type, nitrogen or chlorine; or solid type, sodium chloride-sodium fluoride base.
15 *Heat treatment.* Precipitation, at 180 C (356 F), 10 hr; cooling not critical. An optional 21-day aging at room temperature may be substituted.
17 *Joining.*
Soft solder with Alcoa No. 802; no flux. Rub-tin with Alcoa No. 802.
Braze with Alcoa No. 717; Alcoa No. 33 flux in furnace atmosphere.
Oxyacetylene weld with 40 E alloy; Alcoa No. 22 flux; flame neutral.
Resistance welding. Spot, seam, and flash methods

COPPER AND COPPER ALLOYS

Prepared under the direction of

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71 Cu – 1 Sn – 3 Pb – 25 Zn (Leaded Yellow Brass)	938
66 Cu – 1 Sn – 3 Pb – 30 Zn (Leaded Yellow Brass)	939
60 Cu – 1 Sn – 1 Pb – 38 Zn (Leaded Yellow Brass)	939
62 Cu – 26 Zn – 3 Fe – 5.5 Al – 3.5 Mn (High-Strength Yellow Brass)	939
58 Cu – 39.25 Zn – 1.25 Fe – 1.25 Al – 0.25 Mn (High-Strength Yellow Brass)	940
59 Cu – 0.75 Sn – 0.75 Pb – 37 Zn – 1.25 Fe – 0.75 Al – 0.5 Mn (Leaded Manganese Bronze)	940
66 Cu – 5 Sn – 1.5 Pb – 2 Zn – 25 Ni (Nickel Silver)	940
64 Cu – 4 Sn – 4 Pb – 8 Zn – 20 Ni (Nickel Silver)	940
57 Cu – 2 Sn – 9 Pb – 20 Zn – 12 Ni (Nickel Silver)	941
60 Cu – 3 Sn – 5 Pb – 16 Zn – 16 Ni (Leaded Nickel Brass)	941
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The Copper Industry

By T. E. Veltfort*

COPPER and copper alloys pass through so many processes from mine to consumer that no adequate review of the copper industry is possible without at least a cursory study of the sequence of processes. To permit such a study, Fig. 1 is presented.

Statistics on copper and copper products at various stages included in Fig. 1, are assembled by several organizations in varying degrees of detail and from divers viewpoints. No effective attempt to reconcile and co-ordinate

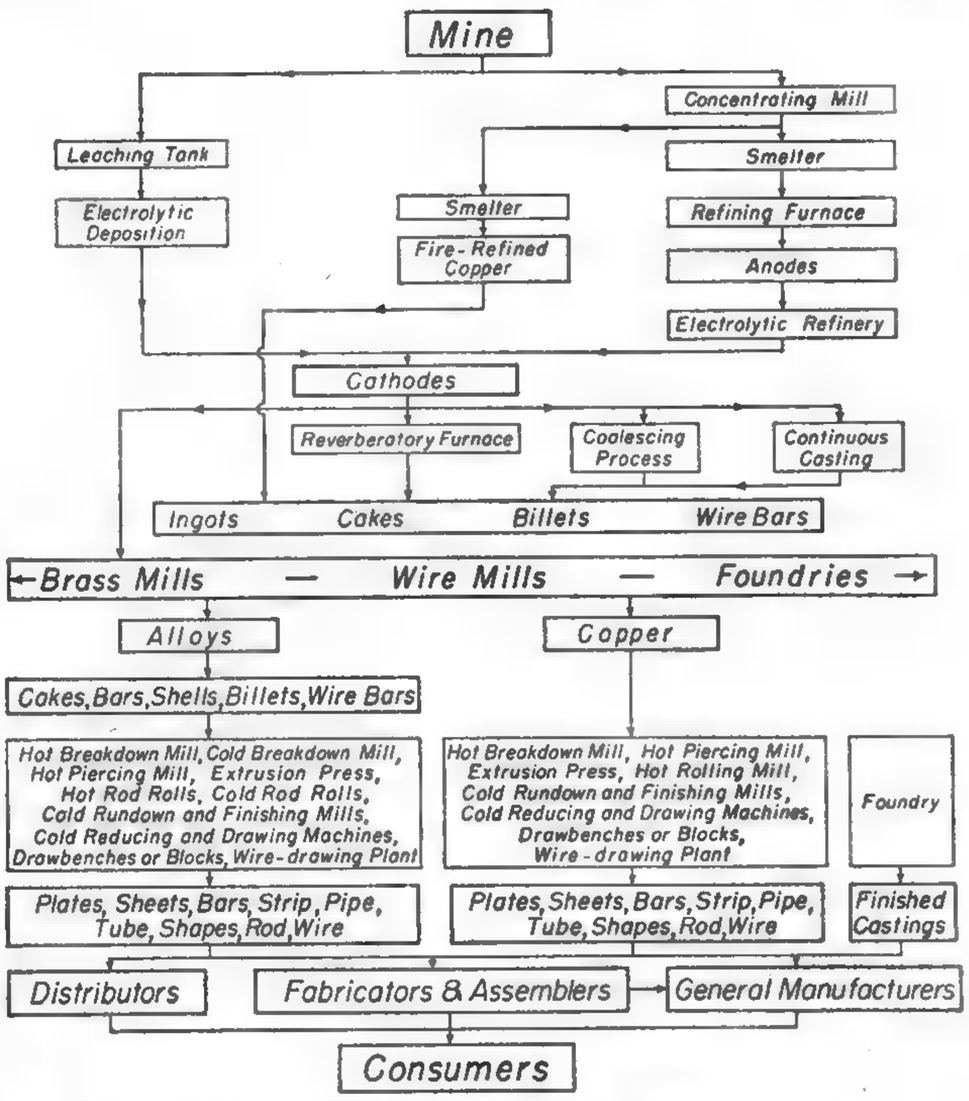

Fig. 1 Flow chart showing copper from mine to consumer

such statistics has been practicable so far and, accordingly, the use of available statistics requires an appreciation of their limitations. Accuracy is not in question since most statistics of this kind are essentially accurate at the level and source compiled. The important need is for interpretation and reliable use of these available data for comparative purposes. Copper statistics in the United States are collected principally by the American Bureau of Metal Statistics, by the U. S. Bureau of Mines, by the Copper Institute and the U. S. Copper Association. Each of these authoritative bodies covers somewhat different areas, a circumstance that leads to differences in their findings; but even where the areas overlap there are differences. Basic data are the same, for they must come from the same mines, smelters and refiners. Each authority, however, has its own questionnaire or report form, which differs from the others and, therefore, produces answers that also differ.

The situation is further complicated by the effect of stocks at various levels of use. To illustrate this, advantage may be taken of the results of a study made by the War Production Board concerning the flow of copper in a representative month in 1943. Figure 2 presents this information in simplified form. It will be noted that at every point of use, copper flows into stocks, and because these stocks form a reserve that is constantly increasing or diminishing, the inflow of copper for any short period of time is likely to differ from the outflow of copper content in processed material. Statistics will differ, therefore, depending on whether they represent the copper content of the raw material in process, the copper content of material actually processed, or the copper content of the material actually delivered to the next process. Aside from the necessity of making allowance for these factors, there is the difference of opinion among the reporting organizations as to what constitutes stocks. Thus, for example, in reporting stocks of copper actually on hand at refineries, one authority treats cathodes (which are refined copper and, as shown in Fig. 1, may be delivered in that form for consumption) as refined stock; another treats them as stock "in process", because, as also shown in Fig. 1, cathodes may pass through a melting furnace to be cast into wire bars, cakes, ingots or other shapes.

Imports and exports also create statistical difficulties. During normal times considerable copper in various forms reaches this country from abroad to be processed in bond and then returned. Statistics of imports and exports must make appropriate allowance for such material. A difference in the classification of exports, moreover, arises from the fact that some statisticians classify copper rod, of which a substantial quantity is exported, as a primary product, and include it in wire bars because much of it is used for drawing into wire. Others consider copper rod a manufactured product, rod.

Secondary copper occasions a particularly confusing disagreement. Statistical treatment of this metal differs among authorities and there is no accepted definition of what secondary copper is. One authority holds that the only true secondary copper is that reclaimed from industrial use, excluding all turnings, borings and other processing

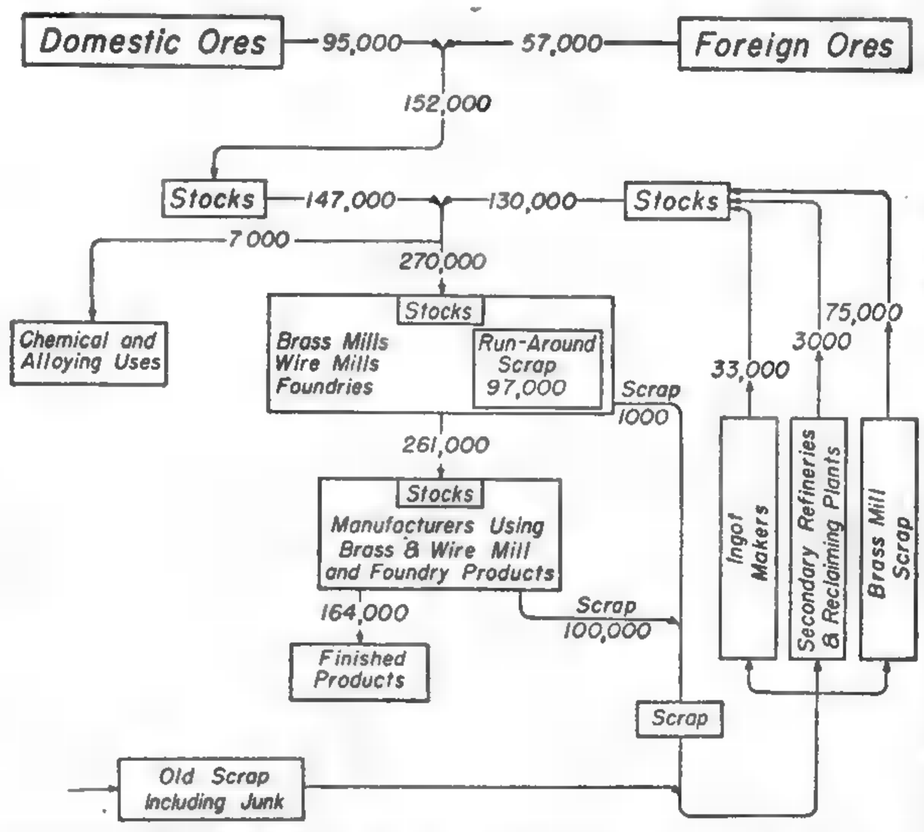

Fig. 2 Course of copper from origin through fabrication and reuse for a representative month in 1943. (Quantities represent copper content in short tons.)

scrap, which he considers run-around copper. There is sound logic for this viewpoint, as indicated in Fig. 2. It will be noted that in the brass mills, wire mills and foundries, a considerable quantity of copper is designated as "run-around", consisting of gates, croppings, ends, and process scrap, which in normal operations never leaves the plants. Also, a minor quantity of unusable scrap is shown leaving the mills, and a much more substantial quantity of scrap, such as turnings, borings, and skeleton scrap, is shown leaving the fabricating plants. However, the major part of this material returns to the mills as scrap or is processed immediately into ingots and other forms for use by the mills and foundries. In that sense, such scrap may be considered an extension of the mills' own run-around. Other statisticians, however, do not adopt this view. This was a factor of particular importance during World War II because of the high proportion of

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scrap resulting from the manufacture of cartridge cases from brass disks.

The sources of the following statistics have been selected with a view to affording consistent and comparable data derived on a basis that should make them significant for the anticipated users of this section of the Handbook. Because of the situation outlined above, it has appeared needless to show production and related data in units smaller than thousands of tons of 2000 lb each.

In the following tabulation, the available statistics for the period from 1928 to 1945 have been organized and presented thus:

Table I. Production of Copper on the Basis of Origin of Ore. This represents copper as mined, and is a convenient and significant series for over-all information on world and domestic mine production and the relation of the two.

Table II. Production of Refined Copper Regardless of Origin of Ore. This indicates the actual refining activity in this country. Normally, half again as much copper is refined in the U. S. as is mined here. It will be noted, by comparison with Table I, that during some years the copper refined in the U. S. has been about twice the volume mined domestically, though that proportion appears to be abnormal.

Table III. Production of Refined Copper in U. S. Comparison of Data. This presents first, parts (*a*) and (*b*), volume of copper refined, as compiled from the American Bureau of Metal Statistics and the Bureau of Mines data, respectively. The results on lines 13 and 16 are in substantial agreement, for ordinary comparisons.

As a second approach, this table in parts (*c*) and (*d*), presents comparable data as given by the Copper Institute and as compiled from the figures of the American Bureau of Metal Statistics, respectively. These data, however, are limited to copper refined by primary refiners from domestic ore and from secondary copper. Here again the agreement is fairly close (*compare* lines 17 and 20).

Table IV. New and Old Copper Used in U. S. This table presents information as compiled (*a*) from data of the American Bureau of Metal Statistics and (*b*) from data of the Bureau of Mines. In general, the first series is on a mine production basis, the second on a refinery basis. Considering the difference in approach for these two series, it is significant that the totals (lines 30 and 41) for most of the years covered, are in reasonable agreement. This table, in lines 31 and 42, also shows the percentage of copper used that has been derived from old scrap.

Tables I to IV. Significant Copper Statistics (1928 to 1945)

(In thousands of tons of 2000 pounds)

Line	Item	1928	1929	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941	1942	1943	1944	1945
	Table I																		
1	**Production of Copper on Basis of Origin of Ore**																		
2	World production	1894	2118	1735	1488	998	1146	1401	1617	1849	2499	2187	2402	2689	2904	3039	3064		
3	U. S. production[1]	935	1026	711	525	256	234	240	380	615	835	557	735	892	983	1097	1114	1006	805
4	U. S. production, per cent of world production	49	48	41	35	26	20	17	24	33	33	26	31	33	34	36	36		
	Table II																		
5	**Production of Refined Copper Regardless of Origin of Ore**																		
6	Production of refined copper in U. S.																		
7	Primary refiners																		
8	Primary or virgin	1255	1376	1098	762	396	316	421	571	803	1080	814	971	1268	1378	1420	1401	1250	1095
9	Secondary[1]	115	166	136	62	67	88	111	142	131	157	90	116	125	97	83	120	97	85
10	Secondary refiners	30[3]	44	35[3]	26	20[3]	29	24	24	29	32	26	33	33	25	14	12	5	2
11	Total	1400	1586	1269	850	483	433	556	737	963	1269	930	1120	1426	1500	1517	1533	1352	1182
	Table III																		
12	**Production of Refined Copper in U. S.—Comparison of Data**																		
13	(*a*) Refined copper, primary—from line 8[1]	1255	1376	1098	762	396	316	421	571	803	1080	814	971	1268	1378	1420	1401	1250	1095
14	U. S. production from domestic ore[2]	896	991	696	537	222	241	233	338	645	822	552	705	927	975	1065	1082	974	775
15	Refined from foreign ore or matte[2]	348	379	383	214	118	130	212	251	177	245	240	305	387	420	350	297	247	
16	(*b*) Total (compare with line 8)	1244	1370	1079	751	340	371	445	589	822	1067	792	1010	1314	1395	1415	1379	1221	
17	(*c*) Production of copper (compare with line 20)[4]							337	497	749	964	638	818	1034	1066	1136	1207	1099	843
18	Production from U. S. ore—from line 3[1]	935	1026	711	525	256	234	240	380	615	835	557	735	892	983	1097	1114	1006	805
19	From reclaimed copper[1]	115	166	136	62	67	88	111	142	131	157	90	116	125	97	83	120	97	85
20	(*d*) Total	1050	1192	847	587	323	322	351	522	746	992	647	851	1017	1080	1180	1234	1103	890
	Table IV																		
21	(a) **New and Old Copper Used in U. S. (Mine Production Basis)[1]**																		
22	Production—line 3		1026	711	525	256	234	240	380	615	835	557	735	892	983	1097	1114	1006	805
23	Imports (unmanufactured) based on Bur of M		492	411	294	197	144	214	258	193	283	254	339	494	736	764	717	787	847
24	Total		1518	1122	819	453	378	454	638	808	1118	811	1074	1386	1719	1861	1831	1793	1652
25	Exports, refined		451	330	244	155	172	312	299	246	333	405	394	368	107	133	176	68	49
26	Remainder		1067	792	575	298	206	142	339	562	785	406	680	1018	1612	1728	1655	1725	1603
27	Increase (+) or decrease (—) in stocks of blister and in process of refining		+23	—53	—48	— 7	+12	+ 4	+51	—29	+24	— 5	+55	— 9	—21	+18	—24	+ 3	+34
28	Total new copper		1044	845	623	305	194	138	288	591	761	411	625	1027	1633	1710	1679	1722	1569
29	Old copper (from old scrap only) (Bur of M)		404	342	261	181	260	311	362	383	409	267	287	334	413	427	428	457	
30	Total		1448	1187	884	486	454	449	650	974	1170	678	912	1361	2046	2137	2107	2179	
31	Per cent of old copper		28	29	30	37	57	69	56	39	35	39	31	25	20	20	20	21	
32	(b) **New and Old Copper Used in U. S.[2]**																		
33	Refined copper from refineries—see line 16	1244	1370	1079	751	340	371	445	589	822	1067	792	1010	1314	1395	1415	1379	1221	
34	Imports, refined, incl material under bond	42	67	43	87	84	▮	27	18	5	7	2	16	68	347	401	403	492	
35	Total	1286	1437	1122	838	424	376	472	607	827	1074	794	1026	1382	1742	1816	1782	1713	
36	Exports, refined	510	452	335	232	125	132	272	275	236	310	385	396	377	115	132	177	69	
37	Remainder	776	985	787	606	299	244	200	332	591	764	409	630	1005	1627	1684	1605	1644	
38	Increase (+) or decrease (—) in stocks—refined	—29	+96	+155	+155	+40	—96	—122	—110	—65	+69	+ 2	—86	— 4	—14	+ 7	—16	+13	
39	Total new copper	805	889	632	451	259	340	322	442	656	695	407	716	1009	1641	1677	1621	1631	
40	Old copper (from old scrap only)		404	342	261	181	260	311	362	383	409	267	287	334	413	427	428	457	
41	Total (compare with line 30)		1293	974	712	440	600	633	804	1039	1104	674	1003	1343	2054	2104	2049	2088	
42	Per cent of old copper		31	35	37	41	43	49	45	37	37	40	29	25	20	20	21	22	

NOTES: (1) American Bureau of Metal Statistics, (2) Bureau of Mines, (3) Estimated by Interpolation, (4) Copper Institute

Table V. Estimated Use of Copper in the United States*

(In tons of 2000 lb)

Purpose	1932	1933	1934	1935	1936	1937	1938	1939	1940
Electrical manufactures[a]	90,000	90,000	101,000	128,000	164,000	212,000	150,000	185,000	247,000
Telephones and telegraphs	27,000	18,000	18,000	18,000	26,000	40,000	30,000	39,000	49,000
Light and power lines[b]	49,000	33,000	36,000	55,500	72,000	83,000	62,000	67,000	74,000
Wire cloth	4,200	5,000	4,600	5,600	6,500	6,800	6,000	8,000	9,200
Other rod and wire[i]	30,000	46,000	40,000	48,000	90,000	102,000	60,000	95,000	120,000
Automobiles[c]	32,300	49,000	63,000	95,000	108,000	112,000	55,000	85,000	103,000
Buildings[e]	29,000	36,000	36,000	49,000	71,000	70,500	67,500	89,000	102,000
Castings, n.o.s.[d]	27,000	36,000	36,000	36,000	39,000	40,000	31,000	33,000	35,000
Clocks and watches	1,500	2,800	2,200	2,400	3,400	4,000	3,000	4,000	4,400
Copper-bearing steel	800	1,500	2,100	2,300	3,900	4,600	2,600	4,200	4,700
Radiators, heating	1,000	2,400	1,000	1,100	2,000	2,100	2,000	3,600	2,900
Radio	7,000	11,500	12,500	16,000	24,000	23,100	21,000	27,000	32,000
Railway equipment[f]	700	800	2,100	1,800	4,000	7,100	1,700	2,700	5,700
Refrigerators[h]	9,000	11,400	15,700	15,400	15,000	13,500	6,700	10,000	10,500
Shipbuilding[h]	2,100	1,800	3,200	1,100	5,000	6,400	6,000	8,500	8,700
Air conditioning[g] [h]	....	....	3,800	4,800	6,400	7,200	6,000	6,000	6,000
Ammunition	3,900	10,500	13,500	13,700	11,900	14,100	12,500	14,500	26,000
Other uses[j]	30,900	43,700	46,800	51,500	65,300	66,600	46,200	67,600	81,500
Manufactures for export	22,600	15,600	25,500	29,500	31,600	45,000	38,800	51,900	148,400
Totals	368,000	415,000	463,000	574,700	749,000	860,000	608,000	801,000	1,070,000
Use in lb per person[k]	5.53	6.35	6.91	8.55	11.17	12.61	8.74	11.42	14.00

*** Based on end use of refined copper adjusted for exports and change in stocks**

(a) Generators, motors, electric locomotives, switchboards, light bulbs and the like. (b) Transmission and distribution wire and bus bars, accounting only for the public utility companies. (c) Does not include starter, generator and ignition equipment. (d) Bearings, bushings, lubricators, valves and fittings. (e) Excludes electrical work. (f) Includes air conditioning beginning with 1933. (g) Other than railway. (h) Exclusive of electrical equipment. (i) Includes industrial wire and cable, wire in buildings, railway cars and ships, military, railway and municipal signaling, railway electrification, trolley wire, rod and wire for governmental projects, blasting wire, flexible cord and sundries. (j) Includes condenser tubes, oil-burner tubing, welding rod, screw machine products, nickel silver and phosphor bronze products, rivets and burrs, toilet pins, eyelets and grommets, electrotyping and engraving sheet, spark plugs, inner tube valve stems, jar tops and rouge boxes, flash-light tubes, kerosene lamps, kitchen utensils, kitchen range boilers, linotype matrices, safety razors, blasting caps, asbestos textiles, water meters, thermostats, soldering coppers, yacht fittings, coinage, washing machines, household water heaters, fire extinguishers, pumps, airplanes, engines and sundry machinery, all reckoned in terms of copper content. (k) Computed after deduction of manufactures for export. Exports in 1940 increased because of foreign military demands and similar requirements.

Table VI. Use of Copper in the United States by Percentage

Purpose	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940
Electrical manufactures	23.11	24.91	24.46	21.69	21.81	22.27	21.90	24.65	24.67	23.10	23.08
Telephones and telegraphs	12.76	10.77	7.33	4.34	3.89	3.13	3.47	4.65	4.93	4.87	4.58
Light and power lines	13.60	13.08	13.32	7.95	7.78	9.66	9.61	9.65	10.20	8.36	6.92
Other wire	10.76	9.21	9.29	12.29	9.63	9.33	12.89	11.86	9.87	11.86	11.21
Automobiles	9.10	9.48	8.78	11.81	13.61	16.53	14.42	13.02	9.05	10.61	9.63
Buildings	5.23	6.92	7.88	8.67	7.78	8.53	9.48	8.20	11.10	11.11	9.53
Refrigerators, automatic	1.57	2.00	2.45	2.75	3.39	2.68	2.00	1.57	1.10	1.25	0.98
Other uses	16.43	16.21	20.35	26.74	26.60	22.74	22.01	21.17	22.70	22.36	20.20
Manufactures for export	7.44	7.42	6.14	3.76	5.51	5.13	4.22	5.23	6.38	6.48	13.87
Totals	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

This tabulation is an accounting for final use of refined copper exrefineries and copper content of mill products. Annual discrepancies are ascribable to (1) plus or minus in stocks and (2) statistical error. In this table the production of the ingot manufacturers does not enter except in so far as they used copper from the primary refiners.

Statistics relative to the uses of copper are compiled regularly by the American Bureau of Metal Statistics. These statistics from 1932 to 1940 are given in Table V. Similar data, on a percentage basis, are given in Table VI.

During World War II, copper was used entirely for war material and related essential uses. The normal pattern of use was therefore radically changed. This is clearly shown by Table VII, summarizing the deliveries of copper during two years of the war, under the Controlled Materials Plan, which governed the allocation of steel, copper and aluminum during the war.

As indicated in Fig. 1 and 2, the three prime industries using copper are the brass mills, the wire mills and foundries. A minor fraction of the copper produced is consumed in chemicals and for alloying steel, aluminum and other base metals. However, reliable statistics are not available concerning copper used for these purposes.

In the following sections are outlined briefly the statistics applicable to each of the three prime industries using copper.

Brass Mill Products. Monthly shipment data representing almost 100% of brass mill production are compiled by the American Bureau of Metal Statistics. During World War II, the War Production Board also compiled data on brass mill production. These two series are given in Table VIII. The large difference between the figures of these two series results from the fact that the War Production Board totals include the output of several concerns which, though not brass mills, were rolling substantial quantities of sheet and strip brass for ammunition, in order to meet the greatly increased demand. The data from the War Production Board also include the output of the Defense Plant Corporation plants, which were built specifically for producing mill products for ammunition. Normally also, where the output is in the form of circles or disks, brass mill shipments are stated in terms of net weight of these products. The statistics of the War Production Board, however, give the weight of the strip from which such circles and disks were cut, thus considerably increasing the total, particularly in view of the abnormally large production of ammunition disks.

The output of brass mill products shows some interesting relationships with other features of the national economy. Thus it follows rather faithfully the trend of national income, as shown in Fig. 3. Statistics concerning shipments from brass mills are available only as far back as 1926, while copper production is indicated back to 1918, so there is an overlap from 1926 to 1932 to develop the relationship between the two series. Copper in tons is approximately equivalent to brass mill products in thousands of pounds. The correlation between brass mill shipments and national income is even more obvious in Fig. 4.

A still closer relationship exists between brass mill shipments and industrial production, as indicated by Fig. 5 and 6. It is interesting to note that the rate of change of brass mill shipments is greater than that of industrial

Table VII. Deliveries of Copper and Copper-Base Alloy Products on Authorized Controlled Material Orders

(From Mills, Foundries and Warehouses)
July 1943 to June 1945
Copper Content, in Thousands of Tons of 2000 Pounds
(From Information Published by Civilian Production Administration)

Product	Tons	%
Ammunition	2619	44.8
Ships (navy, cargo, and such) including MRO[a]	520	8.9
Industrial and miscellaneous equipment and machinery	428	7.3
U.S.S.R.	232	4.0
Automotive, engines, bearings and accessories	213	3.6
Miscellaneous, not otherwise classified	190	3.3
Utility equipment, including MRO	187	3.2
Valves and fittings	176	3.0
Airplanes and accessories	165	2.8
Ordnance (other than ammunition) and tanks	159	2.7
Electric motors and generators	152	2.6
Railroad and other transport	147	2.5
General MRO	126	2.2
Signal Corps	126	2.2
Miscellaneous Army requirements	113	1.9
Radio, electronics and radar equipment	88	1.5
Building materials, including electrical	87	1.5
Bolts, nuts and parts	53	0.9
Foreign, other than U.S.S.R.	44	0.7
Various expansion programs	22	0.4
Total	5847	100.0

(a) Maintenance, Repairs and Operating Supplies

Table VIII. Brass Mill Shipments and Production

Year	Brass Mill Shipments,[a] millions of pounds	Brass Mill Production,[b] millions of pounds
1926	1090	....
1927	1043	....
1928	1257	....
1929	1363	....
1930	916	....
1931	733	....
1932	485	....
1933	742	....
1934	781	....
1935	966	....
1936	1262	....
1937	1284	....
1938	780	....
1939	1241	....
1940	1602	....
1941	2594	....
1942	3180	....
1943	3608	5610
1945	3229	5013
1944	2644	3717[c]

(a) Statistics begin in 1926
(b) Note explanation in text
(c) Deliveries

production in general—particularly during times of high activity. Because of the extraordinarily great use of brass mill products in war armament, this effect is, of course, accentuated in time of war, as from 1940 to 1945.

Wire Mill Products. No statistics are available for wire mill products, comparable with those for copper and brass mill products. The War Production Board published data covering wire mill production for several years during World War II, but there are no criteria for comparison with normal production.

Foundry Products. Up to the beginning of 1946, there have been no direct statistics on the quantity of castings made of copper and copper alloys. This has been quite natural, considering the fact that such work is done in a large number of small shops and that the production of many such castings is incidental to other processes.

Beginning with January 1946, the Bureau of the Census has initiated the release of data on shipments and unfilled orders of nonferrous castings, based on reports submitted by the larger foundries on Bureau of the Census Form M24E. These data, applicable to copper and copper alloy castings, are "blown up" to an estimated 100% from foundry reports representing about 90% of the total. Figures for January and February 1946, the only ones now available (June 1946) are given in Table IX.

Recently, fairly complete data have become available concerning deliveries of brass and bronze ingots, which

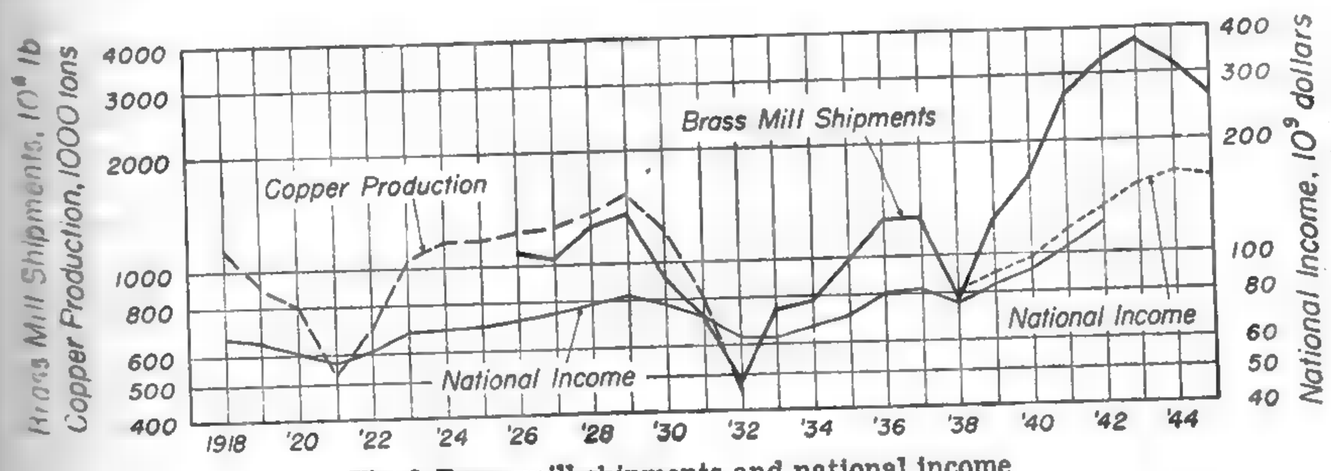

Fig. 3 Brass mill shipments and national income

Sources

Brass mill shipments: American Bureau of Metal Statistics
Copper production (refined): American Bureau of Metal Statistics
National income (total income adjusted by the cost of living, 1926 = 100):
To 1942, National Industrial Conference Board
To 1945, Department of Commerce

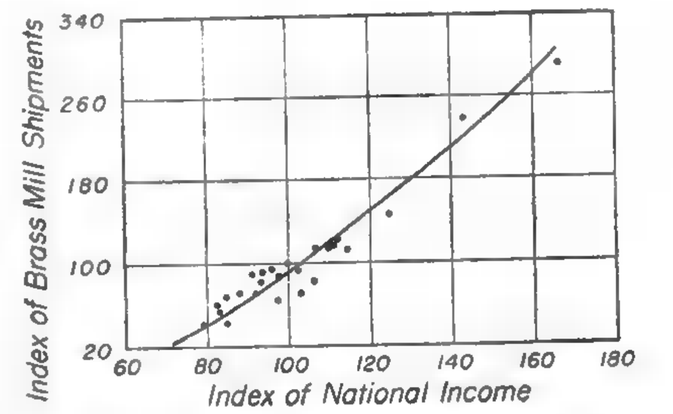

Fig. 4 Brass mill shipments and national income
Based on index numbers for the period 1918 to 1942 with 1926 = 100

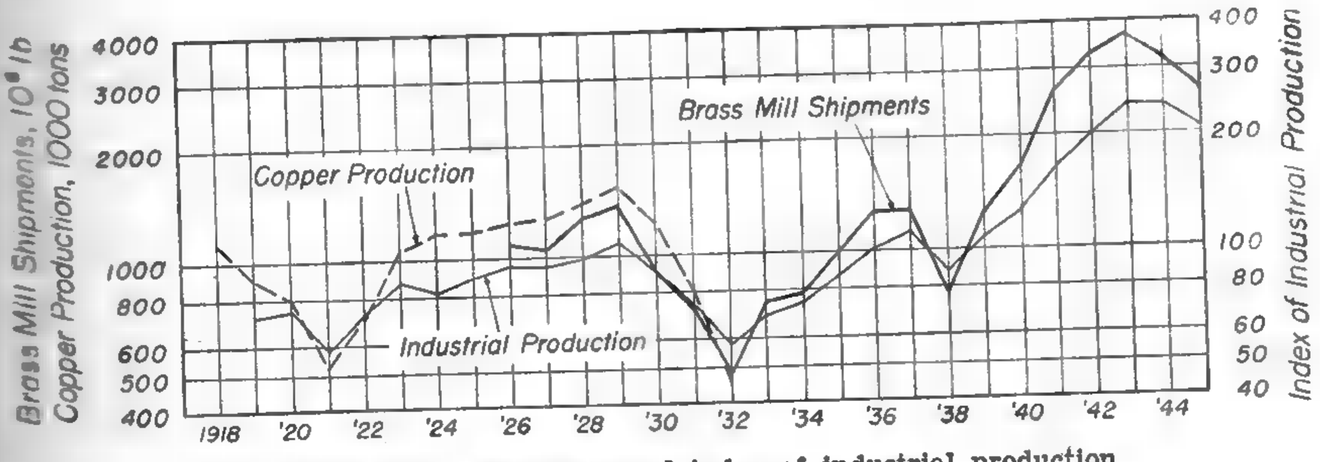

Fig. 5 Brass mill shipments and index of industrial production

Sources

Brass mill shipments: American Bureau of Metal Statistics
Copper production (refined): American Bureau of Metal Statistics
Index of industrial production, 1935 to 1939 average = 100: Board of Governors of the Federal Reserve System

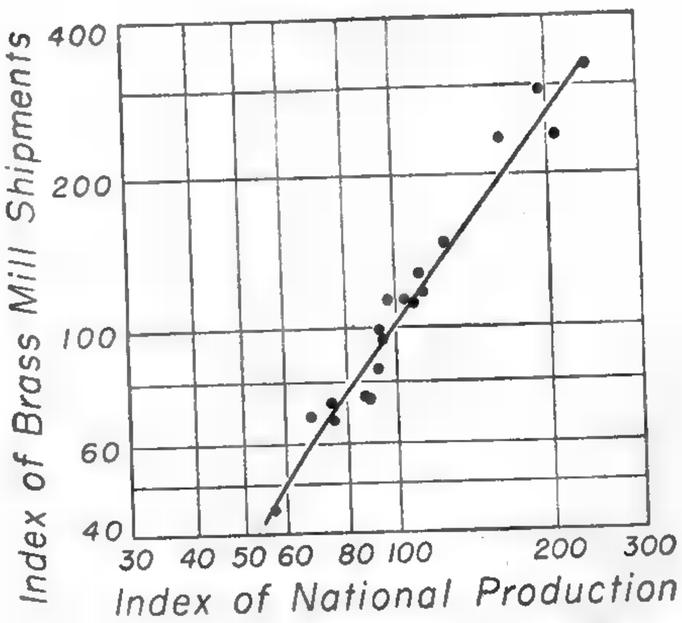

Fig. 6 Brass mill shipments and index of industrial production, 1935 to 1939 = 100

are the raw material for castings and which, therefore, may be considered an index to activity in that field. Beginning with 1941, the Defense Council of the Ingot Brass and Bronze Industry has been compiling such data for virtually the entire brass and bronze ingot industry and,

Table IX. Shipments of Copper and Copper Alloy Castings
(In Thousands of Pounds)

Type of Casting	January 1946 — For Sale	January 1946 — For Own Use	January 1946 — Total	February 1946 — For Sale	February 1946 — For Own Use	February 1946 — Total
Sand	38,579	26,528	65,107	33,225	23,767	56,992
Permanent mold	748	1,138	1,886	736	977	1,713
Die	466	380	846	389	356	745
All other	899	1,274	2,173	1,084	1,164	2,248
Total	40,692	29,320	70,012	35,434	26,264	61,698

based on these data, the American Bureau of Metal Statistics has presented the following tabulation.

Year	1941	1942	1943	1944	1945
Deliveries of Ingot[a]	299	397	490	512	385

(a) Brass and bronze ingots, in thousands of tons of 2000 lb. Published data from the Bureau of Mines, presumably based on the same source, agree substantially with those given above.

Course of Prices. Several trade papers publish regularly the prices for copper and various copper products. Such information is compiled conveniently in a book called "Metal Statistics", published yearly by American Metal Market, New York. These data, too extensive to include here, cover copper prices, giving the dates of all changes in prices, as well as monthly and annual high, low and average prices; extras for various shapes; prices for brass and wire mill products; brass ingot prices; and scrap prices.

On August 12, 1941, the price of copper was pegged by the government at 12 cents per pound for electrolytic copper delivered in Connecticut (equivalent to 11.87 cents f.o.b. refinery, New York), with cost-plus contracts arranged for all producers unable to meet this price. On February 1, 1942, a premium price plan was inaugurated under which quotas were set for the various producers and 5 cents per pound above the ceiling price of 12 cents per pound was offered for all production exceeding the quota, through the Metals Reserve Company, a government agency. Later a special additional premium up to 15 cents a pound was awarded to small copper mines. The over-all result has been that while the ceiling for copper during the war was maintained at 12 cents per pound, the actual prices paid, according to an OPA report, were as follows, with the government supplying the difference between the ceiling price and the higher prices paid:

Year	1942	1943	1944 (Jan. to June)	1945 (Jan. to June)
Price, ¢ per lb	12.25	13.30	13.54	13.73

During the war, also, the government controlled the procurement of the large quantities of copper obtained from abroad, paying any difference between the ceiling price and the cost. According to an official statement in February 1945, the Foreign Economic Administration, which was purchasing the foreign copper, was obtaining it at a cost of less than 12½ cents per pound.

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The Production of Finished and Semifinished Copper Alloy Castings

BY THE SUBCOMMITTEE ON COPPER ALLOY CASTINGS*

THIS ARTICLE describes the production of copper alloy castings in the foundry. The following processes are discussed: melting, sand casting, permanent mold casting, die casting, centrifugal casting, precision investment casting, and plaster molding.

For some statistics concerning copper alloy foundry products the reader may refer to the preceding article. The physical and mechanical properties of 25 cast copper alloys are presented on pages 935 to 942.

Melting

BY H. M. ST. JOHN*

BRASS FOUNDRY PRACTICE is exceedingly variable both as to the kind of melting equipment used and as to procedure. There are sound reasons for much of this variability but some of it is probably unnecessary and uneconomical. The industry has been somewhat slow to take advantage of modern developments, but in recent years there has been an increasing trend toward modernization, strongly influenced by a necessity for reducing costs and improving working conditions.

The term "brass" is widely used to include the high-grade bronzes as well as compositions that consist primarily of copper and zinc. Since this discussion of melting practice deals only with foundry alloys, most of which contain substantial percentages of lead as well as zinc and tin, the word "brass" will be used rather loosely to include all such compositions. The number of alloys in this category is excessively large, in spite of much recent progress toward standardization and the elimination of many meaningless variations. However, with few exceptions, the same melting practice applies to all.

Furnaces. The types and sizes of melting equipment in common use are widely different because of the great differences in size and scope of brass-foundry operations. "Captive" foundries, producing castings only for the manufacturing establishments of which they are a part, may be large or small, may work with many alloys or few. The volume of castings produced may favor highly mechanized production methods, or the diversity of production in kind or size may make such methods unprofitable. The same applies to jobbing foundries, although a large proportion of these are small and thus are not in a position to take full advantage of equipment and practices that have been developed for volume production.

Electric Furnaces. Most large brass foundries make some use of electric furnaces and some foundries employ no other type. The electric furnaces in most common use are: (1) indirect-arc furnaces that oscillate or rock during melting, to ensure a thorough mixing of the charge and a uniform distribution of heat; (2) vertical-ring induction furnaces that also keep the metal in motion during melting, by means of electromechanical forces inherent in the design of the furnace. In less common use are high-frequency induction furnaces—which have a definite place in the melting of brass, but are more widely employed in other fields of the foundry industry—and a type of oscillating furnace that employs an incandescent resistor instead of the electric arc.

The initial investment for electric furnace installations is high, yet when these furnaces are properly operated under suitable conditions, the cost of operation is low. Both the efficiency and the "fixed charges" economy of the furnace depend on steady use with a minimum of interruption and delay. The supply of electric power must be reliable and reasonably cheap. Skilled labor must be

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Each member of this subcommittee has written on a particular process of casting. The authors of the sections are indicated below each subtitle.
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available for the installation and maintenance of refractory linings and for electrical and mechanical repairs and adjustments. Supervisors of the melting operation must be fully versed in the requirements of the process, but the melters themselves need not be highly skilled or trained.

When the above requirements can be met, many foundrymen consider electric furnaces to be the most economical type of melting equipment for brass foundries. The utilization of electric energy is efficient if the furnaces are operated steadily for at least five 8-hr days per week. The induction furnace requires some electric current to keep it hot during standby periods and thus benefits greatly from longer hours of operation. It is particularly well adapted for melting high-zinc alloys, such as manganese bronze. In both arc and induction furnaces, losses of metal are low and metal quality and pouring temperatures are easily controlled. The cost of labor is low and working conditions are excellent if adequate ventilation is provided. Mechanical charging and handling of the metal can readily be arranged.

Both arc and induction furnaces are production machines and are less flexible in their use than the crucible. In the arc furnace, successive heats of different alloys can be made if minor contaminations of metal (lead, for example) trapped in the refractory lining are not a serious consideration. If necessary, the body of the furnace can be removed and replaced by a body with a new lining or one that does not carry the undesirable contamination; but this, if done during the working day, involves an interruption of operation. The induction furnace must ordinarily be started with molten metal, melted elsewhere, and carries a considerable heel of metal from one heat to the next, in order to maintain the electrical circuit. For this reason, changes of alloy are made infrequently.

The high-frequency induction furnace is essentially a crucible furnace and, in one of its designs, employs a removable crucible. It is thus as flexible as the older types of crucible furnace and, compared with fuel-heated crucible furnaces, it has the advantage of melting the charge much more rapidly; so it can be used to produce a heat of any metal, ferrous or nonferrous, on short notice. For this reason the high-frequency induction furnace is often employed in large plants that do not operate a production foundry but occasionally need small amounts of various alloys. It is less efficient than arc or low-frequency induction furnaces and is not commonly used for volume production work in red-brass foundries.

The resistor type of oscillating electric furnace has been designed primarily for use with manganese bronze and other high-zinc alloys. It is probably somewhat less economical than the arc furnace in the melting of red brasses and bronzes.

Fuel-Heated Furnaces. The direct-flame furnace, employing either gas or oil, is popular in both production and jobbing foundries of large and medium size. Except for rather high losses of metal, the operating costs are low. The cost of the equipment and installation is much lower than for electric furnaces. Melting is rapid and flexibility of use is about the same as with indirect-arc electric furnaces. More skill is required on the part of the melter to control metal quality and pouring temperatures, and working conditions are only fair. However, irregular operation has no great effect on costs and, in some instances, the supply of gas or oil is cheaper or more reliable than that of electricity. Where the foundry's requirements for metal vary greatly from day to day, direct-flame fuel-heated furnaces are sometimes used to supplement electric melting.

Cupolas* for melting brass use a special quality of coke, high in fixed carbon and low in impurities, to avoid contamination that would otherwise result from direct contact between metal and fuel. The charge is melted rapidly in cupolas and excellent metal can be produced. The unavoidable loss of metal during melting is somewhat high, but other operating costs and the initial investment are low. The principal use for cupolas has been in the volume production of bearing alloys.

* For a more detailed discussion of the use of cupolas in melting brass and bronze, the reader may refer to Chapter XXI of the "Handbook for Cupola Operation", American Foundrymen's Association, 1946.

Crucible furnaces that employ oil or gas as fuel are much used in medium-sized and small foundries. The charge is melted almost as rapidly as in direct-flame furnaces, and with a considerably lower loss of metal. However, crucible furnaces are less economical in their use of labor and fuel, and the cost of replacing crucibles is a considerable item. Furnaces employing a fixed crucible, usually of several hundred pounds capacity, melt brass and bronze more cheaply than the smaller "lift-out" type, but have the disadvantage that failure of the crucible, when it occurs, puts the furnace out of commission for several hours. Working conditions are fairly good, but the melter must have a considerable amount of skill if best results are to be obtained.

Crucible furnaces heated by solid fuel are much less widely used than formerly, although many furnaces of this type are still in operation. With few exceptions they are of the "lift-out" type with crucibles that are employed for pouring as well as melting. Such furnaces are flexible and, properly handled, they produce metal of excellent quality, but they melt the charge slowly and necessarily expose it for a long period to gases and other contaminating elements that may be present.

Most foundries use a few crucible furnaces of one type or another to take care of unusual or odd-lot requirements not so easily handled in larger furnaces or production batteries.

Contamination of the Charge. The melting furnace does not refine or improve the quality of the metal it melts. Instead care must be taken not to impair quality as a result of the melting operation. In best practice, the metal charged into the furnace is carefully selected and known to be of good quality. It is not considered good economy to use miscellaneous scrap, despite the comparatively low cost of such material, nor is it common practice to make extensive use of virgin metals. Aside from foundry returns, such as sprues and gates, and machine-shop turnings from the foundry's own castings, the charge usually consists of "composition ingot" produced by secondary smelters and refiners and made to meet exacting specifications. Small percentages of virgin metals are sometimes used to increase fluidity, which otherwise is likely to be somewhat variable.

During melting, the metal is exposed to gaseous and solid impurities that may contaminate it unless suitable precautions are taken. Possibly the most dangerous of these contaminants is hydrogen or water vapor, which, in the red brasses and tin bronzes, may produce a porous open structure in cast metal, utterly destructive of its quality.

In open-flame gas-heated or oil-heated furnaces care is taken to maintain a slightly oxidizing flame, preferably 0.1 to 0.2% excess oxygen, to ensure the absence of unburned fuel. Although an experienced eye can judge the oxidizing character of the flame quite accurately, the occasional use of an Orsat apparatus is desirable for analyzing the combustion gases. An oxidizing flame is an essential precaution in crucible furnaces also, when liquid or gaseous fuels are employed. On the other hand, an excessively oxidizing condition is not economical and does not yield the highest quality of metal.

In electric furnaces there are no combustion gases and it is both possible and desirable to operate with a truly neutral atmosphere. Care must be taken to avoid introducing water with the charge. Damp charcoal is one potent source of trouble. Unless recently patched furnace linings are dried thoroughly before use, trouble will result. Pouring ladles made with rammed linings are commonly baked for hours before the preheating that immediately precedes use.

The foundry industry has not yet adopted air conditioning, but most foundrymen would probably agree that it is difficult to pour the highest quality of red metal from any type of furnace on a humid day.

Oxidizable impurities, if present as traces only, may be removed in the oxidizing atmosphere of fuel-heated furnaces. Electric furnaces have no such refining action; consequently the presence of such impurities in the charge must be scrupulously avoided. On the other hand, electric furnaces produce excellent metal from charges that consist entirely of borings; in an oxidizing atmosphere, such

a charge would suffer great loss and inferior castings might be produced.

The most important oxidizable impurities are aluminum, silicon and sulfur. Aluminum and silicon are extremely deleterious in the red brasses and bronzes and must be avoided at all costs. In the indirect-arc furnace it is essential that no finely divided carbon or soot should be on the surface of the melt, since when carbon is mixed with sand or other siliceous material and exposed to the intense heat of the arc, this combination will produce metallic silicon, with deleterious effects. Finely divided carbon will result if oil, even in small quantity, is present in the charge. In general, carbonaceous material should be avoided in electric-furnace charges, although dry charcoal is not harmful and even serves a useful purpose in induction-furnace melting. The graphite electrodes employed in the indirect-arc furnace will not be a source of injurious carbon if a clear, free-burning arc is maintained. If the voltage at the arc is insufficient or if the electrodes are damp, a smoky hissing arc will result and the carbon deposited by this smoke is likely to cause reduction of silica to silicon, thus contaminating the charge.

Fluxes. Numerous proprietary fluxes are available and are widely employed. Some of these fluxes are useful when employed in the right way at the right time; however, the indiscriminate application of any flux as a cure-all, is as likely to cause trouble as to cure it. The more powerful fluxes, like powerful drugs, should be administered "by prescription only". Probably without exception, strong fluxes shorten the life of crucibles and furnace linings. For this reason, if for no other, they should be used sparingly.

Pouring. When metal is melted in lift-out crucibles, these crucibles are naturally used for pouring. Crucibles are designed to be good conductors of heat and so lose heat rapidly during pouring. Brass is sensitive to pouring temperature and most brass castings have a short pouring range. If each mold requires only a small quantity of metal, small crucibles should be used. Refractory-lined ladles lose heat less rapidly and can be of larger size economically. It is essential that ladles be preheated thoroughly before use; otherwise they absorb heat rapidly from the metal and thereby chill it.

Pyrometry and Control of Temperature. Effective means are not in common use for measuring the temperature of metal in the furnace. It is desirable not to overheat the metal and particularly desirable not to keep it in the furnace any longer than necessary. As a rule this is subject to the melter's judgment and he must make sure that the metal is hot enough. In fuel-heated furnaces the melter has little to guide his judgment and molten metal temperatures 200 F above the desired pouring temperature are not uncommon. In electric furnaces the switchboard meters are a valuable guide and maximum temperatures 50 to 75 F above the desired temperature can be attained consistently. Pyrometers for measuring temperatures in the ladle are now widely used and are essential to good foundry practice.

Sand Casting

By R. W. Parsons*

SAND CASTING, with the lowest pattern cost and widest tolerances, is the cheapest and most widely used method of producing copper alloy castings in quantities. The process is most flexible in ability to produce various designs and sizes of castings, as well as to handle the variety of alloys that may be cast in this way. Sand casting offers the fewest limitations and castings can be obtained the most rapidly by this method.

In some respects, results do not quite equal those of other methods; the surface obtained is the least desirable, while intermediate density and pressure tightness may be expected in the casting.

Allowances. As with any casting method, sections as uniform and symmetrical as possible are desirable, with proper fillets, draft and machining allowances. The minimum section is about 3/32 in., but a casting should not be so thin over too great a length. For production, about 3 deg of draft should be allowed, though the draft angle is sometimes as small as 1 deg. Finish allowances should be $\frac{1}{16}$ in. for dimensions up to 1 ft; $\frac{1}{8}$ in. from 1 to 2 ft; $\frac{5}{32}$ in. from 2 to 3 ft; and if the equipment is crude, additional finish should be allowed. Shrinkage of $\frac{3}{16}$ in. per ft is usual for most copper alloys, but $\frac{7}{32}$ in. is used in special instances.

A relation should exist between runner and in-gates so that the runner is greater in cross section than the total area of in-gates leading from the runner to the casting or castings. Inadequate runners can cause too great chilling of the metal and may produce misruns. The association of crucible melting with copper alloys has resulted in molds being poured rather generally from one end.

The gating should ensure that the metal enters the mold as quietly as possible in order to minimize the formation of dross from metal agitation. Strainer cores are not used extensively, but either such a core or a choke in the runner is useful for controlling the flow of metal in order to avoid "washing" and dirty castings. Too much choke, especially in heavy castings, may result in such slow pouring that "wormy" surface is produced from alloys that contain zinc. The size of sprue should be related to the runner, so that the sprue can be kept filled by pouring at a fairly uniform rate. Runners should be free from sharp edges and in-gates should be filleted; where possible, in-gates should take metal between the top and bottom of the runner to avoid both dross and spilling of metal into the gates before the runner is filled.

In both design and gating, consideration should be given to directional solidification, so that the portion of the casting farthest from the gate will freeze first, the heaviest section last. The risers must remain fluid the longest so as to supply liquid metal to feed the heavy section of the casting. Passage of metal over the sand will heat the mold so that cooling will be slowest next to the gate, and also in the lower portion (drag) of the casting.

Some designs make it impracticable to employ risers for feeding heavy sections of large castings, and chills are then used to hasten solidification and make cooling more uniform. Chills can be made from cast iron. They should be given a coating of shellac and dipped in sand where the metal comes in contact with them.

Insulating the necks of heavy risers delays solidification and promotes feeding. A cup of insulating material may be used to insulate the entire riser and allow superior feeding from smaller risers.

Much thin-sectioned work is made without the use of risers, and if sections are uniform and the runner is adequate to feed out the shrinkage at the gate, satisfactory results can be obtained. With heavier sections, risers must be provided to ensure sound castings.

The metal in the riser should be hotter than the casting when the metal comes to rest. If open risers are possible, metal may be poured into them to ensure hot risers, and an insulating cover on top will help to maintain temperature. Improperly located risers (as a "dead riser"), which are not hotter than the casting, are often worse than none at all. Open risers also act as vents for the steam and gases generated during pouring. In many production shops the permeability of the sand is expected to permit the escape of steam and mold gases, and vents are not liberally used; but venting of molds wherever practicable is recommended strongly.

Blind risers (not open to the air) are employed more frequently in production foundries. However, if these risers freeze, forming a shell completely surrounding the liquid interior, atmospheric pressure is cut off, rendering the riser less effective than an open riser would be. Gas pressure within the mold may act on the blind riser to force metal into the casting effectively.

Certain alloys, such as the high-strength brasses, have higher liquid shrinkage, or localized shrinkage, and require larger risers than some of the higher-copper alloys.

Results from a given pattern or gating should be checked by some means before a pattern is released for production. In addition to the checking of external dimensions (by the pattern shop), some attention should be directed toward the internal soundness and degree of

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freedom from shrinkage, and corrective steps should be taken, if necessary, before actual production is begun.

Molding. Natural molding sands are used for the majority of copper alloy sand castings because the requirements are less exacting than where higher temperatures are encountered (for instance in the casting of steel), and such castings are usually produced by smaller concerns that do not have the equipment necessary to produce synthetic sands. Many of the alloys are more "searching" than irons, so finer (tighter) sands are used to give the desired finish.

Cores made from sands prepared as mentioned in the article entitled "Steel Castings", page 523, are usually baked, and are sometimes dipped in graphite, talc, mica, or similar material, to produce a coating that will prevent metal penetration and still allow passage of gas. Molds are sometimes given a wash for the same purpose—to produce superior finish.

Although most copper alloy sand castings are poured into green sand molds, in special instances other methods are used, as with steel (*see* page 523).

Liquid partings (composed chiefly of stearic acid in kerosene) are sprayed on the pattern plates to facilitate drawing the pattern; such partings work well on metal patterns provided no wax fillets or gates are present, and they present no dust hazard. Dry partings may be vegetable or mineral powders treated to make them water repellent. Tripoli works well but creates a silicosis hazard.

Hand molding (as compared with machine molding) requires molders with the greatest skill in order to get results, especially when gates must be cut and loose patterns used. A standardized gating will be found helpful with loose patterns. Split patterns may be mounted on wooden boards to save time and reduce the skill required in molding. At best, hand molding gives least uniformity.

Machine molding gives uniform molds with greater daily production and requires less skill on the part of the molder. It is possible to make temporary mounts of patterns and gating and to derive the benefits of machine molding without the expenditure of a large amount of money for pattern equipment. Unmounted patterns in a hard sand match, make machine molding possible and are useful where parting lines are irregular.

For large quantities and better results, metal patterns should be mounted on metal plates, or cast aluminum match plates should be used.

In machine molding, sand may be rammed by squeezer, jolt machine or slinger. A squeezer may be operated by hand, by air, or hydraulically. Air and hydraulic pressure squeeze more rapidly than hand pressure. A squeezer produces molds that are hardest at the squeezer board and softer next to the pattern; for relatively shallow flasks, this difference is not great. The jolt machine works in just the opposite way; the molds are hardest next to the pattern. As flask depths increase, a combination of jolt-squeeze may be used to produce more uniform molds.

When a double-faced match plate is used, only the drag can be jolted, because after the drag has been jolted, the bottom board placed, and the mold rolled over, a second jolting would undo the work of the first. The cope must be entirely squeezed. For full jolt-squeeze molding, single-faced match plates must be used, and either identical cope and drag halves must be made on the same machine, or the drag on one machine and the cope on another.

Machines that draw the pattern simplify the molding operation and increase production; this feature may be incorporated in squeezers, jolt-squeezers, and slingers.

Sand slingers act to throw "handfuls" of sand, at considerable velocity, on and around the pattern. The slinger head is moved around, back and forth, to obtain a uniform ramming throughout the flask. These machines are adapted to large molds and, equipped with a special head to fit over smaller flasks, are used in production shops for smaller molds on draw machines.

With snap flasks, the cope is usually deeper than the drag in some relationship such as 5 to 3. This is a highly desirable condition, because it provides an extra head of metal during pouring and increased pressure as the metal comes to rest. Since the amount of sand that the molder handles is a basic part of the cost of the mold, the height of the cope is sometimes reduced. On the other hand, where flasks are standardized and cope and drag are made on the same machine, and are the same depth, frequently there is insufficient sand above the top of some of the larger castings. Where such a condition exists, pouring cups may be used for necessary added height.

Pouring. Metal melted in stationary crucible furnaces is usually poured from the crucible directly into the molds; the melting crucible is a fairly good pouring vehicle. For transporting metal from larger furnaces, of whatever type, the best pouring medium is an insulated ladle lined with crucible material. Such ladles have a high initial cost, long life, and cannot damage the metal. Ladles are commonly lined with various ramming mixtures. Crucibles and ladles should be dried thoroughly and preheated before use.

The lip of the pouring ladle should be held as close as possible to the sprue and the metal should be introduced with a minimum of turbulence and agitation. The sprue can be shaped so as to minimize swirling. The first metal should be poured directly into the center of the sprue, not splashed around the rim, and the sprue should be kept filled during the pour. Some molds must be poured "hard" while others will be strained unless the pour is fairly easy. "Uphill" pouring of the mold cavity is recommended and uphill pouring may be followed by tilting of the mold.

It may be advantageous for the molder to pour his own mold, because he is the person most interested in seeing that it is properly done; however, in order that the molder can devote more of his time to molding, pouring crews sometimes do all the pouring. In this way the pouring specialist should become expert.

Pouring Temperature. An extremely important variable in the production of copper alloy castings—particularly those for pressure work—is the matter of pouring temperature. The optimum temperature is the lowest one that will produce sound castings. This is not the same as the lowest temperature at which the job will "run", since feeding is sometimes improved by the use of a slightly higher pouring temperature.

The pouring temperature should be maintained closer than 50 F. This *cannot* be done by eye because the appearance of the metal varies widely with the darkness or brightness of the day and with the time of day. The use of a pyrometer is imperative for good results.

A pyrometer should be used with an immersion type of thermocouple, either bare or enclosed. The bare wire gives faster readings, but the enclosed type lasts longer and can be used with all the alloys. The pyrometer may be of either the millivoltmeter of the potentiometer type. The millivoltmeter type is more common, and may be of either the high-resistance or the low-resistance type. The high-resistance type is more accurate and is affected less by variations in the thermocouple.

The pouring temperature controls the fluidity; temperature also influences the quality and finish.

When castings are made from some of the copper alloys that contain appreciable percentages of lead for ease in machining, such castings can be damaged if shaken from the molds at temperatures where the alloys are "hot short". Several of the alloys can be damaged by cooling in water from an excessively high temperature. Castings of such alloys may develop cracks through the grain boundaries.

Defects. Of great importance is the analysis of defects and the remedial measures required. A committee of the American Foundrymen's Association reported on Analysis of Defects in 1938, and the Nonferrous Ingot Metal Institute rearranged the material in chart form in the Brass and Bronze Manual.

Permanent Mold Casting

By H. G. Schwab*

PERMANENT and semipermanent mold casting may be defined as the art of producing castings in metal molds operated mechanically or by hand, with or without sand cores and without the application of external pressure. The name of the process is something of a misnomer. Although the life of a permanent mold is long and an individual

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unit may be used repeatedly, the mold can hardly be considered permanent. Mold cost is high and many factors should be considered before choosing the process. In general, however, 500 castings may be regarded as the minimum number for which a permanent mold may be built economically.

Permanent mold castings have numerous advantages over sand castings. A few of these advantages are (1) higher production per unit time per unit of equipment, (2) finer grain size and improved mechanical properties, (3) closer dimensional tolerances, (4) lower costs for machining and (5) greater yield.

The permanent molding process has not been applied extensively to the casting of copper and copper alloys. However, it is gradually gaining favor and today large tonnages of rods and tubes are being produced in this way. The process has been applied successfully in the production of bearing bronzes, with superior bearing properties as a result.

The Mold. In the design of a permanent mold, attention must be focused on the necessity for the control of solidification. Directional solidification is not too difficult to attain in simple castings such as slabs or billets. However, as castings become more intricate in shape, control of solidification becomes more difficult and serious consideration must be given to the location of cores, the relation of light and heavy sections to mold partings, and the position of the gate and feeding risers. The mold cavity should be laid out so that heavy sections of the casting, wherever possible, are at the parting of the mold. If arranged in this way, such sections may be fed directly by the gate or by suitable risers. Permanent molds are costly; therefore, it is advantageous to consider all variables before the design leaves the paper stage.

A permanent mold is generally made of close-grained cast iron. Varying amounts of nickel or chromium may be added to improve the high-temperature properties of the base material. Cores may be machined from the same material or from a heat treated die steel.* After rough machining, mold sections should be stress relieved. It is also good practice to heat the finished mold thoroughly before placing it in production, as an added precaution against warping and cracking.

Painting the Mold. The most important phase of the permanent molding process is the painting of the mold. Basically, mold paints consist of a refractory material, a binder, and a lubricant (such as rouge or graphite) suspended in water and mixed to a consistency suitable for application with a spray gun. There are two general types of mold coatings—those that adhere tightly to the mold surface, giving a number of castings per coat, and those that flake off readily with the casting when it is removed from the mold. The latter type is preferred for copper alloys, especially the tin bronzes containing phosphorus. Generally the coating that flakes readily when the casting is removed, is porous and provides a good means for venting the mold cavity. Also, such a coating permits the metal to lie quietly against the mold surface, thus promoting improved casting finish. Flaking also permits cleaning of the mold cavity simply by using an air jet, and close dimensional tolerance is thus obtained. Careful thought must be given to the selection and application of the mold coating, since the quality of the casting, the surface finish and dimensional tolerance, as well as the life of the mold, depend on it.

Mold Temperature. Control of mold temperature is necessary for the production of sound castings, but at times it is rather difficult to achieve. Such control is usually effected by accurate control of the pouring temperature of the metal being cast, by the thickness of the mold sections, and by the number of molds poured per unit of time. Occasionally, localized areas must be heated or cooled externally. There are probably limiting minimum and maximum temperatures between which a mold will operate successfully and, since each mold has its own temperature range, these temperatures should be determined experimentally and maintained. In general, molds for copper alloys are operated between 250 and 700 F. A good rule for the production of copper alloy castings is this: Operate with as small a differential as possible between the mold temperature and the pouring temperature of the metal being cast.

Pouring. In the pouring of a permanent mold casting, every effort should be made to eliminate the effect of the human element. If the metal to be cast is poured too fast, agitation takes place, causing slag and dross to be trapped in the mold cavity. If the pouring is too slow, freezing takes place in the runners or feeders and misruns occur. Many devices may be used to reduce the variations in the rate of pouring, such as sumps to control turbulence, chokes in the runners, or reduction in the volume of the feeders that act to slow down the flow of metal.

The pouring temperature of a permanent mold casting is determined by the size and shape, by the thickness of section, and by the alloy being cast. The pouring temperatures of the copper alloys cover such a wide range that it is impossible to give any definite information here. However, far better results are obtained by pouring each alloy at the lowest possible temperature. High pouring temperatures lower the rate of solidification and may cause tears, cracks and general porosity. Gas holes are also a direct result of high temperatures.

The permanent mold process has proved rather difficult to apply to copper alloys, primarily because of their long freezing range and their ability to wet the mold surface. To minimize the wetting effect, great care must be taken in the selection and application of the coating material. Nevertheless, compared with sand casting, the advantages to be gained by this process are numerous. Among these advantages are better mechanical properties, finer grain size and better orientation, and lower costs of machining. The complexity of the casting need not rule out the permanent mold process, since sand cores can readily be used in conjunction with metal molds. The control of solidification is of first importance, and every effort must be expended to promote directional solidification by the proper placing of gates and risers, by the use of chills or anti-chills, and by maintenance of the right temperature in both the mold and the metal being cast. Control of the mold temperature is necessary for producing sound castings and for keeping the mold serviceable as long as possible. Close control of pouring temperature is a means for controlling the temperature of the mold and the soundness of the casting. Control of pouring must be considered from every angle for the purpose of reducing the effect of the human element to a minimum.

* See "Composition and Heat Treatment of Die-Casting Dies and Permanent Molds", page 673 in this Handbook.

Die Casting

By J. C. Fox*

AS IN the production of die castings of other alloys, the essential requirements of the die-casting process for brass are (1) a correctly designed die of suitable material, (2) a machine with a means for injecting the molten alloy into the die, and (3) a suitable alloy. A discussion of brass die castings must necessarily start with these three requirements.

Dies. Since about 1930, when the first brass die castings were produced on a commercial scale, attention has been concentrated on seeking out the most suitable die material that will yield a serviceable and economical die.

The fact that such a die material has not yet been found, has been the sole restricting influence in the die-casting of the metals and alloys that have high melting temperatures. Brass die castings can be produced with almost the same facility as those of other alloys now regularly die-cast; but because of the higher casting temperatures necessary for copper alloys, the serviceable life of dies in which copper alloys are cast, is much shorter than the life of dies in which alloys of lower melting temperatures are cast (for example, aluminum or magnesium alloys). The die steels employed for the casting of aluminum or magnesium alloys with casting temperatures up to 1300 F, are definitely unsuited for copper alloys with casting temperatures up to 1700 F.

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During operation, the extreme surface of a die-casting die for brass, may reach temperatures well above the transformation range of steels. Continued heating of the surface decreases the hardness and strength, lowers the resistance of the steel to the erosive action of the molten alloy, and generally nullifies the effect of any previous heat treatment. While casting is in progress at these high temperatures, the temperature gradients at the die surfaces are very steep, ranging from 1700 to 1750 F down to temperatures from 1100 to 1300 F only 0.050 in. beneath the die surface; and from about 900 to 1000 F at about 0.200 in. beneath the die surface. As a result of these thermal gradients, large stresses are set up that cause early heat checking of the die surfaces.

It is apparent that a suitable die material should resist the effects of these high temperatures. The ideal material should retain its hardness and other mechanical properties in use. In addition, a suitable die material should possess the following characteristics: resistance to thermal checking, resistance to thermal shock or sudden changes in temperature, resistance to erosion or the solvent action of the molten alloy, stability in heat treatment, sufficient hardness to resist deformation, and machinability.

The type of steel most commonly used at present in dies for casting brass, is one of the so-called "hot work" steels that are used for forging, swaging, extrusion and other similar methods for fabricating brass. A typical composition of a steel used in dies for casting brass is 0.30% C, 0.25% Mn, 0.25% Si, 3.5% Cr, 0.50% V, 9.0% W. The heat treatment of this type of steel is discussed in the article on "Composition and Heat Treatment of Die-Casting Dies and Permanent Molds", page 673.

Die Life. In present practice, dies for brass die castings operate from 10,000 to 50,000 cycles before replacement is necessary. The life of the die depends on the size, weight and wall section of the casting. Under similar conditions, dies for thin-walled castings outlast those for heavy-sectioned parts.

For small, thin-walled parts, a life of 50,000 or more cycles may be expected. Some of the die parts require more frequent replacement than the impression parts—particularly the gate block and sprue, which receive the full charge of the molten alloy entering the die and are consequently heated to higher temperatures than more remote parts of the die.

Design of the Dies. Dies for die-casting brass are fabricated in the same manner as dies for other alloys, except that ordinarily the dies for brass are made up in smaller sections to facilitate heat treatment and easy replacement.

The methods of gating and venting dies for brass are similar to those for other alloys.

The minimum for wall sections of brass die castings should be about 0.075 in. with an average of $\frac{1}{16}$ in. for small parts. The wall stock required depends on the size, shape, design and application of the part. Uniformity of wall section and the avoidance of heavy sections wherever possible are important in the control of limits. The walls of brass die castings, as well as the cores, require larger drafts than those used with other alloys of lower melting point. Holes $\frac{3}{16}$ in. in minimum diameter may be die-cast. The necessary taper is $\frac{1}{64}$ in. per in. depth of hole. In general, threads are not die-cast in brass.

Machines.* Brass die castings were first produced on a vertical "cold chamber" type of machine introduced by Polak about 1930. They are now also produced on the horizontal cold chamber machine that is used for the die casting of aluminum and magnesium alloys.

In the Polak process, the molten alloy is held in the furnace as a unit apart from the casting machine. The metal, at a temperature close to the melting point, is ladled into the cold chamber of the machine. Then prompt application of pressure forces the metal into a die.

In the casting cycle of the Polak machine when the die is closed, the brass alloy is ladled into a cup or chamber on top of an ejector plunger. The ejector plunger at this point blocks the gate or inlet into the die. Above the cylinder is a hydraulic ram, controlled by a valve that the casting operator opens immediately after the alloy has been ladled into the chamber. As the ram forces the ejector plunger downward, the metal is forced into the die under ram pressures ranging from 3000 to 10,000 psi. When the pressure is released and the ram withdrawn, the ejector plunger is forced upward by its spring action, which causes it to shear off the gate and sprue and to eject a solid slug of excess metal. The cycle of the casting operation is completed when the die is opened and the gate of castings is ejected.

In the horizontal type of cold chamber machine, a piston, operated by a hydraulic cylinder, applies pressure on the metal, which has been ladled into a chamber held in a horizontal position. The essential difference between the vertical and the horizontal cold chamber machines is that the latter is usually operated more rapidly and is more economical.

The speed of the injection plunger may be varied from 10 to 250 in. per sec. The proper co-ordination and regulation of such factors as speed and pressure of the plunger, temperatures of the dies and metal, gating and venting influence the quality of die castings, especially as related to soundness of structure and surface finish.

Alloys. ASTM Specification B 176-42T covers two brass alloys for pressure die casting. The limits for the composition of these alloys are shown below:

Element	Alloy *A*	Alloy *B*
Copper	57.0 min	63.0 to 67.0
Silicon	0.25 max	0.75 to 1.25
Lead	1.50 max	0.25 max
Tin	1.50 max	0.25 max
Manganese	0.25 max	0.15 max
Aluminum	0.25 max	0.15 max
Iron	0.25 max	0.15 max
Other elements	0.50 max	0.50 max
Zinc	30.00 min	remainder

Alloy *A* is a general-purpose low-cost brass with wide limits for impurities. Alloy *B* is an alloy of higher purity, capable of excellent castability and mechanical properties in the die-cast condition.

The minimum tensile properties of the alloys shown in the above ASTM specification are as follows:

Property	Alloy *A*	Alloy *B*
Tensile strength, psi	45,000	58,000
Yield strength (0.2% offset), psi	25,000	30,000
Elongation, % in 2 in.	10	15

Die-cast test bars of these alloys actually show properties far superior to these minimum figures. For instance, reports from three laboratories, concerning die-cast test bars of these alloys, show an average tensile strength of more than 60,000 psi for alloy *A* and more than 80,000 psi for alloy *B*. The average yield strength reported was more than 37,000 psi for alloy *A* and more than 50,000 psi for alloy *B*. The average Charpy impact strengths were 20 ft-lb for alloy *A* and 30 ft-lb for alloy *B*.

In addition to these brasses, another alloy is being extensively used, particularly for high strength, hardness, and resistance to wear and corrosion. This alloy has the following nominal composition and mechanical properties:

Copper	80 to 81.5
Silicon	3.5 to 4.5
Zinc	remainder
Tensile strength, psi	85,000 to 95,000
Yield strength, psi	45,000 to 50,000
Elongation, % in 2 in.	16 to 18

Die castings of this composition have been found to outwear other hard materials, and in a number of applications this alloy has replaced mild steel.

Die castings can be produced from other copper alloys, but present practice permits the use of only those alloys that have melting points not exceeding 1650 F. Aluminum bronzes, tin bronzes, low brasses and other high-copper alloys can be die-cast readily, but the melting points and casting temperatures are too high to be feasible or economical, considering their effect on the die materials available at present.

* For line drawings of machines used for die casting, see the article "Casting and Production of Zinc Alloys", page 1078.

Applications. The salient properties of brass die castings—high strength, toughness, and resistance to corrosion and wear—make these castings suitable for many varied uses, thus opening to industry a source of engineering parts that have the accuracy, intricacy, stability and economy of the die-casting process. The applications of brass die castings are too widely varied for detailed inclusion in this article, but the following partial list should indicate the potentialities: automotive gears, transmission forks, clutch parts, shock-absorber parts, pumps, bearings, parts for electrical switchboards, contactor parts, brush holders, refrigerator parts, steam-fitting valves, trunnion bearings, oil-burner parts, general engineering fittings, and household hardware.

Centrifugal Casting

By W. W. Edens*

CENTRIFUGAL CASTINGS are of three types: true centrifugal, semicentrifugal and centrifuge castings. A centrifuge casting is not truly a centrifugal casting, but rather a casting in which centrifugal force is used to provide pressure in a mold revolving outside the axis of rotation. Both true centrifugal and semicentrifugal castings can be described as castings that are spun on their own axes during casting.

The axis of rotation may be horizontal or inclined at any angle up to the vertical position. The molten metal is poured into the spinning mold cavity through a suitably sized hole at the top, and the metal is held against the wall of the mold by centrifugal force. The outside surface of the casting or the mold surface proper can be modified from the true circular shape by the introduction of flanges or small bosses but, to secure balance, the shape must be generally symmetrical around the axis. The inside surface of a true centrifugal casting is always cylindrical, although when the axis of rotation is vertical, the gravitational forces, as related to the centrifugal forces, will produce an inside surface that takes the form of a paraboloid, with the smaller inside diameter at the bottom of the casting. In correct operation, using optimum speeds and temperatures, this paraboloid effect can be held to a minimum and, in any event, is readily removed by the rough boring operation.

Semicentrifugal castings are much the same as true centrifugal castings except that, in this type of casting, a central core is used that will allow for shapes other than a true cylinder to be produced on the inside surface of the casting; and the mold is always spun vertically. Not all shapes and sizes can be produced by this method. Successful application depends on the specific size, shape and balance of the particular casting to be produced.

Centrifuge castings are not truly centrifugal castings. In basic principle they employ a static type of mold into which the metal is poured usually through a central sprue on the axis of rotation. Centrifugal force, ordinarily of an extremely low order, is used for helping to feed the castings, which are mounted around the central sprue.

The Production Process. *Equipment.* The equipment for producing centrifugal castings may vary considerably in detail, but basically it consists of a shaft, suitably mounted in bearings and supporting a spider or face plate to which the mold is bolted or otherwise fastened. Individual molds may be bolted to this face plate or, more frequently in small work, a suitable liner is fastened to the face plate, into which the actual molds can be fitted, allowing for easy interchangeability. On the end of the mold opposite the face plate, a suitable cover is placed and fastened by some mechanical means, such as bolting. In the center and on the axis of rotation of the entire mold proper, the cover has a suitably sized hole through which the molten metal can be introduced into the mold. The size of the hole will vary with the inside diameter of the casting, as well as with the size and weight of the casting.

Speed of Rotation. The speed of rotation and the rate of introducing the metal into the mold, vary with the individual casting to be produced. Generally the speed of rotation is governed by either one of two means:

1 Spinning all castings at a speed that will give a fixed amount of centrifugal force expressed by the term G. The centrifugal force will vary anywhere from 50 to 100 G's, using the formula $G = 0.0000142n^2d$, where d is the inside diameter of the casting in inches and n is the number of revolutions per minute. G is then expressed as centrifugal force in pounds per pound.
2 Spinning the molds at a speed that will give a standard velocity of the mold face, where the mold velocity in feet per minute equals πdn, where d is the diameter in feet and n is the number of revolutions per minute.

Common practice seems to favor the first method.

Rate of Pouring. The rate of pouring is usually kept as rapid as possible within the limitations of the diameter of the cover hole, as determined by the inside diameter and weight of the casting. For molds spun on a horizontal axis, the metal is poured at a rate of speed within the ability of the metal to be picked up onto the rotating wall of the mold, so that an excessive pool of metal cannot accumulate in the lower portion of the mold, making it possible for molten metal to run out of the entry hole. The rate of pouring is generally higher than for the same size of castings produced by static methods, primarily sand molding. The rate may vary considerably with the type and size of casting being made.

Molds. The molds used in centrifugal casting are of three general types.

1 Metal molds of cast iron or mild steel are frequently used, particularly when the quantity required will justify the original expense of making the mold. The tin bronzes cause some difficulty in cast-iron molds, but proper washing of the mold with a refractory coating, usually applied by spraying, minimizes this difficulty effectively. Other metals, such as copper, are selected occasionally as mold materials, but are ordinarily limited to extremely small castings. It is normal practice to provide a taper of as much as ⅛ in. per ft on the wall of the mold from top to bottom, as provision for removal of the casting after solidification. In castings 12 in. or more in diam, this taper can be minimized, and in some castings eliminated entirely, since the shrinkage of the casting is usually sufficient to allow reasonably easy removal.
2 Graphite is commonly used as a mold material, giving intermediate service life for jobs that entail medium-length runs. The use of graphite permits some economies, primarily in machining the original mold. Electrode stock is frequently used in making these molds. In such instances the size of the molds is limited primarily by the size of the electrodes available. Since graphite is relatively soft, it is quite easily scratched and marred, requiring fairly frequent dressing. Therefore this type of mold material is usually recommended only for relatively short-run jobs. Graphite does have an advantage, in casting, like that of the metal mold in that it is an effective chill or cooling medium, causing progressive solidification of the casting in a relatively short period of time.
3 Dry sand molds are frequently employed, particularly in the larger sized work, although they have the disadvantage of being usable only once. The low thermal conductivity of the sand mold provides for relatively slow cooling, which, in heavier-walled castings, is frequently less desirable than chill molds. This type of mold material has perhaps the greatest degree of flexibility and is excellent for the larger castings made in limited quantity. The mold is usually covered with a mold wash and baked dry in a core oven, much as dry sand cores are made in ordinary sand foundry production. Dry sand molds are usable for virtually all the copper alloys; but in the heavier sections and in alloys that contain lead, problems of segregation will arise, as well as possible porosity on the inside diameter of the casting. For short-run production, sand is the cheapest material even though the production is limited to one casting per mold.

Preheating. It is desirable to preheat all molds, particularly metal or graphite molds. Dry sand molds do not need to be preheated, although it is better to have their temperature above the dew point. Preheating and operating temperatures for molds will vary from about 150 to 800 F, depending on pouring temperature, size of the casting, frequency of pouring and such considerations. Temperatures above 800 F, as may be achieved in steady frequent pouring, are not recommended because of the serious effect on the durability of metal molds. For cast-iron molds, much lower temperatures are recommended.

Primary Benefits. *Yield.* Because no gates and risers are used in centrifugal casting, the yield or ratio of casting weight to weight of metal poured, is high—usually 90% or higher. The inside diameter of the casting and the top of the casting contain any dirt or dross that might have been present in the molten metal or generated in the casting operation. These inclusions are removed by a simple boring and facing operation. Of course this removed metal is in the form of turnings and borings and may or may not be reworked directly back into castings, depending on equipment available and on the particular alloy.

* Badger Brass and Aluminum Foundry Co., Milwaukee

Uniformity. The uniformity of centrifugal castings approaches that of wrought material, with the added advantage that the mechanical properties are nearly equal in all directions, in contrast with the directional properties of some wrought alloys and shapes. When ordinary sections are cast centrifugally, no noticeable or significant variation in chemical composition exists in alloys of the solid-solution type. This is true of castings made in sand molds as well as of those made in metal or graphite molds. Alloys that contain lead will show some variation in composition from the inside to the outer wall of the casting, depending on the amount of lead, the mold material and the section of the casting. This variation in composition is increased by greater amounts of lead, heavy sections, and mold materials that allow the metal to cool slowly. Table I shows typical results of chemical analysis of samples taken from a gear ring, 36 in. in diam and 8 in. long with a wall 4 in. thick, cast in a metal mold. In general, the usual composition of any specific alloy will not require modification for centrifugal casting.

Table I. Results of Chemical Analyses of Gear Rings Centrifugally Cast in a Metal Mold

Dimensions of castings: 36 in. in diam, 8 in. long, 4 in. thick wall

		Composition, percentage							
Alloy	Position	Cu	Al	Fe	Ni	Mn	Sn	Pb	Zn
SAE 68	OD	87.09	8.88	2.90	....	....	....	....	....
	ID	87.16	8.86	2.86	....	....	....	....	....
Navy M	OD	87.80	....	....	0.24	....	6.93	1.62	Rem
	ID	88.29	....	....	0.25	....	6.83	1.32	Rem
Navy G	OD	87.06	....	....	0.28	....	7.96	0.13	3.41
	ID	87.20	....	....	0.26	....	7.86	0.11	3.46
High Lead	OD	70.25	....	....	0.72	....	5.13	23.81	....
	ID	72.04	....	....	0.72	....	4.97	22.34	....
Mn Bronze	OD	58.66	0.96	1.06	....	0.22	0.09	....	Rem
	ID	58.70	1.01	1.10	....	0.23	0.12	....	Rem

Mechanical Properties. The mechanical properties of centrifugally cast copper alloys will vary with the alloy composition and will also depend to a large extent on the mold material. Centrifugal castings made in sand molds, where relatively slow cooling prevails, will have lower mechanical properties than castings made in metal or graphite "chill" molds. But even in centrifugal castings made in sand molds, the mechanical properties will average approximately 10% higher than the properties of castings of equivalent section made statically in sand molds. In centrifugal castings made in "chill" molds, these properties are occasionally 30 to 40% better, in some alloys, than the mechanical properties of similar castings made statically in sand molds. Table II lists typical mechanical properties of several alloys, taken from the same gear rings described in Table I.

Table II. Comparison of Mechanical Properties of Gear Rings Cast Centrifugally in Metal Molds and Statically in Sand Molds

See Table I for compositions of alloys

Alloy	Method of Casting	Tensile Strength, psi	Yield Strength, psi	Percentage Elongation in 2 in.	Percentage Reduction in Area
SAE 68	Static	79,200	28,900	39.8	39.5
	Centrifugal	87,600	32,200	40.1	42.5
Navy M	Static	41,460	21,140	39.3	32.5
	Centrifugal	48,775	21,200	60.6	40.1
Navy G	Static	46,675	23,900	24.8	27.8
	Centrifugal	51,500	27,100	55.0	53.5
High Lead	Static	35,680	19,460	24.4	22.7
	Centrifugal	51,250	24,800	42.0	41.0
Mn Bronze	Static	71,700	26,400	30.3	30.1
	Centrifugal	77,500	33,200	37.2	38.0

Centrifugal castings are a high-quality product and, in reasonable quantities, they can be produced economically. For small quantities, the investment in molds and the time required to set up a machine to produce a few specific castings may make the cost of the few castings seem high, but where quality is important, the additional cost is usually justified.

The production of centrifugal castings requires a thorough knowledge of basic foundry practice, plus a thorough knowledge of rotating machinery and mechanical engineering. The combination of molten metal and rotating equipment is extremely dangerous, making high factors of safety on equipment absolutely necessary, as well as experience and the utmost care and caution in the casting operation.

Precision Investment Casting

By Robert Neiman*

PRECISION INVESTMENT MOLDING consists in casting a metal or alloy into a one-piece refractory investment mold from which a pattern or cluster of patterns has been removed, ordinarily by heat, and into which the molten metal is cast, usually under pressure.

The general features of this process are discussed in the article on page 54 in this Handbook. The present article emphasizes points of the process, applications and cost that are peculiar to copper alloys.

Process. *Shrinkages and Methods of Compensation.* The precision caster has four types of dimensional change to consider. Typical values are given below:

Shrinkage of the wax pattern	−1.0%	
Shrinkage of the metal casting	−1.8%	Total −2.8%
Expansion of the investment during setting	0.3%	
Expansion of the investment during heating	1.0%	Total 1.3%
Net shrinkage		−1.5%

To compensate for the net shrinkage of 1.5%, the pattern die must be made 1.5% larger than the desired size.

Shrinkage in any given pattern material and casting alloy will vary directionally, as well as with cross section and with injection practices or casting processes.

The casting shrinkage of copper alloys in investment molds varies from 0.5% to slightly more than 2.0%. Differences in shape and size of casting and nature of investment have a greater effect than variation in the composition of the alloy.

Investments. These are refractory cements made fluid with water and poured around the patterns in a confining metal ring or flask that will set, while standing, to form a hard, heat-resisting mold. For brass, bronze and aluminum the investment is composed principally of a mixture of finely comminuted plaster and silica. In order to avoid roughness and nodules on castings, the investment is usually placed under vacuum to prevent entrapment of air. The investment molds are heated between 1200 and 1400 F to dissipate the patterns. The alloy may be cast into the hot molds or the molds may be cooled to any desired temperature.

Melting of the Alloy. Small batches of 1 to 15 lb are melted in clay-graphite crucibles by gas or by electrical induction. It is practical to use commercial ingots of the desired composition. Beryllium copper is available in convenient small ingots that weigh ½ lb; other standard alloys in similar form would be a great convenience. Fast melting usually prevents contamination and gassing. Commercial fluxes and deoxidizers may be used advantageously with some alloys.

Finish. Once the comparatively soft investment has been broken away, many copper alloy castings emerge with a smooth, clean, and often bright surface of natural color that needs no further treatment. The surface smoothness compares favorably with that produced by usual machining procedures; there is less waviness but no burnished effect. Some alloys require tumbling or blasting with a fine abrasive.

Secondary Machining. When economy or accuracy requires secondary machining, standard machine-shop practice is used for tapping, reaming, or surface grinding.

Applications. *Intricate Shapes.* The outstanding feature of the precision investment casting process is its ability to produce parts of intricate shape. This is possible because a wax pattern can be made in an exactly fitting, multiple-pieced, cored metal die; after the pattern has been invested, it need not be removed from a split mold. This method usually eliminates from 75 to 95% of the

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Table III. Mechanical Properties of Precision-Cast Copper Alloys

Alloy	Composition, % Cu	Zn	Sn	Pb	Others	Tensile Strength, psi	Percentage Elongation	Rockwell Hardness
Leaded red brass	85	5	5	5		42,500	45	B 85
Leaded yellow brass	62	36	0.7	1	0.3 Al	54,000	33.5	B 86
Silicon brass	80	15	...	...	5 Si	91,000	24	B 90
High-strength Mn bronze	61	28.5	...	...	2.5 Fe, 2.2 Mn, 5.7 Al	117,500	18	B 97
Aluminum bronze	89	...	...	...	1 Fe, 10 Al (quenched)	115,000	2.5	A 64
					(reheated)	89,000	22	A 49
Beryllium copper	97	...	...	...	2.2 Be, 0.5 Ni (quenched)	55,000	35	A 38
					(reheated)	170,000	3.5	A 71

machining operations that would otherwise be necessary to produce a complicated part. Dies can be made for use in plastic molding, powder metallurgy and precision casting.

Sizes. The most practical sizes are 3-in. maximum dimension and ½-in. maximum cross-sectional thickness. Minimum dimensions range down to 0.005-in. sectional thickness. Larger castings have been made, up to 18 in. long and weighing as much as 100 lb. Investment molds are usually about 5 or 6 in. in diam and of equal length, accommodating from 1 to 60 pieces, depending on size.

Close Tolerances. With careful control it is possible to hold most dimensions within ± 0.005 in. per in. On certain dimensions, limits of ± 0.002 in. per in. can be attained. On small dimensions, such as 0.25 in. or less, tolerances down to ± 0.0005 in. are often attained.

Short Runs. For short runs, ranging from several to a few thousand parts, a master part is made with proper allowance for shrinkage and from this part, a die of low-fusing metal is made. This type of die is comparatively inexpensive and can be produced quickly.

Designing for Precision Castings. *Assemblies and Added Features.* At little or no added cost, this process can often provide such features as slots, keyways, holes, splines, square or odd-shaped blind holes, embossed and debossed numerals, graduations, keystones, cams, stops and bevels. Often an assembly consisting of several to a dozen or more separate parts, can be united into a single precision casting with few conspicuous parting lines, if any.

Dimensioning. A blueprint for a part to be made by standard methods in a machine shop leaves many undecided questions for precision casters. A lathe necessarily turns out work that is truly round, and a surface grinder produces flat surfaces; a precision casting is seldom perfectly round nor is any extensive flat surface truly flat. The precision caster wants to know permissible tolerances on all surfaces; for example, "drill 21 drill" is not explicit enough. Instead, the specification should be given in exact decimals with permissible tolerances added. When all necessary facts are available to him, the precision caster can make a suitable pattern, allowing for the possible desirability of some secondary machining operations where economy and accuracy dictate.

Alloy Specifications. Usual specifications call for leaded yellow brass or 85-5-5-5 for castings that are to be machined. These alloys are not the best for precision casting. For recent information concerning suitable copper alloys for precision casting, the reader may refer to a series of articles by Lipson, Markus and Rosenthal.*

In precision casting, a wide range of mold temperatures is available at the time of casting—from room temperature to 1400 F—and the rate of cooling may vary from slow cooling in air to a rapid quench in water. By making the right choice of conditions it is possible to achieve best combinations of tensile strength, elongation and hardness. Typical mechanical properties are shown in Table III. Rapid quenching immediately after solidification, followed by low-temperature reheating, provides aluminum bronze that will meet ASTM specifications for cast material, and beryllium copper that will meet requirements for wrought material. Most manufacturers prefer alloys that contain at least 0.1% Al, since smoother and cleaner surfaces are obtained. Lead is generally not included because of its opposite effects. If given an indication of the mechanical properties necessary or desirable, the precision caster can usually suggest an acceptable and often superior alloy.

* Iron Age, Nov 1, 1945; Nov 8, 1945; Sept 19, 1946

Cost Factors. Because of the need for making a separate pattern for each casting, this process is in reality a double die-casting process. Articles produced by precision casting cannot compete in price with parts made by automatic screw machines or with sand castings that require only a few finishing operations. The number of castings that can be assembled into one mold, is a controlling factor in the cost, and most manufacturers quote on a piece basis. Standard molds are usually 4, ▮ or 6 in. in diam and of about the same height. Therefore, the smaller the part and the more compactly it can be assembled into the mold, the lower the cost. It costs very little more to cast a mold with 30 small, intricate parts than to cast one with only a few simple, large parts.

For parts weighing a few ounces or less, it is often economical to use better alloys, since the cost of the metal is insignificant compared with better castability and elimination of expensive and difficult machining operations. For these reasons copper alloys may replace ferrous alloys.

Because of shrinkage and many related factors, it is usually necessary to make a preliminary or experimental die, run test pieces, and then make necessary changes in the final die. When the user requests close tolerances throughout the article, additional experimental dies may be necessary. The use of close tolerances where essential, and more lenient ones where permissible, enables die designers to construct a successful die more economically.

Simplicity in the construction of dies, and the need for only a few special tools, jigs, and the like, make quick tooling-up possible and permit lower costs, whether with small runs and experimental parts or large quantities.

Plaster Molding

By H. Hagemeyer*

THE ACCURATE CASTING of metals by the plaster molding method is a refinement of the sand foundry method and employs the match-plate system, cope and drag assembly, separately made cores, and gravity pouring.

The major difference is in the control of all physical factors that are involved in guiding liquid metal into molds made of an investment of calcined gypsum (plaster of Paris) and magnesium silicate (fine-fiber asbestos or long-fiber talc), properly treated with water and baked.

In comparison with other methods for casting metals, this process uses a molding investment that has probably the lowest thermal conductivity of all current commercial processes. The thermal conductivity is approximately 1/10 to 1/15 that of green sand molds.

The plaster of Paris used in this casting process has the following rating of consistency (commercial standard employed by gypsum manufacturers): water, 85 to 95; plaster, 100 (parts by weight).

Typical mixtures used in this process will contain from 70 to 80% plaster of Paris mixed with 20 to 30% magnesium silicate. Depending on the purpose, the water content may be as high as two parts of water to one part of the above mixture. A dried mold will have compressive strength between 8 and 20 psi, depending largely on the ratio of water to solid material.

The wet mold is dried in a continuous radiant-heated oven with minimum circulation of air. The temperature in the initial zone may be as high as 1500 F for the first 10 or 15 min, but it gradually decreases to about 200 F at the

* Castings Patent Corporation, Chicago

discharge end. The complete time cycle for the dehydrating period depends on the height of the mold and requires from 1½ to 2½ hours for mold halves that vary from 1½ to 2¼ in. in height.

Because of its high ratio of water to solid materials in the wet state, the mold material, when dehydrated, has insulative values much higher than those of sand molds. The method employed in controlling the chemical combination, together with the continuous open-faced mold-drying system, produces a mold that results in a smooth casting surface, free from blowholes, run marks, surface pits, and other blemishes.

Some of the principal features inherent in the plaster investment casting method are these:

1 Since the mold material will yield before the contracting alloy when the metal cools to the solidification temperature, the plaster thus prevents cracking and reduces to a minimum the development of stresses in the product.
2 The water content, both free and combined, has been reduced to the point where no bubbling or turbulence develops when the molten metal strikes it. The mold is also free from any volatile materials, since these were eliminated during the drying process.
3 This method makes possible the exact duplication of hydraulic and pneumatic conditions in the mold, and is not critical in regard to the temperature of metal nor the time period of filling. The pouring time can be lengthened from 6 to 10 times that required in sand casting. This is made possible by the use of an orifice inlet to the mold cavity, no greater than 0.0007 sq in. per ounce of metal for any nonferrous alloy. Consequently, riser or shrink bobs can be proportioned accurately to perform their function of supplying metal exactly where required to eliminate microshrinkage.
4 Directional solidification can be controlled, largely for the following reasons: (*a*) Because the molding material has relatively high insulative properties, small orifices can be employed at or near the bottom of cavities, making it possible to control the flow of metal into place over a long period of time, and thus to establish a temperature differential between the feeder and the metal in the farthest section of the mold. (*b*) Because of the small orifices, the sprue can be filled quickly and a column of metal of a definite height can easily be maintained, with a definite hydrostatic head.

The process is largely automatic and is continuous in its operation, resulting in fixed time relations in the various stages and allowing maximum control.

Engineering Characteristics of the Process. *Advantages.* *1 Unit Strip.* The plaster molding process utilizes a standard interchangeable unit-strip match-plate system, which permits assembling as many as 20 different patterns in the same match plate within the dimensional limits of a 12 by 18-in. mold.

2 Patterns. Patterns are made in cope-and-drag match-plate style, with the halves mounted on either side of an accurately machined unit strip. The patterns are not subjected to abrasion, pressure, or shock. Their life is virtually unlimited; consequently very little maintenance is involved. Changes in design that are not too extensive can be made quite readily, since the material used for the patterns is either brass or hard tin base and can be soldered readily.

3 Dimensional Tolerances. The control of dimensions depends on the accuracy of the pattern and on control of the physical factors involved in the process. In most instances an over-all tolerance of ±0.010 in. can be held; and where required, this tolerance can be held to ±0.005, depending on the size and nature of the part to be cast. Outside surfaces normally have ½-deg draft angle; inside surfaces require from ½ to 3-deg draft.

4 Density. Castings made by the plaster molding process are sound in structure and free from porosity.

5 Residual Stresses. Because of slow cooling and the yielding quality of the investment, the product is relatively free from stress.

6 Machining. A primary object in making castings by this process is the reduction of the number of machining operations, and the elimination of machining scrap. Elimination of machining operations is possible, because of the smooth finish and dimensional accuracy of the casting. During machining, castings can be handled easily and the designer can be sure that finished surfaces will always clean up. Roughing operations and roughing scrap are reduced because of lack of porosity and inclusions, a condition that also promotes longer tool life.

Limitations. The process is continuous and involves the handling of a fixed quantity of molding material for a given production unit. This means that there is a definite limitation to the dimensions of articles that can be produced; that is, the dimensions of the molds cannot be varied for this given production unit. One standard molding flask in operation has the dimensions of 12 by 18 in. and an over-all depth, for combined top and bottom halves, of 3½ to 4 in., depending on the volumetric displacement of the pattern on the match plate. Other standard molding flasks in operation are 10 by 18 by 2½ in., 12 by 21 by 6 in., and 24 by 36 by 12 in.

The relatively slow cooling rate in this process produces lower mechanical properties in the leaded bronzes and high properties in tin bronzes, because of segregation of elements; but the average mechanical properties of the product vary less than in castings produced by other methods. To obtain the finest possible surface finish in the copper alloys cast in plaster molds, a small amount of aluminum, beryllium, or silicon should be used, depending on the alloy desired. It is important that the lead content should not exceed 2½%.

General Design Considerations. *Wall Thickness.* A wall 0.040 in. thick can be regularly cast where the area does not exceed 2 sq in.; 0.0625 in. thick in areas up to 6 sq in.; 0.093 in. thick in areas up to 30 sq in.

Part Numbers, or Descriptive Matter. Markings can be either depressed or raised, as desired, and very fine lettering or designs can be reproduced clearly.

Casting Design. This method has great flexibility, because of its use of loose cores made by the same method as the mold and with the same degree of accuracy and smoothness of surface. Transverse holes and passages, undercuts and the like, can readily be incorporated.

For the most popular size of molds made today, the depth of parts that are to be produced depends on the location of the parting line and also on the maintenance of a reasonable margin of plaster over the pattern. Symmetrical parts up to 3 in. high are feasible. In nonsymmetrical parts, the maximum depth from one side of the parting line is limited to 2 in. Greater depths are possible in the larger special-size molds referred to above.

Gear teeth, ratchet teeth, stops, and other shapes difficult and expensive to machine, can be cast by this method.

General Manufacturing Problems. *Inspection.* To ensure the maintenance of a quality product, all products should be inspected rigorously. Original samples are usually submitted for the approval of the customer, and at periodic intervals thereafter the inspection department repeats the dimensional check. Gages are regularly used for checking dimensions. Every casting is inspected visually for defects.

For each heat of metal poured, test specimens are cast regularly in standard molds under standard conditions of production, with gating the same as that used for the commercial product in question. Thus, specimens are truly indicative of casting quality.

Table IV. Comparison of Casting Methods

The following is a table of evaluation of various factors involved in a comparison of casting methods for copper alloys. These factors are rated 1 through 4, number 1 being the most advantageous. The evaluation is based on castings in the as-cast state and may help the application engineer to determine which of the methods is most advantageous in the ultimate use of the product.

This table is based on casting sizes up to a maximum that can be produced practically in a 12 by 18 by 4-in. mold, or the equivalent die size required to produce a casting of similar size in brass or bronze.

Factor	Sand	Die	Perm Mold	Plaster Paris
Tolerances	3	1	2	1
Surface	4	2	3	1
Thickness of section	4	2	3	1
Structural density	1	3	2	1
Pattern cost	1	4	3	2
Speed of getting into production	1	4	3	2
Speed of production	2	1	3	4
Cost per piece	2	1	3	4
Flexibility as to alloys	1	3	4	2
Low casting stresses	2	4	3	1
Flexibility of design	2	3	4	1
Limitation of size	1	4	2	3
Reproducibility of successive castings[a]	2	4	3	1
Pressure tightness	2	4	3	1

(a) As to dimensions, surface finish and uniformity of physical properties for successive castings

Metal. For greater economy of plant operation, alloys that are being cast regularly have been standardized. However, many other alloys can be produced. Virtually all nonferrous alloys can be cast by this process. For fine surfaces it is desirable that from 1/10 to 2/10% Al, Si, or Be should be added to the alloy. It is also required to limit the lead content to 2½%, and nickel to approximately 7%, since these two metals in larger amounts react chemically with the plaster.

Temperature. In this method, lower pouring temperatures can be used than are required with sand molds, provided a sufficient hydrostatic head is employed, exceeding 2¼ psi.

At high pouring temperatures the hydrostatic head can be reduced so that sprue height is only an inch or so above the highest point in the casting.

Experience indicates that 2400 F is the maximum temperature of the metal to be poured into molds of the above composition if dimensional stability is to be retained.

Comparison. Table IV shows a comparison of the plaster molding method with sand, die, and permanent mold casting, as applied to copper alloys.

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The Production of Copper Alloy Castings for Working

BY THE SUBCOMMITTEE ON COPPER ALLOY CASTINGS FOR WORKING*

MANY TYPES of furnaces have been used for melting copper and copper alloys, but present practice is quite uniform throughout the industry. Crucibles heated by coal and oil have been virtually eliminated in large-scale operation. For copper, oil-heated and gas-heated reverberatories, and for brasses and bronzes, low-frequency (60-cycle) induction furnaces are generally employed.

The low-frequency induction furnaces are rated from 150 to 450 kw, with a capacity for holding from 800 to 3000 lb more metal than is needed to fill the heating duct. They are capable of melting any brass mill alloys, none of which require a pouring temperature higher than 1430 C.

Melting Practice for Copper Alloys. Electrolytic copper in the form of cathodes or ingots, fire-refined copper ingots, clean copper scrap from mill operations or secondary sources, slab zinc in one of five commercial grades, alloyed mill scrap, and clean secondary alloy scrap are the raw materials used for making copper alloy castings that are to be wrought. It is the general practice to melt copper, high-copper scrap and additions that have high melting points, before adding the required amount of zinc. Keeping the bath thus rich in copper until it is nearly ready for pouring probably results in the formation of less dross. However, some operators consider that copper additions will dissolve faster in a zinc-rich liquid, and consequently make zinc additions early.

All copper-zinc alloys require a protecting cover on the liquid bath in order to reduce heat losses and to prevent excessive loss of zinc through vaporization and dross. Charcoal is generally used for this purpose. Alloys con-

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taining 20% Zn or less form comparatively little dross; higher zinc content and the use of dirty or oxidized scrap will produce more and heavier dross, which holds an appreciable amount of metal globules in suspension. No flux has been developed to free this heavy dross completely from the suspended metal, but soda ash, common salt and borax are frequently used as fluxes to reduce it. Economy necessitates the reclamation of the metal content in the dross; this is accomplished by standard methods of screening and concentration.

Hydrogen and perhaps other gases have relatively low solubility in high-zinc alloys but, as the copper content increases above approximately 80%, the solubility of these gases rises rapidly and may be the cause for porous castings. The addition of lead or tin to these alloys increases the susceptibility to gas absorption. Even so, moderate precautions, such as avoiding excessively high temperature or adding fresh charcoal near the end of the heat, will minimize the absorption of detrimental quantities of gas.

Copper alloys that do not contain zinc require more precautions to prevent the absorption of gases. Oil or lubricating compounds, particularly if they contain sulfur, should be removed from scrap before melting; and if charcoal is used as a cover, it should be preheated. Charcoal may be used with caution on phosphor bronzes, but the use of an oxidizing slag is common. Charcoal is not used as a cover for aluminum or silicon bronzes. These alloys are melted in a slightly oxidizing atmosphere, using as a cover either their own dross, fused cryolite, a layer of molten glass, or slag.

Nickel silvers and cupro-nickels may be melted under charcoal but are always treated with manganese and sometimes with a further addition of magnesium. These additives, like the phosphorus in phosphor bronze, are deoxidizers in a strict sense, but at the time of pouring they serve the important additional purpose of preventing secondary reactions between air and gases dissolved in the metal. Such reactions are not perfectly understood but probably result in H_2O or CO_2, which are directly responsible for unsoundness.

A few high-frequency induction furnaces are used for melting copper alloys, and all statements concerning the low-frequency furnace apply also to these furnaces.

The rocking-arc furnace finds a small but well-established application for the melting of alloys. It is used for cupro-nickels, phosphor bronzes, aluminum bronzes and silicon bronzes; though not for alloys containing high percentages of zinc, because of the high local temperature in the arc zone, which overheats the metal and results in excessive loss of zinc.

A suitable pouring temperature for copper and copper alloys is usually from 100 to 150 C above the liquidus. Higher temperatures are destructive to equipment, favorable to gas absorption and serve no useful purpose. In the range of 25 to 40% Zn, the maximum pouring temperature is limited by the boiling point, which serves as a safeguard against overheating. Such alloys are poured at temperatures only slightly below the boiling point. Alloys with less zinc, or without zinc, have no such safeguard and it is usual to establish a definite pouring temperature for each alloy, a temperature that may vary slightly among fabricators, because of slight differences in pouring arrangements. A suitable pyrometer is used for temperature measurement.

Casting Practice for Copper Alloys. Copper alloys to be wrought are cast into the following forms: slabs for cold rolling into flat products, cakes for hot rolling into flat products, bars for hot rolling into wire rods, billets for extrusion into rods, shapes or tubes, billets for piercing into tubes, cored tubes for drawing, and rods for cold rolling and drawing. Two types of permanent molds are used for castings intended to be wrought. The older type is made of gray iron with small uniformly dispersed graphite particles. It is designed with a ratio of mold weight to casting weight from 1½:1 up to 5:1.

In the newer type of mold, which is water cooled, the surface in contact with the casting is usually copper. Water is circulated through these molds at the rate of approximately ½ gal per min for each pound of metal cast. The temperature of the inlet water is controlled and ranges from 100 to 160 F, depending on the size and shape of casting, on the alloy, and on plant practice.

It is general practice in the brass industry to use a "runner box" or "strainer" placed on top of the mold to receive the metal from the furnace. These boxes are generally made of mold iron, but when used with some alloys they have refractory linings or refractory inserts. In the bottom is either a single hole or a series of holes varying from ¼ to about ⅝ in. in diam, depending on the size and shape of the casting. The functions of the strainer are to control the rate of flow, distribute the metal evenly across the width of the mold, direct the pouring stream down the center, and keep the dross and dirt from entering the mold. It will be recognized from the functions of the strainer that its proper design and use for each particular application are very important in producing clean, sound castings.

Most nonferrous metal tubes are made by piercing or extruding a solid billet to make a heavy-walled shell of relatively large diameter, and by then drawing this shell, as described in the articles on working processes. However, some alloys cannot be pierced or extruded and equipment ordinarily available cannot be used for larger billets or all alloys. By pouring around sand cores positioned in chill molds, these alloys are cast into a heavy-walled tube shell. The cores are made on perforated steel pipes that are covered first with porous, shock-absorbing core paper, then with a coat of rough sand, including suitable binders —bran, molasses and such. After drying, a second finish coat of fine sand with clay is applied and dried. Cores are then finished with a wash of silica flour or whiting to prevent metal penetration and to obtain a smooth inside surface. After thorough baking, the cores are kept hot until used, since they will absorb appreciable moisture if allowed to stand in room atmosphere.

The production of castings of good surface quality necessitates a suitable dressing on the mold. The dressings in general use for copper alloys that contain zinc include lard oil, wool grease, tallow or mineral oil, or combinations of these, frequently with additions such as carbon black, graphite, silica flour, or the foundry preparation known as black lead. An important function of a mold oil is to produce a reducing atmosphere in the mold, in this way preventing the formation of excessive quantities of dross. Secondarily, oil on the mold evolves gas more or less violently as the molten metal comes in contact with it. This continuous agitation at the top of the metal column blows dirt and dross from the mold surface and so prevents the inclusion of these impurities in the surface of the casting. Too light a dressing or too slow a rate of rise in the mold will result in a casting with a poor surface. A dressing too heavy or a rise too rapid will cause some of the evolved gas to be entrapped, resulting in blowholes in the casting. There is a rather fine balance between the rate of pouring and the amount of oil on the mold. To ensure internal soundness it is important to pour at a rate that will give the lowest rate of rise in the mold consistent with a clean surface. In practice this rate varies between 0.4 and 1.5 in. per sec.

On the operating face, iron molds develop characteristic cracks, which increase rather rapidly and limit the useful life. When used for alloys that contain zinc, iron molds also develop a peculiar scale composed mainly of zinc oxide with some zinc, carbon, and small amounts of oxides of any other constituents of the metal. Soft and friable when first precipitated, mold scale hardens with further use of the mold and consolidates into a rocklike layer, which must be removed by chipping or scraping. Mold scale is important because, in combination with mold cracks, it soaks up oil and retains it too long after the metal rising in the mold has covered a given area. The gassy products of oil decomposition, thus entrapped, produce blowholes in the casting. The great advantage of water-cooled molds is that the cooled copper plate does not crack or build up a scale.

Alloys that do not contain zinc are all susceptible to hydrogen in solution and some of them are better poured without any oil on the mold. In this group, deoxidized copper and cupro-nickels are poured into oiled molds. The phosphor bronzes are sometimes poured into oiled molds, sometimes into dry molds. Such alloys as silicon bronze,

aluminum bronze and chromium bronze are usually poured into dry molds. Gas dissolved from the mold oil would cause these metals to "swell" or "spew" during solidification. "Dry" dressings may be composed of graphite, carbon black, bone black, bone ash, silica flour or like substances, in a vehicle of water or alcohol. The mold must be warm enough to evaporate the vehicle between the time of application and that of pouring.

A distinction is made between unsoundness caused by dissolved gas and that caused by entrapped gas. They both produce cavities in the casting, but the precautions for their prevention are different, as explained above.

A third type of unsoundness to which all alloy castings are more or less subject, has been called "interdendritic shrinkage" and is associated with the mode and rate of freezing in the center of the mass. Since there is substantial contraction in volume from liquid to solid, it is important that liquid metal be always available to a solidifying area to make up this difference. Thus, the end of a casting is always "fed" with fresh metal from the furnace to prevent the deep "pipe" that tends to form as the center shrinks away. But, deep down in the casting there is usually an area to which adequate "feed" was not available, resulting in a zone of low density or intercrystalline voids. If not too large, these voids will weld during hot working operations and at least to some extent during cold working and annealing. In this they differ from unsoundness caused by gas—either dissolved or entrapped—which does not weld readily.

In summary, the five important variables affecting the surface quality and the soundness of a casting are metal temperature, mold temperature, condition of mold surface including the amount and type of dressing, the rate at which the metal rises in the mold, and the pressure of gas either dissolved in the original melt or entrapped. These are interrelated and none of them can be varied without affecting the general result.

Melting and Casting Practices for Copper. Reverberatory furnaces, heated by natural gas, oil or pulverized coal, and having a capacity of 250 to 350 tons, are used for melting copper cathodes. Sulfur, hydrogen, and other gases absorbed by the metal are removed by blowing air into the metal until 5 to 8% is converted to cuprous oxide, which is held in solution in the copper. The copper oxide oxidizes the sulfur (present as Cu_2S) to sulfur dioxide (according to the equation $2Cu_2O + Cu_2S \leftrightarrows 6Cu + SO_2$). This sulfur dioxide is flushed from the metal along with hydrogen and other gases, by the nitrogen, which keeps the partial pressures of these gases below their equilibrium concentrations. The removal of sulfur and gas progresses as the oxide concentration of the bath increases, so that when the bath reaches the concentration of copper oxide stated above, the oxidizing process is complete.

Subsequently the excess oxide is removed by covering the copper with charcoal and forcing green wood poles under the surface. This operation is called "poling" and is continued until the oxygen is reduced to between 0.02% and 0.04%. The residual sulfur is between 0.001% and 0.002% and a sample at this point will have a wrinkled but flat "set" surface. This "tough pitch" copper is then cast into solid copper molds dressed with bone ash.

The casting of electrolytic copper is somewhat unique, because in this process a controlled amount of cuprous oxide, sulfide, and gases is left in the liquid metal.

During solidification, pure copper crystals solidify first, increasing the concentration of the residual oxide and sulfide in the remaining liquid. These react as shown above and the resulting sulfur dioxide is entrapped in the metal in numerous minute globules that prevent normal shrinkage.

Hydrogen and other gases reabsorbed during the poling operation and from the charcoal cover are also liberated and entrapped at the time of casting. Some metallurgists maintain that H_2O, formed at this point by reaction of liberated hydrogen with cuprous oxide, is chiefly responsible for the "level sets"; this theory is not accepted by all investigators. At any rate, proper control results in the finished castings having a flat to a slightly crowned set surface, which eliminates the necessity of cropping the gate or filling the pipe that normally forms when gas-free metal contracts as it solidifies.

The process of eliminating shrinkage by the evolution of gas can be used with copper, since the surface of the resulting porosity will weld during subsequent hot working. In all other copper alloys, every effort is made to have the liquid as free as possible from gas before casting.

Most copper to be wrought is marketed as "tough pitch", but there is a substantial volume of deoxidized copper. Just before casting, most of this is treated with about 0.02% P, which removes the last traces of cuprous oxide. However, some metal is treated with less than 0.01% P so that the resulting deoxidized copper will have an electrical conductivity comparable with that of tough pitch. Because such metal behaves like a copper alloy, it is poured into molds dressed with a relatively inert dressing and shrinks normally while solidifying.

A special type of copper is called "oxygen-free high-conductivity". In such "OFHC" copper the last traces of cuprous oxide are removed by charcoal treatment in the furnace and the metal is then transferred to the molds without contact with air. The result is an oxygen-free product that has the high conductivity of tough pitch copper, since it contains no residual deoxidizer.

Continuous Casting. Briefly stated, continuous casting can be defined as a process wherein liquid metal enters one end of a mold continuously at a substantially uniform rate and solid metal emerges simultaneously from the other end.

The concept of continuous casting is very old. However, this idea has been developed only recently on a practical commercial scale. The size and number of continuous casting installations are increasing both in the United States and in Europe.

Virtually all the large tonnage in production is confined to three processes, each of which, without stopping, produces castings of any desired length. The three processes have several factors in common: water-cooled copper, copper alloy, or graphite molds; mechanical means for withdrawing or controlling the billet speed through the mold; and traveling saws to cut the casting into desired lengths without stopping the continuous pouring.

The stationary mold process is one in which the mold remains fixed; the molten metal enters at the top and emerges at the bottom as a solid continuous casting. A mold of this type is usually in one piece and rather short. This process is used for copper and for alloys difficult to cast by more conventional methods.

The vibrating split-mold process consists of two water-cooled mold sections that together form the contour of the desired casting. These sections are mechanically opened and closed laterally, with a very small gap and at high frequency. The molten metal, entering at the top, solidifies, is withdrawn at constant speed, and is then cut into the desired lengths by integral saws. This process is used principally for casting copper.

In the reciprocating-mold process, the liquid metal is underpoured from a reservoir furnace through a downspout, and is discharged underneath the surface of the liquid metal in the mold. The mold has a downward and upward motion. The downward motion is synchronized with the speed of the billet, and the upward speed is about three times that of the downward speed. The total travel of the mold is about ¾ in. in each direction.

The surface of the molten metal at the top of the mold is protected from oxidization by a gas flame, and oil is occasionally sprayed on top of the liquid metal where it spreads to the edges and lubricates the casting surface of the mold. This process is used principally for copper-zinc alloys of all proportions.

In all the foregoing processes, further cooling is necessary after solidification. This secondary cooling is either by direct application of water sprays or by secondary cooling jackets, the choice and location of which are determined by the conductivity of the metal, the area of cross section, freezing range, nature of the alloy, speed of production, and amount of superheat in the metal. The linear casting rate of these machines varies from ■ to 20 in. per min, depending on the alloy and cross-sectional

area. Best results are obtained by using low temperatures for casting.

Copper, copper alloys, aluminum, silver, lead, magnesium, and possibly other nonferrous metals are produced by continuous casting in industry. The principal application of continuous casting is in large units, but the process is also applicable to small units for some alloys difficult to cast by other methods.

The metallurgical advantages are as follows: less segregation, high density, and absence of shrinkage porosity. The operational advantages for continuous casting are these: straight-line continuous production, lower pouring temperatures, elimination of gate scrap, exact lengths delivered to the mill, minimized hard labor, greater uniformity of composition, and general over-all economies. In continuous casting, care must be taken that all variables are under precise control. Disadvantages are the high initial cost and lack of flexibility of alloy changes.

The bulk of the tonnage produced by continuous casting is in the form of billets, slabs and rod for standard fabricating processes.

Characteristics of Copper Alloy Castings. The characteristics of copper alloy castings vary somewhat, depending on the type of mold used, the mold temperature, mold dressing, metal temperature, rate of rise in the mold, and heat conductivity of the metal or alloy.

Virtually all castings intended to be wrought are cast in some form of chill mold. A small number of castings are made in chill molds using a sand core; however, they are of minor importance and their general characteristics are quite similar to the chill-mold casting.

Copper alloy castings have four noteworthy features:

1 They are less ductile than wrought materials as a consequence of the coarse crystal structure and, in some instances, directional arrangement of the crystals. Castings are subject to cracking along crystal boundaries during shrinkage in the mold, and during the initial stages of rolling or other fabrication, and from bending.

2 The mechanical properties (such as tensile strength, elongation, reduction in area, and hardness) are usually lowest in the cast alloys. However, the hardness number on the outer skin is frequently higher than in the interior of the casting, because of the presence of a layer of very small crystals on the outer surface, because of segregation, or because of precipitation of a harder constituent.

3 Frequently more than one phase is present, and except in very pure metals, segregation or coring is encountered. Segregation—normal or inverse—occurs in certain types of alloys where constituents present have either a low solubility in the alloy or a freezing point that differs greatly from the major phase or phases. Usually a homogenizing treatment of the metal is desirable before working.

4 The surface of copper alloy castings may vary from one that requires complete removal during fabrication to one suitable for fabrication to the finished article without any overhauling or surfacing operation.

Pure copper is cast at the copper refineries with a surface suitable for fabrication to the finished product, but most copper alloys require removal of the surface during fabrication.

Castings of copper and copper alloys are generally considered free from residual stresses. However, some stresses are set up during solidification and subsequent cooling. These sometimes result in intercrystalline cracks on the surface and internal fractures between crystals.

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The Hot Working of Copper and Copper Alloys

BY THE SUBCOMMITTEE ON HOT WORKING OF COPPER ALLOYS*

HOT WORKING is the plastic deformation of a metal at a temperature sufficiently high to prevent strain hardening or, as more commonly defined, it is the working of a metal above the recrystallization temperature. Hot working accomplishes the following purposes: (1) a reduction or change in the shape and cross-sectional area, (2) refinement of the grain structure, and (3) forming of a usable product—plate, sheet, bar, rod, tube or shapes.

Above the recrystallization temperature there is a limited temperature range (hot working range) at which the optimum hot working characteristics are obtained for each metal or alloy. These temperatures vary widely for various alloys. Copper, for instance, may be hot worked at temperatures ranging from 750 to 1900 F while leaded alpha brasses containing more than 64% Cu and more than 0.02% Pb are impossible to hot roll at any temperature, though they are workable to a limited extent in the other hot working operations. A metal that lacks sufficient ductility and malleability to permit hot working is commonly said to be "hot short".

Suitable temperatures for hot working many commercial copper-base alloys are listed in technical publications[1, 2, 3] and also in Tables II, III, IV and V.

Copper and copper alloys may be hot worked by any of the following operations, which are listed in the approximate order of importance, based on the tonnage of metal processed by the operation: (1) rolling, (2) extruding, (3) piercing, (4) forging and pressing, (5) bending and forming.

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In Table I are classifications based on the performance of the commercial alloys in these operations.*

The mechanical properties that a copper alloy requires if it is to be hot worked are known only generally, though the properties commonly accepted as best indications of the ability of a metal to be hot worked are good values of ductility and malleability at elevated temperatures. Considerable work has been done by various investigators, using different tests to determine the properties of alloys at elevated temperatures; thus data have been obtained concerning the ordinary static tensile strength and ductility of many commercial alloys.[4, 5, 6, 7] It should be pointed out, however, that these test results have not always been consistent, particularly when compared with known results of commercial hot working practice.

Another important factor affecting the hot working characteristics of a metal is the nature and quantity of impurities present in the metal. Small quantities of various impurities such as oxygen,[8] sulfur,[9, 10, 11] tellurium,[11, 12] selenium,[11] lead,[1] bismuth,[13,14] antimony,[15] arsenic,[16,17] iron,[18] cadmium, silver,[17] and phosphorus,[19] have effects on copper that are fairly well known. Impurities that are notable for their impairment of the hot working properties of copper are bismuth and lead. Selenium and tellurium in amounts as great as about 1% have been used to promote machinability with little adverse effect on the hot working of copper. Sulfur is generally regarded as being harmful to electrolytic tough pitch copper. Also particular note should be made that when this type of copper has been heated to elevated temperatures, exposure to highly reducing atmospheres should be avoided, since the cuprous

* Table I was adapted from a similar compilation that was prepared by R. S. Pratt for the 1939 edition of this Handbook.

Table I. Classification of Copper and Copper Alloys According to Hot Working Characteristics

Metal	Nominal Composition				Hot Working Operations				
	Cu	Zn	Sn	Pb	Rolling	Extrusion	Piercing	Forging & Pressing	Bending & Forming
Electrolytic Copper	99.92	...	...	...	E	G	E	G	E
Deoxidized Copper	99.94	...	...	...	E	G	E	G	E
Leaded Copper	99.0	...	...	1.0	P	F	P	P	P
Gilding Metal, 95%	95.0	5.0	...	...	E	G	G	G	G
Commercial Bronze, 90%	90.0	10.0	...	...	E	G	G	G	G
Red Brass, 85%	85.0	15.0	...	...	E	G	G	F	F
Low Brass, 80%	80.0	20.0	...	...	E	G	F	F	F
Cartridge Brass, 70%	70.0	30.0	...	...	G	G	G	G	G
Yellow Brass	65.0	35.0	...	...	F	G	F	P	F
Muntz Metal	60.0	40.0	...	...	E	E	E	E	E
Leaded Commercial Bronze	89.0	9.25	...	1.75	P	F	P	P	P
Low-Leaded Brass (Tube)	67.0	32.5	...	0.5	P	G	P	P	F
Low-Leaded Brass	64.5	35.0	...	0.5	P	F	P	P	F
Medium-Leaded Brass	64.5	34.5	...	1.0	P	F	P	P	P
High-Leaded Brass (Tube)	67.0	31.4	...	1.6	P	F	P	P	P
High-Leaded Brass	62.5	35.75	...	1.75	P	G	P	P	P
Extra-High-Leaded Brass	62.5	35.0	...	2.5	P	F	P	P	P
Free-Cutting Brass	61.5	35.5	...	3.0	P	E	P	P	P
Leaded Muntz Metal	60.0	39.5	...	0.5	G	E	F	E	G
Free-Cutting Muntz Metal	60.5	38.4	...	1.1	G	E	F	E	G
Forging Brass	60.0	38.0	...	2.0	F	E	F	E	G
Architectural Bronze	57.0	40.0	...	3.0	P	E	P	[illegible]	G
Admiralty Metal	71.0	28.0	1.0	...	F	G	P	P	F
Naval Brass	60.0	39.25	0.75	...	E	E	E	E	E
Leaded Naval Brass	60.0	37.5	0.75	1.75	F	E	F	G	G
Phosphor Bronze, 5% (A)	95.0	...	5.0	...	P	P	P	P	P
Phosphor Bronze, 8% (C)	92.0	...	8.0	...	P	P	P	P	P
Phosphor Bronze, 10% (D)	90.0	...	10.0	...	P	P	P	P	P
Phosphor Bronze, 1.25% (E)	98.75	...	1.25	...	G	F	P	F	F
Manganese Bronze, (A) [a]	58.5	39.2	1.0	Fe 1.0	E	E	P	E	E
Manganese Bronze, (B) [a]	65.5	23.3	Al 4.5	3.0	G	E	P	G	G
Aluminum Brass	76.0	22.0	2.0	...	G	G	F	F	F
Aluminum Bronze, 5%	95.0	...	5.0	...	G	F	G	F	G
Aluminum Bronze, 8%	92.0	...	8.0	...	G	G	G	G	G
Aluminum Bronze [b]	89.5	...	9.0	1.0	F	G	F	G	G
Aluminum Bronze [c]	87.0	...	10.0	3.0	F	G	F	G	G
Nickel Silver, 10% Leaded	45.0	42.5	Ni 10.0	Pb 2.5	P	G	P	G	G
Nickel Silver, 18% (A)	65.0	17.0	18.0	...	F	P	P	P	P
Nickel Silver, 18% (B)	55.0	27.0	18.0	...	F	P	P	P	P
Cupro-Nickel, 20%	80.0	...	20.0	...	G	G	P	F	G
Cupro-Nickel, 30%	70.0	...	30.0	...	G	G	P	F	G
High-Silicon Bronze, (A) [d]	96.0	...	...	Si 3.0	G	F	P	G	G
Low-Silicon Bronze, (B) [e]	97.7	...	...	1.5	G	G	P	G	G

(a) Normally, 0.3% Mn is found in the (A) bronze and 3.7% Mn in the (B) bronze.
(b) Other additions, including Sn, Ni, and Mn may be present to a total of 2.25%.
(c) This alloy is susceptible to heat treatment.
(d) One of the following elements—Fe, Zn, Mn, Sn—may also be present in the alloy to about 1%.
(e) One of the following elements—Fe, Zn, Mn, Sn—may also be present in the alloy to about 0.8%.

Explanation of Code letters used in classification:

E	Excellent	Capable of sustaining very severe total working, at high rates, within a relatively wide range of temperature, showing substantial freedom from hot shortness, consuming low power input, having a low rate of wear on dies and rolls, and using commercial equipment generally available.
G	Good	Somewhat less amenable to working with respect to one or more of the factors under Excellent, but still economically feasible.
F	Fair	Decidedly less amenable to working with respect to one and usually more of the factors enumerated under Excellent, and of questionable or marginal economy.
P	Poor	Either impossible to work, or so deficient in at least one of the factors under Excellent, that the operation is not practicable.

oxide present (the form in which oxygen is found in this type of copper) will be reduced to pure copper, leaving voids in the metal. When oxygen-bearing copper has once been so reduced (gassed) it is brittle and unusable.

In alpha brasses, lead in quantities exceeding 0.02% will cause brittleness at any hot rolling temperature. If bismuth[14] is present in the order of 0.006%, it also impairs the hot rolling of these brasses.

Alpha-beta brasses, that is, those containing from 55 to 64% Cu, may be hot rolled even if they contain 1% Pb. This characteristic is believed to result from the fact that the beta phase will hold 1% Pb in solution. It is also possible to hot forge alpha-beta brasses containing as much as 2.25% Pb, while brass containing as much as 3.75% Pb can be extruded. However, it is impracticable to hot roll a brass that contains as much as 3.75% Pb. Bismuth[14] also has an adverse effect on the hot rolling characteristics of the alpha-beta brasses, though the indications are that it need not be restricted to the small quantity permissible in the alpha brasses, especially if phosphorus is present.

Naval brass, which is a tin brass, can be hot worked readily in any operation. Admiralty metal, another tin brass, though fairly easy to extrude, can be hot rolled only provided the lead is kept to a trace; otherwise cracking will occur. It is helpful to soak the castings several hours at a temperature of 1350 to 1450 F to absorb the delta phase or eutectoid produced during solidification of the casting. The presence of delta produces hot shortness and causes cracking.[1] The addition of small quantities of either arsenic, antimony or phosphorus to inhibit corrosion, has no ill effect on extrusion of admiralty metal.

Aluminum brass is generally produced by the extrusion process and, as in admiralty metal, arsenic, antimony or phosphorus in small amounts does not hinder extrusion.

Among the nickel silvers (Cu-Ni-Zn), the alpha alloys have poor hot working characteristics. The alpha-beta alloys can be hot worked by any process. Lead, sometimes added to improve machining, makes these alloys unsuited for hot rolling but does not interfere with hot extrusion and forging.

The cupro-nickel alloys may be hot rolled or extruded without too much difficulty but close control is required.

The silicon bronzes can be hot worked readily, but lead

must be limited to a trace if the metal is to be hot rolled or forged.

The aluminum bronzes, both alpha (containing as much as 9% Al) and alpha-beta types, have excellent hot working characteristics. The alpha-beta type is less resistant to plastic deformation.

Copper-tin alloys (phosphor bronzes) are generally not considered hot working alloys, though some mills are now hot rolling copper-tin alloys containing as much as 4% Sn.

Hot Rolling. Hot rolling is a mechanical method of hot working by passing metal between two rolls while it is heated above the recrystallization temperature. In this operation the flow of metal is continuous and almost entirely in the direction of rolling.

Equipment. Hot rolling of rods and shapes is performed in a series of grooved rolls. The grooves are designed to reduce the cross section of the metal as it progresses from one pass to the next. Mills for hot rolling rods in sizes suitable for drawing into wire, are of the looping or continuous type. Rods in larger sizes are rolled in a merchant type of mill, which is slower than the looping or continuous mill, but can be employed for more kinds of work.

The mills usually consist of a three-high type of "breakdown" or "roughing" roll and a train of finishing rolls. In the "breakdown" mill, where the wire bar is reduced to a section suitable for the finishing train, the first passes are usually "box" type; that is, the grooves are designed to maintain a rectangular cross section so as to support the bar at all points and to avoid cracking the bar during the breakdown operation. The sequence of passes in this mill is from square to rectangular to square; the rectangular bar is turned 90 deg on its axis as it enters the square pass. Subsequent passes in the breakdown and finishing train are alternately oval and square in section. The oval sections are turned 90 deg as they go into a square pass, and the square sections are turned 45 deg as they pass into the succeeding oval. The finishing pass is from oval to the finished round size.

Rods. Rods for subsequent drawing to wire sizes are produced in coils approximately 36 in. in diam to facilitate handling. Rods produced on the merchant mills are either coiled or left in relatively straight lengths, according to their size or the capacity of the coiling equipment.

Rolls for the hot rolling of rods are generally made of cast iron or steel for the breakdown stands and of chilled iron for the finishing stands. A generous flow of water on the rolls cools them during the rolling operation.

In the production of copper rods, the starting material is commonly a tough pitch wire bar of electrolytic copper.[20] This bar is approximately 4 by 4 in. in cross section and is characterized by a "set" surface (the top surface of the casting exposed to the air during solidification). The bars are pointed on both ends to facilitate entrance into the rolls. For the last 10 or 15 years, because of the demand for rod of higher quality, the practice has been to remove the set surface by a "scalping" operation. Vertically cast bars with the "set" on one end are also available and one refiner now furnishes a "no set" bar. Electrolytic copper bars are subject to embrittlement if exposed at elevated temperatures to a reducing atmosphere. Careful control of the furnace atmosphere is therefore essential. Oxygen-free or deoxidized copper wire bars are not subject to this type of embrittlement, so control of the furnace atmosphere is less important for them, and also for bronze and brass alloys, than for electrolytic copper.

Besides copper, the alloys most commonly processed into rods by the hot rolling operation are the silicon bronzes, commercial bronze (90% Cu), red brass (85% Cu), low brass (80% Cu), cartridge brass (70% Cu), naval brass, Muntz metal, cupro-nickels (30% and 20% Ni) and the alpha-beta nickel silvers. These alloys are cast into billets that have approximately the same cross section as a copper wire bar. In designing grooves for rolling alloy rods, provision should be made for the greater tendency of some alloys—notably Muntz metal and naval brass—to spread. This spreading will result in overfilling improperly designed grooves, leaving in the rod a fin that will show up as a lap or sliver in the finished material.

Suitable temperatures to which copper and copper alloys should be heated before hot rolling are listed in Table II.

Shapes. The most common shapes that are hot rolled are round, wedge, square, and narrow rectangles. Though special shapes are produced, they are not common.

Flat Products. The hot rolling of flat products is restricted mostly to the production of heavy plates, or of the breakdown product that is subsequently finished to thinner gages by cold rolling.

Before 1940 the breakdown of flat products by hot rolling was generally limited to copper, commercial bronze (90% Cu) and red brass (85% Cu). All the nickel silvers, phosphor bronzes and brass mixtures having higher zinc contents were cold worked from the original casting. In the ten years preceding 1940, however, several manufacturers experimented with the hot rolling of all these alloys on a production scale, and demonstrated that hot rolling was possible if certain precautions were taken. The second World War made necessary a great increase in the nation's capacity for producing cartridge brass (70% Cu) and commercial bronze (90% Cu). The facilities added for this high production called for hot rolling exclusively in the breaking down stages.

The equipment for breaking down flat products consists essentially of a heavy pair of plain rolls made usually of chilled iron and cylindrically ground, with provision for cooling the rolls with water and further provision for applying oil to the rolls to prevent scaling or metal pickup. A pair of edging rolls is sometimes used in conjunction with the main reduction rolls and has marked advantages.

Copper, electrolytic or fire-refined, is available in either end-poured or wedge cakes.[20] Heating is usually performed in a continuous type of furnace with atmosphere controlled to prevent the formation of scale. Although theoretically a reducing atmosphere will deoxidize electrolytic copper, resulting in embrittlement of the metal, in actual practice a slightly reducing atmosphere is not harmful and is desirable if copper plates are to be produced without objectionable scaling.

Table II. Copper Alloys Commonly Hot Rolled

Metal[a]	Suitable Temperature for Hot Rolling, deg Fahr	Properties as Hot Rolled[b] Tensile Strength, psi	Percentage Elongation in 2 in.
Electrolytic Copper	1300 to 1600	33,000	50
Deoxidized Copper	1300 to 1600	33,000	50
Gilding Metal, 95%.....	1400 to 1600	36,000	45
Commercial Bronze, 90% ..	1400 to 1600	36,000	50
Red Brass, 85%.....	1450 to 1650	40,000	50
Low Brass, 80%.....	1450 to 1600	45,000	55
Cartridge Brass, 70%.....	1350 to 1500	48,000	55
Muntz Metal	1250 to 1450	55,000	50
Naval Brass	1250 to 1450	55,000	45
Phosphor Bronze, 1.25% (E)	1450 to 1600	40,000	45
High-Silicon Bronze (A) ...	1350 to 1550	55,000	60
Low-Silicon Bronze (B) ...	1350 to 1550	40,000	50

(a) See Table I for nominal compositions of these metals.
(b) The mechanical properties shown are *average* and are not to be used as minimum requirements.

The cakes or castings are heated to approximately 1600 F as a maximum, before being fed to the rolls. A series of passes applied as rapidly as possible will reduce the metal to whatever gage is desired since, during cooling, copper has no temperature at which it becomes hot short or brittle. It merely becomes more resistant to further reduction. Hot rolling of copper normally stops at thicknesses of approximately 0.200 in. Further rolling beyond this point is generally done cold, though there are some exceptions where copper sheets are hot "pack" rolled; several sheets are packed one on top of another, thereby permitting hot rolling to relatively light gages.

When castings are being heated for hot rolling, care should be taken so that the temperature is right for each alloy and so that the castings are heated uniformly throughout to the right temperature. Rolling the metal at temperatures outside the proper temperature range will result in considerable cracking, since most of these alloys are hot short at temperatures below and above the correct hot working range. In rolling these alloys too cold there is also the danger of breaking the rolls.

The advantage in hot rolling strip metal, as compared with cold rolling, is that the hot rolling method is more economical and lends itself more readily to the handling of a larger cake, producing longer finished rolls.

Extrusion. Hot extrusion of metal is an operation in which metal, while heated above its recrystallization temperature, is made to flow through a restricted orifice by the application of sufficient pressure, thereby forming a greatly elongated product that has uniform cross section. The shape is controlled by the orifice or die opening. Although essentially the same in principle, two distinct methods of extrusion are possible;[21] one is known as "direct" extrusion, the other as "inverted" extrusion. In the direct method the extruding die is located at one end of the extruding-press container and the metal to be extruded is driven toward it (thus moving relative to the container) by the ram entering the extruding container from the opposite end. In inverted extrusion the die is placed on the end of the ram, which has been bored out to allow passage of the extruded product, and the die moves through the container from one end; the opposite end is closed.

Inverted extrusion of copper and copper alloys was not developed until after 1926, and resulted from attempts to eliminate the characteristic defect commonly known as "pipe", encountered in the products made by direct extrusion. Although the inverted process has roused considerable interest, not much headway has been made, and the direct method is still generally preferred both in this country and in Europe.

Equipment. During the past decade, numerous mechanical improvements applying to copper and copper alloys have broadened the scope of the extrusion process appreciably. Mechanically operated presses, though still in use, are being replaced at a steady rate by presses operated hydraulically, since these presses are more flexible, more compact, more easily controlled and less subject to damage from improper operation. For hydraulic presses also, the trend has been towards greater capacity. Small vertical-tube presses that have a capacity from 600 to 1100 tons, are now being replaced by horizontal presses that have 2200 to 7500-ton capacity, enabling the use of billets as large as 10 in. in diam, whereas billets as small as 4 in. in diam were previously extruded. The majority of presses now being installed for producing rods and shapes, have capacities of about 2500 tons. Another innovation has been the adoption of hydropneumatic accumulators, wherein the hydraulic fluid is pumped into a group of steel "bottles", compressing the residual air in them to act as a pressure reservoir for the extrusion operation. This has replaced the previous alternatives of directly connected pumps or the pumping of fluid into a gravity accumulator, and has the advantages of greater flexibility and simplicity.

Today the principal limiting factor in extrusion of copper alloys is the inability of the steels used for container liners, dies, rams and dummy blocks to withstand pressures of much more than 125,000 psi at the extrusion temperatures required. In this connection, dies of the tungsten-carbide type have shown considerable promise, although the inherent brittleness of the material and its low resistance to thermal shock cause some difficulties.

Extrusion Pressures. The pressure required to extrude the more common alloys—for example, free-cutting brass and naval brass—which all fall within the range from 60 to 63% Cu (*see* also Chapter VI of reference 21), is relatively low (about 35,000 psi); whereas some of the silicon bronzes, leaded phosphor bronzes, and other engineering alloys, may require pressures as high as 140,000 psi, and extrusion of these alloys is somewhat restricted by the previously mentioned limitation of pressure on tools. The required pressure depends on extrusion temperature, reduction in area from billet to extruded product, and speed of extrusion; the influence diminishes in that order. Generally, the pressure at the beginning of extrusion will be high, diminishing gradually as the action proceeds, and returning rapidly to ■ pressure as high as the initial pressure, or higher, at the end of the operation when only a thin "butt" is left in the container. It is always necessary to preheat the container, dummy block and die before their introduction into the machine, because the plasticity of copper alloys decreases rapidly with decreasing temperature in the extrusion range. A suitable temperature for continuous operation is maintained by abstraction of heat from the billet. Sometimes it is necessary to cool the ram, container, die and dummy block either with direct water sprays, oil or an air blast.

The flow of metal during extrusion depends on numerous factors, including the copper content of the material, the amount of lubrication employed, and the design of die aperture and dummy block. Generally the first metal extruded through the die is very slightly deformed, giving evidence of little departure from the cast structure. As the billet is shortened progressively, metal emerging from the die becomes more and more fine-grained until, at the end of the operation, the metallographic structure usually bears little resemblance to that of the end extruded first. The variation in microstructure is accompanied by a corresponding variation in physical properties, and some alloys require subsequent cold working and annealing to enable the entire length of the extrusion to meet physical specifications.

Flaws. One characteristic flaw encountered in extruded products is known as "pipe" or "extrusion defect", caused primarily by the rough, oxidized outer surface of the billet flowing into the center of the extrusion. Because of interfacial friction with the container wall, the forward flow of the billet "skin" is retarded, while metal at the center is forced through the die. This causes the skin at the dummy-block end of the billet to flow toward the center, and thence downward in the direction of the die opening; the resulting action amounts to turning the billet inside out. The point at which the skin first emerges as "extrusion defect" in the extruded product, may occur halfway through the operation, but it usually comes in the last 15 or 20%, and the skin continues to emerge for the duration of the extrusion.

With the alloys that have high copper content, the flow is somewhat modified, so that the skin emerges as a subsurface layer separating a sound central portion and a clean outer layer. Although the outer layer is generally fractured and split, appearing as rough bark, it may sometimes show only as unbroken blisters, or may even give no visual evidence of its existence. With alloys that have intermediate copper contents, modifications of either or both types of extrusion defect may appear. Consequently, it is necessary to examine internally the back ends of all extrusions. This is done by cutting the product progressively with a nick-and-break shear, starting at the end extruded last, and continuing until visual examination of the breaks indicates sound metal. The examination is not completely reliable, since occasionally the defect may be intermittent. For many years the usual method of avoiding excessive defect in the extruded piece, was to stop the operation at the approximate point where the outer skin began to flow through the die as core, leaving a heavy butt end unextruded in the container, amounting to as much as 20% of the billet weight.

This defect has been largely overcome during recent years by widespread adoption of the practice of extruding so as to leave a "shell" or "sleeve" in the container, simply by using a dummy block about ¼ in. smaller in diameter than the container bore. If all elements of the press are in good alignment, the dummy block will shear through the billet, and will leave in the container the aforementioned "shell", consisting principally of the rough, oxidized outer surface of the billet. This practice reduces the extrusion defect to a minor quantity; the weight of the shell is so slight that net operational scrap may be 10% or lower. Extrusion pressure with this practice is midway between that obtaining when a "dry" container is used and that obtaining when a lubricated container is used. No lubricant may be used on the container when extruding with a shell, and care must be taken to have the shell as concentric and continuous as possible.

Another common defect in extrusion practice is known as "checked" rod. This is simply a series of closely spaced cracks occurring transverse to the direction of extrusion, and especially prevalent on sharp corners of extrusions, as in a hexagonal cross section. Although the direct cause is obscure, checked rod can usually be corrected by reducing

Table III. Copper Alloys Commonly Processed by Extrusion (Rod, Bar and Tube)

Metal[a]	Suitable Temperature for Extrusion, deg Fahr	Mechanical Properties as Extruded[b] — Rod and Bar: Tensile Strength, psi	Rod and Bar: Percentage Elongation in 2 in.	Tube: Tensile Strength, psi	Tube: Percentage Elongation in 2 in.
Electrolytic Copper	1500 to 1650	32,000	40	.....	..
Deoxidized Copper	1500 to 1650	32,000	40	.....	..
Leaded Copper	1500 to 1650	32,000	40	.....	..
Red Brass, 85%	1450 to 1600	.....	..	38,000	50
Muntz Metal	1250 to 1350	52,000	45	.....	..
Free-Cutting Brass	1300 to 1400	48,000	45	.....	..
Forging Brass	1250 to 1350	50,000	45	.....	..
Architectural Bronze	1200 to 1300	54,000	45	.....	..
Admiralty Metal	1400 to 1500	.....	..	46,000	65
Naval Brass	1200 to 1350	55,000	45	.....	..
Leaded Naval Brass	1200 to 1350	55,000	45	.....	..
Aluminum Brass	1450 to 1550	.....	..	48,000	65
Aluminum Bronze, 5%	1500 to 1600	50,000	60	50,000	55
Aluminum Bronze, 8%	1350 to 1450	60,000	60	.....	..
Cupro-Nickel, 30%	1900 to 2000	.....	..	54,000	35
Cupro-Nickel, 20%	1800 to 1900	.....	..	48,000	40
High-Silicon Bronze (A)	1400 to 1500	53,000	70	53,000	65

(a) See Table I for nominal compositions of these metals.
(b) The mechanical properties shown are *average* and are not to be used as minimum requirements.

the temperature of the billet or the speed of extrusion, or can be traced to a deformed die.

Dies. Extrusion dies are a controversial subject. The design of the die depends somewhat on whether the extrusion is a rod, tube or shape. In general practice a die blank of alloy steel is used, hardened to about Rockwell C 40, and having a diameter-to-thickness ratio of approximately 4:1. When in use, the die is supported in the die holder by ■ "backer die" with a slightly larger aperture. The great majority of extrusion dies fail because the aperture becomes smaller as a result of the upsetting pressure on the blank. A die must be resistant to flow at elevated temperatures, and yet withstand high thermal shock.

Die profiles may range from the 135-deg bell used in the extruding of tube, to an almost parallel-sided profile; the most common type has an opening with radius of approximately 45 deg.

Rods. Most extruded rods are of round, hexagonal or square cross section. Rods as small as $\frac{9}{32}$ in. in diam may be extruded in particularly soft alloys, but standard practice is not to extrude rods smaller than $\frac{7}{16}$ in. or ½ in. in diam. Multiple-hole dies are in general use for sizes smaller than about 1 in. in diam, depending somewhat on limitations of pressure and diameter of the billet. Rod smaller than about ¾ in. in diam is usually coiled hot as it comes out of the die; rod larger than about ¾ in. in diam is extruded in straight lengths. With multiple-hole dies, the extrusion pressure is approximately the same as for dies with one hole equivalent in area.

Billets for the extrusion of rods and bars are usually cast with diameters ranging from 6 to 10 in., depending on the capacity of the press, and in lengths ranging from 4 to 10 ft. These billets are then sawed into lengths from 10 to 32 in., depending on the container available, the alloy, and the required weight of the extruded product. One exception to the use of cast billets for extrusion is in the production of oxygen-free copper by the "coalescence" process,[22, 23] in which electrodeposited copper cathodes are extruded into rods and bars without being melted. This operation is based on the principle that when cathode copper is subjected to reducing gas at a high temperature, and the clean surfaces of the copper are brought together under pressure, the copper will cohere or coalesce, resulting in complete metallic union with intergrowth of crystals across the surfaces of the particles. By this process, brittle copper cathodes broken into small pieces are processed cold into cylindrical briquettes 9¾ in. in diam and approximately 16 in. long. These briquettes are heated in a highly reducing atmosphere for approximately 3 hours and are then transferred from the furnace to a hydraulic press. To avoid reoxidation of the copper, special measures are taken to keep the briquettes in an atmosphere the same as that used in the furnace.

Alloys that are commonly processed by extrusion are listed in Table III along with their tensile characteristics.[2]

Shapes. Successful extrusion of complex shapes depends almost entirely on die design. Considerable skill is required in order to obtain a uniform velocity of flow through the various components of the shape. The regulation is obtained by varying the length of bearing and the angularity of the entrance bell of the components—in other words, choking the flow through the larger elements and expediting it through the smaller ones. This manipulation depends largely on experience and common sense. Before each time it is used, the die may be lubricated by a mixture of cylinder oil and graphite in order to obtain preferential flow. There is also a limit to the depth of recesses in the shape, since the corresponding spur on the die cannot exceed about 1:1 as a ratio of length to thickness. Wide shapes, such as corrugated stairtread stock, are commonly extruded in a semicircle and subsequently flattened so that a finished section perhaps 12 in. wide can be obtained from a billet 9 in. in diam. Another practice often used to advantage is to finish a hollow shape by extruding it partly open with matching lugs on each open end. The lugs are closed and locked when the stock is drawn through a forming die.

Tube. Tube is extruded on both vertical and horizontal presses in this country. Horizontal presses are used increasingly. Original claims that vertical extrusion would produce more concentric tubing, through better tool alignment, have not been substantiated.

The common type of press for extruding tubes has a supplementary piercing mandrel operating within the main ram and concentric with it. The sequence of operations in extrusion of tubes is as follows:

1 Place the hot billet in a container, and place a dummy block behind it. The dummy block has a central hole for the piercing mandrel.
2 Advance the main ram to the point where the billet is compressed sufficiently to fill out the container, but does not extrude.
3 Advance the piercing mandrel through the billet, and thence through the die, until it projects slightly beyond the outlet end of the die.
4 Advance the main ram, forcing the metal through the annular space between mandrel and die, until extrusion is complete.

In some presses not equipped with an auxiliary piercing ram, the piercing mandrel is affixed to the main ram.

Another method, not commonly used on copper alloys, employs a "porthole" die. This consists of a die assembly, split at right angles to the direction of extrusion. Operation of the die consists simply in forcing several "streams" of metal through the ports into the central chamber. In this chamber, in the absence of oxidizing agents, the streams weld into a homogeneous mass and pass out, through the space between the mandrel and die, as a tube or hollow shape.

The production of extruded tubing within close tolerances of eccentricity is not easy. The present trend is toward the use of centrally drilled billets to ensure against

deflection of the mandrel during the piercing operation. For extrusion of drilled billets, a single-action press may be used advantageously, with a "floating" attachment of the mandrel to the ram. When the regular double-action press and solid billets are used, alignment of ram and container must be as nearly perfect as possible or eccentric tubing will result; and maintenance of this alignment is a difficult problem. The floating mandrel, which is more or less self-centering, obviates this difficulty.

Piercing. The first patent on a device for rotary piercing was granted to the Mannesmann brothers in 1885. The process is considered a probable development from a type of straightening machine in which a pair of rotating rolls —one concave and one convex, inclined at an angle to the horizontal but with intersecting centers—moves the tube or rod forward and straightens out kinks and bends.

Equipment. The development of the piercing process was a result of increasing demand for seamless steel tube for bicycle manufacture. Later, the advantages of seamless tube in automobile parts, in gasoline manufacture and as boiler tubes gave further impetus to progress, in spite of the waning popularity of bicycles. A number of variations of the original Mannesmann machine were evolved—the Steifel mill, for example. In this mill, beveled disks replaced barrel rolls as working members. In another machine, three barrel-shaped drive rolls were used instead of the original two. In spite of variation in detail, all these machines embodied the same basic principle of

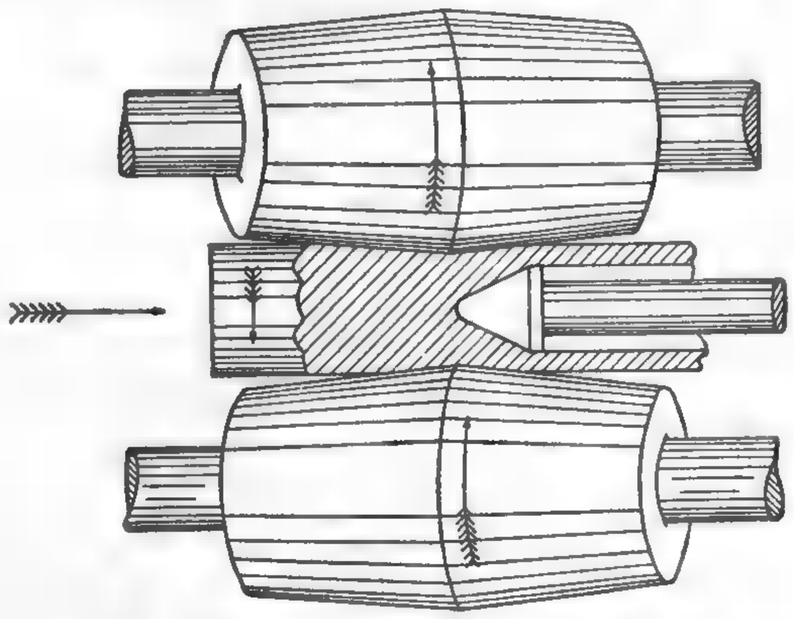

Fig. 1 Fundamental operations involved in piercing (Mannesmann patent, 1886)

forming a hollow shell from a solid billet by rapid rotation of the billet between roll surfaces that give a forward movement over a specially shaped piercing point or mandrel. A popular misconception is that metal is actually forced over this point. In reality, the point serves as a rolling surface to reshape the metal at the outlet side of the roll pass.

In present practice there is considerable variation in details of design. (*See* "The Piercing of Steel", page 351 of this Handbook.) The values given in the following discussion represent current practice in large-scale production of copper and copper alloy tubes but these values are not applied everywhere. Limitations of equipment and varying opinion bring minor changes in the various plants.

Process. Figure 1, taken from a Mannesmann patent granted in 1886, is still an excellent illustration of the fundamentals of the piercing process.[24] In modern mills, the two barrel-shaped driving rolls are coupled, by means of long spindles with universal joints, to a common reduction-gearing unit, so that both rolls rotate at the same speed and in the same direction. The usual drive is by an electric motor connected directly to the reduction gearing.

The rolls are inclined at an angle to the horizontal with intersecting axes to provide the necessary helical rotary motion. Parallel rolls would merely rotate the billet without advancing it. Although in many instances the angle of inclination is fixed, in certain designs the rolls are mounted in cradles held at both sides by adjusting bolts. This arrangement permits the selection of various angles as the need arises. An increase in the angle of inclination, increases the rate of travel through the roll pass to a point where slippage becomes excessive and rupture of the metal begins. On the other hand, if the angle is too small, the forward feed will not open the last portion of the billet to pass over the piercing point. A good compromise for copper and copper alloys is ▮ deg, although this value is not particularly critical.

The driving rolls are mounted in housings that permit lateral movement in reference to the piercing axis, for adjustment for the various sizes of billet. An approximate rule is to have the space between the maximum roll diameters, called the "gorge", about 0.8 of the billet diameter. In general this works fairly well, but closer regulation must be made by trial and error for different piercing conditions, various alloys, or different types of copper, since metal flow differs widely with different materials or even with temperature variations for the same alloy.

The center of the roll pass may or may not coincide with the center line of the machine. If it does coincide, the billet is held in position by adjustable idler rolls both above and below. These rolls should not be adjusted too closely in contact with the billet, since the resulting added frictional drag would then prevent the forward feed of the billet. Because of the necessity for some clearance, vertical movement of the billet is possible between the idler rolls. Copper is not harmed by this action, but alpha brasses may have breaks on the inside surface because of the added working of the metal incident to this movement.

The recent trend is to have the center of the piercing pass below the center line of the machine, necessitating only a single idler roll. Some machines have been made in the reverse manner; that is, having the piercing axis above the machine center. In such machines, a single idler roll is provided. Each of these three roll systems holds the portion of the billet that is in contact with the working surface of the rolls, in the proper position in relation to the piercing axis.

The piercing point is mounted on a long mandrel or arbor, which, depending on the length, may have sliding bushings of approximately the same outside diameter as the pierced shell. The purpose of the bushings is to prevent the mandrel from whipping and consequent disturbance of the relation between point and gorge.

The outlet side of the piercing machine is provided with adjustable table rolls, which guide the shell as it emerges from the piercing operation. It is quite important to adjust these rolls so that there is no whip of the mandrel and so that the forward progression of the pierced shell does not deviate greatly from the piercing axis. This adjustment is more important for copper alloys than for copper, which apparently has a considerable amount of hot ductility and does not develop breaks on the inside surface. Movement of the point, because of the whip of the arbor, may result in nonuniform gage and eccentricity. Shape and position of the idler roll are very important in the control of the horizontal position and helical rotation of the shell in the roll pass.

The far end of the mandrel is mounted in a thrust bearing that permits free rotation of the mandrel. This thrust bearing is on a reciprocating carriage with provision for adjustment of the point position. During piercing, the carriage is latched in position but can later be moved horizontally along the axis of the machine to permit withdrawal of the point from the pierced shell.

The shapes of the driving rolls, the point and the idler rolls are all interrelated with the particular operation, that is, size of billet, size of point, and alloy. In general an inlet roll angle of about 5 deg has been adequate to provide driving force to pierce billets completely in the range of diameters from 3 to 9 in. This angle, together with the lateral spacing of drive rolls previously mentioned, gives a length of contact with the driving rolls approximately equivalent to the billet diameter. Smaller inlet angles may produce excessive internal rupture of the metal before the point is reached in the roll pass, especially in the alloys that are more susceptible. This rupturing is particularly noticeable in commercial bronze (90% Cu) and red brass (85% Cu) billets, 7 and 8 in. in diam.

The outlet angle of the rolls may range from 3 to 10

deg. The smaller angle is used when shells are desired that have a diameter smaller than that of the billets; the larger angle allows for the flare that results in shells of a diameter greater than that of the billets. If the pierced shell is to have approximately the same diameter as the billet, which is ordinary practice for brasses, an angle of about 8 deg is sufficient.

Copper tubes of large diameter are frequently produced in two separate piercing operations. For example, billets 7, 8 or 9 in. in diam may first be pierced to the same diameter and then expanded or "rerolled" in a second operation until the outside diameter is 10 to 12 in. In such instances, the outlet angle must be increased to allow for this expansion. Angles of the order of 12 to 14 deg have proved satisfactory. It is advantageous also to increase the angle of taper of the idler roll in order to allow for the increase in diameter.

The function of the idler roll is to hold the billet in the proper position in the pass. Vertical adjustment is provided for different diameters of billets. Small adjustments can be made to vary the "pinch" on the billet as the need arises. The metal is in contact with the idler roll in two separate zones but not along the entire length of the working pass. On the inlet side the idler roll is at a point opposite that where the billet is first gripped by the driving rolls. This zone may be only about 1 in. wide. On the outlet side of the pass, the idler roll reshapes the shell and controls the final dimensions. The last point of contact is with this idler roll, leaving a light helical marking on the shell. Opinion differs as to the best shape for the idler roll, but a straight taper of a few degrees, with the smaller end on the outlet side of the pass, has served satisfactorily with all the copper alloys when there is little change in diameter. Such a roll permits comparatively free movement of the shell as it is formed.

In experiments with a number of shapes of piercing points, the best results have been obtained with a simple rounded point that has a radius of curvature slightly larger than the diameter of the point.

In the action of piercing, a heated billet is forced through a guide tube, or "cannon" as it is sometimes called, into the inlet side of the working pass. The helical rolling motion imparted by the driving rolls reduces the billet until the maximum drive-roll diameter or gorge is reached. In this reduction, which may be greater than one-third of the original cross section, the billet is compressed between the rolls as it is rotated, setting up torsional forces, in the zone near the gorge, which finally result in pulling metal away from the center of the billet and causing internal rupture.[24]

A shell with a somewhat irregular hole can be made by merely putting a steel or copper billet through a piercing machine without a piercing point, because of the formation of this ruptured area in the converging or inlet pass. When a piercing point is used, with its tip adjusted so that it anticipates the zone of internal rupture, a shell or tube that has a relatively smooth and uniform diameter may be formed by rolling the metal between the point and the driving rolls. This tube, at first slightly elliptical in shape when the metal is rolled away from the point, is rounded out by contact with the idler roll. During the rolling over the point, any irregularities formed in the metal at the converging pass are smoothed out under the action of pressure and high temperature.

Piercing practice in brass mills differs from that in the steel industry in that brass billets are pierced in the as-cast state, while steel billets are rolled to size from large ingots. This makes a great difference in ease of piercing and limits the alloys that can be pierced. Metal in the as-cast state is much more hot short than it is in the wrought condition.

Alloys. The binary copper-zinc alloys can be pierced, provided the lead content of the alpha alloys is held to less than 0.01%. However, medium-leaded alpha-beta brass can be pierced without difficulty. An example is leaded naval brass with 1% Pb. The addition of tin or aluminum to alpha brass always causes severe breakup during piercing, because of coring in the as-cast structure. If tin or aluminum bronzes are first extruded in billet form, they can be pierced under carefully controlled conditions, but such a process is not economical. Naval brass and leaded naval brass, which are alpha-beta brasses containing tin and tin plus lead, are readily pierced.

Temperature. Close control of temperature is necessary in the piercing of brass, since the permissible temperature ranges are narrow. Temperature controllers of the radiation type, which sight directly on the billets, are satisfactory for indicating the temperature of the billets. Each alloy has a temperature range within which it is sufficiently plastic to be worked, yet stiff enough for the pierced shell to remain straight and free from bulges. If the metal is overheated, cracks may form on the inside surface. The temperatures required for those alloys commonly processed by piercing are listed in Table IV.

Table IV. Copper Alloys Commonly Pierced (Tube)

Metal[a]	Suitable Temperature for Piercing, deg Fahr	Mechanical Properties as Pierced[b] Tensile Strength, psi	Percentage Elongation in 2 in.
Electrolytic Copper	1500 to 1600	33,000	35
Deoxidized Copper	1500 to 1600	33,000	35
Commercial Bronze, 90% ...	1500 to 1600	35,000	40
Red Brass, 85%	1500 to 1600	40,000	40
Cartridge Brass, 70%	1400 to 1450	45,000	45
Muntz Metal	1300 to 1400	50,000	45
Naval Brass	1350 to 1450	52,000	45

(a) See Table I for nominal compositions of these metals.
(b) The mechanical properties shown are *average* and are not to be used as minimum requirements.

Time. The values for piercing time and consumption of power depend on so many factors that they must be considered comparative only for the particular machine and operation. Piercing time shorter than 20 sec has been maintained for copper billets ranging up to 9 in. in diam and 4 ft long. During this short time, pierced shells approximately 10 ft long are produced. Billets made of copper, commercial bronze (90% Cu) and red brass (85% Cu) measuring 3 in. in diam and 4 ft long are pierced in about 15 sec to a 10½-ft shell, in a piercing machine with 12-in. diam driving rolls, having a surface speed of 700 fpm at the maximum roll diameter. Alloy billets higher in zinc content tend to whip and chatter violently under the same conditions. When the surface speed of the roll is reduced to about 500 fpm, the piercing action is smooth and the piercing time is again about 15 sec.

Power. The following tabulation shows the difference in amounts of power consumed during the piercing of red brass (85% Cu) and deoxidized copper (approximately 0.01% P) at 1550 F with billets 5 in. in diam. The copper followed directly after the brass, on a machine equipped with rolls 24 in. in diam with a surface speed of 760 fpm, a point 4⅜ in. in diam, a 4-in. gorge and a 6-deg angle of feed or inclination of the rolls.

Metal	Horsepower Required	Piercing Time, sec	Size of Shell
Red brass (85%)	1400	15	5¾ by ½ in.
Deoxidized copper	1000	15	5⅜ by ½ in.

The hot working characteristics of the various alloys differ markedly, as shown by the helical markings on the pierced shell. These markings, which come from the last point of contact with the idler roll, are harmless as long as an ample flow of water is kept on all the rolls. A study of these markings has given valuable information, since they indicate the progress through the rolls. Cartridge brass (70% Cu) tends to form much wider bands at slow roll speeds than copper does at higher speeds. This fact indicates a more rapid rate of feed through the rolls.

The various types of copper likewise have distinct characteristics. Deoxidized copper (high-phosphorus, 0.025% P) requires the most power to pierce, while tough pitch copper requires the least. Deoxidized copper (low-phosphorus, 0.01% P) and oxygen-free copper not phosphorized, are

intermediate. An attempt to evaluate these differences under identical conditions is not possible because of the necessity for making minor adjustments of point and rolls for each type in order to obtain the same size of shell. This fact has been demonstrated repeatedly when the type of copper has been changed in the same setup, and is thought to be caused by differences in flare in the outlet pass, because of the differences in plasticity. In the comparisons cited, the temperature was closely controlled.

In studying the piercing operation, it has been found very instructive to obtain a sample by stopping the machine purposely when a billet is partially pierced. The section of billet and shell in contact with the rolls may be cut out and split and the section may be etched. Such samples give a clearer picture than can be obtained during the actual operation. They show the degree of breakup in the converging pass and the rolling on the point in the diverging or outlet pass. Excessive distortion in the outlet pass shows improper shaping of driving rolls or idler.

Such information has been particularly valuable in piercing billets of commercial bronze (90% Cu) and red brass (85% Cu) having larger diameters. The as-cast billet has a large central zone of equiaxed grains, which tend to break up ahead of the point more rapidly than in copper billets of the same diameter. The use of sharper points to direct the flow of the metal earlier in the zone of internal rupture, helps reduce the incidence of internal defects, and a bevel of a few degrees on the inlet side of the idler roll, gives the billet more support and also helps prevent undesirable breakup. However, an extremely sharp point has a very short life and in actual practice optimum results are obtained with a point that has a somewhat elongated tip shaped like a Gothic arch, the arc of which has a radius approximately 1⅛ times the point diameter.

Because of the many mechanical and metallurgical factors involved, close prediction of behavior is difficult. It is unfortunate that trial and error methods must still be used. Undoubtedly closer definition of conditions will be obtained with further study, since the use of the piercing process has greatly increased in the copper industry during the last few years.

Forging and Pressing. The growth of the copper alloy forging industry may be divided into three periods. The first period took place during World War I, when brass forgings were first introduced and were used principally for ammunition fuse parts. During the second period, between 1919 and 1938, the commercial market for forgings was developed in the fields of refrigeration, automotive parts, plumbing, compressed gas equipment, and engineering, and alloys were developed that had high strength and resistance to corrosion. The third period has been during World War II, when forgings were used for the same purpose as in the first two periods, as well as in the aviation industry. During this period the copper alloy forging industry attained a sizeable production.

Forging or pressing may be defined as the hot shaping of metal by single or repeated blows under a hammer or press, in open or enclosed dies. Briefly, the process consists in heating, to a semiplastic state, suitably shaped bars or "slugs" that have been extruded previously, or chill-cast and scalped; then placing these bars between a set of accurately machined, highly polished, hardened steel dies in a press or hammer, and subjecting the bars to one or more blows under great pressure. The plastic metal is caused to flow and fills the contour of the die; the excess metal becomes flash, which is later trimmed cold. Thin flash in cavities is usually pierced out. Although the process is generally used for irregularly shaped parts with cavities in one plane, parts can be made with cavities in two planes by the use of split dies and side rams. Copper alloy forgings may range in weight from a fraction of an ounce to more than 130 lb.

Stock. Round extruded stock is generally used, since it is the least expensive. For certain forgings that are unsymmetrical in form, extruded shapes approximating the cross section of the forging may be used to advantage. Forgings of large diameter and weight can be made from scalped chill-cast billets cut into slugs.

The extruded rod is cut into lengths, with care to avoid rough ends that might cause forging laps. Excess metal should be minimized to increase die life. Some forgings are forged directly from the heated end of a long bar.

Equipment. The types of machines generally used for forging copper alloys are the following: hammers, varying in size from 1000 to 5000 lb; crank or screw presses, varying in size from 200 to 2500 tons; and forging machines or upsetting machines.

Hammer forgings are especially suitable when the parts are to be unsymmetrical in shape, or when special shaping or bending is required before actual finish forging.

Crank presses or screw presses are more suitable for symmetrical shapes and for operations sometimes designated as "forging-extrusion", which combine forging and extrusion in the same operation, as in the production of parts that have a long shank and a greatly enlarged diameter at the base of the shank. Modern crank presses may utilize a blocking impression and finishing impression, the same as are used on a drop hammer.

Forging machines or upsetting machines are used for producing certain types of small forgings and for enlarging the ends of bars used in making valve stems, bolts and the like.

Dies. Forging dies are designed with draft so that the resultant forging can be removed readily from the die. The draft on hammer forgings may vary between 3 and 7 deg, while on press forgings the draft is usually between 1 and 5 deg, depending on the forging design. To increase die life and to aid in metal flow, no sharp corners should be left in die cavities. An allowance for shrinkage between 0.010 and 0.015 in. per in. must be made on the die, for the cooling of the forging to room temperature. A flash allowance of 0.035 to 0.080 in. is made on the die, depending on the design of the forging and the alloy used. Where the design of the forging permits, dies are made with multiple impressions.

For discussion of the composition and heat treatment of die blocks, die inserts, and tools for forging machines, see the TOOL STEEL SECTION of this Handbook.

It is common practice to lubricate the die with oil to which a little graphite has been added. This lubricant facilitates the flow of metal in the die, prevents overheating, and keeps the forgings from sticking to the die. The use of a lubricant also has a marked effect on the life of the die.

Die life depends on the steel used for the die, the design of the forging, the alloy used for the forging, tolerances required on the forging, and the care taken by the operator in using the die—for example, preheating the die before using, lubricating the die, cleaning the die at proper intervals and operating the press at the proper speed to avoid overheating the die excessively. Dies fail as a result of heat checking, washing, cracking, or becoming oversize from cleaning. Die life may vary between 5000 and 100,000 pieces, depending on all these factors.

Alloys. The copper alloys commonly used for forging are listed in Table V. Most of the alloys are of the alpha-beta type. As shown in this table also, not all copper alloys can be cold sheared successfully. When stock for shearing is ordered, the purpose should be specified.

The tolerances on forgings will vary with the diameter. While forgings can be made to a tolerance of plus and minus 0.005 in., a tolerance of plus and minus 0.010 in. is generally used. Objectionable draft can be removed from small parts by a cold shaving or piercing operation.

Forgings are furnished with a bright dip finish by pickling in a bichromate-sulfuric acid solution and then rinsing in both cold and hot water.

The advantages obtained in a forging include high mechanical properties, freedom from porosity, excellent surface finish, close tolerances, good machinability and low scrap loss.

Bending and Forming. Under this heading can be grouped all the forming operations that have for their main purpose a change in the shape of the article fabricated. Any reduction that may occur in the cross-sectional area of the article is largely coincidental rather than intentional. In this respect hot bending and forming operations differ from the other hot working operations, which both change the shape drastically and reduce the cross section of the material being processed.

Table V. Copper Alloys Commonly Hot Forged and Pressed

Metal[a]	Suitable Temperature for Forging, deg Fahr	Probable Range of Mechanical Properties[b] as Forged: Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Percentage Elongation in 2 in.	Rockwell Hardness	Ability to Be Cut by Cold Shearing
Electrolytic Copper	1400 to 1600	30 to 38	8 to 10	45 to 50	F 25 to 65	Yes
Deoxidized Copper	1400 to 1600	30 to 38	8 to 10	45 to 50	F 25 to 65	Yes
Muntz Metal	1150 to 1450	45 to 60	20 to 30	25 to 50	B 35 to 50	Yes
Forging Brass	1200 to 1500	45 to 60	20 to 30	20 to 35	B 35 to 50	Yes
Naval Brass	1200 to 1500	50 to 65	25 to 35	35 to 55	B 45 to 60	Yes
Leaded Naval Brass	1200 to 1400	50 to 65	25 to 35	20 to 35	B 45 to 60	Yes
High-Silicon Bronze (A)	1300 to 1600	50 to 65	18 to 24	50 to 70	B 35 to 50	Yes
Low-Silicon Bronze (B)	1300 to 1600	40 to 55	16 to 22	50 to 70	B 30 to 45	Yes
Aluminum Bronze	1450 to 1600	75 to 90	33 to 40	15 to 30	B 75 to 90	Yes
Aluminum Bronze	1450 to 1550	80 to 90	36 to 45	15 to 30	B 80 to 95	No
Manganese Bronze (A)	1150 to 1450	60 to 75	35 to 45	25 to 45	B 65 to 80	Yes
Manganese Bronze (B)	1150 to 1450	85 to 105	55 to 75	15 to 30	B 85 to 100	No
Nickel Silver, 10% Leaded	1350 to 1500	65 to 75	40 to 50	20 to 40	B 62 to 77	No

(a) See Table I for nominal compositions of these metals.
(b) The mechanical properties shown are *average* and are not to be used as minimum requirements.

Hot bending and forming operations are usually performed when sharp bends are desired in the shape of the metal, or other drastic changes are required that are impractical to perform cold because of possible strain hardening of the metal to such an extent that rupture may occur. This hot method is employed also whenever the available equipment for bending or forming, and the size of the article to be fabricated, are such that cold fabrication is impractical.

The bending of heavy pipes, tubes, rods, bars and shapes, or dishing of heavy plates for large heads of pressure vessels, are typical operations that may be performed hot with relatively greater ease and without the possibility of strain hardening that could lead to early failure of the material.

The equipment generally used in these operations includes sledge hammers, bending hickeys, bar folders, brakes, drawbenches, roll-forming machines and hydraulic presses.

Since the bending or forming operations are often restricted to only a portion of the article, it is common practice to heat only the portion to be worked. As in other hot working operations, care must be taken so that the temperature will be correct for the metal fabricated, in order to avoid the possibility of cracking.

To avoid possible collapse of thin tubes at the point of bending, it is sometimes advisable to fill the tube with a material such as sand before the bending operation.

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The Cold Working of Copper and Copper Alloys

BY THE SUBCOMMITTEE ON COLD WORKING OF COPPER ALLOYS*

THE ABILITY of a metal to be cold worked depends largely on its mechanical properties, such as tensile strength or hardness and ductility. Ductility is particularly necessary, since without it no cold work can be done, but strength is also an important factor, controlling the ability to support loads and influencing machine capacities, tool life and lubrication. Ductility is highest and strength is lowest in fully annealed metal; therefore such metal has the greatest potential capacity for cold working.

The effect of cold working is to increase the tensile strength, yield strength and elastic limit, and to reduce the elongation and contraction in area. This relationship is best expressed in the form of characteristic curves, showing some of these properties (*see* Fig. 1). Besides recording the properties resulting from cold work, these curves give an approximate indication of the extent to which cold working is possible. The elongation curve, for instance,

* The members of this subcommittee are R. S. Pratt, *Chairman* (Bridgeport Brass Company), O. B. Atkin (Chase Brass & Copper Co.), W. R. Hibbard (The American Brass Company), D. H. Mead (Revere Copper and Brass Incorporated), F. R. Reutter (Scovill Manufacturing Company), J. S. Rodgers (Wolverine Tube Division, Calumet & Hecla Consolidated Copper Co.) and R. A. Schatzel (Rome Cable Corporation).

indicates from its starting point in the annealed condition, the extent of cold working that can be accomplished by free-stretching operations, as in expanding or bulging processes. This same curve indicates, relatively at least, the amount of cold work that can be accomplished in a single operation by drawing. The decrease in elongation values with cold work indicates the lack of capacity for stretching operations in the cold worked condition, but does not measure the ability of the metal to be redrawn.

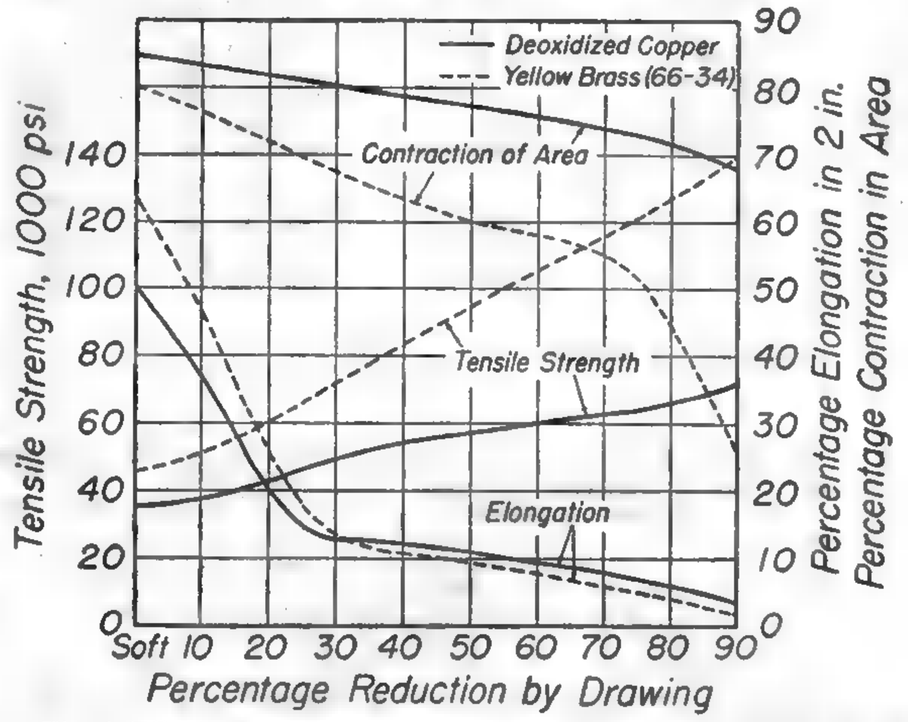

Fig. 1 Effect of cold reduction on the mechanical properties of copper and brass

The values for contraction in area are more useful in this respect, because material with a flat curve depicting contraction in area, and with high values for that property, is most likely to be capable of repeated cold working operations. Material with low initial values and rapidly decreasing values of contraction in area is not usually capable of repeated cold working operations. The curves shown in Fig. 1 indicate these differences.

The initial values shown in these curves may vary somewhat for the annealed material, depending on the temperature of annealing and other factors, but such variations affect the general level of the values rather than the shape of the curves. Alloys that consist of two structural constituents, such as alpha-beta or leaded alloys, are ordinarily less readily cold worked than are the single-phase alloys. In the alpha-beta alloys, this reduced ability is shown by the characteristic curves. In the leaded alloys, the normal mechanical properties do not give so clear a picture, possibly because these properties do not indicate the increased tendency toward failure by shearing in these alloys.

The rate at which metals harden during cold working is also indicated by the curves of tensile strength. The forces involved in cold working, the pressures on tools, and the lubricants are related not only to the initial strength of the original material but also to the rate at which the metal hardens during the operation. This rate is indicated by the slope of the tensile curves as a result of cold working, and it varies considerably in the different copper alloys. While the tensile strength increases at a relatively uniform rate, the yield strength increases very rapidly in the early stages of cold work and then parallels the tensile strength after about 20% reduction. Based on tensile strength alone, copper work hardens at a rate of about 400 psi for each 1% of reduction in area by drawing. In comparison, yellow brass hardens at a rate of about 880 psi, silicon bronze at about 1100 psi, and some of the aluminum bronzes at 1400 psi. Although these figures are only approximations, they do indicate the range of variations fairly well. Generally the rate increases together with an increase in initial annealed strength of the different alloys, although there are exceptions to this rule, such as cupronickel, which work hardens at a rate similar to that of the 85-15 copper-zinc alloy.

This outline of the relation of mechanical properties to the ability to be cold worked is of particular interest here, but other effects of cold work are equally important. For information on the more theoretical aspects of cold working, the reader may refer to the article on page 259.

Cold Working Flat Products

Rolling. "Rolling" is a term applied to the operation of reducing metal in thickness by passing it through rolls which compress it. The rotation of the rolls causes the metal to proceed at a uniform rate of speed.

The first stage of rolling is known as "breaking down". This covers rolling from the casting to a thickness of about ½ in. for alloys, and to about ¼ in. for copper. The surface of alloys is usually removed by a scalping or milling operation at this stage.

The next rolling, known as "running down", takes the metal to a point approximately 2 to 4 times the finish gage. The rolling from this point on to the finish is known as "finish rolling". For metals that require acid cleaning following the anneals in lighter gages to remove oxide and scale, the rolling after such cleaning operations is commonly conducted on rolls of the finishing type.

Rundown and finishing rolls are ordinarily of forged alloy steel, subsequently hardened and ground, although for some types of work cast-iron rolls and cast steel rolls may be used. During the rolling, lubricants of various types are used on the metal to decrease friction and to avoid excessive heating, which would change the roll shape. Rolls must be ground frequently to maintain proper surface and shape. Since rolls are subject to spring or deflection during a heavy roll pass, it is common to compensate for this by grinding them with a crown, a practice that prevents a heavy center and wavy edges in the rolled strip.

A limiting factor in rolling has been the difficulty in obtaining satisfactory bearings to operate under the high pressures involved. Early bearings were bronze, later improved by babbitt coating. With the advent of higher speeds and heavier reductions, the former bearings have been replaced by those of the antifriction type, such as pressure-lubricated sleeve bearings, phenolic bearings and roller bearings.

The most common rolling equipment is the two-high mill, consisting of two parallel horizontal rolls, one above the other. The rolls are of the same diameter and rotate at the same speed, but in opposite directions, so that their surfaces travel in the same direction at the point of contact. Metal introduced into the rolls is driven between them during the pinch or reduction, commonly termed a "roll pass".

Copper ordinarily receives breakdown rolling when the metal is hot, and a large amount of sheet copper was formerly rolled hot all the way to the finish gage, with such intermediate reheating as was necessary. As the metal becomes thinner, such rolling is conducted in packs (several sheets on top of one another). This type of rolling results in a large amount of scrap on the end and side of each sheet, inferior control of gage, and poor surface quality. As equipment suitable for the cold rolling of coils in wide widths became available, the range of widths that could be rolled was increased. Copper that is cold rolled to finish has more uniform dimensions and better mechanical properties.

Most copper alloys were formerly broken down cold and cold rolled to finish. When rolled on conventional rolls, these alloys will not stand much more than 50 to 65% reduction in thickness without serious cracking at the edges. Thus the amount of reduction between anneals is limited, and it is necessary to anneal frequently to soften the material for further cold rolling. The early castings were of thin cross section to avoid an excessive number of cold roll passes and anneals. For cold rolling, castings are usually limited to a maximum thickness of about 2 in.; the maximum bar weight is limited also, since attempts to increase the cast length met with difficulties in casting quality. In recent years the industry has adopted hot rolling for the breakdown rolling of a number of the more common alloys, thus permitting a considerable increase in the weight of the bars.

After the breakdown rolling, the alloys are rolled cold

during the rundown and finishing rolling. The increase in bar weight has resulted in a decrease in time interval, and in scrap from the ends. The heavier units have necessitated the use of improved handling equipment.

Tandem rolls consist of two to as many as five stands of rolls in a series. In such equipment the strip is reduced in gage simultaneously in the several stands. The speed of each roll requires careful adjustment to give proper tension between successive roll stands. Tandem rolling results in less manual and mechanical handling. Disadvantages include inflexibility when changing from one type of work to another, and the fact that the number of passes is fixed by the number of rolls in the installation.

So far only conventional two-high rolls have been considered. For breakdown rolling, a large number of passes is needed, and the time required to return each bar to the entering side of the rolls for each subsequent pass was such that the metal cooled off too much to be hot rolled to the desired thickness. This led to the development of three-high rolls. A roll stand of this type incorporates one additional roll above the conventional pair of two-high rolls. The metal receives a reduction when traveling in one direction between the lower and center roll, and in the other direction between the center and upper roll. This type of equipment was rather commonly employed before reversing mills became usual. With this kind of roll, the direction of pass is changed by the use of a reversing motor, and each alternate pass is taken in the opposite direction, which saves moving the metal by hand from one side of the roll to the other.

Four-high rolls, as the name implies, are designed with four rolls, one on top of another. The middle two are the work rolls between which metal is reduced in thickness. The other two rolls are back-up rolls, for the purpose of supporting and lending rigidity to the work rolls. The back-up rolls generally run idle; the work rolls are driven. The work rolls are of considerably smaller diameter than the ordinary two-high rolls. Most of the modern tandem installations make use of four-high rolls.

It has been found that as the working rolls are decreased in diameter, the power requirements are lower, and the amount of reduction may be relatively increased. Since it is possible to reduce the metal more between anneals without cracking the edges, the number of anneals is decreased.

The proven advantages of small working rolls supported by back-up rolls have led to the development of numerous types of mills that have four or more rolls. Some of these mills are still in the experimental stages; some are already in use for production purposes. On many of the newer installations of rolls, powerful take-up reels and tension devices are used at the front and back, helping to keep the metal flat and straight.

Slitting. This process is used to bring rolled flat products to final width by cutting them on a rotary slitter. The operation serves the dual function of eliminating imperfect edges and of bringing the rolled flat material to the desired width.

The machines used for slitting consist of rotary cutting shears mounted on two parallel shafts that are rotated in opposite directions and are driven by a motor through suitable reduction gearing. The rotary cutters are from about 4 to 13 in. in diam, and from ⅛ to ¾ in. thick. Good service is obtained from cutters made of high-carbon tool steel. In addition to the removal of imperfect edges in the slitting operation, it has been found expedient also to slit several strips from one roll of material. When numerous pairs of properly spaced cutting shears are employed, several different widths of strip or several strips of the same width can be slit simultaneously from the same roll. A coiling mechanism at the exit end of the slitter is used for rewinding the slit strip. The maximum thickness that can be slit on modern slitting machines in the copper and brass industry is about ¼ in.; however, this value depends somewhat on the capacity of the slitter, the number of cuts per roll, the alloy, and the temper of the rolled material. Rolled flat products more than ¼ in. thick must be sheared or sawed to width.

Flattening and Shearing. Shearing is a process used to bring rolled flat products to final width and length by cutting on a press shear. The operation is performed when it is desired to produce metal with accurately straight edges and with ends at right angles to the edges.

Material with sheared edges is first flattened by rolls and cut to a predetermined length on an automatic cutoff machine; then it is brought to final width and length by press shearing. The automatic machines used to flatten and cut the rolled material have an upper and a lower set of rolls staggered so that when the sheet or strip passes through, the metal is flexed repeatedly but is not reduced in thickness during this operation. An automatic shear built into the machine, next cuts the product to the predetermined length. The entire operation offers a means of flattening and cutting rolled products rapidly and efficiently without the danger of scratching the high-quality surface. Annealed or lightly worked material may or may not be stretcher-straightened or patent-leveled to remove buckles, ripples or wavy edges after being flattened and cut to length.

When it is desired to produce metal with accurately straight edges and with ends at right angles to the edges, the material is press-sheared and the product is classified as square sheared metal. This material is available in lengths up to 120 in., and in widths up to 60 in.

Blanking. Blanking is a process used to cut or to punch flat pieces of desired shape from rolled flat products, and offers a rapid method of cutting identical flat pieces. The blanking operation is performed through a shearing action applied by means of a punch and blanking die, each of which has a sharp edge and clearance in proportion to the thickness of metal cut. Ordinarily the die is fixed in a horizontal rigid position and the punch moves up and down in relation to it. The press is usually equipped with an automatic gage to regulate the forward movement of the strip or sheet between successive strokes of the punch. Guides keep the strip properly aligned in the press, and a stripper plate strips the skeleton from the punch. Since the blank takes the shape of the face of the punch, this face is usually ground flat and normal to the axis to reduce distortion of the blank. However, if the dies are ground at a slight angle to the plane of the blank-cutting edge, so that the punch enters the metal progressively, the maximum blanking pressure can be greatly reduced. This progressive shearing is particularly helpful in cutting blanks from relatively thick sheet or strip.

A number of factors influence the maximum pressure required for the blanking operation. The alloy composition and mechanical properties of the sheet or strip, the thickness and temper of the rolled flat product, the size and shape of the blank, the clearance between the punch and blanking die, the angle at which the tools are ground, and the sharpness of the cutting tools—all exert an influence on the maximum working pressure and ease of blanking.

In blanking sheet or strip of the same thickness and temper, yellow brass and cartridge brass have greater resistance to shearing than low brass, red brass and commercial bronze. Copper has still lower resistance to shearing than this latter group of alloys. In blanking sheet or strip of the same alloy and thickness, cold worked material is found to have greater resistance to shearing than annealed material. As an approximation, the shearing strength of the copper alloys is about 60 to 75% of the tensile strength.

Some clearance must be maintained between the punch and the blanking die in order to facilitate the shearing action. A greater clearance is required for soft materials than for hard, and a greater clearance is required for non-leaded brasses than for the leaded alloys. The size of the blank is determined by the size of the blanking die. The clearance is subtracted from the die size in order to determine the size of the punch.

Punching. Although "blanking" and "punching" are terms often used synonymously, the two operations are not the same. The ultimate product of the blanking operation is a flat shape cut from the sheet or strip. Later the blank may or may not be formed, bent or drawn. "Punching", on the other hand, is a term applied to the making of holes or irregular openings in flat products.

As a general rule, the minimum diameter of the hole that is punched in a sheet is approximately equal to the

thickness of the sheet. If it is desired to make holes smaller in diameter than the thickness of the sheet, these holes should be drilled. The size of the punched or pierced hole is determined by the size of the punch, and the clearance is added to the punch in order to determine the diameter of the die. The shear also is applied to the punch in piercing holes in sheet or strip.

Stamping, Coining, Embossing.* The making of coins and simple stampings, probably one of the earliest methods of cold working metals, was a practice in England as early as 1750, and probably earlier in Southern Germany or Northern Italy. Coffin and coach hardware was embossed shortly afterward. Embossing of buttons and novelties of various kinds followed.

The early dies were the so-called "hinge" type, which were struck with a sledge; later, pressure was exerted by a screw. Mechanical presses were introduced about 1833. On these presses the earliest known mechanical feed was installed, consisting of a tube filled with blanks and a pair of finger levers to carry the blanks to the die and to remove the coined blank.

Stamping, coining and embossing are accomplished in various types of mechanical or hydraulic presses and rope stamps. The comparatively thin metal blank is confined and forced to take the outline of the die. The cold work varies from the flattening of a small washer or disk to the formation of a radiator shell, automobile part or section of an aircraft wing.

The earlier machines were the rope stamps. Then followed dual-action and knuckle-joint presses, hydraulic presses, and presses with or without hydropneumatic, pneumatic or spring-pressure equalizing equipment. Many articles are formed and embossed in the same operation. Tools for stamping, coining or embossing may be used at positions on an eyelet press.

Among articles made on such equipment are coins, tokens, vanity cases, jewelry, brass novelties, flatware, key blanks, clips, gear blanks, handles, emblems, arms, nuts, segments, tacks, rivets, washers, disks, cover plates, buttons, bottle tops, box tops, wall plates, name plates, builders' hardware and parts for electrical, radio, automotive and other industries. Castings and forgings are sized to final shape on stamp presses to avoid costly machining.

Many articles are now made by stamping two or more parts and then assembling them by lock-seam joints, soft solder, silver solder or welding. Articles formerly forged or cast are made in this manner at lower cost.

Stamping presses are also used for preforming slugs of copper or copper alloys before hot pressing or forging. This provides better flow and distribution of the metal in the finished forging or pressing.

All copper or copper alloys that can be cold formed or drawn can be stamped, coined or embossed. Because of its ductility, copper cold works more easily than the others of this group. Sometimes, depending on the thickness and the amount of cold work in the operation, the metal is one-eighth or one-quarter hard temper instead of annealed material in order to give the finished product the stiffness desired. The material with some temper in it will blank better and give a better finish to the article.

Bending and Forming. The forming of strip by blanking and subsequent bending operations is a very important factor in the production of springs, clips and similar widely used parts in the electrical industry.

In most of the copper alloys, spring properties are improved by cold working and, as a result, the strip used in forming springs and clips is not in the annealed condition but has been cold rolled to increase the tensile and yield strengths. The operation of bending does not change the temper of the part except locally at the point of bending. The amount of forming or bending that can be done, depends on the gage, temper of the strip, radius of the bends, and also on the direction of the bend with respect to the direction of rolling. The more forming the part is to receive, the less cold rolling it can be given. Thus the design of the part and the layout of the bending operations are limiting factors in the development of maximum spring characteristics in the finished parts.

* Stamping, coining and embossing are similar to press drawing and forming, which are described on page 874 of this article.

Cold rolled strips vary in ductility with the direction of the applied stress. The least ductility is shown when the strips are stressed across the direction of rolling. It is therefore necessary to arrange the strip for blanking so that no severe bends are made in that direction. This frequently results in the blanks being cut at 45 deg to the direction of rolling and bent so that the major bending stresses are at 45 deg or parallel to the direction of rolling. Quite often this results in a more economical use of material than when the blanks are cut square with the length of the strip.

Considerable work has been done to determine what effect the gage, temper, and radius of the bend have on the degree of bending possible. In general the thinner gages, smaller amounts of cold work and larger bend radii, will permit the larger angle of bend.

In forming the bends, allowance must be made for spring-back. This requires that the metal be bent slightly more than the required angle of bend so that after forming, the spring-back will result in a final bend of the desired amount. The same effect can be produced in parts of lighter gage by stamping the angle of the bend to set the metal in place.

Occasionally strip parts that are not required for spring parts are formed by bending operations, and in such instances annealed material will permit more severe bending operations. In applications of materials capable of hardening by heat treatment, it is sometimes desirable to do the forming before hardening while the metal is in the fully softened condition. Material such as beryllium copper is formed before hardening if the forming operation is particularly severe, but even in this material it is desirable, if possible, to work with metal that has been at least partially hardened by cold work, since this will improve the ultimate spring characteristics after final heat treatment.

Many of the copper alloys can be formed by bending operations, but the materials most commonly used for springs or clips are phosphor bronze, nickel silver, cartridge brass, silicon bronze and beryllium copper. The usual requirements involve metals of high elastic limit, fatigue limit and resistance to corrosion. When maximum electrical conductivity is required, some of the higher-copper alloys or pure copper can be used, although this will necessitate some sacrifice of desirable spring properties.

Production of Rod and Wire

Cold Rolling. The cold working of rods was probably started in this country in about 1873. In the early process, square cross sections of brass were slit or sawed from brass sheet or plates and then rolled into rod. Usually the rods were finished by a drawing operation.

Later, castings 2 or 3 in. in diam were made in the so-called "cannon" molds and were rolled to size by various passes, according to equipment in the rod mill. After each pass, the rod was turned 90 deg around its axis to avoid the formation of fins and to straighten it.

The operations are usually divided into roughing rolls, intermediate rolls and finish rolls. After roughing, the rods may be die scalped or rotary scalped.

A typical practice for the production of an annealed phosphor bronze rod 1½ in. in diam is as follows:

Cast 2⅛ in. in diam by 72 in. long.
Medart straighten.
Anneal at 650 C.
Roll to 1⅞ in., to $1\frac{13}{16}$ in., to 1¾ in. successively.
Anneal at 650 C.
Roll to 1⅝ in., then to 1½ in.
Spring.
Anneal at 600 C.

This method is used today in some mills, although largely as a breakdown operation on alloys that are not readily hot worked. The number of suitable anneals and the amount of reduction in cross-sectional area between anneals is determined by the composition of the metal or alloy. Brass rods containing 70% Cu and 30% Zn can be given greater reductions than leaded hardware bronze or leaded commercial bronze. These last two alloys are red brass and commercial bronze with additions of lead to

make them free-machining. Phosphor bronze can be given greater reductions than leaded phosphor bronze.

In other mills, the castings are square cross sections of suitable length instead of long cylinders. These bars are rolled in either alternate diamond or oval grooves and round grooves in the rolls, until the final rolling is accomplished. Suitable anneals and scalping are used, as mentioned before, depending on the metal or alloy.

The selection of lubricants used during cold rolling depends on the alloy and the amount of cold work between anneals.

Among the alloys that are commonly cold worked without extrusion or hot rolling are the phosphor bronzes containing more than 4% Sn, leaded phosphor bronze, nickel silvers both leaded and unleaded, beryllium copper, hardware and leaded commercial bronzes.

The most modern method of cold rolling rods and wire rods on multiple cold rolling rolls is described later.

Cold Drawing. Most wrought copper alloys are available in rod form and in one or more tempers or degrees of reduction. Cold drawing is a process by which these alloys can be produced with desired size, section and mechanical properties. Rods—either extruded, hot rolled or cold rolled—are brought to final dimensions by one or more cold drawing operations with suitable intermediate anneals when necessary. After the final draw, the rods are straightened mechanically and cut to desired length.

Rod of large diameter is drawn on a drawbench, which consists of a horizontal frame that has a mechanical drive at one end and, at the opposite end, a die through which the rod is drawn. An endless square-linked chain runs through the center, lying in a channel at the top of the frame and returning beneath the bench. The chain passes over a sprocket at the driving end of the drawbench, and over an idler at the opposite end of the bench. The sprocket is driven by a variable-speed motor. A carriage, equipped with jaws to grip the pointed end of the rod, runs on tracks along the top of the drawbench and is automatically engaged with the continuous chain. Modern drawbenches are constructed to draw a single rod or often two or three rods simultaneously.

Both intermediate and final drawing reductions on small rod are performed customarily on a block, which has provision for a die and a rotating drum on which the drawn material is coiled. Particularly in the drawing of long coils, it has been found advantageous to use a variable-speed motor and suitable reduction gearing, so as to permit slow starting and subsequent high-speed drawing. After being drawn to final size, the coiled material is subsequently straightened and cut to predetermined individual lengths on an automatic rotating-head straightener and cutoff machine.

Regardless of size, the extruded or drawn and annealed rod is first pointed. This pointing operation is accomplished either in a rotary swaging pointer or in a rotary cutting pointer. The pointed rod is next pickled in a 10% sulfuric acid bath to remove any abrasive oxide. It is then rinsed in cold and hot water and dipped in a hot aqueous soap solution. An additional lubricant is usually employed in drawing the rod through the die. Various materials are used for this purpose; some of the more popular include lard oil, pulverized soap, tallow, and specially prepared drawing compounds.

Hardened steel dies yield satisfactory results in drawing copper and copper-zinc alloys. However, the use of sintered carbide dies assures longer life for the die and less tendency toward scratching of the die, particularly in drawing the refractory alloys.

Cold drawing of copper and copper alloys increases the strength, hardness and stiffness, and at the same time reduces the ductility of the material. The amount of increase in strength and hardness, and the extent of reduction in ductility effected by cold drawing, depend on the alloy, the total reduction in area and the number of draws used to obtain this total reduction. Copper, nonleaded brass, silicon bronze and cupro-nickel about 1 in. in diam are usually drawn with reductions of 20 to 35% in area, depending on the ultimate mechanical properties desired. The leaded brasses in this size range are usually drawn with reductions from 15 to 25% and the naval brasses and aluminum bronzes are usually drawn with reductions from about 10 to 20%.

Drawing Shapes. Drawn shapes include all sections other than the simple symmetrical ones, such as round, hexagonal, octagonal, square, rectangular, and so forth that are brought to final dimensions by drawing through a die. The origin of the shapes is in all instances determined by the complexity and the specific dimensions. The more massive sections, or sections where there is a considerable change in thickness of section from one portion to another, are started most frequently by extrusion, but sometimes by hot rolling. Shapes of considerable complexity but relatively light uniform thickness are more commonly started from rolled flat strip. Finally, any generally tubular section, regardless of complexity, is commonly started from round seamless tube.

The production of extruded sections is discussed in the article on "Hot Working Copper Alloys", page 859. A large number of extruded shapes are not drawn to final dimensions and would therefore not properly come into the present category. Only the relatively simple shapes lend themselves to such final drawing, and this is resorted to usually when greater precision is required than is obtainable in the material when merely extruded. The reason why such sections are not more frequently drawn to final size is that the alloys most commonly used, namely, architectural bronze and free-cutting brass, do not lend themselves well to cold drawing except in simple rod.

When drawing shapes from either flat strip or round seamless tube, it is usually necessary to use at least two drawing operations in order to bring the material to the desired shape and accuracy of dimension.

Regardless of the starting procedure, the shapes must be pointed by cutting, swaging, rolling or a combination of two or more of these procedures in order to start the section through the die. The shape is next pickled in a 10% sulfuric acid solution to remove any abrasive oxide, then rinsed in cold and hot waters and dipped into a hot aqueous soap solution. The section is then drawn through a hardened steel die on a drawbench. An additional lubricant is usually employed in drawing the shape through the die. The cold drawing operation increases the strength, hardness and stiffness, and at the same time reduces the ductility of the material. Various means are employed for straightening drawn shapes. Mechanical roll straightening, stretcher straightening and hand straightening methods are used, depending on the intricacy of the section.

Drawn shapes fabricated from extruded sections are commonly made from copper, architectural bronze, free-cutting brass, naval brass or manganese bronze. Obviously the alloys that are not well suited for extrusion cannot be processed in this way.

Shapes formed from either strip or tube are commonly made from copper or any of the brasses containing 65% Cu or more, with or without the addition of lead for machinability. Such shapes are also somewhat less frequently drawn from silicon bronzes, phosphor bronzes and nickel silvers. As indicated above, the choice of the alloy depends partly on the size and complexity of the shape, but is frequently influenced by color and less frequently by the mechanical properties desired.

Multiple-Stand Rolling of Wire. Modern production requirements encountered in the nonferrous wire industry have led to the comparatively recent development of multiple-stand rolling equipment for breakdown and rundown operations. These multiple-stand rolling machines consist usually of ten pairs of grooved rolls of graduated reduced sizes. The rolls are mounted in a straight line and each pair of rolls is assembled at 90 deg to the next pair.

The three popular size 10-stand mills reduce 0.750-in. wire to 0.325 in. square, 0.625-in. wire to 0.250 in. square, and 0.500-in. wire to 0.187 in. square respectively. A 12-stand mill that will reduce 0.75-in. wire to 0.250 in. square will be in production soon.

The 10-stand mills that reduce 0.750-in. wire to 0.325 in. square and 0.625-in. wire to 0.250 in. square are operated by 125 hp, variable-speed d-c motors and the finished wire comes from the mills at the maximum rate of 180 fpm. The mill that reduces 0.750-in. wire has grooved rolls 7 in. in diam by 2 in. thick and the mill that reduces 0.625-in.

wire has grooved rolls 6 in. in diam by 2 in. thick. The rolls have a 90-deg groove with a small radius, and the shape of the resulting wire is approximately a round-cornered square. Excellent service has been obtained from rolls made of carburized SAE 3115 steel. The rolls are geared independently of each other to a solid line shaft. Reference to Table I will show the groove sizes of the individual rolls and the approximate reduction per pass in rolling 0.750-in. wire to 0.325 in. square. A tolerance of plus and minus 0.002 in. is maintained on the setting of the rolls in order to prevent slippage during the rolling operation and hence, to prevent scoring of the rolls.

Table I. Groove Size and Reduction on Rolling from 0.750 in. to 0.325 in. Square. Total Reduction Approx 81%

Roll Number	Groove Size, inch	Approximate Percentage Reduction of Area
1	0.652	24
2	0.601	15
3	0.554	15
4	0.511	15
5	0.472	15
6	0.434	15
7	0.400	15
8	0.369	15
9	0.340	15
10	0.325	9

Extruded, hot rolled or annealed coils are first fed through a five-roll straightener before entering the ten-stand mill. A three-roll coiler at the opposite end of the mill forms the cold worked wire into coils approximately 24 in. in diam.

A lubricant composed of 80% machine oil, 15% kerosene and 5% lard oil is flowed continuously onto each roll while in operation. The lubricant falls into a trough, which runs the entire length of the mill, and is collected in a tank beneath the floor. From here it is pumped through a filter, which removes any grit or sharp particles that might be injurious, and redistributes the oil on the rolls. All bearings are lubricated with a suitable grease by means of a semiautomatic lubricating system, and indicators on each grease line to the bearings are visible to the operator. The wire passes through a stream of compressed air that removes all excess oil after the wire has left the last pair of rolls, but before it enters the coiler.

In the brass industry, nonleaded alloys with a copper content of about 58 to 100% Cu are successfully rolled to a total reduction of 80% in these multiple-stand machines. Alloys with a lead content up to 1% Pb can be reduced 70% by rolling from 0.625 in. square to 0.325 in. square. The cupro-nickels, nickel silvers, phosphor bronzes and silicon bronzes possess sufficient ductility to withstand 80% reduction, although the roll life experienced with these alloys may be somewhat less than that obtained with the copper-zinc alloys.

Wire Drawing. Wire drawing is one of the oldest commercial arts and has until recent years remained an art rather than a science. This is particularly true of copper wire, because of its great ductility.

Copper has been drawn from 1-in. diam rod to 0.002-in. diam wire with no intermediate anneal. However, this is not good commercial practice in industry where high-speed continuous drawing and exacting requirements of application make necessary an understanding and control of factors influencing the properties of the wire and the process of wire drawing. Even with copper the process of drawing has a definite bearing on the characteristics of the finished wire. This applies with greater force to the alloys of copper. In general, good practice is to anneal copper after each 90% reduction in area. Copper alloys may be reduced 25 to 60% in area before annealing, depending on the rate at which the alloy work hardens. The percentage reduction in area, annealing time and temperature are factors in determining grain size and ultimate properties. In drawing alloys it is therefore necessary to set up definite drawing and annealing schedules for the particular alloy under consideration. The following are important factors in wire drawing:

Composition. Copper that complies with ASTM specifications is so pure that if the material is properly hot rolled, the impurities present have little influence in limiting the drawing of wire. Where extreme conditions are required for the mechanical working of copper wire, and where the surface must be free from flaking or other minor imperfections, special grades of copper or additional operations are used. These include oxygen-free copper, scalped wire bars and shaved copper rod.

Dies. In the drawing of copper, difficulty with dies is the greatest source of trouble. The shape and alignment of dies may cause difficulties frequently ascribed to copper. In general, it is good practice to use well-polished dies of tungsten carbide, having an angle of approach of approximately 17 deg and a land approximately one-half the diameter of the wire drawn. In processes employing a single die or slow speed, the shape and alignment are less critical but are still important. For wire sizes smaller than No. 18 AWG when finished, it is customary to use diamond dies. A volume could be written on dies alone; the importance of die shape, polish and maintenance justifies strong emphasis.

Lubricant. In the drawing of copper and its alloys, soap solutions are generally used. It is important that such solutions be only slightly alkaline. The fat content generally varies from ½ to 3%, depending on the size of wire.

Machines. In high-speed machines, too tight drafting may produce the defect known as cuppiness or cup and cone fracture, even when properly shaped dies, suitable lubricant and proper compositions of alloy are used. Care in the alignment of dies and proper relationship in the delivery of wire to each die is of prime importance in continuous drawing at high speed. Where single passes or machines with a high percentage of slip are used, the drafting schedule need not be so closely controlled but power is wasted and flakiness often occurs because of abraded surfaces.

Many studies have been made in recent years to develop satisfactory theories of wire drawing; these have been useful in determining the shape of the die and in designing more efficient machines. It is now rather generally accepted that a reactive tension, which reduces pressure in the die, also reduces power requirements.

Cold Heading* Cold heading is an upsetting operation by which a head is formed on a piece of wire or rod, or a flange is upset at some portion of the blank. The cold heading properties of various materials may be compared quite accurately by stating the number of "diameters" that may be upset. The "diameters upset" is the ratio of the length of the portion of the wire to be upset to the diameter of the wire.

The nonleaded high brasses, ranging from 60 to 70% Cu, have very good heading properties, and as a general rule can be upset about three diameters. The low brasses, ranging from 85 to 100% Cu, can be upset more than three diameters in many instances. However, the shear strength of the material may easily be exceeded in the formation of certain head shapes, causing shear failures.

The leaded high brasses, containing less than 2% Pb can rarely be upset more than 2½ diam, and 2 diam would be the general rule. A lead content of more than 2% will limit the upset to approximately 1½ diam. Naval brass, containing a small percentage of tin, behaves in somewhat the same manner as leaded brass except that the stiffness is perceptibly greater and more power is required to perform a given upsetting operation.

Silicon bronze, Type A, is a moderately useful cold heading alloy and Type B is an extremely useful one. In the tensile range usually supplied for cold heading, three diameters can be upset, and a strong corrosion-resistant product will result.

In the manufacture of screw blanks in particular, consideration must be given to the machinability of the raw material concerned, if there is need for performing machining operations later. It is common practice to sacrifice some cold heading qualities in order to gain better machinability in products involving many secondary operations.

Cold Forging and Extrusion. These operations are closely allied with cold heading. The term "forging" implies a

* See also the article on page 43 of this Handbook.

lengthening or spreading action formed in a drop hammer or similar press with open dies. This type of operation has fairly limited application in cold working procedures, although it is widely used in hot working. The alloys used in cold heading can be as readily forged. Cold extrusion of rod or rod blanks implies the production of a reduced section by compressive forces transmitted through the blank. Such operations are frequently combined with heading operations in the same types of alloys.

The term "extrusion" also applies to the production of tubes or shells by the "Hooker" process and impact extrusion process, both discussed below.

Thread Rolling. Threads may be rolled on solid cylinders or on hollow cylinders where the wall is thick enough not to collapse if metal is displaced to form threads.

Rolled threads are produced on solid or heavy-wall cylinders by placing predetermined cylinder blanks between two hardened steel dies that have surfaces machined to the proper thread pattern. One of these dies is mounted on a stationary unit and the other is attached to a reciprocating member. The blank cylinder is wedged between the two dies and rotates about its own axis while moving between them; at the end of the stroke, the threading operation is completed. This is "flat-die thread rolling".

Cylinder-die thread rolling is accomplished by using three cylindrical dies in a rotating type of machine. Cams open and close these cylindrical dies. The open position is used for placing and removing the blanks, and the closed position for forming the threads.

These rolling operations have been described as cold forging the threads into shape by forcing the ridges on the dies into the blanks to approximately half their depth, thus forming the roots, while the displaced metal forms the crests of the threads. Rolled threads are generally stronger, and sometimes smoother and more uniform than cut (machined) threads.

Most of the copper alloys are suitable for roll threading, although free-machining rods and other leaded alloys will not take as deep a thread as the copper-zinc alloys. The aluminum and manganese bronzes are also difficult to roll-thread because of their greater hardness.

Production of Tubes

Drawing. Bench drawing to smaller sizes is the principal cold working process performed on copper alloy tubes that are made by extrusion or piercing methods.

The drawbench is essentially a machine for cold working by pulling tubes through a die in order to reduce the diameter or cross-sectional area, to make various shapes from round tubes, and to increase strength and hardness with resultant loss in properties of elongation.

Cold drawing reduces the outside and inside diameters and at the same time reduces the wall thickness and circular area of the tube. The inside diameter, as a general rule, is reduced slightly less than the outside diameter, and the operation results in a smooth finished surface inside and outside. During this operation the metal becomes hardened; hence, at intermediate stages the tubes are annealed. Actually, copper is so ductile that it can be reduced without intermediate annealing. However, to ensure the highest standard of quality, after two or three drawing reductions, the tubes are annealed to restore maximum ductility and refine the grain structure. Brasses and bronzes, however, work harden so rapidly that ordinarily the alloy is annealed after each draw.

Benches are usually rated in capacity by the pounds pull that the main chain and die block will withstand, and vary in capacity generally from 1000 to 200,000 lb.

Fundamentally, drawbenches are similar in operation and are usually constructed of steel or cast iron. The most widely used are those of the fixed-mandrel type, which may have a single or double mandrel.

Benches consist essentially of a mandrel support or table on the feed end and means for adjusting the position of the mandrel relative to the die. The draw die is held rigidly in a die stand or die block. The drawing end is of heavy structural sections with planed surfaces on which the main chain and tong carriage ride; the main chain is driven continuously in one direction. The carriage is returned either by cable or by friction. Actual drawing then requires a loading rack, movement for the mandrel in line with the loading rack, and a pusher motor or pinch rolls to feed the tubes on the mandrel. On heavy or large benches, mandrels are raised or lowered in line with the loading rack or draw die, either hydraulically or by air cylinders. Tube drawing is normally accomplished by one of three methods: (1) drawing over a fixed mandrel or "plug", (2) drawing by sinking through a die with no mandrel on the inside, and (3) drawing on and with a mandrel on the inside; in this method, the mandrel or arbor travels through the die with the tube. Before drawing, the tubes are pointed.

Pointing consists in hammering or squeezing the end of a tube between die blocks to a predetermined diameter and to a length governed by an adjustable stop on the pointer spindle.

Fixed-Mandrel or "Plug" Drawing. The draw die, which is usually of carbide or chromium-plated steel, is held rigidly in the headblock of the drawbench. The pointed end of the tube, which has been threaded over the hollow mandrel rod, is passed through the die until the point extends slightly beyond the outer face of the die and is gripped there by the jaws of the bench tongs. A suitable lubricant is immediately pumped onto the outside of the tube and through the hollow rod onto the mandrel, or the tubes may be dipped into a suitable soap solution for lubricating. Efficient lubrication ensures minimum friction, prevents tool scratching and imparts a highly polished finish to the tube, inside and outside. When the hook of the tong is dropped into the link of the endless chain, tension or pull on the tube causes the jaws to bite tightly into the point. The tube is thus pulled through the die and over the mandrel until the entire tube has passed through the die. When the tube is free from the die, release of the tension opens the jaws, disengages the hook and releases the tube, which is thrown into a rack while the tong returns to the headblock for further drawing.

Sink Drawing. This operation is similar, in all respects, to drawing over a mandrel except that the tube is simply pulled through a die with no mandrel on the inside. Both the outside and the inside diameters are reduced. However, since there is no plugging action, the thickness of the wall increases slightly and the inside surface is not smoothly polished.

Movable-Mandrel or Arbor Drawing. The tube to be drawn is threaded over a mandrel bar, which is usually tapered 0.006 to 0.010 in. in its length, to facilitate extraction from the tube when drawing is completed. Tubes are not pointed on the end. The mandrel bar and tube are simply drawn through a die; hence the travel of the mandrel bar, controlling the inside diameter of the tube, coincides with the travel of the tube. The extension of the tube, because of reduction of circular or cross-sectional area, is absorbed in the extra length obtained. A similar type of drawing has been done in hydraulic pushbenches using a movable arbor or mandrel and stripping the tube on the reverse stroke against mechanical strippers behind the die.

Generally, copper, copper-zinc of 70% Cu or more, Muntz metal and leaded brasses, are readily made into tubes.

Alloys difficult to fabricate are cupro-nickels, nickel silver, beryllium copper, and brasses and bronzes containing tin, aluminum, silicon or manganese.

Tube Rolling (Rocking). The first Pilger rolling machine, which is the predecessor of the tube-reducing machine, was developed by the Mannesmann brothers, who built the machines for piercing tubes. Consequently the Pilger or Pilgrim process for making tubes has been used in Europe, while the tube-rocking process, which was developed in this country, has been used more often here.

Tube rocking or tube reducing is the cold sizing of a tube by means of semicircular grooved dies that are rocked back and forth over the tube on a mandrel that controls the inside diameter of the tube. This is a decided departure from the previous method, whereby a tube is drawn through a die and over a mandrel.

The grooves of the semicircular dies are tapered, one end of the grooved section is somewhat larger than the outside diameter of the tube to be sized. The gradually

decreasing cross-sectional area of the grooves pinches the tube walls against a correspondingly tapered mandrel, which results in reduction in the wall thickness and increase in the tube length. The tubes are fed longitudinally and a suitable mechanism turns the tube on its axis so as to distribute the cold work over the entire circumference of the tube. These operations are timed after the dies have completed their forward stroke. The resulting tube is concentric, with accurate dimensions and close tolerances.

Tapered tubes, bimetal tubes and tubes with special bores, may be made by this process. Tube-rocking methods may be used with all alloys that can be drawn on tube drawbenches. The tube-rolling machine may require some adjustment or change of the grooved dies, according to the alloy being processed.

Spinning. This process is a method of forming tubes by spinning to a predetermined shape without the application of external heat. The process combines reducing, closing the tube end and thickening the wall on the closed end section. One of the advantages of spinning is the possibility of forming closures and at the same time increasing or maintaining the original thickness of the tube wall. Generally, tubes having walls 0.015 in. or thicker can be successfully spun. There is virtually no limit to maximum wall thickness.

The process, unlike that used in the spinning of sheet metal, where very little heat is developed, depends on the controlled plastic flow of metals at elevated temperatures developed by friction between the tube and die, one of which is rotating while the other is stationary.

The operation can be performed on lathes, screw machines, drill presses, spinners and other rotating machines. Large production runs are made on automatic machines designed for continuous operation. In the process, the tube may be held stationary in a suitable holder with practicable means for feeding the tube into the die. Equipment includes a suitable die holder, a recessed die of the required shape, and means of rotation at speeds of approximately 1200 to 3000 rpm. The process works as well if the tube is rotated and the die is held still.

The process is very rapid and usually the desired shape can be obtained in a matter of seconds.

The inside diameter can be controlled by a mandrel; the outside diameter is controlled by the dies.

Temperatures developed during spinning are sufficiently high that in the copper alloys, as a general rule, annealing takes place in the spun section, or stresses produced by cold drawing are removed from that section; the remaining length of tube is of unaltered temper. Because of this softening, and hence increased ductility, subsequent forming can be performed readily on the spun section.

Tube Bending. The operation of bending pipes or tubular products is one requiring considerable care. The nature of the operation is such that the circular cross section is severely deformed if not well supported on the inner surface. When the wall of the pipe or tube is great in comparison with the diameter, more severe bends can be taken without collapse of the unsupported tubes. Therefore, with the standard pipe sizes and annealed tempers it is possible to make bends that have a large radius without internal support. This is particularly true of the smaller sizes of pipe when wall ratios are 10% of the diameter or more. Also in the heavier gage type of copper water tubes with annealed tempers, bends can be made on large radii. In all this type of bending, however, a certain amount of departure from a perfectly round cross section is not objectionable.

Some form of support is necessary in tubes with wall ratios of less than 5% and in larger tubes generally. In occasional bending jobs the tube section can be supported with sand or resin, and in some instances with alloys such as Woods metal that have a low melting temperature. For quantity production jobs of this type, the tubes are supported by flexible arbors that will bend as the tube bends and can be pulled from the tube readily after bending. Removing the flexible arbor corrects any deformations from a true circular cross section during bending.

Annealed tempers are ordinarily used for bending operations, particularly when accurate cross sections are required. Tubes of some drawn tempers can be bent in the smaller diameters and heavier wall thicknesses, although such bends must be on a larger radius and some deformation permitted. Copper and all the alpha solid solution copper alloys are suitable for bending, although high brass and copper are most commonly used.

Press Drawing and Forming

Cupping. The first step in press forming is the conversion of a flat strip to a cup or short shell with a closed bottom. The simplest form of this cupping operation is the conversion of a circular blank into a cylindrical cup. The operation may be performed in several ways, but the most conventional method is by use of a double-action press. Some consideration of the metal flow in this operation will be helpful in understanding all press drawing and forming operations.

During the cupping operation the diameter of the blank is reduced by circumferential forces in the perimeter of the blank, which would tend to produce wrinkles if the metal were not held tightly by the blank holder. The outer punch of the double-action press is designed to do this. Although the blank holder is intended to prevent wrinkling, it must not be so tight as to prevent thickening of the blank while it approaches the drawing radius of the die. This thickening is the natural result of the contraction in diameter and, if it is prevented, there will be a consequent increase in the force required to form the cup and fracture of the cup may result. The clearance between the inside of the die and the punch, is slightly greater than the gage of the metal, so as to allow for some thickening of the cup wall near the top. Generally only a short length of the cup is actually squeezed between punch and die. This action that pinches or thins the wall is usually called ironing.

The portion of the cup first formed by the punch is required to support the load during the remainder of the operation. This portion of the cup is therefore stretched and thinned slightly, so in a conventional cup the wall is thinnest at the bottom and thickest at the top. An excessive pinch between punch and die or excessive hold-down pressure is likely to cause failure by stretching in the bottom of the cup. The metal is supported to some extent by friction on the punch or deep cups could not be made by this process.

Two radii are important in this operation—the radius formed on the bottom of the punch, which is often controlled by further operations to be performed on the cup, and the radius on the drawing edge of the die. Large radii at both of these points will promote easy flow of metal. On the punch, a large radius will permit thinning of the bottom of the cup, whereas a small radius has the opposite effect and may localize severely the normal thinning of the side wall at this point. Too large a radius on the die permits wrinkling of the blank, and results in a poor surface or tears and folds at the top of the cup. Too small a radius may tear the outer surface of the cup by the sharp reversed bend that the metal is forced to undergo. The usual die radius is between ▮ and 10 times the metal thickness, but occasionally certain designs require sharper radii, particularly if the cup is to be left with a flange.

The surface finish on the tools that are used is frequently an important factor in the success of the operation. In cupping or drawing there is little relative motion between the metal and the punch, while there is a great deal between the metal and the die; therefore, careful polishing of the die is highly desirable. The die should be lapped and polished in such a way that any scratches left are in the direction of metal flow. Cupping punches are usually polished less than the dies because of the need to control metal flow in the bottom radius. Since failure may occur by pushing out the bottom of the cup, actual roughening of the lower side wall and radius may prevent excessive thinning and failure. Such roughening should not be carried to the point where it interferes with the normal stripping action. Chromium-plated tools, particularly dies and punches for deep drawing, are helpful in reducing friction and "brassing up" of tools, but me-

chanical strippers are usually necessary with chromium-plated dies. If it is desired to hold the metal at the bottom of the punch, chromium-plated punches are not so satisfactory. When the quantity of production and the size of the tools permit, hard alloy tools such as the sintered tungsten carbides are found useful. These tools also may reduce friction and generally permit much more uniform control of gage and dimension, as well as longer tool life.

A double-action press is ordinarily set up in such a way as to permit the outer punch to cut the blank as well as to provide the necessary blank-holding pressure. In the single-action process, the blank-holding pressure is provided by rubber pads that deform under pressure but are quite effective in providing a smooth flange. Flanged cups may be produced on either single-action or double-action presses, but in both types the cup must be pushed back through the die. Single-action presses may also be used to produce complete cups of heavy gage, such as cups for cartridge cases, in which the blank is heavy enough to contract without wrinkling.

The extent of reductions in diameter between blank and cup cannot be standardized because of the variety of conditions under which cups can be made. In the production of the normal cup for redrawing, it is customary to reduce the diameter between 40 and 45%. In very thin blanks, 0.015 in. or less, these reductions are not so readily obtained, although in heavier blanks somewhat larger reductions can be made.

The lubricants used in cupping operations vary considerably, depending on the exact type of operation, tools, design, condition of the metal and other factors. In many of the lighter cupping operations, it will be found that a simple solution of high-grade soap and water is the best that can be used. With heavier blanks and greater depths of cupping, a soap paste is preferable that contains some fatty acids and animal or vegetable oils. Where the cup is ironed severely or a large reduction in gage is involved, heavier pastes that contain solid lubricants such as talc or graphite are sometimes found desirable. The use of mineral oils is seldom found necessary, except when they may be compounded as a diluent in some paste lubricants. Lard oil is sometimes used for severe cupping operations, but generally a paste that is soluble in water is just as good a lubricant and is much easier to remove. Ease of removing the lubricants is an important factor if the cups are to be annealed for reworking. Lubricants are one of the most common sources of the red stains frequently found in redrawn yellow brass shells.

Drawing. Further cold working of cups by redrawing operations is normally performed in single-action mechanical presses or hydraulic presses. Redrawing can be achieved by two general procedures: one involves a reduction in diameter of the shell with little or no pinching or ironing of the wall; the other involves a relatively slight reduction of diameter and considerable reduction of wall thickness. These two procedures represent extreme conditions, and it is probable that all copper alloys lie between these two extremes, but wall pinching is much more common with the brasses than it is with steel. However, there are occasions when both methods of drawing must be followed. In reductions of diameter, the original shape of the cup bottom is maintained during drawing, in order to prevent wrinkling and tearing.

It is also possible, of course, to accomplish some reductions in diameter without a sleeve, but the extent of such reductions is limited to about 20%. This amount varies somewhat with the diameter and wall thickness. During redrawing with a heavy wall pinch, the amount of reduction in diameter should be very small with just enough difference in inside diameter to permit insertion of the succeeding punches. This method of drawing proved very effective in reducing the number of operations required for producing brass cartridge cases during World War II.

Two general practices are followed in the press drawing of brass: (1) to start with a small thick blank and reduce it by ironing, and (2) to start with a larger but thinner blank and make reductions in the diameter. With regard to the number of draws and annealing operations, the first method seems preferable; but other factors, such as the shape of the final product, cost of metal and scrap loss, may affect the relative advantages and change the selection of procedures.

For most redrawing, forming or reducing operations on brass, a simple soap solution is perhaps the best possible lubricant—best not only for performance but also for ease of removal after drawing. Within recent years a heavily concentrated soap solution has been used for coating the shell; such a solution, when dried, leaves a film of soap on the surface. This film makes a very effective dry lubricant that helps to eliminate the sloppy conditions normally found in pressrooms. Dry soap is not satisfactory for finish work that must be buffed or plated, because it eliminates much of the surface ironing required in producing highly polished work. Both the dry soap and the soap solution can be removed by washing in warm water.

The amount of cold work that can be done on the various copper alloys in press drawing, is as much affected by the tool design and lubricant used as it is by the properties of the alloy. The alloy strip is always furnished to the press room as annealed material. The grain size of the strip is a considerable factor since it is well known that material of coarse grain size generally permits greater reductions than fine-grained material of the same alloy. There are instances, however, in which coarse-grained thin strip will not be strong enough to support the depth of cup required, and the bottoms will break out. For material of heavy gage, coarser grain sizes generally permit deeper drawing with less load on the press. For finishing work directly from the cup, without subsequent annealing and ironing draws, coarse grain is objectionable because it develops a rough "orange peel" surface and is very difficult to polish. In some classes of press drawing, fine grain is essential for this reason, and frequently the extent of forming must be limited by what this fine-grained metal will permit. It is impossible to be specific about the maximum permissible grain size, because it depends entirely on the amount of stretching or ironing and on the amount of polishing or buffing that the finished piece can be given economically.

The most common brass alloy for press drawing is yellow brass (65% Cu, 35% Zn) and the amount of redrawing that it can be given without annealing is limited by the rate of hardening under cold deformation. Copper and some of the softer copper alloys can be redrawn indefinitely in the form of tubes with open ends, but in press drawing there are limitations. Deoxidized or phosphorized copper, for instance, can be redrawn almost indefinitely without annealing, if the reductions in diameter are held to a minimum, and the piece is a simple straight-sided shell. If, however, the diameter is to be reduced appreciably, a sleeve is required to prevent folding and tearing, and the extent of redrawing without annealing is limited. To a slighter extent, this is also true of some of the other soft alloys, such as red brass and gilding metal. Reductions in diameter are difficult without annealing, because the relatively soft bottoms that must first be drawn before the diameter can be reduced, are not strong enough to withstand the load; consequently the bottoms are punched out and failure occurs.

The harder and more refractory copper alloys, such as phosphor bronze and silicon bronze, are not widely used in press drawing, but they can be drawn if the abrasive tin and silicon oxides are eliminated by bright annealing. This also applies to the nickel silver and cupro-nickel alloys, which can be drawn readily if bright annealed, or if processed by successive reductions of the wall thickness so as to eliminate the need for annealing. The low-copper Muntz metal type of alloy is not normally used in press-drawing operations, and if so used may be difficult to form, requiring extra operations and extra care in annealing.

Spinning of Sheet Metal. As a general rule, sheet metal is spun only when the required quantity of an article is small. High rates of production cannot be expected. However, the initial outlay for equipment and maintenance of tools is relatively small; hence for small production lots, the cost per piece is low.

The equipment required consists of a lathe with a drive

on the headstock capable of providing speeds of 1200, 1400 and 2400 rpm; the lower speeds are used for thick and large sections where heavy pressures are required; the higher speeds for thin and small sections.

Chucks may be of wood, cast iron or steel, preferably chromium-plated to produce a very smooth planished surface. Where the part to be spun is of a shape that does not allow removal of a solid chuck, sectional chucks are used and care must be taken to have all sections fit perfectly; otherwise the impression of the joint may show on the spun part.

Spinning rolls or form rolls may be made of hardwood or steel. Depending on the shape to be produced, specially shaped tools are made usually from steel rod of 1.1% C and are chromium plated. A tool flat on one side and rounded on the other side is considered suitable for general spinning. All such tools are usually mounted on the compound rest of the lathe. Lubricants may be lard oil, soap, beeswax, or paraffin, depending on the preference of the operator, the speed, and the pressure required.

The metal section to be spun is mounted on the lathe by clamping between the chuck and the wood form, with a hardwood pad on the tail spindle. The spinning tools are mounted in the compound rest and are moved into and against the metal section to be spun, with just sufficient pressure to deform the sheet into and against the form.

In bulging operations, a form roll is used that is generally of hardwood and placed on the outside of the spun part. The spinning roll is usually mounted on an extension to the compound rest of the lathe. The roll is set on an angle and moved into the inside of the metal form; pressure is then applied by the roll forcing the metal outward and against the form roll.

In all spinning operations the edge of the metal must be slightly flared, thus avoiding wrinkling or buckling. The correct amount of flare is largely a question of operational experience. The number and sequence of operations to produce the finished part depends on the shape and area of surface to be spun. The production of cylindrical shapes or shells usually requires three steps—dishing, cupping and finish shaping. Since copper is ductile it can be shaped almost at will; however, the alloys strain harden rapidly. The sheet metal that is being spun at room temperatures, and the extent of cold working and strain hardening govern the necessity for annealing.

The metals most commonly used for spinning are copper, gilding metal, commercial bronze, red brass, yellow brass and nickel silver. Any choice among these metals depends largely on the color desired in the spun part, though occasionally the mechanical properties may be the controlling factor.

Temper of the sheet metal should be soft, annealed to a grain size of 0.015 to 0.030 mm. Where the spinning and number of operations is not excessive a special temper may be used.

Impact Extrusion. Impact extrusion and extrusion by the Hooker process are closely related and are sometimes confused with each other, but are two distinct processes. All types of copper can be used successfully; the best, however, is oxygen-free copper that has maximum ductility. Copper-zinc alloys are also used, but the amount of cold working is reduced as the copper content is lowered.

Crank presses of the conventional type are used, but best results are obtained with high ram speeds; a sharp impact blow is superior to a slow-moving ram. The reason for the high speed of the ram is to move the required amount of material quickly, without hesitation.

In impact extruding, either a slug sawed from bar stock or a blank cut from sheet metal is used. The material is generally ordered as cold worked, to facilitate either the sawing or the blanking operation. Parts are then annealed and should be pickled to remove all traces of copper oxide. The blank or slug is fed into a shallow set edge, the diameter of which should be a few thousandths of an inch larger than the diameter of the part to be impacted. Directly under this set edge is a flat solid die. The punch has a slight angle on the face and a straight portion from the face of approximately ⅛ in., with a relief of a few thousandths of an inch from there back in order to minimize friction. Pressure exerted by the punch forces the metal upward around the punch to produce a shell, the inside diameter of which is controlled by the punch.

By this process a shell is produced with a relatively heavy bottom. Decreasing the bottom thickness increases greatly the pressure required. Where shells with heavy bottoms are needed, this process is ideal. Shells that have relatively thin sidewalls can be produced, but care must be taken in proportioning the size of the punch and the wall, and also the length. These punches are under extraordinary pressure and there is a possibility of bending, which will result in uneven wall thickness and high maintenance costs for tools.

Cold Extrusion. This process is generally referred to as the "Hooker" process. The metals and alloys used in impact extrusion can be used in the Hooker process. The presses and equipment used are also similar, with a like need for a sharp, rapid blow, but the initial form of blank is different.

In extrusion, either a cup or a shell is used, depending on the size and length of the finished extrusion. Two methods are used to prepare the cup or shell for the extruding operation: (1) employing a double-action press to produce a cup and performing secondary redrawing operations to provide the correct size of shell; (2) using rod sawed off to the required length, impacting it and redrawing, if necessary, in order to produce the required size of shell.

If the shell to be extruded has been severely cold worked during preparation, it should be annealed before the extrusion operations. It is essential that the annealed shells be cleaned thoroughly to remove all traces of copper oxide.

The shell produced is fed into a sleeve, the diameter of which is a few thousandths of an inch larger than the shell; directly under this sleeve is located the extrusion die, the diameter of which is determined by the finished diameter of the required extrusion. The punch has a front-end diameter that fits into the inside diameter of the shell, and also has a shoulder that is equal to the outside diameter of the shell. The shoulder on the punch exerts pressure on the open end of the shell and extrudes it through the smaller opening in the die. Relatively little heat is generated in this operation because the material is moved rapidly and the bearing in the die is very short, which minimizes friction.

Bulging. In bulging, a mechanical operation performed on copper and copper alloys, the center portion or body of a shell having a straight wall is expanded or enlarged to form some desired shape. The operation is carried out in a mechanical press of suitable construction, by means of a rubber insert or similar device, such as a segmented or split die.

A drawn shell is placed in the die in such a manner that, with the action or stroke of the press, an insert enters the shell and expands, causing the metal to expand or bulge and assume the inside shape of the die. Devices involving split dies act in a similar manner. The amount of cold work must be controlled in order not to exceed the plastic working properties of the metal, thus causing fracturing or splitting. An extreme bulge may be obtained in several steps with intermediate annealing between the bulging operations.

Articles such as kettles, pots, cans and pitchers are typical illustrations of bulging operations.

Flanging. Flanging is an operation that consists of turning out the open end or edges of a hollow article made of sheet metal in cylindrical, rectangular or other shapes. Thus the operation is somewhat in the nature of a beading action and, since it is similar to beading, the equipment for flanging resembles that used for beading. A flanging operation is very common in can-making.

The most usual flange is a component part of a drawn shell, where the edges at the open end are not completely drawn into the die. When it is impossible to produce a desired flange by this method, the flange is formed either by a series of rolling operations or by a forming operation with a punch and die.

A combination of the above methods may be used, sometimes with intermediate anneals, where it is necessary to accomplish a particularly severe flanging operation.

Beading. The operation of beading consists in the formation of strengthening ribs or beads around hollow shapes, usually cylindrical. The beading may be accomplished by one of several methods. The simplest consists in rolling a bead on suitable equipment, such as a formed arbor and shaped roll placed parallel to each other. The arbor is usually a rotating fixed member, while the rotating roll is ordinarily operated by a cam that moves it into position toward the object; the beading is thus accomplished by squeezing the object between roll and arbor.

A less common and more complicated method requires the use of segmental dies. This method is similar to that used for bulging.

A shallow bead is frequently formed on a drawn shell or tube by the use of a punch and die. The portion of the body beneath the bead is held closely in a confined die, while a shouldered punch applies pressure at the open end.

Necking. Necking, as applied to the working of copper and copper alloys, is a combination of mechanical operations involving tapering, swaging or reducing the circumference of drawn shells, and is accomplished on various types of mechanical equipment. For example, tubes are tapered in rotary swaging machines, while the tops of drawn shells and caps are reduced in diameter in redraw dies. Usually the metal should be soft and ductile in order to prevent cracking. Depending on the amount of cold work to be performed, or on the extent of reduction, it may be necessary to make use of intermediate anneals during a series of necking operations.

Thread Rolling. Threads may be rolled on thin metal cylinders by means of rolls and arbors that have the desired thread pattern machined on them. The shells or caps that have a thin wall are fed onto the arbors, and the roll, which is cam operated, is pressed against the outside of the shell or cap to form the desired depth of thread, which is predetermined by the design of the arbor and rolls. The peripheral speed of arbor and roll must be determined carefully to ensure properly rolled threads. Screw shells for lamp sockets, bottle caps, canning jar caps and similar articles are threaded in this manner and special thread-rolling machines are used for high production of these parts.

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The Annealing and Heat Treating of Copper and Wrought Copper Alloys

BY THE SUBCOMMITTEE ON HEAT TREATING COPPER ALLOYS*

DURING PRODUCTION and fabrication, copper and wrought copper alloys may be heated for homogenizing, for hot working, for reworking and control of final temper, for stress relief, for solution treatment and precipitation hardening.

Heating for Homogenizing. "Homogenizing" is defined as a heat treatment at high temperature to eliminate or decrease segregation in an alloy by equalizing the chemical composition throughout the casting. When applied to alloys that have been cold worked after casting, the homogenizing period may be decreased and the treatment can then also change the shape of the crystals.

The rate of diffusion of atoms of one metal through an alloy, depends to a large extent on the fundamental characteristics of the two metals. The following observations serve to illustrate this generalization: When brass is annealed, some zinc is volatilized from the surface. Ordinarily, however, the surface color does not change to red, typical of a higher copper content, but remains yellow because zinc diffuses very readily through the alloy from the interior, and therefore the composition of the brass is rapidly equalized at a slightly lower zinc content during annealing. In silver-copper alloys, the surface layer is frequently found to be free from copper because the copper originally present there has been oxidized during annealing and removed by pickling or machining. Little or no copper diffuses from the interior, during annealing, to replace that oxidized and removed from the surface.

The coring found in castings of the plain, leaded or special brasses is removed, in most instances, by the regular process anneals. Diffusion and subsequent homogenization are somewhat slower and more difficult in the silicon bronzes, cupro-nickels, nickel silvers and phosphor bronzes than in most of the other copper alloys. Therefore with these alloys special prolonged homogenizing anneals are frequently resorted to.

For instance, high-tin bronze castings have a cored structure and unstable hard delta crystals that make the metal brittle. When the alloy is heated at 1100 to 1450 F, diffusion of tin decreases irregularities in composition and makes the crystals more uniform in shape and size. At the same time, strength and ductility are increased and hardness is decreased.

Heating for Hot Working. Many alloys are quite plastic within some range of temperature higher than the recrystallization point but lower than the melting point, and in that range these alloys will withstand much more extensive working with considerably less expenditure of power than when cold. Such alloys are usually hot worked in the early stages of fabrication when heavy reductions can be made. Such hot working operations include hot rolling of cakes and bars for sheet and wire, extrusion for rod, shapes and tube, piercing for tube, and hot forging or pressing for special shapes.

Heating for hot working usually requires higher temperatures than annealing for cold working. Most alloys have a relatively wide hot working range, but some have a narrow range. The working temperatures depend on alloy and operation and may vary from about 1150 F for high brass to about 2000 F for cupro-nickels, with copper and high-copper alloys in the range from 1350 to 1650 F.

Drop-hammer tests will establish the highest practicable temperature below the melting point, at which the best results may be expected. The empiricism necessary in this work is well stated by Morris: "For instance, we wish to extrude a metal *M*. We know that we can extrude another metal *Q* at temperature *T*. We make a drop-hammer test of metals *M* and *Q* and find that in order to obtain the same reduction in height as we find in metal *Q* at temperature *T*, we must heat metal *M* to temperature *T'*. *T'* is therefore the temperature at which we first try to extrude the metal *M*, with fair assurance that we shall be able to force the metal through the die." Much the same kind of reasoning can be applied to hot rolling. However, the tendency to crack in extrusion, piercing or rolling must be ascertained largely through experience.

No hard and fast rules can be established for hot working temperatures. They can be formulated only after all the contributing factors of each specific job are known and considered, as affected by variations in equipment and the types of working operations that are being performed. The temperatures commonly used both for heating for hot working and for annealing after cold working are given in Table I. Where hot working temperatures are not listed, it means that the alloy is not commonly hot worked except for initial extrusion of the casting.

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Table I. Hot Working and Annealing Temperatures for Copper and Wrought Copper Alloys

	Composition, percentage									Hot Working Temperature, deg Fahr	Annealing Temperature, deg Fahr
	Cu	Zn	Pb	Ni	Sn	Si	Al	Mn	Fe		
Copper	99.93	....	....	....	....	....	....	....	....	1300 to 1650	700 to 1200
Gilding metal	95	5	....	....	....	....	....	....	....	1300 to 1650	800 to 1450
Commercial bronze	90	10	....	....	....	....	....	....	....	1400 to 1600	800 to 1450
Red brass	85	15	....	....	....	....	....	....	....	1450 to 1650	800 to 1350
Low brass	80	20	....	....	....	....	....	....	....	1450 to 1650	800 to 1300
Cartridge brass	70	30	....	....	....	....	....	....	....	1350 to 1550	800 to 1300
Yellow brass	65	35	....	....	....	....	....	....	....	(a)	800 to 1300
Muntz Metal	60	40	....	....	....	....	....	....	....	1150 to 1450	800 to 1100
Leaded commercial bronze	89	9.25	1.75	....	....	....	....	....	....	(a)	800 to 1200
Low-leaded brass (tube)	67	32.5	0.5	....	....	....	....	....	....	(a)	800 to 1200
Low-leaded brass	64.5	35	0.5	....	....	....	....	....	....	(a)	800 to 1300
Medium-leaded brass	64.5	34.5	1	....	....	....	....	....	....	(a)	800 to 1200
High-leaded brass (tube)	67	31.4	1.6	....	....	....	....	....	....	(a)	800 to 1200
High-leaded brass	62.5	35.75	1.75	....	....	....	....	....	....	(a)	800 to 1100
Extra-high-leaded brass	62.5	35	2.5	....	....	....	....	....	....	(a)	800 to 1100
Free-cutting brass	61.5	35.5	3	....	....	....	....	....	....	1300 to 1450	800 to 1100
Leaded Muntz metal	60	39.5	0.5	....	....	....	....	....	....	1150 to 1450	800 to 1100
Free-cutting Muntz metal	60.5	38.4	1.1	....	....	....	....	....	....	1150 to 1450	800 to 1100
Forging brass	60	38	2	....	....	....	...	....	....	1200 to 1500	800 to 1100
Architectural bronze	57	40	3	....	....	....	....	....	....	1200 to 1400	800 to 1100
Admiralty	71	28	....	....	1	....	....	....	....	1200 to 1500	800 to 1100
Naval brass	60	39.25	....	....	0.75	....	....	....	....	1200 to 1450	800 to 1100
Leaded naval brass	60	37.5	1.75	....	0.75	....	....	....	....	1200 to 1450	800 to 1100
Manganese bronze	58.5	39.2	....	....	1	....	....	0.3	1	1250 to 1450	800 to 1100
Aluminum brass	76	22	....	....	....	....	2	....	....	1450 to 1550	800 to 1100
Phosphor bronze "A"	95	....	....	....	5	....	....	....	....	(a)	900 to 1250
Phosphor bronze "C"	92	....	....	....	8	....	....	....	....	(a)	900 to 1250
Phosphor bronze "D"	90	....	....	....	10	....	....	....	....	(a)	900 to 1250
Phosphor bronze "E"	98.75	....	....	....	1.25	....	....	....	....	1450 to 1600	900 to 1200
Cupro-nickel 30%	70	....	....	30	....	....	....	....	....	1700 to 2000	1200 to 1600
Nickel silver 18% (A)	65	17	....	18	....	....	....	....	....	(a)	1100 to 1500
Nickel silver 18% (B)	55	27	....	18	....	....	....	....	....	(a)	1100 to 1400
High-silicon bronze (A)	....	....	....	....	....	3	....	....	....	1300 to 1650	900 to 1300
Low-silicon bronze (B)	....	....	....	....	....	1.5	....	....	....	1300 to 1650	900 to 1250

(a) These alloys are usually hot extruded after casting but further hot working is uncommon.

Heating for Reworking and for Control of Final Temper. The drawing of wire or tube, rolling of sheet, drawing of shells, and other cold working operations, result in straining and distortion of the grain structure of a metal with accompanying increase in hardness and decrease in ductility. In progressive cold working, a point is reached at which further deformation cannot be made economically or without structural damage to the metal. To restore the ductility for further cold working, the metal must be heated to a temperature where it will recrystallize and the grain will change to the proper size. This process is known as "annealing".

The requirement for annealing, in preparation for further working, varies considerably and depends on a number of factors—the alloy composition, the extent of previous cold working, the amount of additional cold working yet to be done, the thickness of the metal, the proximity of the anneal to the final operations, and the final specifications of the article. For the more commonly used copper alloys, annealing consists simply of heating the cold worked metal to the recrystallization temperature and, if necessary, somewhat beyond that so as to cause grain growth. Annealing is primarily a function of metal temperature and time at temperature. Except for the alpha-beta type alloys and the special alloys described below under Precipitation Hardening, the rates of heating and cooling are relatively unimportant, provided uniformity is maintained. Source and application of heat, design of furnace, kind of atmosphere, shape of work piece, and other factors are also important since they affect the uniformity, finish and costs of the operation.

Because of the factors mentioned above, it is difficult to tabulate a definite schedule for time and temperature that will result in a specific grain size of a completely recrystallized metal after annealing. The following general statements explain these factors as applied to commercial coppers and brasses. The curves of Fig. 1 through 5 illustrate the effects of time, temperature and deformation for 65–35 Cu-Zn alloys, and represent generally all wrought copper alloys.

After complete recrystallization, any increase in the temperature of the metal results in an increase in grain size. The grain growth is not directly proportional to increase in temperature but tends to accelerate with such an increase (Fig. 1). The mechanical properties of the metal also change with grain growth. Tensile strength, elastic limit and hardness decrease while elongation and reduction in area increase.

With any fixed temperature of metal, an increase in time at that temperature results in an increase in grain size (Fig. 4). In promoting grain growth, this time factor is not nearly so effective as an increase in temperature.

An increased amount of cold work before annealing, lowers the recrystallization temperature (Fig. 2).

The average grain size is larger, the smaller the degree of prior deformation (Fig. 2).

For fixed duration of annealing and temperature of the metal, the larger the original grain size before working, the larger is the grain size after recrystallization (Fig. 3).

The general effect of alloy composition on annealing is as follows: For a fixed time and metal temperature and for the same previous cold working in copper-zinc alloys, an increase in copper content above 65%, results in a decrease in grain size after annealing (Fig. 5).

In commercial mill practice copper alloys are usually annealed at lower temperatures as the material approaches the final anneal, with intermediate cold reductions of at least 35% and as high as 50 to 60% wherever practicable. The higher temperatures initially used, serve to accelerate complete homogenization and the resulting large grains permit more economical reduction during the early working operation.

During subsequent anneals, the grain size should be decreased gradually to approximate finally the grain size required. This point is usually reached one or two anneals before the final anneal. With such a sequence and with sufficiently severe intermediate reductions, it is then possible to produce a uniform final grain size within any lot and from lot to lot.

The grain size and mechanical properties required for further cold working, will vary considerably with alloy and amount and kind of further cold work to be done. The object of the annealing for cold working is to obtain the maximum combination of ductility and strength and, if

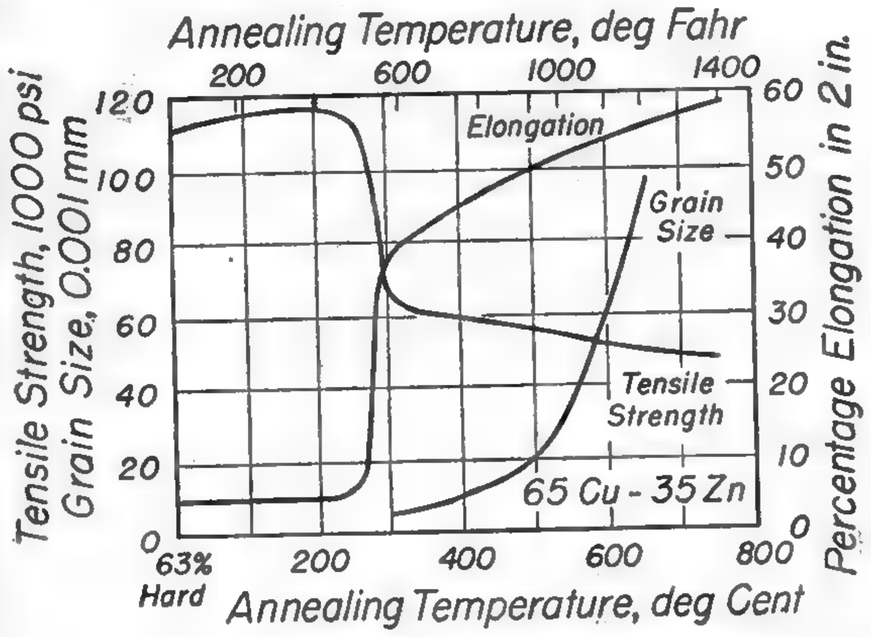


Fig. 1 Characteristic annealing curve for yellow brass wire drawn 63% hard and annealed 1 hr at indicated temperature (Pratt)

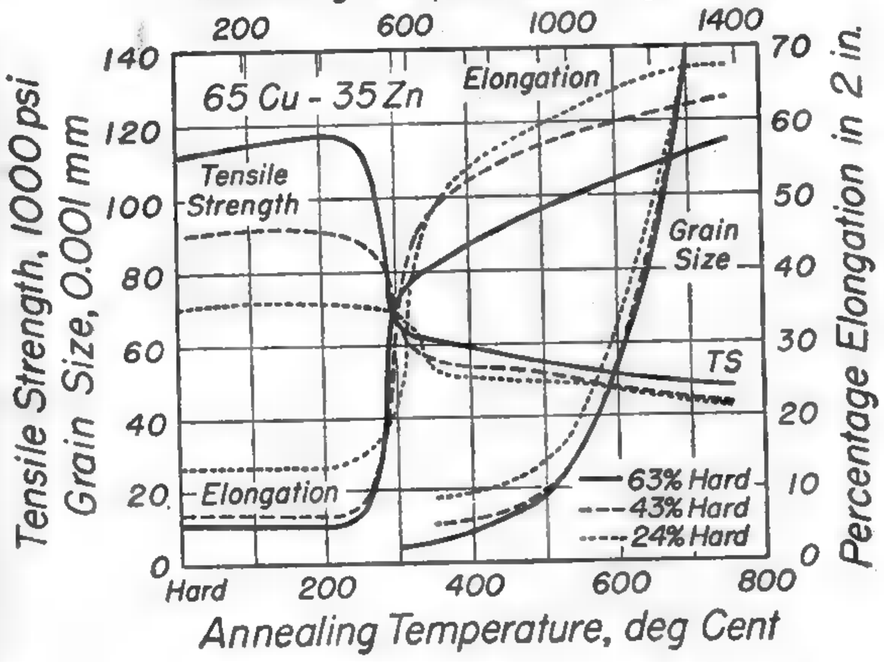


Fig. 2 Effect of varying amounts of cold working on annealing characteristics of yellow brass wire (Pratt)

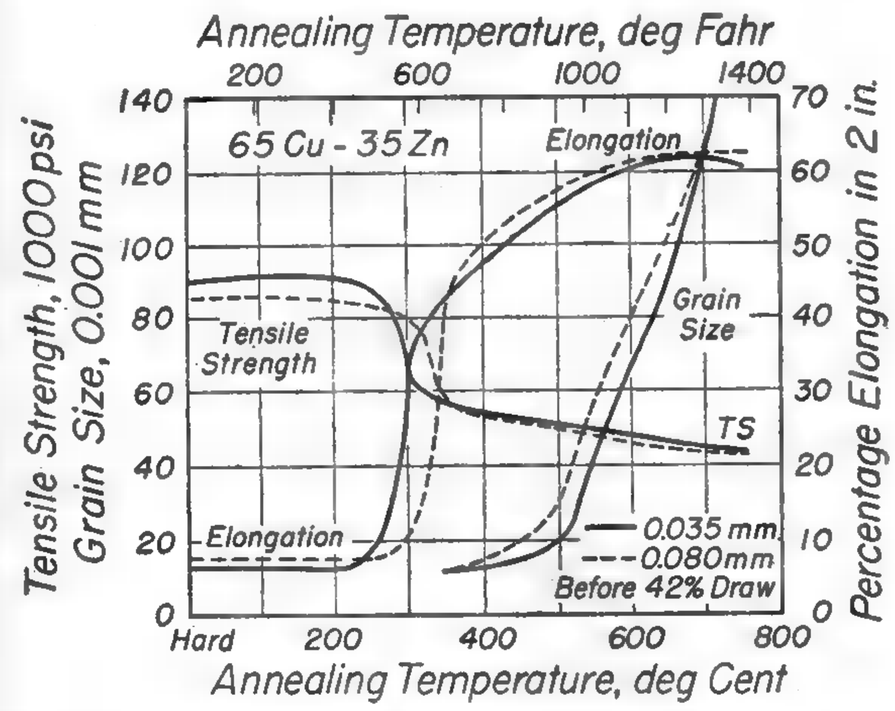


Fig. 3 Effect of varying anneals before drawing, on annealing characteristics of yellow brass wire (Pratt)

preliminary to final drawing operations, to keep the surface texture refined sufficiently to obviate the necessity for excessive buffing. The anneal must be governed by definite specifications and co-ordinated with cold working operations to give the desired properties when finished. Table II is informative in a general way, and applies only to the type of copper alloys usually considered; that is, alloys that consist of a single solid solution.

The full range of grain size in Table II is applicable particularly to copper-zinc alloys that contain 30 to 35% Zn. It is relatively difficult to obtain the larger grain sizes in brasses that contain less than about 20% Zn.

The best and most accurate test for the extent of anneal is the size of the average grain. Grain size is the standard test for most metals, and acceptance and rejection usually depend on the grain size. This determination requires special equipment that is not always available in the plants of consumers or fabricators. For convenience in testing, the Rockwell or Rockwell-type hardness testers are used as approximate and informative. ASTM specifications list Rockwell hardness and values of grain size for many alloys of copper.

Heating for Stress Relief.* Metals that are subjected to nonuniform plastic deformation below the recrystallization temperature, develop residual stresses of varying magnitude. When subjected to service conditions at atmospheric temperatures, some materials are susceptible to a type of

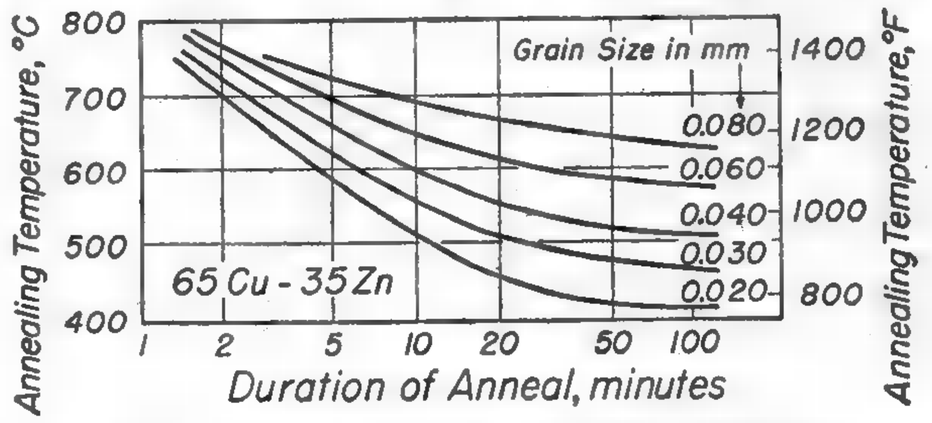


Fig. 4 Effect of time on annealing yellow brass strip, gage 0.050 in. (Pratt)

failure known as "stress-corrosion cracking", or "season cracking", which is most frequent in drawn rods, tubes and hollow ware. Cracks in deep-drawn articles may be longitudinal or circumferential, and in rod and tube, either parallel or transverse to the length, or sometimes in spirals. Similar cracking, encountered when the parts are heated rapidly to above the recrystallization temperature, is known as "fire cracking".

Generally the alloys most subject to cracking are brasses containing 20% Zn or more, and the susceptibility increases with the zinc content. Phosphor bronze, cupro-nickel and some other copper alloys have a comparatively slight tendency toward season cracking, but are susceptible to fire cracking.

Fundamentally, there are three methods of reducing or eliminating the detrimental effects of residual stresses: (1) thermal stress relieving, (2) the application of special cold deformations, and (3) combinations of both.

Treatments for relief of stress by means of special cold deformation do not completely eliminate the residual stresses, but when such treatments are suitably applied,

Table II. Grain Size of Cold Worked and Annealed Copper Alloys

Nominal Grain Size, mm	Typical Use
0.015	Slight forming operations
0.025	Shallow drawing
0.035	For best average surface combined with drawing
0.050	Deep drawing operations
0.100	Heavy drawing on thick gages

they do eliminate the detrimental effects of these stresses. This type of treatment is frequently applied to alloys before annealing, when there is a possibility of fire cracking. In this category are alloys that contain lead, and rolled and drawn shapes that have been cold worked to such a slight extent that complete recrystallization is not attainable in the subsequent anneal. The special deformations in this relief treatment are many and varied; essentially, they are bending operations or roller straightening.

Heating for stress relief is usually applied to finished parts. Emphasis should be placed on the use of the terms

* For additional information concerning this subject the reader may refer to the article on "Relief of Residual Stress", page 237.

"thermal stress relieving" or "stress-relief heat treatment" instead of "stress-relief anneal". The word "anneal" implies softening, which is unnecessary and usually undesirable for articles that are being stress relieved. In stress relieving, materials are heated to a temperature lower than the recrystallization point, for a time sufficient to relieve the stresses. The usual temperature for this treatment is approximately 100 to 200 F lower than the recrystallization point. Occasionally, when the best mechanical properties are desired, a lower temperature is used for a considerably increased period of time—as long as 24 hr in some instances, as compared with perhaps 1 to 2 hr at higher temperature.

When the optimum combination of time and temperature is used, there is virtually no decrease in hardness or strength, but there may be an increase in elastic properties. Severely cold worked material will usually exhibit an increase in hardness and strength, particularly when the lower temperature is used.

The best practice in thermal stress relieving is to use as low a temperature and as long a time as is commercially practicable. Since the stress relieving is conducted at a relatively low temperature—usually between 300 and 650 F—and since excessively high temperature is hazardous to results, very little temperature head can be carried in the furnace without danger of overheating some part of the load. Furnaces provided with forced convection at high velocity, or well-agitated salt or oil baths are best suited for stress-relieving operations.

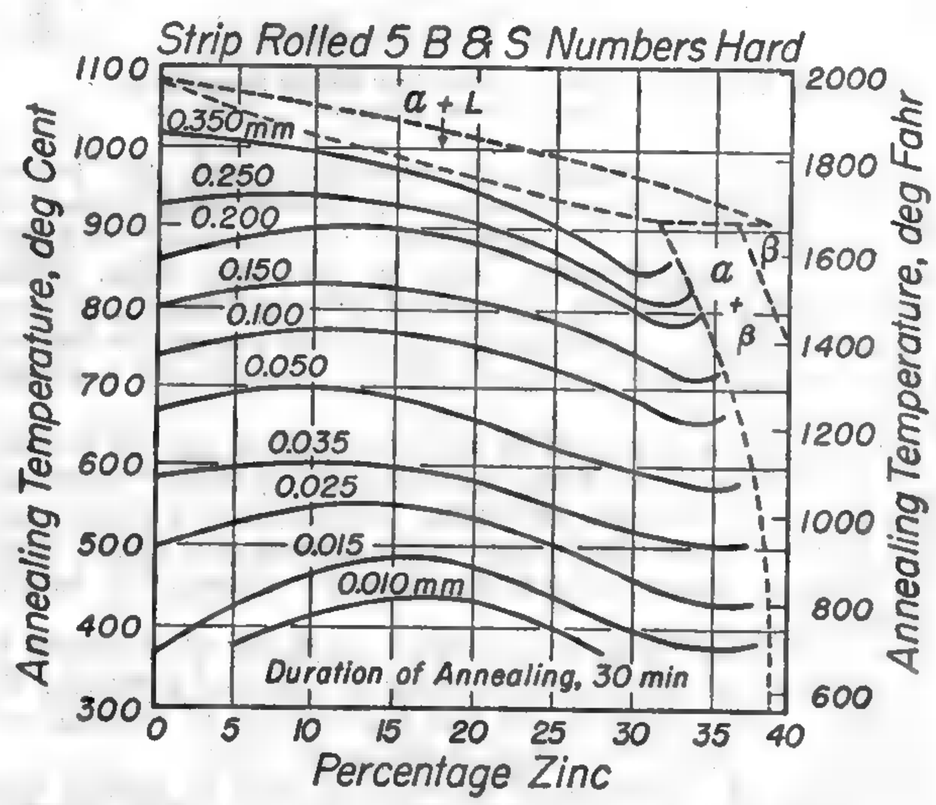


Fig. 5 Grain size of copper-zinc alloy strip cold rolled 5 B & S numbers hard and annealed 30 min (Bassett and Davis)

Solutions of mercury salts are ordinarily used to determine whether or not a copper alloy is free from dangerously high residual stresses. The test procedure, as described in ASTM Standard Method B 154, requires freedom from cracks after an immersion for a specified time. This test is the most reliable guide in selecting a time-temperature combination for thermal stress relieving, and in obtaining material free from the detrimental effect of residual stresses.

Solution Treatment and Precipitation Hardening. The single common characteristic of all precipitation hardening alloys is the greater solid solubility of some phase or constituent at an elevated temperature rather than at a lower temperature. In such systems, cooling at appropriately rapid rates from a temperature within the field of highest solubility will preserve the alloy in a condition of supersaturated solution with relatively high ductility and low hardness, strength and electrical conductivity. This treatment is known as a "solution anneal". Although the objective is to produce a single solid solution during this treatment, in practice some amount of the second phase may exist. A second heat treatment at a lower temperature will cause precipitation of the unstable phases, usually accompanied by an increase in hardness, strength and conductivity, and is known as a "precipitation hardening heat treatment".

The hardening heat treatment may follow the solution treatment with no intermediate working; the material may be subjected to some cold work between the solution and precipitation treatment; or cold work may follow the combined solution and precipitation treatment. The most effective sequence of operations depends on the alloy and the specific properties desired.

A number of copper alloys respond to precipitation hardening. Some of the alloys more commonly used are listed in Table III.

Table III. Precipitation Hardenable Copper Alloys

Alloy	Composition, percentage					
	Cu	Be	Ni	Co	Cr	P
Beryllium copper	97.65	2.00	0.35 or 0.35		....	....
Nickel beryllium copper	98.10	0.40	1.50	....	....	....
Cobalt beryllium copper	97.00	0.40	....	2.60	....	....
Chromium copper	99.40	....	....	....	0.60	....
Copper nickel phosphorus	98.50	....	1.25	....	....	0.25

Since beryllium copper has gained the widest industrial application of all the alloys listed, specific reference will be made to the treatment of this alloy.

All the alloys listed in Table III require a rapid quench after the solution anneal. Heavier sections are usually quenched in water; thin sections can be quenched sufficiently by contact with water-cooled drums, a blast of cold air, or water spray. For batch annealing, the water quench is required; for strand annealing, the other quenching methods are frequently used. If the material has not attained the required temperature, or if quenching is delayed, the properties obtained in the final hardening treatment will be affected adversely.

The precipitation hardening process is a function of time and temperature; hardening occurs more rapidly at higher temperatures. The temperature that can be used is limited because optimum hardness is not obtainable at higher temperatures. In short-time treatments at the higher temperatures, the time factor is so critical that considerable skill is necessary in order to obtain good results. For beryllium copper, a temperature between 600 and 625 F and a time period of 1 to 3 hr are commonly used. A lower temperature can be used, but with a considerable increase in time. From 625 to about 700 F, a treatment can be conducted for time periods less than one hour and even as short as 10 min, but this treatment is critical. At more than 700 F, the highest values of hardness are not obtained. If heating is continued too long or if the temperature is too high, a condition of "overaging" or resoftening occurs.

An increase in cold work following the quench, results in a more rapid rate of precipitation and higher obtainable hardness. The commercial requirements for beryllium copper strip, as covered by ASTM Tentative Specification B 194-46aT, specify the tensile strength and hardening treatments listed in Table IV.

Table IV. Tensile Strength and Hardening Treatments for Beryllium Copper Alloy Strip (ASTM B 194–46aT)

Condition	Tensile Strength, psi	Precipitation Temperature, deg Fahr	Time, hours
Soft	150,000	600	3
¼ Hard	160,000	600	2½
½ Hard	170,000	600	2
Hard	180,000	600	2

Most of the hardenable copper alloys, except for beryllium copper, may be cold worked after a combined solution and precipitation treatment.

General Precautions. If the following general precautions are heeded, they may be of considerable help to those who are responsible for the annealing and heat treatment of the copper alloys:

Control of Temperature. In all annealing, the actual temperature of the metal is not necessarily the same as the temperature indicated by the furnace control instru-

ment and may vary from it by as much as several hundred degrees. Great care should be used to locate the control thermocouples where they will represent the temperature of the work material as accurately as possible, and the work material should be loaded in such a way that all parts are heated uniformly. Thermocouples and instruments should be checked regularly for accuracy. (*See* the article entitled "Pyrometry", page 174.)

Sampling and Testing. When anneals are checked, care should be taken to ensure that test specimens are representative of the extreme conditions found on a load. Much trouble and many complaints can be eliminated if good judgment is used in selecting specimens for testing.

Effect of Pretreatment. Since the amount of cold working and also the anneal prior to that cold working, greatly affect the results obtained from annealing after the cold working, any schedule that is set up must take this pretreatment into account. Once a schedule has been established, both the anneal and the pretreatment must be adhered to for consistent results.

Effect of Time. In most furnaces there is a definite difference between the temperature of the metal and that of the furnace; consequently the time in the furnace has a very important effect on the final temperature of the metal. For a fixed anneal and furnace temperature, time must vary with the type of load.

Oxidation. It is generally economical and advisable to keep oxidation at a minimum in order to reduce loss of metal and costs of pickling and to improve finish. In some instances specially prepared atmospheres are used, which result in a bright or clean annealed material, depending on the alloy and the condition of the metal before annealing. Control of furnace atmosphere usually results in better furnace economy as well.

Effect of Lubricants. Lubricants on metal to be annealed, may cause staining that is very difficult to remove. Regardless of the type of furnace or the article to be annealed, it is advisable to eliminate as much of the lubricant as possible before the metal is heated.

Hydrogen Embrittlement. When copper that contains oxygen is to be annealed, the hydrogen in the atmosphere must be kept to a minimum in order to reduce the danger of embrittlement caused by the combination of the hydrogen in the atmosphere with the oxygen in the copper, forming water vapor under pressure, and resulting in minute ruptures in the metal. For temperatures lower than about 900 F the hydrogen should preferably not exceed 1%, and as the temperature is increased, the hydrogen content of the atmosphere should approach zero.

Impurities. Occasionally it is difficult to obtain proper grain growth when annealing under standard conditions that have previously given the desired grain size. This trouble may sometimes be traced to impurities in the alloy, and if other causes cannot readily be found for the retarded grain growth, it would be well to have the material analyzed in the laboratory.

Annealing to Obtain Desired Tensile Properties. It is impracticable to anneal for definite properties of tensile strength or hardness between the normal cold worked and the fully recrystallized or softened range, because of the extremely rapid rate of change of properties with only a small change in metal temperature. Rates of heating and control of temperature are not accurate enough to obtain any desired tensile strength or accompanying physical property. The best practice is to anneal completely and then to obtain the desired properties by controlled cold working to the necessary extent.

Loading. It is usually not practicable to anneal a variety of different sizes or kinds of material in the same charge, because of the different rates of heating and the resulting final metal temperatures.

Fire Cracking. This is a type of cracking that occurs when some alloys that contain residual stresses are heated too rapidly. Leaded alloys are particularly susceptible to this cracking. The remedy is to heat slowly until the stresses are relieved. Special cold deformations, such as "springing", aid considerably in preventing fire cracking.

Thermal Shock. Hot short materials should be heated slowly to avoid thermal shock.

Sulfur Stains. Excessive sulfur in the fuel or lubricant will cause discoloration of the metal; red stains appear on yellow brass and reddish brown on copper-rich alloys.

Joining Copper and Copper Alloys

By the Subcommittee on Joining Copper Alloys*

COPPER and copper alloys can be joined by welding, soldering and brazing. The application of these methods is considered here under the subdivisions: carbon-arc welding, gas welding, metal-arc welding, resistance welding, and soldering and brazing.

Welding

All the welding methods commonly employed are applicable in the joining of copper and copper alloys, but all are not suitable for any one of these metals. In fusion welding, it is desirable to consider the metallurgical characteristics of the filler metal in relation to the method in order to produce a weld of high quality. In turn, the characteristics of the joining method should be considered, because they may influence the metallurgical and physical properties of the metal or alloy to be joined. To facilitate such considerations the copper-base materials may be grouped according to the effect of the main alloying element, as follows: coppers, special bronzes, brasses, cupronickels and nickel silvers, tin bronzes, and other alloys.

Carbon-Arc Welding. *Coppers.* This process is applicable to the welding of tough pitch copper, provided comparatively high rates of progression (10 to 20 in. per min) are attained without preheating, in order to minimize the time-temperature effect on the remigration of cuprous oxide to the grain boundaries, causing an appreciable reduction in the mechanical properties of the base metal immediately adjacent to the joint. The fluid phosphor-bronze filler metals, which may be employed to attain the necessary speed, must be used in conjunction with a long arc to minimize porosity. Their use is generally limited to flat welding and to plate thicknesses that may be welded in one layer. Although the welds produced are of satisfactory strength, the ductility is erratic because of porosity. The less fluid silicon and aluminum bronzes, which may be employed with shorter arc lengths, yield much sounder welds, but because of the limited speeds possible, their use is restricted to the oxygen-free and deoxidized base metals. Such metals may be preheated for lower rates of progression, or lower arc currents.

Special Bronzes. The carbon-arc method is the most widely employed and most satisfactory for welding the copper-silicon alloys, since its use is accompanied by the rapid cooling necessary to prevent hot cracking at joints where allowances cannot be made for the high shrinkage characteristics. The carbon-arc method may be employed either manually or automatically for sheet metal fabrication, and manually for the layer welding of plate. Best results are obtained when the work material is kept in a flat position. Carbon-arc welding is also applicable to the copper-aluminum and the copper-aluminum-silicon alloys with which coated aluminum bronze electrodes may be employed for filler metal. Bare wire, in conjunction with a flux high in cryolite, may also be used as filler metal for these alloys.

* The members of this subcommittee are J. J. Crowe, *Chairman* (Air Reduction Sales Company); J. L. Christie (Handy & Harman); R. T. Gillette (General Electric Company); J. Imperati (The American Brass Company); James Hunter (Revere Copper and Brass Incorporated) and C. W. Steward (Westinghouse Electric Corporation)

Copper-Zinc Alloys. Although the carbon-arc method has been employed to weld the copper-zinc alloys with copper-zinc filler rods of the "low-fuming" type, this method is generally employed with zinc-free rods, made of material such as the silicon, aluminum or phosphor bronzes. The arc is struck and maintained on these filler metals to minimize fuming. Preheating of the base metal to allow the use of reduced currents is also helpful in this respect. In conjunction with the shrinkage of the weld metal, the sharp temperature gradient obtained in the absence of moderate preheat temperatures will establish a stress gradient in the base metal adjacent to the joint. Stress relieving should follow the welding of alloys containing more than 15% Zn, in order to preclude failure through stress corrosion.

Copper-Nickel Alloys. The carbon-arc method has no particular merit recommending it for the cupro-nickels and nickel silvers, and its infrequent use is restricted generally to the very thin gages for which the metal-arc electrodes of small diameter present problems in the low-current ranges.

Copper-Tin Alloys. The tin bronzes are readily welded by the carbon-arc method, utilizing the standard phosphor-bronze filler rods previously mentioned. The alloy rods for carbon-arc welding contain appreciably higher percentages of phosphorus than either the base metal, electrode core wire, or gas welding rods, to ensure that a sufficient phosphorus content will remain after subjection to the intense heat of the carbon arc. The best results will be produced by striking and maintaining medium to moderately long arcs on the added filler metal.

Other Alloys. The coated aluminum bronze electrodes employed for the metal-arc welding of beryllium copper can also be used as filler rods for carbon-arc welding, with comparable results if the procedure is properly controlled.

Gas Welding. Compressed coke-oven gas and bottled liquid gases find some use in low-temperature joining and preheating operations on the copper-base alloys, but the oxyacetylene flame is the most widely employed, because of its high temperature and the variety of atmospheres readily obtainable.

Coppers. The gas method is considered the most satisfactory for producing copper welds in copper base metal. Because the effects of time, temperature and atmosphere are such that hydrogen embrittlement of tough pitch copper cannot be avoided, and internal oxidation, followed by embrittlement of unprotected oxygen-free copper, is likely to be encountered even with the best of practice, the use of both these coppers is to be avoided in gas-welded fabrication. The filler rods available for use in conjunction with phosphor-deoxidized base metal may be added to the first two in order to increase the strength of the weld metal at high temperatures. Soundest welds are produced by the silicon-deoxidized filler metal, which, in conjunction with a slight alloying effect, accounts for weld strength slightly superior to that of the dead-soft base metal adjacent to the joint. The phosphor-deoxidized and manganese-deoxidized welds tend to be porous unless welded with care, yielding weld strengths varying from one-half to the full strength of dead-soft copper. When such rods are employed, it is common practice either to hot peen in the course of welding or to cold peen on completion of the joint, in order to produce a weld joint comparable in strength with the base metal.

Special Bronzes. Although the gas method will yield very satisfactory results in the copper-silicon alloys, its use is generally restricted to joints where compensation can be made for the high shrinkage of the weld metal, so as to avoid cracking caused by hot shortness. Proprietary fluxes are available that should remove adequately any refractory silicon dioxide formed. The coated aluminum-bronze electrodes employed for both metal-arc and carbon-arc welding may also be the source of filler metal for gas welding of the copper-aluminum and copper-aluminum-silicon alloys.

Copper-Zinc Alloys. The gas method is the preferred choice for making welds comparable with the base metal in composition. The available filler rods are slight alloy modifications of the 60–40 copper-zinc composition (Muntz metal); however, where necessary for better corrosion resistance or color match, filler rods cut from the base metal may be employed. Because of the tendency for zinc to volatilize, it is common practice to employ an oxidizing flame to develop an oxide film that is quite effective in suppressing such fuming. The addition of silicon to the welding rod is by far the most practical method for suppressing such losses with their attendant effect on the soundness of the weld metal. Lead-free alloys are always to be preferred for welded applications since lead, because of its low melting point and insolubility in the metal, produces hot shortness.

Copper-Nickel Alloys. Because of the refractory nature of nickel oxide, which is formed, and the difficulties that nickel oxide introduces in gas welding, this method is rarely employed. A small addition of silicon to the filler rod helps appreciably both in preventing the formation of oxide, which is difficult to handle, and in producing sound welds. The presence of zinc in the nickel silvers improves, but does not eliminate, the oxide problem. Because strips cut from the base metal can be employed as filler metal, the gas method is, in general, the most versatile for producing color-matching welds.

Copper-Tin Alloys. The gas method is the least practicable method for welding tin bronze. The slow cooling rates often obtained with this method, along with characteristic high shrinkage, may lead to cracking of the weld as a result of hot shortness. The filler rods for gas welding contain considerably less phosphorus than those produced for carbon-arc welding; use of carbon-arc filler rods for gas welding only aggravates the above difficulties.

Other Alloys. The formation of an oxide difficult to flux makes gas welding unsuitable for beryllium-copper.

Metal-Arc Welding. *Coppers.* Because of the high heat conductivity of the coppers, the metal-arc method is not applicable to any but the light gages without the use of a preheat. Although copper welds of satisfactory strength have been produced with coated electrodes, they are not widely employed for vessels of code quality because of poor ductility resulting from microporosity. Somewhat better results can be obtained with alloy electrodes, such as the phosphor bronzes, but the soundest welds are produced by coated aluminum bronze electrodes. Because of the high preheat temperatures necessary to offset heat losses, phosphor-deoxidized base metal is always to be preferred. The time-temperature relationships are such that the hydrogen in preheating flames (resulting from only partial burning) will embrittle tough pitch copper, and the possibilities of an internal oxidation-reduction cycle make oxygen-free copper a questionable choice.

Special Bronzes (Copper-Silicon, Copper-Aluminum, Copper-Aluminum-Silicon). The reduced thermal conductivity resulting from alloying, obviates preheating for metal-arc welding. Coated copper-silicon electrodes are available, but their deposition characteristics are such that they find little use in the metal-arc welding of the comparable base metals. The newer copper-aluminum coated electrodes weld all alloys in this subgroup satisfactorily.

Copper-Zinc Alloys. The loss of zinc through volatilization necessitates the use of a substantially zinc-free electrode. Phosphor bronze and aluminum bronze electrodes are the ones commonly employed; aluminum bronze electrodes produce sounder welds and stronger, more satisfactory joints. Preheating is necessary to permit use of electrodes of proper diameter within their range of working current, to offset heat losses by conduction, and to minimize zinc losses from the fused base metal with attendant deleterious effect on the soundness of the weld. Preheat temperatures between 500 and 600 F are desirable for the alloys of moderate thermal conductivity (such as manganese bronze and Muntz metal) and temperatures as high as 800 to 1100 F may be necessary for the alloys of higher conductivity (such as gilding metal, 95% Cu–5% Zn). Minor base-metal alloying elements, such as tin, aluminum, iron and manganese, are not detrimental; but because of its insolubility, lead, frequently employed to improve machinability, will promote hot short cracking.

Copper-Nickel Alloys. The low-conductivity 70–30 composition is the most widely employed in the fabrication of weldments. Coated electrodes with core wire of the same composition as the alloy being welded have the best depo-

sition characteristics of any in the copper-base alloy group, approaching those of steel electrodes. This preferred method may be employed in all positions, but best results are obtained when the work material is laid flat. The addition of varying amounts of zinc to copper-nickel alloys of reduced nickel content, in order to produce a variety of nickel silvers, alters the conductivity only slightly; however, the presence of zinc with its low boiling point permits some loss through volatilization, which may be minimized by the use of low current strengths made possible by moderate preheating of the base metal.

Copper-Tin Alloys. The wrought phosphor bronzes are alloys of moderate thermal conductivity, and while the lighter gages may be metal-arc welded without preheating, on medium to heavy thicknesses of plate a preheat of 200 to 400 F is desirable in order to employ the coated phosphor bronze electrodes in the lower current ranges and to obtain maximum weld soundness. Preheating temperatures should be held as low as possible, consistent with the foregoing recommendations, since rapid cooling is essential in the prevention of hot short cracking.

Other Alloys. Metal-arc welding with coated aluminum bronze electrodes is the preferred method for fusion welding beryllium-copper. Fusion welding cannot be accomplished without partial destruction (in the region of the joint) of the superior mechanical properties obtained in the alloy through heat treatment.

Submerged-Arc Welding. This process has been successfully adapted to the welding of sheet and light 70–30 cupro-nickel plate. A modified flux has been employed and there are indications that, when further improved, submerged-arc welding will be applicable to the production of code-quality welds in the copper-silicon alloys.

Resistance Welding. Resistance welding is being used increasingly for copper and copper alloys. Several factors common to all these materials will be mentioned first; then each group of alloys will be treated separately.

Welding Equipment. Welding machines—whether they are spot, projection, seam, or butt welders — must have sufficient electrical capacity to make welds in a minimum length of time, since most of these materials are good heat conductors and long welding times tend to heat too large an area, so that excessive oxidation and distortion result. With extremely low input of energy it might be possible to conduct heat away so rapidly that a weld could not be made at all.

The moving member of these welding machines should be as light as possible to reduce inertia, and as free from friction as possible to ensure rapid follow-up or application of pressure as soon as fusion temperature is reached. Because these materials have little or no plastic range, the welding machine must follow rapidly in order to apply pressure at the proper time and to prevent expulsion of molten metal with consequent weakening of the weld as a result of cavitation.

All resistance-welding machines should be equipped with precisely synchronous electronic controls, since copper and copper alloy materials are particularly sensitive to variations in welding procedure, and this type of control is capable of repeating application of power to the machine with the accuracy of the circuit frequency.

The precisely synchronous control also eliminates transient currents sometimes encountered in random switching of power to the welding machine. The current in these transients may be several times the normal current value and, since the heating effect is as the square of the current, a transient may burn a hole through the work material, and may also destroy the electrodes.

Cleaning. To weld satisfactorily, copper and copper alloys must be carefully cleaned so that no oil, grease, oxide or scale remain, because, though some of these oxides are quite refractory, other oxides are of high resistance and consistent results cannot be obtained unless they are removed.

Use of the proper type of electrode material is also important. Generally materials of high conductivity require electrodes of low conductivity and materials of low conductivity require electrodes of high conductivity. Ordinarily the leaded copper alloys weld less satisfactorily than those containing no lead.

Coppers. The spot, projection, and seam welding of the various types of copper are difficult; however, the materials of thinner gage are sometimes weldable by the use of electrodes faced with material like tungsten or molybdenum and possessing high resistance. A trace of tin, as from tinned wire or sheet, is helpful in welding copper. Tinned wire of relatively small size can sometimes be spot or projection welded to other members. Copper can be butt welded quite easily. However, high input of energy and short times with a somewhat special procedure are required.

Commercial Bronzes, Red Brass, Low Brass. Copper alloys of this class weld slightly better than copper, but in general the same factors hold true as with copper.

Brazing, Spring, Admirality, Commercial, Alpha and Yellow Brasses. These brasses, with lower thermal and electrical conductivity than copper, may be welded by the various types of resistance welding. However, because they are sensitive to any variations in surface condition and procedure, these metals must be carefully cleaned and all welding procedures carefully controlled.

Muntz Metal, Tobin Bronze, Naval Brass, Manganese Bronze, and Extruded Brass. Materials of this group may be welded by all the methods of resistance welding but they require careful handling with high current and as short a time as can be used practicably. All the copper alloys must be clean and free from oxide, dirt, oil and grease.

Nickel Silver. This alloy can be welded successfully by the various methods of resistance welding. Preferably somewhat higher pressure and lower input of current are used than for welding the alloys of higher conductivity.

Phosphor Bronze. Phosphor bronze can be welded quite readily by all the resistance welding methods; the procedure is similar to that for welding low-carbon steel. However, this alloy is inclined to be hot short in the heavier sections and care must be used not to overheat it or to employ excessive welding pressures.

Copper-Silicon Alloys. The copper-silicon alloys are perhaps the most easily resistance welded of all the copper alloys. The procedure should include relatively short welding time and average pressure. As with all the copper alloys, the material should be thoroughly cleaned.

Cupro-Nickel. Cupro-nickel is a good alloy to weld by the various resistance welding methods. All the types of resistance welding may be used. Since the oxides of this alloy are quite refractory, the metal must be carefully cleaned before welding.

Soldering and Brazing

Definitions. Brazing and soldering are methods of joining metals in similar or dissimilar metal combinations by means of a nonferrous filler metal, without fusion of the base metal. Brazing is ordinarily understood to refer to those processes that use filler metals with melting points higher than 800 F, while soldering covers the processes carried out at temperatures lower than 800 F.

Accordingly, brazing includes the processes that use the silver brazing alloys with melting points ranging from 1175 to 1600 F, those that use the copper-phosphorus alloys with melting points from 1300 to 1530 F, and those that use the high zinc-copper alloys with melting points from 1600 to 1650 F.

Commonly, soldering refers to the use of the so-called soft solders, most of which melt below 700 F.

With the few exceptions noted below, all these materials can be used successfully on all the coppers and the copper alloys. The choice of an alloy for any particular application will be influenced by several factors — cost of the alloy, cost of flux, and cost of heating to the required temperature, strength and ductility required in the finished joint, required resistance to corrosion, operating temperature for the finished joint, and color of the joint.

Methods of Application. Usually brazed and soldered joints are made by flowing the molten filler metal between closely fitting surfaces of the metal or metals to be joined. Examples are the common lapped and scarfed joints. In the one special process, known as the "bronze

welding process", a copper-zinc alloy filler rod is used with the flame of the oxyacetylene torch to fill an open V-groove or a fillet.

Heating of joints is accomplished by the following methods: by use of flames from the oxyacetylene torch or other gas torches; by use of furnaces, with or without special atmospheres; by use of a soldering iron or copper for the soft solders; by use of carbon holders heated by electric resistance (*see* Resistance Welding).

Materials. The common brazing alloys and soft solders are listed in Tables I and II, along with the fluxes usually employed with them. The silver brazing alloys include the eight ASTM grades and two proprietary alloys.

Fluxes used with these alloys are ordinarily the proprietary paste fluxes (mixtures of borax and boric acid with fluorides and potassium salts) that are fluid at 1100 F. For the alloys that melt at temperatures higher than 1400 F it is possible to use the common borax and boric acid fluxes made for brazing purposes.

The common solder fluxes are solutions of zinc chloride with some ammonium chloride. A noncorrosive flux is made by dissolving rosin in alcohol or kerosene.

Applications. The brazing and soldering alloys described above and the accompanying fluxes may be used with facility on all the coppers and copper alloys except the following: (1) The soft solders will not bond readily with the copper-silicon alloys. (2) The silver brazing alloys will not bond with the aluminum bronzes unless a special flux is used that contains halogen compounds. Proprietary fluxes of this type are available.

Table I. Copper Brazing Alloys

Type	Composition, percentage	Approximate Flow Point, deg Fahr
1[a]	Copper-phosphorous alloys in rod or strip form 4 to 8 P 0 to 1 Sn Remainder Cu	1300 to 1530
2[b]	Brazing metal, Muntz metal in rod or wire form 38 to 42 Zn Remainder Cu	1625
3[b]	Spelter brazing alloys in powder or lump form 45 to 55 Zn 0 to 10 Ni Remainder Cu	1550 to 1650
4[b]	High zinc-copper alloys in rod form—the commonly used "bronze welding" alloys 0 to 0.50 Mn 0 to 1.50 Sn 0 to 1.50 Fe 0 to 10 Ni 0 to 0.15 Si 38 to 42 Zn Remainder Cu	1600 to 1650

(a) Brazing alloys of type 1 are self-fluxing when used on copper. For the other alloys it is advisable to choose one of the proprietary paste fluxes made for the low-melting silver brazing alloys. These fluxes are usually mixtures of borax and boric acid with fluorides and potassium salts and are fluid at temperatures higher than 1100 F.

(b) Fluxes for types 2, 3 and 4 are usually mixtures of borax and boric acid. They are generally used in powder form, although it is preferable to use them as pastes made by mixing with hot water.

Table II. Silver Brazing Alloys

In rod, wire, sheet, strip and powder form

ASTM Grade	Composition, percentage Ag	Cu	Zn	Cd	P	Flow Point, deg Fahr
1	10	52	38	..	..	1600
2	20	45	35	..	..	1500
3	20	45	30	5	..	1500
4	45	30	25	..	..	1370
5	50	34	16	..	..	1425
6	65	20	15	..	..	1325
7	70	20	10	..	..	1390
8	80	16	4	..	..	1460
[a]	15	80	..	..	5	1300
[a]	50	15.5	16.5	18	..	1175

(a) Proprietary alloys

Table III. Soft Solders

In ingot, bar, wire and powder form

Type	Composition, percentage Tin	Lead	Antimony	Flow Point, deg Fahr
1	5	95	...	592
2	10 to 20	90 to 80	...	567 to 523
3	15 to 35	85 to 65	...	543 to 469
4	38 to 40	62 to 60	...	462 to 460
5	45	55	...	437
6	50	50	...	421
7	60	40	...	376
8	95	..	5	464
9	..	95	Ag 5	725

Machining Copper and Copper Alloys

BY THE SUBCOMMITTEE ON MACHINING COPPER ALLOYS*

FREE-CUTTING brass rod has always been considered one of the most easily machined metals, and in this discussion of the machining of copper and wrought copper alloys, free-cutting brass rod serves as the standard.

"Machinability" is a term not readily defined but usually described by its effect on cutting properties. Where wrought copper alloys are concerned, machinability depends more on chemical composition than on physical or mechanical properties. Metal to be machined must be rigid enough to stand up against the turning tool without distortion. Accordingly the temper of wrought copper alloys for automatic screw machining should be hard, but the alloys may need to be soft enough to withstand other subsequent cold working. Generally machinability improves with an increasing amount of lead (usually 0.5 to 4.0% Pb; also 0.5% Te or 0.5% Se) and decreases with increasing amounts of tin, silicon, aluminum, nickel and other elements. For the purpose of discussion, copper alloys may be divided into three principal groups.

Rating of Machinability. *Group 1. The Free-Cutting Alloys.* These are copper alloys to which a small percentage of lead, tellurium or selenium has been added. This group includes the alloys that have a machinability rating of 70 to 100, as given in Table I. (Free-cutting yellow brass = 100) These alloys, most frequently used in rod form for the production of screw-machine parts, give short brittle chips when machined.

Group 2. Moderately Machinable Alloys. These have a machinability rating of 30 to 70, and include the group of nonleaded brasses from Muntz metal or naval brass containing 60% Cu, to red brass containing 85% Cu. This group also includes leaded phosphor bronze, leaded silicon bronzes and leaded nickel silver containing 12 to 18% Ni.

Group 3. Alloys Machinable with Difficulty. This group includes nonleaded coppers, nickel silvers and phosphor bronzes, as well as cupro-nickel and beryllium copper. When machined, these alloys usually produce long, tough, stringy turnings.

These ratings of machinability are arbitrary values to be considered only as an approximate indication. They are a reasonable guide to relative tool life and to the amount of power required for cutting.

Turning. On copper alloys the larger portion of "form" turning operations are performed by circular, dovetail or flat tools that reduce diameters and produce shaped contours by feeding toward the axis of a rotating rod or blank in a "plunge cut". This type of tool often performs its function simultaneously with a drilling or reaming operation. The tool should have the shape shown in Fig. 1 for the various groups. The materials in Group 1 require very little or no rake, but ductile materials usually require a com-

* The members of this subcommittee are W. S. Girvin, *Chairman* (The American Brass Company), W. C. Cleveland (Scovill Manufacturing Co.) and H. P. Croft (Chase Brass & Copper Co.)

Table I. Composition and Machinability Rating of Free-Cutting Alloys[a]

Alloy Name	Nominal Composition, percentage					Machinability Rating	Weight Conversion Factor[b]
	Copper	Nickel	Zinc	Lead	Tin		
Group 1. Free-Cutting Alloys							
Leaded copper	99.00	....	....	1.00	...	80	1.052
Selenium or tellurium copper	99.40	(0.50 Te or 0.60 Se)				90	1.049
Leaded commercial bronze	88.00	....	10.00	2.00	...	80	1.039
Low-leaded brass (tube)	67.00	....	32.50	0.50	...	60	1.000
Low-leaded brass	64.50	....	35.00	0.50	...	60	0.967
Medium-leaded brass	64.50	....	34.50	1.0	...	70	0.997
High-leaded brass (tube)	67.00	....	31.40	1.6	...	80	1.033
High-leaded brass	62.50	....	35.75	1.75	...	90	1.007
Free-cutting brass	61.50	....	35.50	3.00	...	100	1.000
Forging brass	60.00	....	38.00	2.00	...	80	0.994
Leaded naval brass	60.00	....	37.50	1.75	0.75	70	0.994
Architectural bronze	57.00	....	40.00	3.00	...	90	0.994
Special free-cutting phosphor bronze	88.00	....	4.00	4.00	4.00	90	1.042
Extruded leaded nickel silver, 10%	46.50	10.00	40.75	2.75	...	80	0.994
Group 2. Moderately Machinable Alloys							
Red brass, 85%	85.00	....	15.00	...	...	30	1.029
Low brass, 80%	80.00	....	20.00	...	...	30	1.020
Muntz metal	60.00	....	40.00	...	...	40	0.987
Naval brass	60.00	....	39.25	...	0.75	30	0.990
Manganese bronze, (A)	58.50	(0.3 Mn and 1.0 Fe)	39.20	...	1.00	30	0.984
Leaded phosphor bronze, 5% (B)	94.00	....	....	1.00	5.00	50	1.049
Leaded nickel silver, 12%	65.00	12.00	22.00	1.00	...	50	1.023
Leaded nickel silver, 18%	63.25	18.00	17.75	1.00	...	50	1.033
High-silicon bronze, (A)	95.80	(1.10 Mn or Zn and 3.10 Si)		...	...	30	1.003
Leaded silicon bronze, (D)	95.60	(0.40 Pb and 1.00 Mn or Zn)		(3 Si)	...	60	1.003
Aluminum-silicon bronze	91.00	(7.00 Al and 2.00 Si)		...	...	60	0.906
Group 3. Alloys Difficult to Machine (Machinability rating for all is 20)							
Electrolytic tough-pitch copper	99.90+	....	....	...	....	20	1.049
Deoxidized copper	99.90+	(0.02 P)	....	...	...	20	1.052
Commercial bronze, 90%	90.00	....	10.00			20	1.036
Phosphor Bronze, 5% (A)	95.00	....	....	...	5.00	20	1.042
Phosphor bronze, 8% (C)	92.00	....	....	...	8.00	20	1.036
Phosphor Bronze, 10% (D)	90.00	....	....	...	10.00	20	1.033
Nickel silver, 18% (A)	65.00	18.00	17.00	...	...	20	1.029
Nickel silver, 18% (B)	55.00	18.00	27.00	...	...	20	1.023
Nickel silver, 20%	75.00	20.00	5.00	...	...	20	1.042
Cupro-nickel	70.00	30.00	....	...	...	20	1.052
Aluminum bronze, 5%	95.00	....	....	...	5.00 Al	20	0.961
Aluminum bronze, 8%	92.00	....	....	...	8.00 Al	20	0.915
Aluminum bronze, 9%	89.25	0.50	(0.60 Fe)	0.40	9.25 Al	20	0.892
Aluminum bronze, 10%	82.00	5.00	(1.00 Mn)	(2.50 Fe)	9.50 Al	20	0.892
Beryllium copper (Not heat treated)	97.60	0.35	....	...	(2.05 Be)	20	0.967
Chromium copper	99.50 max	....	(0.40 Cr min)	...	(0.10 Si or Zn)	20	1.046

(a) Approximate relative machinability rating (Free-cutting brass = 100)
(b) Weight conversion factor (Free-cutting brass = 1.000 based on a density of 0.307 lb per cu in.)

paratively steep rake. The moderate rake angles suggested for use on alloys in Group 1 reduce the tendency of the tool to "hog" into the work piece. More pronounced rakes are used for the alloys of Group 2 and 3 to provide a free flow of chip.

When parts that have a small diameter are made from the alloys in Group 1, they are usually machined at the highest practical spindle speed; the feeds are adjusted to suit such conditions as depth of cut, available power, coolants and finish requirements.

Turning Speeds and Feeds for Use with High Speed Steel Cutters

(When carbon steel cutters are used, the suggested speeds should be reduced by approximately 50%.)

	Surface Speed, fpm	Roughing Feed, inch	Finishing Feed, inch
Group 1	300 to 700	0.006 to 0.020	0.003 to 0.015[a]
Group 2	150 to 300	0.015 to 0.035	0.005 to 0.015[a]
Group 3	75 to 150	0.015 to 0.040	0.005 to 0.020

(a) An 8 to 15-deg end cutting edge angle should prove satisfactory for most rough and finish turning operations. When the end cutting edge of a finishing tool is ground with a drag or parallel with the axis, considerably heavier feeds may be employed on light finishing cuts. Tools should be ground and set so that the tool point is on center, with the effective rake angles in correct relation to the center line of the work.

Form tools are usually of two types, circular and dovetail (Fig. 2). The circular form tool is used to best advantage in automatic screw machines. In general, the speeds and feeds used with form tools are controlled to a considerable extent by the width of the tool in relation to diameter of the work piece, the amount of overhang and the contour. It is good practice to adjust only the cutting speed to the alloy that is being machined and to maintain a light feed of 0.001 to 0.003 in. for roughing operations and 0.0005 to 0.002 in. for finishing operations.

Cutting speeds and feeds for carbide-tipped tools (Fig. 3), as for other types of cutting tools, will vary over a wide range, depending on the material to be cut, the available power and rigidity of the machine, the diameter of the work piece, the desired finish, tolerances and other such factors. Roughing cuts of ¼ in. or more are frequently used, producing a satisfactory finish. The following suggested cutting speeds and feeds are typical for copper and copper alloys and are based on a depth of cut of approximately 0.045 to 0.125 in. for roughing, and 0.015 to 0.030 in. for finishing. A starting point may be taken as halfway between the limits given, adjusting the speed upward or downward until the best results are obtained.

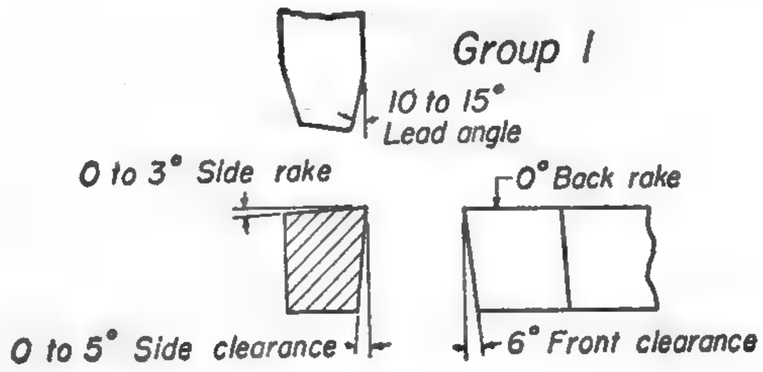
Turning Speeds and Feeds with Carbide-Tipped Tools

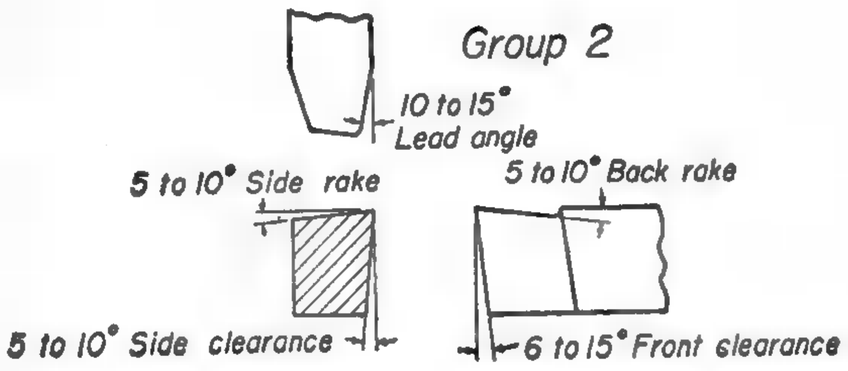
Group 1
- Roughing surface speed, from 400 to 800 fpm
- Roughing feed, 0.015 to 0.025 in.
- Finishing surface speed, from 500 to 1000 fpm
- Finishing feed, 0.005 to 0.015 in.

Group 2
- Roughing surface speed, from 300 to 500 fpm
- Roughing feed, 0.015 to 0.030 in.
- Finishing surface speed, from 400 to 600 fpm
- Finishing feed, 0.005 to 0.015 in.

Group 3
- Roughing surface speed, from 250 to 600 fpm
- Roughing feed, 0.015 to 0.030 in.
- Finishing surface speed, from 300 to 800 fpm
- Finishing feed, 0.008 to 0.015 in.

Milling. Copper alloys can be milled at very high speeds. Because of rapid removal of metal, coarse-tooth cutters are desirable and, if they are even moderately wide, they should





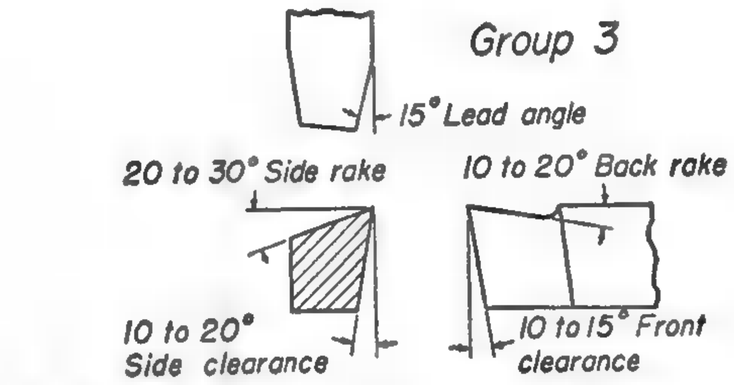


Fig. 1 Carbon and high speed steel lathe turning tools. An angle of 8 to 15 deg at the end cutting edge should prove satisfactory for most rough and finish turning operations. When the end cutting edge of a finishing tool is ground with a drag, or parallel with the axis, considerably heavier feeds may be employed on light finishing cuts. Tools should be ground and set so that the tool point is on center with the effective rake angles in correct relation to the center line of the work.

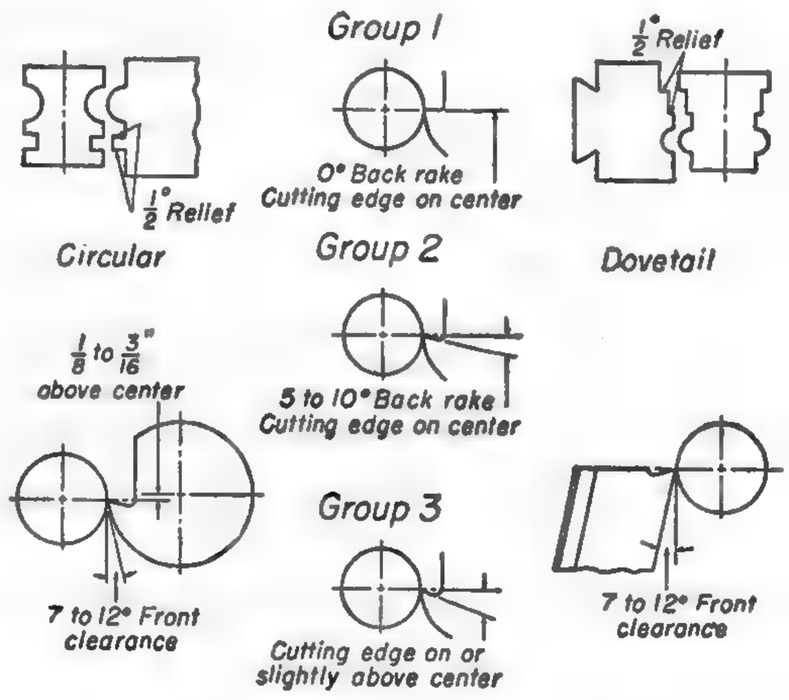
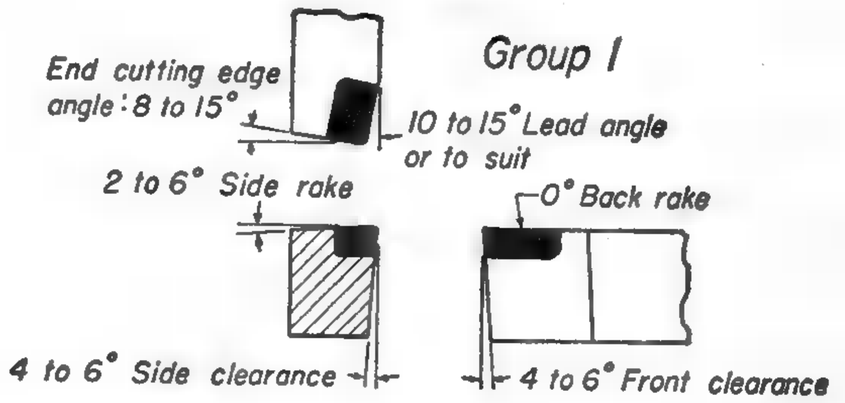


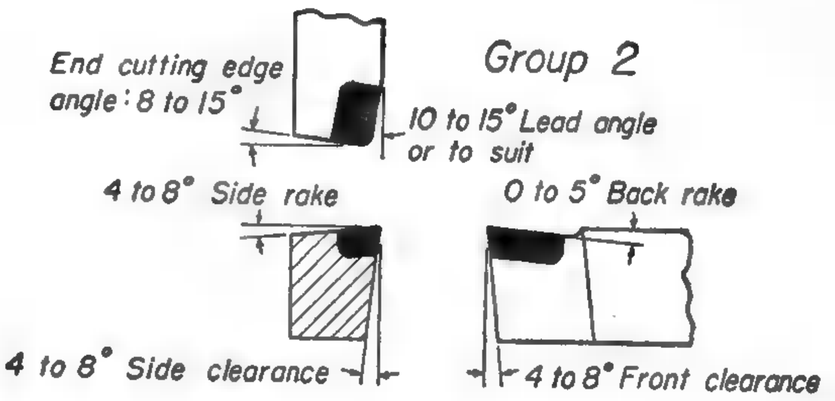
Fig. 2 Circular and dovetail forming tools

be spiral. High speed steel cutters are commonly used, and cutters having inserted teeth of cemented carbide are efficient for large tools and heavy cuts. Combined cutters are inefficient, unless they have interlocking teeth, since rapid production of chips wedges fine chips between the cutters. Conditions of milling are listed in Table II.

Leaded brasses are readily machined dry and with no hook on teeth, but Groups 2 and 3 require a coolant and hooked teeth. Cutting edges and sides must be especially smooth to avoid a "plating" or "loading" action.

For straight-blade and circular cutoff tools, see Fig. 4.





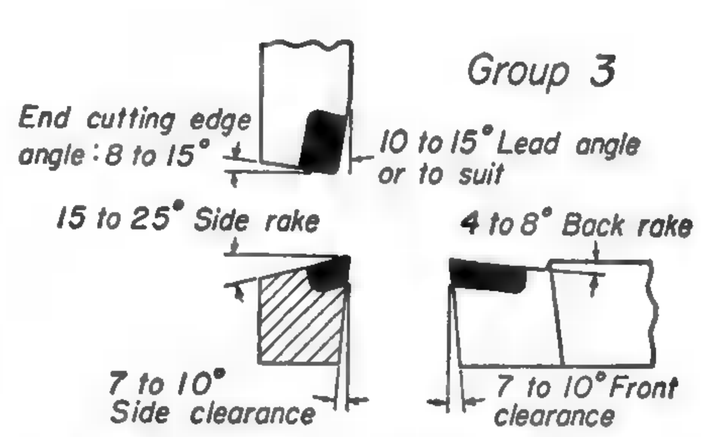


Fig. 3 Carbide-tipped lathe turning tools. For establishing rake angles, the tool shank should be set parallel with the center line of the work and with the tool point on center. Placing the tool point above or below center will change the effective rake angles appreciably, particularly on work of small diameter. On a setup where the tool holder is not parallel with the center line, the rake angles should be ground so that, when the tool is mounted, they are in correct relation.

Table II. Milling

Many variables enter into milling practice but, in general, conditions are determined by the finish desired. The high tooth of the cutter will always leave a series of parallel ridges. For finish cuts the following conditions are advisable.

	Group 1
Rake angle, degrees	0 to 10
Clearance angle, cutters more than 3 in. in diam	10 to 12
cutters less than 3 in. in diam	6 to 7.5
Feed, fpm	1 to 2
Speed, fpm[a]	150 to 200
Depth of cut may vary between wide limits	0.010 to 0.250
For very rough cuts on heavy slabs—cutters 6 in. in diam	
Rake angle, degrees	0
Clearance angle, degrees	8 to 12
Feed, fpm	15 to 20
Speed, fpm	1100

(a) Actually governed by finish desired.

At high speeds the greater the helix and the feed, the greater should be the clearance.

Use of a coolant is recommended.

Engraving tools Class I; diameter < ⅜ in.; surface speed 400 fpm.

Drilling. For free-cutting brass rod, the conventional twist drills are ordinarily used, although some work pieces require straight-flute, slow or fast spiral, gun or standard drills. Where the volume of production does not warrant the use of special drills, standard carbon or high speed steel drills are satisfactory for Group 1. It is often helpful to thin the web at the point to reduce pressure at the end, and for metals of Group 3 the cutting edge may be notched to split the chips.

The slow spiral with wide polished flutes and a thin web provides larger chip clearance with a decreased rake angle and is often used for drilling deep holes.

Alloys of Group 1 are occasionally drilled dry but can be drilled to better advantage when conditions permit the use of a suitable lubricant. On alloys of Groups 2 and 3 a lubricant should always be used. The drill should be kept cutting without interruption as long as the chips are being ejected. In holes that are deep in relation to the diameter of the drill, a depth no greater than five diameters can be drilled satisfactorily without relief or chip clearance.

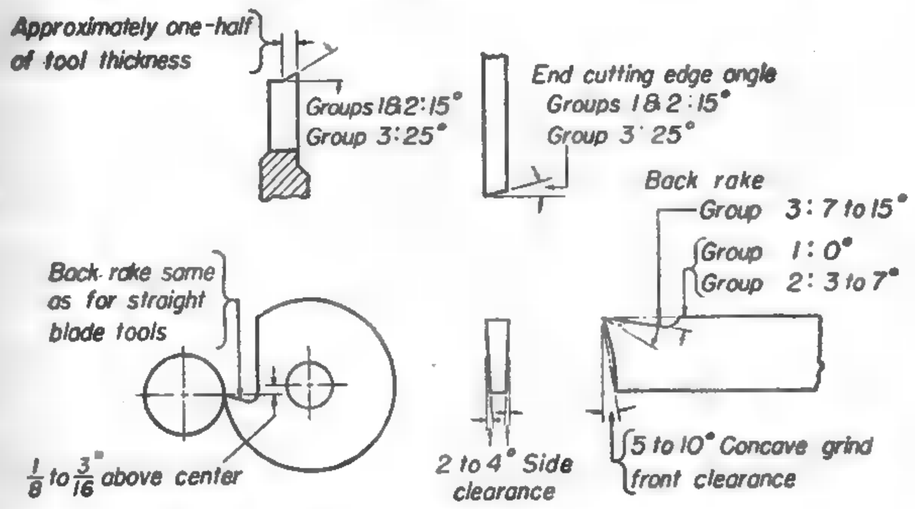


Fig. 4 Straight-blade and circular cutoff tools

Many factors control the speed and feed of drilling operations, depending on the diameter of the drill, the wall thickness of the work and the depth of the hole. Drill point and clearance angles are shown in Fig. 5 and Table III.

Threading and Tapping. This operation is probably more severe than that of any other cutter. Because copper alloys are easy to machine, the operation is inexpensive compared with similar operations on metals that necessitate milling

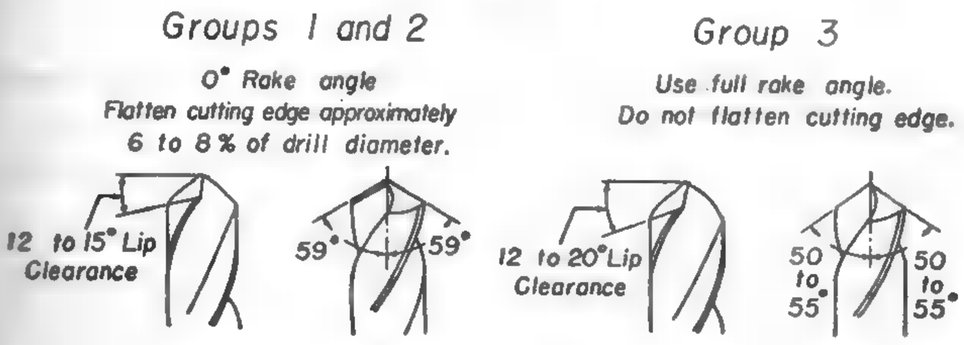


Fig. 5 Drill point and clearance angles for twist drills

or rough and finishing operations. The cutting action is unfavorable for any tool, since the tap or chaser must often have a short lead and must produce a smooth, commercially full thread to close tolerances in one cut. As compared with using a self-opening die or tap, it is slow and expensive to mill threads by rotating a multitooth hob and the work piece. Ground thread-chasers and taps made of high speed steel are conventional tools for copper alloys. The milled

Table III. Drilling

	Group 1
Helix angle, degrees	24 to 40[a]
Clearance angle, degrees	12 to 15
Web to edge angle, degrees	135
Included point angle, degrees	118
Speed fpm for depths as great as 10 diam	350 to 700
For small diameters (less than 0.080 in.)	200 to 300
Lubricant	Dry, or paraffin oil

(a) For quick removal of chips, but it tends to "pull" into work.

type of chaser is used for Group 1 and the hobbed type for tough alloys and tubular sections that have a thin wall. Three-flute or four-flute taps are ordinarily used. However, a greater number of flutes is advisable on sections that have a thin wall and a large diameter. Alloys in Group 3 often require a slight back taper on deep holes. Tools should be smooth, not too keen-edged and with no rake for Group 1, but sharp and hooked for Group 3.

The cutting speeds suggested are for threads of moderate pitch; for coarse threads, speeds in the lower range should be used. On automatic screw machines working Group 1 alloys, the maximum spindle speed is frequently used when threading work pieces that have small diameter or thread of fine pitch.

Threading Speeds:

Group 1, from 100 to 150 fpm
Groups 2 and 3, from 50 to 90 fpm

When automatic screw machines are working on Group 1 alloys, maximum spindle speed is frequently used when tapped holes are of relatively small size or when the thread has a fine pitch.

Tapping Speeds:

Group 1, from 150 to 250 fpm
Group 2, from 60 to 150 fpm
Group 3, from 30 to 60 fpm

Knurling and Thread Rolling. There are two methods of producing knurls on brass parts and differing results are produced with different tooling and alloys. One method is by "ploughing" from the end, and the other is by "butting" or plunge-feeding from the side. Neither of these methods will produce an especially clean knurl from leaded brass, because leaded brass will stand only a limited amount of upsetting without "roughening". High-copper and non-leaded alloys will produce a cleaner job. However, knurling as produced on leaded alloys is generally acceptable.

Thread rolling is produced by "butting" against a diameter that approximates the pitch diameter of the thread. A much better thread will result from low-leaded brass. It is important that a suitable temper of leaded brass be used when that alloy is required for knurling.

Sawing. Saws that have a large number of cutting edges can rotate at very high speeds, especially on leaded brass. Thinner high-speed saws or blades can be used on copper alloys than on other metals, because of the smaller frictional heat developed. Because of rapid removal of chips, coarse-tooth saws are best with no hook for leaded alloys and with hook increasing with copper content. Usually no coolant is required for leaded brass. Naturally, the contact with the part should be at a minimum; a rectangular shape should be sawed through its thinnest section. If finish is required, metal-slitting saws should be used with side chip clearance that minimizes "rubbing" and "chip wash". Tooth shapes for circular saws are illustrated in Fig. 6. Other data are listed in Table IV.

Carbide-tipped blades are efficiently used in automatic sawing machines.

Lubricants and Coolants. Some machining operations on copper alloys, particularly turning and drilling, are performed dry when the quantity and other considerations do not justify the use of cutting fluids. However, higher speeds and feeds may be used and a finer finish obtained where the use of a coolant or lubricant is practicable.

The functions of a cutting fluid are threefold: (1) As a coolant, it reduces the temperature of the cutting tool and

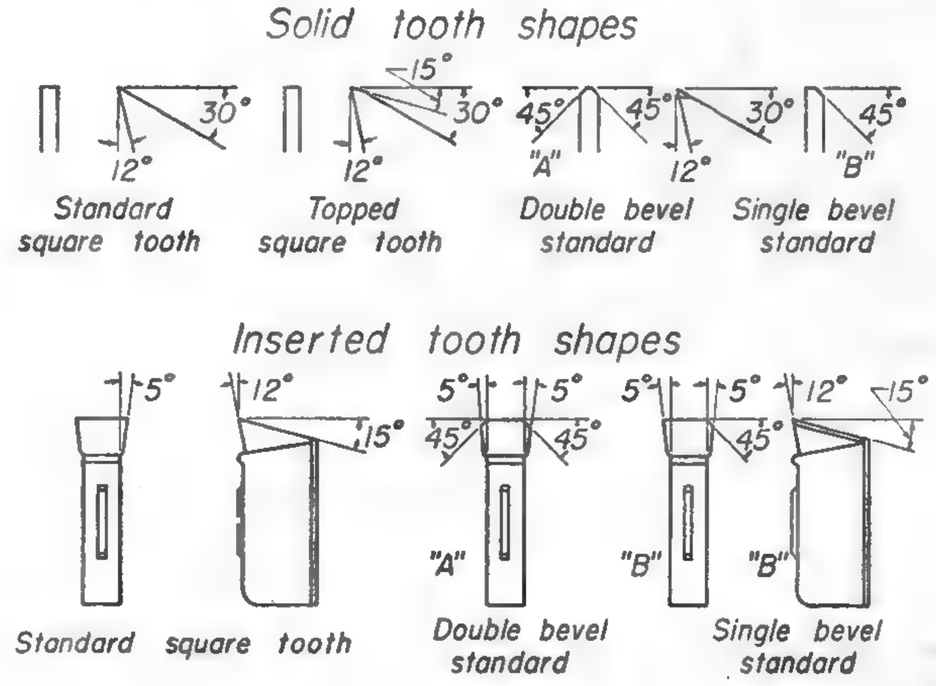


Fig. 6 Solid and insert tooth shapes for circular saws

thereby preserves the hardness and prolongs tool life. (2) As a lubricant, it provides a film of oil between the work piece and cutting tool, thereby reducing abrasion and erosion. (3) As an anti-weld agent, where some elements such as sulfur are added to the cutting fluid to minimize or eliminate the deposit built up on the cutting edge by high cutting pressures and temperatures.

Table IV. Sawing with Circular Saws

Form and Size	Alloy Class	Grade Steel[a]	Tooth[b] Type	Diam, inches	Thickness, inch	No. Teeth	Hook Angle, deg	Rim Speed, fpm	Feed, ipm	Lubricant[c]	Rockwell C Hardness	Chromium Plated 0.002 in. per side	Hollow Ground Taper per in.
Sheet, ¼ to 1 in....	1, 2, 4	SHSS	SST	12	⅛	70–80	0–5	1500	10–20	Sol. Oil	52–56	Yes	0.0035
	3, 5	HSS	Ins.BST"A"	12	1/16	28–32	5–10	2500	10–20	Sol. Oil	60–62	No	0.0010
Rod, up to 1½ in...	1, 2, 4	SHSS	SST	12	3/32	150–200	10–15	4–5000	60	Grease stick	52–56	Yes	0.0035
	5	SHSS	TST	12	3/32	100–125	10–15	4–5000	30	Grease stick	52–56	Yes	0.0035
	3	HSS	Ins.SST	12	⅛	75–100	5–10	2–3000	20–30	Grease stick	60–62	No	0.0010
Rod, 1½ to 4 in.....	1, 2, 4	HSS	Ins.Alt.SST &BST"A"	16	1/16	60–64	10–15	1000	30–40	Compound	64–66	No	0.0035
	5	HSS	"	16	1/16	60–64	10–15	1000	20–30	Compound	62–64	No	0.0010
	3	HSS	"	16	¼	60–64	5–10	750	10–20	Compound	62–64	No	0.0010
Rod, 4 to 8 in.....	1, 2, 4	HSS	"	28	¼	60–80	10–15	6–750	20–30	Compound	64–66	No	0.0010
	5	HSS	"	28	¼	60–80	10–15	6–750	15–25	Compound	62–64	No	0.0010
	3	HSS	"	28	¼	60–80	5–10	5–650	10–15	Compound	62–64	No	0.0010
Tubing, diam up to 1 in.; wall thickness up to 0.050 in.	1, 2, 4, 5	HSS	SST	10	1/16	180–200	10–15	5–6000	100–200	None	60–62	Yes	0.0035
	3	HSS	SST	10	1/16	180–200	10–15	5–6000	50–100	Grease stick	57–61	Yes	0.0035
Tubing, diam up to 1 in.; wall 0.050 to 0.250 in.	1, 2, 4, 5	HSS	SST	10	3/32	180–200	10–15	5–6000	50–100	None or grease stick	60–62	Yes	0.0035
	3	HSS	SST	10	3/32	180–200	10–15	4–5000	25–75	Grease stick	57–61	Yes	0.0035
Tubing, diam 1 to 3 in.; wall up to 0.100 in.	1, 2, 4, 5	SHSS	SST	12	5/64	110–120	10–15	4–5000	75–100	Grease stick	52–56	Yes	0.0025
	3	HSS	Ins.SST	12	⅛	90–100	5–10	3–4000	25–75	Grease stick	62–64	No	0.0025
Tubing, diam 1 to 3 in; wall 0.100 to 0.250 in.	1, 2, 4, 5	SHSS	SST	12	3/32	110–120	10–15	4–5000	50–100	Grease stick	52–56	Yes	0.0025
	3	HSS	Ins.SST	12–16	1/16	110–120	5–10	3–4000	25–75	GS & compound	62–64	No	0.0025
Tubing, diam over 3 in; wall over ¼ in.	1, 2, 4	HSS	Ins.Alt.SST &BST"A"	16 & more	1/16–¼	3–4 per in. diam	10–15	2–3000	25–75	Compound	64–66	No	0.0010
	5	HSS	"	16 & more	1/16–¼	3–4 per in. diam	10–15	2–3000	25–50	Compound	64–66	No	0.0010
	3	HSS	"	16 & more	¼	3–4 per in. diam	5–10	1–2000	10–20	Compound	62–64	No	0.0010

(a) SHSS is a trade designation for semihigh speed steel saw and HSS for high speed steel saw.
(b) See Fig. 6 for tooth types.
(c) Compound made up as water emulsion of soluble oil. Use 10% oil by volume and 1 lb heavy soap per 20 gal of compound.

Because of the many considerations that govern cutting operations, it is impossible to make specific recommendations. The following suggestions may serve as a guide.

Group 1. For the free-cutting alloys included in this group, a light mineral oil, frequently called "paraffin oil", is used in large quantities on automatic and hand screw machines and is directed at the cutting edge of the tools. Unblended light mineral oil is particularly desirable when machining alloys of this group at high speed, light feed and moderate depth of cut. An inexpensive cutting compound with good coolant properties may also be used, consisting of 20 parts water to 1 part soluble oil.

Group 2. The soluble coolant compound mentioned under Group 1 may also be used for this group. A mineral oil base, fortified with 5 to 15% lard oil, will be likely to prove more satisfactory as both lubricant and coolant; the higher percentage of lard oil is used on those alloys producing tough, stringy chips.

Group 3. A cutting fluid frequently used for this group of alloys is a mineral oil base with 10 to 20% lard oil. For copper and the alloys that have a high nickel content, sulfurized mineral oil, or sulfurized mineral–lard-oil compounds have given excellent results. When a sulfurized compound is used on copper alloys, the parts should be cleaned as soon as possible after machining, to avoid discoloration. This tarnish can be removed by immersion for 20 minutes in a 10% sodium cyanide solution.

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Finishing of Copper and Copper Alloys

BY THE SUBCOMMITTEE ON FINISHING COPPER ALLOYS*

THIS ARTICLE outlines methods and practices used in industry for preparing the surface of copper and copper alloys for subsequent fabricating, and for finishing the surface of completely fabricated products. Unless otherwise stated, the procedures will apply to the following metals: copper, brasses, special brasses, aluminum bronzes, silicon bronzes, phosphor bronzes, manganese bronzes, nickel silvers and copper-nickel alloys.

* The members of this subcommittee are R. W. Belfit, *Chairman* (Scovill Manufacturing Co.), Wm. E. Baulieu (Bridgeport Brass Co.), E. W. Lovering (Seymour Manufacturing Co.) and B. H. McGar (Chase Brass & Copper Co.).

Mechanical Cleaning and Surface Conditioning*

Barrel Deburring. Small cut parts, such as disks, eyelets, cups and the like, often have a sharp edge with a burr that would interfere with subsequent operations.

* *See also* the article on page 301 of this Handbook.

Small articles are deburred inexpensively by tumbling in a barrel. Two distinct types of barrel are used—an open-end oblique barrel that may be tilted for unloading, and a cast-iron horizontal, polygonal barrel with removable tight-fitting cover. The tilting barrels, made of copper-silicon alloy, iron or stainless steel, have four or more ribs inside to aid in the desired rolling action.

The deburring procedure varies considerably for different sizes, weights and shapes of work pieces. Experiments must be conducted to determine the preferred size of the load in the barrel, the speed of rotation, the length of time in the barrel, and the abrasives and chemicals that may be used. Generally, copper alloy parts will be received in the rolling room with oil still on them from the previous mechanical operation, so a typical deburring procedure will start with cleaning.

Cleaning and Deburring Small Copper Alloy Articles. *Equipment.* A horizontal, octagonal cast-iron barrel or an obliquely tilting steel barrel with narrowed mouth and centrifugal dryer.

Materials. Caustic soda flakes (sodium hydroxide), sodium cyanide eggs, No. 2 pumice, sea sand, soapbark, and cream of tartar or a substitute.

Procedure. 1 Add hot water to cover 50 to 250 lb of work; add approximately 5 lb of caustic soda and 4 oz of sodium cyanide (*poison*).

2 To remove oil, roll for 10 min at a speed of approximately 30 rpm.

3 With water piped to the mouth of the barrel, wash the parts until they are free from alkalies, that is, until red litmus paper no longer turns quickly blue. (Operators sometimes judge by elimination of the slippery feel.) In oblique barrels, the parts are washed during rotation.

4 Add 3 lb of No. 2 pumice and 6 lb of sea sand (screened through 40-mesh) with a cover of water.

5 Roll until burrs are removed from work pieces. The time may vary from ▪ to 24 hr.

6 Dump the work into a perforated centrifuge basket and wash free from abrasive.

7 Dry the work in a centrifuge equipped with a hot air blast. Work will have a smooth, dull matte finish.

Remarks. The abrasive used may be different grades of pumice, rottenstone, sea sand, silex, emery, aluminum oxides, silicon carbides, or similar materials. Sometimes when the work pieces are heavy, satisfactory deburring is accomplished simply by rolling the parts in an oblique barrel with water only. Also, the oil may be removed by other alkaline cleaners.

Bright or Water Rolling. *Equipment.* Obliquely tilting steel barrel with narrowed mouth and centrifugal dryer.

Materials. Caustic soda, sodium cyanide, and cream of tartar or a substitute.

Procedure. Operations 1, 2 and 3 for bright rolling are similar to those for deburring, or the work pieces may have been deburred already.

4 Add about 6 oz of cream of tartar to 20 gal of water and roll at 30 to 40 rpm until the desired bright finish is obtained. It is usually necessary to replace the dirty solution with clean water and more cream of tartar.

5 Rinse the work with running water for 5 to 10 min while the barrel is rotating.

6 Dump the work into ▪ perforated centrifuge basket, place in heated centrifuge and dry.

Ball Burnishing. *Equipment.* Horizontal barrel made of wood, steel with wood lining or steel with brass lining; or oblique, tilting stainless steel barrel.

Materials. "Neutral" soap, cream of tartar or a substitute, and soapbark.

Procedure. 1 Work should have been deburred or bright rolled, then treated by "bright acid dipping", before being placed in the barrel for ball burnishing.

2 For each volume of work material, add two volumes of steel burnishing balls, 1/16 in. to ½ in. in diam.

3 If using the preferred horizontal barrel, fill it with water to within a few inches of the cover and add approximately 2 oz of soap for each gallon. If the water is hard, add a water softener first or a proprietary mixture that includes a wetting agent.

4 Roll at approximately 30 rpm for 6 to 48 hr, depending on the luster required and the kind of work pieces.

5 Dump the entire contents of the barrel and riddle out the balls from the work parts while washing the parts.

6 Dry the work by rolling it for about 20 min in a horizontal wooden barrel that contains sawdust slightly moistened with Stoddard solvent to prevent fine sawdust from adhering to the work material.

7 Riddle sawdust from the work.

Remarks. Ball burnishing produces the highest luster that can be obtained in bulk finishing. Such burnishing may be applied to copper alloys before plating or lacquering, or may be used after plating to improve the luster. In ball burnishing, the soap acts as a lubricant, so the metal surface is rubbed (peened) by the hardened steel balls that are marketed for that specific use. When balls are not in use, they should be kept in a soap solution or other alkaline solution to prevent rusting.

Steel shapes other than balls, such as cones, pins and slugs, are sometimes used with balls for special-shaped items, since balls cannot reach into sharp corners.

Wheel Polishing. *Equipment.* A buffing lathe and glue pot with temperature controlled at about 160 F.

Material. Cotton cloth buff sections (18 in. in diam), felt or sheepskin leather wheels, high-gel-strength hide glue, and emery or aluminum oxide (80 to 220-grain).

Procedure. 1 Glue together 8 to 12 sections of the cloth wheel (20 pieces of cloth to each section). Brush glue solution all over one side of each section and stack the sections while they are centered by a temporary 1-in. arbor. Compress the sections beneath about 20 lb of weights and allow 12 hr or more for setting. The cutting face of the wheel will be 1 to 1½ in. thick.

2 Mount the wheel on the spindle where it is to be used, and dress the wheel with a well-worn hacksaw blade.

3 Size the cutting face of the wheel with a solution of approximately 25% hot hide glue, and dry at least ½ hr.

4 Apply glue solution at 160 F to the face of wheel.

5 Roll the wheel in the abrasive until it has picked up all the grain it will hold. Then dry for 1 hr.

6 Repeat operations 4 and 5 but allow overnight drying.

7 True the wheel with a file sharpened to a chisel edge.

8 Crack the wheelhead by striking the wheelface lightly with a round bar at about a 45-deg angle. This should be repeated around the wheel so that "X" series of cracks are formed. These cracks make the wheel more flexible and retain the grease better, making possible a more uniform and higher polish.

9 The wheel is ready for polishing at ▪ speed of approx 2500 rpm. A stick of polishing tallow should be used on the wheel to lubricate the cutting.

Remarks. The most popular abrasive is the 150-grain. Similarly, wheels may be set up with abrasives and glue applied on wool felt or sheepskin leather. Since the felt wheels are much more costly, they are generally used only where a shaped wheel or bob (for inside polishing) is desired. The sheepskin wheels are used on parts that are round and irregular, if a more flexible wheel is required.

Light polishing and deburring are also accomplished by the use of a cotton cloth wheel and a greaseless composition. This type of composition, with glue as the essential binder of various abrasives, is sold in stick form in a moisture-resistant cardboard or lead container. When the stick is placed in contact with the revolving wheel, some of the compound coats the cutting surface and may be used almost immediately. For polishing effects, the most suitable speeds are 4300 to 5700 surface ft per min, that is, 1800 rpm, with a wheel 9 to 12 in. in diam.

Belt Polishing. Many polishing operations are performed on endless canvas or leather belts set up with abrasives and glue. In one method, the abrasive is sprinkled onto a belt that has previously been brushed with hot glue. Another method requires making a thick paste of the hot glue and abrasive and then spreading it on the belt with a brush, knife or trowel. Factory-coated abrasive belts are preferred because of the uniformity of abrasive coating. Polishing belts are run at 4500 to 6000 surface ft per min.

Scratch Brushing. Most scratch brushing is now done with a greaseless composition on a cotton cloth wheel. The chief advantage of this method is that it eliminates both a buffing and a cleaning operation that were necessary after the use of grease-bound, scratch-brush compositions.

Before being scratch brushed, the work should be clean (often, "bright dipped" in acid). Various finenesses of scratch are obtained by means of sharp or mild abrasives of different grain sizes and by variation in the packing of the wheel and its speed. The wheel packing will be discussed under Buffing. Some scratch brushing on surfaces is done with a wire or tampico wheel, wet or dry, with a little soapy water and 0 ½ pumice.

Wheel Buffing. The highest luster on copper alloys is produced by wheel buffing.

Equipment. Either a buffing lathe of variable speed or lathes run at different speeds, 1200 to 3600 rpm. Buffing wheels may be incorporated into semiautomatic or fully automatic machines.

Materials. Cotton cloth (rag) wheels; different finenesses of tripoli composition; lime composition; and red rouge (iron oxide) composition. The abrasives are in bar form, and are bound with a grease mixture that contains a considerable amount of double-pressed stearic acid.

Procedure. 1 Usually start with at least 12-in. sections of cotton cloth buffs that are mounted on a spindle.

2 As the wheel revolves, rake it by means of a strong stick through which nails have been driven so as to protrude about 1 in. apart each way.

3 Apply selected buffing composition to the wheel as needed, taking care not to use too much composition.

4 Buff a work part by holding it up to the face of the wheel. After buffing, withdraw the part in the direction of rotation of the wheel, which is downward. The operator should be careful that a sharp corner does not catch in the wheel and snap the material out of his hands. Small work pieces are often held in a revolving chuck so that a piece will spin as it is held against the wheel.

Remarks. Operators sometimes pack buff wheels differently for the same work. To soften a wheel, "spacers" are used in packing. Spacers are small buff sections that have been worn down and are placed between full-size sections. The larger the percentage of spacers, the softer the wheel. Judicious use of spacers often permits "cutting down" and "coloring" on the same spindle, by packing one side of the wheel hard and the other side soft. For "cutting down", a tripoli composition is used on the rag wheel, while for coloring, a white lime or red oxide rouge (iron oxide) is generally used. The cutting-down operation removes polishing lines and light metal imperfections; the coloring operation develops the ultimate luster.

All operations with a buffing wheel should be adequately ventilated to protect the operator from the dust.

Buffing is a relatively expensive operation, but often costs can be reduced considerably by close co-operation among the designing, buffing and processing departments. The metal should have the minimum grain size consistent with the working operations in order to buff smooth.

Belt Buffing. For some intricate shapes, such as the inside surfaces of an S-bend trap, a woven cotton belt driven at 6000 ft per min, may be used advantageously. The tripoli or other composition is applied to the belt.

Sandblasting. Sandblasting is the process of removing material from the surface of metal by forcibly impinging sand, steel grit or shot onto the surface. The abrasive is introduced into an air stream at air pressures of 25 to 100 psi and the blast is directed over the surface until the desired finish is obtained. The objective may be to produce a dull, rough finish for appearance; to prepare a surface that affords excellent adhesion to enamels and other decorative coatings; or to create designs on the surface.

Chemical and Electrochemical Cleaning

During the course of processing and fabricating, copper alloys may become coated with lubricating oils, drawing compounds, greases, oxides, dirt, metallic particles, or abrasives, which must be removed by cleaning. The type of cleaning employed will depend on the type of lubricant and other materials to be removed, the equipment available and the degree of cleanliness required. The nature and size of the pieces also influence the selection of the equipment or process to be employed.

Mechanical scrubbing, accomplished by turbulent boiling, pressure spraying, or agitating, where permissible, helps in the removal of any substances not too adherent, and thus aids in cleaning. Occasionally, hand brushing may be used, but production requires mechanical methods.

Lubricants made from animal or vegetable oils or greases, such as tallow, lard oil, palm oil and olive oil, can usually be removed by saponification, which is accomplished by immersing the parts in an alkaline solution where the oil reacts with the alkali to form water-soluble soap compounds.

Mineral oils that are not saponifiable, such as kerosene, machine oil, cylinder oil and general lubricating oils, are usually removed from the metal by an emulsification process. Soap is the wetting agent and dispersing medium.

Dirt particles, abrasives, metal dust and inert materials are generally removed by one or both of these processes. To bring about the removal of undesirable materials by saponification, emulsification or similar means, it is necessary to use certain chemicals or combinations of chemicals. A number of cleaning methods employ available chemicals for the removal of lubricants and other materials. The common methods are discussed below.

Solvent Cleaning. This type of cleaning is used for removing the greater portion of oils from coated pieces by immersing them in a solvent, such as Stoddard's solvent, which is a low-boiling fraction of mineral oil, with a minimum flash point of 100 F and no lasting odor. Centrifuging, after the last immersion, removes excess solvent; the pieces are then virtually free from oil. Solvent cleaning is often used for screw-machine work. After a short period of service, the solvent will become contaminated by the materials that it is removing. It is often advantageous to set up a series of interconnected iron tanks leading to and from a still. The still removes the accumulated oil and returns the solvent to the first of the series of tanks, which overflows into the adjacent tank, which in turn overflows into the next one, and so on. The last tank in the cycle feeds the still. The final rinse is nearly clean solvent.

Degreasing. Degreasing, or vapor cleaning, is used when oil must be removed quickly. For cleaning, the metal part is placed in a container where solvent vapors can condense on it. Condensate washes away the oily coating and leaves the piece clean and dry. Degreasing machines with two or three compartments are preferred. The work pieces are immersed in the first compartment, which contains a boiling solution of solvent; they are then dipped into the second section, which contains clean cold solvent; and finally, they are held in the third section, where only clean vapors condense on the work and wash over it. The degreasing unit is usually self-purifying; oils and wastes accumulate in the bottom of the third section. If the quantity of oils removed should justify the expense, this unit may be equipped with an auxiliary still in order to ensure that sufficient clean solvent is returned to the proper section. The solvent used is generally inhibited trichlorethylene.

Alkaline Scouring. Alkaline cleaning baths are used primarily for the removal of oils, greases, solid particles of dirt, and metal particles, by immersing the work in a hot alkaline solution. The chemicals saponify, or make soap of vegetable and animal oils and fats, and emulsify mineral oils and greases, suspending the solid materials. Either the dirt is removed from the metal surface, or its tendency to cling is greatly reduced. The essentials here are a combination of a sufficient quantity of active chemicals and agitation when possible. Soap is used as a direct addition to the cleaning bath, or is formed by the saponification of vegetable or animal fats and oils present.

The following are satisfactory cleaning formulas:

Formula 1	*Formula 2*
85% sodium orthosilicate	46% sodium carbonate (anhydrous)
10% sodium carbonate	32% trisodium phosphate
5% sodium resinate	16% sodium hydroxide
	6% rosin

These formulas are from the Joint Army-Navy Specification JAN-P-116, "Methods of Preservation, Packaging and Packing for Overseas Shipment".

Caustic soda and soda ash are the cheapest and most direct means of producing alkalinity in the bath. However, as a general rule such materials possess less surface activity than materials of more complex chemical structure. Sodium metasilicate, trisodium phosphate and similar salts, with the addition of suitable wetting agents, are often used to obtain alkalinity in a solution.

To be effective, the alkaline cleaners should exhibit the following characteristics:

1 They should wet the surface of the material, which is usually accomplished by lowering the interfacial surface tension.
2 They should have the ability to penetrate the layers of dirt.
3 They should have good emulsification and deflocculation or suspending properties.
4 They should be "free rinsing".
5 They should saponify animal and vegetable oils.
6 They should have the ability to remove mineral oils by the mechanism of wetting, emulsification and deflocculation.

To accomplish the above objectives, the essential requirements for a good alkaline cleaner are that it should be a source of available alkali, should have a buffer to control alkalinity, should be readily soluble, operate at optimum cleaning temperature, be stable, and have good detergent ability and rinsing qualities. Various temperatures and concentrations are permissible. The range of temperature may be from 120 to 200 F and the concentration from 3 to 8 oz per gal, depending on the requirements of cleaning. These characteristics are listed to indicate the need for using a type of cleaner that is compounded for a specific purpose.

For alkaline cleaning, steel tanks where work can be put into baskets or on racks and raised from and lowered into a solution, are the simplest and least expensive to install. The more highly mechanized units consist of belt conveyers where work material passes over and under sprays; and also of spiral drum cleaning units, where alkaline cleaner is scooped up and thrown over the pieces, which are rinsed and dried farther on.

Emulsion Scrubbing. For emulsion scrubbing, a number of proprietary preparations are used. They consist of an emulsifying agent that acts to disperse organic solvents in water solutions. These emulsifiable cleaners, miscible with oils, can be washed off with water, although a slight film of oil may remain on the work, necessitating a subsequent alkaline cleaning. Drag-out costs are fairly high. Parts carrying oils or other substances to be removed are immersed in this type of cleaner. The cleaning agents penetrate and unite with the oils and dirt on the surfaces of the articles, and during subsequent immersion in water solution, both the emulsion cleaner and the oil and dirt that it has wet, are washed away. Steel tanks are usually suitable for holding these materials.

Electrolytic Cleaning. Alkaline solutions are used in electrolytic cleaning, which is performed before plating. Work pieces are usually placed on racks. The tanks are equipped with bus bars, and these in turn are connected to a generator. When work is put on a cathode bar, the procedure is termed "direct cleaning"; when on an anode bar, "reverse cleaning". The bath is maintained at the boiling point or as near the boiling point as is permissible without excessive tarnishing, and the gas evolved, because of the work being made an electrode, tends to lift off the soil, providing a clean surface for subsequent operations. The usual procedure in electrocleaning is to make the work the cathode. The purpose of this is to obtain as high an evolution of gas as possible although, in some present processes, only anodic treatment is employed. The merits of one, as against another, depend on what, specifically, is to be accomplished, and the nature and type of work and chemicals employed. Many formulas are available for electrocleaning, but the one used will depend on the material to be cleaned and the amount of tarnish permissible. Electrolytic cleaning is often as satisfactory as hand scrubbing. It also makes possible the cleaning of many parts for which hand scrubbing would be impracticable or too costly.

Removal of Tarnish. Brass and copper articles often become discolored or tarnished while standing, or during the course of alkaline cleaning. This tarnish can be removed when the work material is free from oil or grease, by immersing the parts in a water solution containing 4 to 8 oz of sodium cyanide per gal. After discoloration has been removed (usually a matter of seconds), the pieces should be rinsed thoroughly. Sodium cyanide is *very poisonous* and extreme care must be used in handling it. When parts are cleaned in alkali, the alkali should be completely removed, because if alkali and cyanide are mixed and allowed to stand, ammonia may be developed. Care must be taken also not to allow any cyanide to come in contact with acid, because of liberation of lethal hydrocyanic acid gas. Even though the above precautions must be carefully observed, many gallons of cyanide solution are used daily, particularly in plating cycles. Steel tanks are suitable for holding the solution.

Tarnish can also be removed by immersing the work pieces in dilute hydrochloric (muriatic) acid or in dilute sulfuric acid solution; usually 5 to 10% by volume is sufficient for this purpose. The hydrochloric acid should be poured into rubber-lined containers or vitrified crocks. The sulfuric acid is usually put into a lead-lined tank or a crock. After the acid treatment the pieces should be rinsed thoroughly with water, so that no acid will remain on the work.

Summary. The fundamentals essential to cleaning that have been considered here, are the reduction of affinity or adhesion of substances to a metal surface, and the equipment required for this reduction.

When the practical application of cleaning cycles is considered, the kind of equipment that can be obtained, that is available or that is required for performing a process, will determine what type of cleaning should be or can be employed. Cleaning equipment may be very simple; however, the fully automatic equipment is not.

The nature and size of the pieces to be cleaned also determine the kind of equipment or process to be employed. Very small pieces are handled in baskets or in bulk. Large, highly polished pieces are handled individually or are placed on racks where there is no chance for one piece to come in contact with another. Oils or other materials should be removed without darkening the metal, since when this occurs, further treatment may be required to restore the original color and luster.

In planning the production of a new article, it proves advantageous to consider the kind of lubricants to be used in manufacturing and processing operations, with particular reference to the ease of removing these substances later, with the cleaning equipment available.

Pickling and Bright Dipping

When copper and copper alloys are annealed in an oxidizing atmosphere, they are discolored by the formation of surface oxides, which can be removed by an acid treatment called "pickling". This treatment leaves the surface free from oxides but without a bright color. A treatment that gives an absolutely clean, bright, lustrous surface is termed "bright dipping" and is always preceded by a pickling operation.

A pickling or bright-dipping solution depends on the action of suitable acids (usually nitric or sulfuric) to dissolve the oxides by chemical reaction. In certain instances oxidizing agents are added to convert lower oxides, which may be insoluble in the acid, to higher oxides that can be dissolved readily.

Pickling Equipment. Pickling tubs, tanks, racks and auxiliary equipment must be resistant to strong acids. Tanks may be made of or lined with stainless steel, lead, ceramics, glass or rubber. Racks or baskets are ordinarily made of stainless steel, monel or nichrome.

Automatic pickling machines are now in common use, carrying the work on trays and belts, and in rotating drums, through the pickling solution. Such machines for volume work have automatic control of the temperature of the solution and wash waters and of the speed at which the parts travel. A uniform pickling is thus assured, as well as a thorough rinsing and drying. For small or intermittent volume work, however, tanks or tubs are generally used with excellent results.

Pickling of Copper and Copper Alloys (including the tin bronzes, phosphor bronzes, manganese bronzes, naval

brasses and aluminum brasses). These alloys, with scale consisting largely of cupric oxide, cuprous oxide, and zinc oxide, are generally pickled in dilute sulfuric acid of the following composition: concentrated sulfuric acid (H_2SO_4, sp gr 1.83) 5 to 10% by vol; the rest, water.

This solution is used from room temperature to between 125 and 150 F. Heating to higher temperatures increases the amount of objectionable fuming and corrosion of equipment without substantially increasing the speed of pickling. The strength and temperature of the solution, as well as the duration of immersion, vary with the alloy being cleaned and the amount of oxides present. A small amount (less than 1%) of copper sulfate may be added to the fresh solution to increase the initial speed of reaction.

Cuprous oxide (sometimes called "red oxide") is only slightly soluble in sulfuric acid; consequently, after pickling in dilute sulfuric acid, brasses may have red stains caused by such undissolved oxide. A stain of similar appearance may also result from a film of copper deposited galvanically, or from localized superficial dezincification. These stains may be eliminated by immersion of the metal in the following solution:

Concentrated sulfuric acid (H_2SO_4, sp gr 1.83) 4 to 10% by volume
Sodium bichromate ($Na_2Cr_2O_7$, commercial) 4 to 8 oz per gal of solution
Water, remainder

This solution is operated at temperatures from 80 to 120 F. The articles should first be pickled in sulfuric acid and then immersed in the bichromate solution to remove red stains. The duration of immersion is determined best by trial; too brief an immersion leaves stains and too long a dip etches the metal.

Commercial ferric sulfate may be used instead of sodium bichromate. About 10 to 25 oz per gal of ferric sulfate is used in a solution containing 4 to 10% by volume of sulfuric acid at temperatures up to 150 F. The ferric sulfate should be dissolved completely before being used. It has been found that this solution has less tendency than the bichromate to etch the metal, although the finish and color are not exactly the same as obtained with the bichromate solution.

Great care should be taken to rinse the metal thoroughly after treating with the above solutions. Generally several water washes, both hot and cold, are used, and sometimes a hot solution of 1 to 2 oz per gal of soap, which neutralizes any residual acid remaining on the metal. The parts should then be dried completely, in hot air, sawdust or by other means to avoid water stain.

Bright and Matte Dipping. When a bright lustrous finish is desired, the metal should first be pickled in the sulfuric acid pickle, and then given a "scale" dip, and finally a bright dip. The pickling removes oxides and the scale dip prepares the surface for the bright dip that follows. Scale dips and bright dips consist of sulfuric and nitric acids, in proportions that vary greatly from plant to plant. In general, nitric acid will speed up the action of the dip, and sulfuric acid will slow it down. The following dips are typical:

Scale Dip

	A	*B*
Concentrated nitric acid (HNO_3, sp gr 1.40)	40%	50% by volume
Concentrated sulfuric acid (H_2SO_4, sp gr 1.83)	30%	....
Concentrated hydrochloric acid (HCl, sp gr 1.16)	0.5%	....
Water	29.5%	50%

Bright Dip

Concentrated nitric acid (HNO_3, sp gr 1.40)	25% by volume
Concentrated sulfuric acid (H_2SO_4, sp gr 1.83)	60% by volume
Concentrated hydrochloric acid (HCl, sp gr 1.16)	0.2% by volume
Water	Remainder

These solutions are used at room temperature. Parts are immersed in the scale dip, are rinsed in water, are immersed in the bright dip and rinsed immediately in cold running water; then they are rinsed in a sodium cyanide solution (2 to 4 oz of sodium cyanide per gal) to remove any acid stains, are rinsed in water again and dried. Care must be taken to clean off the acid completely before dipping the work material in the cyanide; otherwise, deadly hydrocyanic acid gas may form.

In some plants, it is customary to add wood soot to the bright dip to ensure uniformity of brightness on the surface of the dipped articles. The soot is stirred in and then skimmed off, a procedure that is said to overcome the effect of too much hydrochloric acid, which results in irregular brightness.

A matte surface can be obtained after bright dipping, rinsing and drying, by using the following typical solution, which should be agitated occasionally:

Concentrated nitric acid (HNO_3, sp gr 1.40)	65% by volume
Concentrated sulfuric acid (H_2SO_4, sp gr 1.83)	35% by volume
Zinc sulfate ($ZnSO_4$, commercial)	1 lb per gal of solution

This dip is used at 180 F. The parts are dipped, rinsed and dried in the usual manner.

All the above solutions should be provided with an adequate ventilating system.

Pickling of Aluminum Bronzes. Since aluminum bronzes are very difficult to pickle and dip because of the presence of aluminum oxide, it is recommended that they be annealed in a nonoxidizing atmosphere. Alloys that contain up to 7% Al are pickled in a sulfuric acid solution, such as that used for brass. This treatment leaves the metal clean but dull in color, because aluminum oxide is not soluble in sulfuric acid. A solution containing approximately 3% by volume of sulfuric acid and 3 to 4 oz per gal of sodium bichromate, may be used. A bright finish is obtained only by mechanical cleaning, and alloys with more than 7% Al must have a mechanical treatment in order to remove any oxides that are present.

Pickling and Bright Dipping of Silicon Bronzes. Because of the refractory nature of silicon oxide and the insolubility of it in any acid except hydrofluoric, it is advisable to anneal silicon bronzes in a protective atmosphere. However, if the metal has been subjected to an oxidizing atmosphere, a sulfuric acid pickle (5 to 10% of H_2SO_4 by volume) is sometimes used in order to remove copper oxide from the metal, although the silicon oxide is unattacked and the metal is left with a dull finish. Where a clean bright surface is required, the following dip is used after a sulfuric acid pickle:

Concentrated sulfuric acid (H_2SO_4, sp gr 1.83)	5% to 10% by volume
Concentrated nitric acid (HNO_3, sp gr 1.54)	10% to 20% by volume
Commercial hydrofluoric acid (HF, 52%)	3% to 5% by volume
Water	Remainder

Great care should be taken when using this dip. Metal or ceramic tanks are not suitable, because they are attacked by the solution. A wax or carbon-base lining material must be used and the tank should be provided with a hood and an exhaust to remove dangerous acid fumes. The dip should be employed at room temperature, and parts should be rinsed carefully after they have been removed from the solution. This solution is extremely powerful and workmen should be protected carefully from any contact with the fumes or the liquid.

Pickling and Bright Dipping of Nickel Silvers and Cupro-Nickels. The nickel silvers may be pickled and bright dipped with the same solutions as brass and copper.

Cupro-nickels may be pickled in a bichromate bath of the kind used for brass, or in a ferric sulfate bath that contains up to 25% ferric sulfate in a 5 to 10% sulfuric acid solution at temperatures up to 150 F. Cupro-nickels may be bright dipped in the usual solution employed for brass.

Defects from Pickling. By far the most common defect encountered in pickling is the presence of red stain on the metal. It has been mentioned that, when caused by cuprous oxide, this defect may be removed in a bichromate or ferric sulfate pickle. However, red stains may also result from the presence of metallic iron or steel in the pickling solution, causing copper to plate out on the parts because iron is anodic to copper. Great care must be taken to prevent any stray pieces of iron, such as nails or tools, from entering the pickling solution.

Oil and lubricants remaining on formed metal are a source of much trouble in pickling and dipping. If formed material is to be bright dipped directly after having been pressed, it should be degreased because otherwise the

lubricant remaining will prevent the dip from being effective. Also if the work is to be annealed and pickled, it should be degreased (usually a hot water rinse is sufficient) since the oil may cause excess cuprous oxide to form during annealing, with unwanted red staining as a result. In extreme instances, the more volatile constituents of the oil burn off readily, leaving a carboniferous deposit that cannot be removed except mechanically.

Acid stains will appear on the metal if it is not thoroughly rinsed and cleansed of all remaining acid after pickling or dipping. At least two separate washings in water or one thorough running-water wash should be used before drying. A dip in a soap solution or buffered salt solution will neutralize traces of acid.

The metal will be etched or pitted if it is immersed for too long in a pickling solution or dip, or if the solution is too strong or too hot. The proper conditions for operation may be found quickly by a trial of time, temperature, and concentration of solution.

Surface Preservation and Decoration

Immediately before the final assembly of small manufactured articles, the surface finish is often protected by application of a clear transparent lacquer or is decorated by a type of colored enamel. The coating should be adhesive, tough, highly resistant to abrasion and perspiration, and relatively impervious to sulfur fumes.

Often it is desired to preserve the natural colors of copper alloys. In such instances clear finishes are applied, such as air-drying lacquers or synthetic ones of the baking type. The actual selection of the finishing material will be affected by the conditions of use of the product, the number of parts to be finished, the size and shape of the parts, the cost and method of application.

An operator should wear soft cotton gloves when handling the material after the cleaning operation and before lacquering. Enamels or lacquers should not be applied to metals that are even a little dirty. Work pieces should be lacquered promptly after cleaning.

Methods of Application for Lacquers or Enamels. *Hand Brushing.* A soft, firm bristle or camel's-hair brush is used, and the finish should be flowed on with little or no rebrushing.

Hand Spraying. The material is finely atomized in a spray gun by means of compressed air. Striping can be effected with a small spray gun; the other extreme is a fan spray of 15 in. A good smooth coat requires an experienced sprayer. A single coat may be from 0.0002 to 0.002 in. thick.

Automatic Machine Spraying. This method is suited to large-volume production, since the atomizing gun is mechanically operated as the work passes by it.

Dipping by Machine. The work material is mechanically withdrawn, slowly and uniformly, with little or no vibration, from the clear cellulose or synthetic lacquer. This method produces a uniform film, except on edges, and is economical of material. Sometimes this process is limited by the shape of the product.

Basket Bulk Dipping. The work material is placed in screen baskets, is immersed in the clear lacquer and withdrawn; the excess is allowed to drain off while the baskets are revolving slowly in an oblique frame; then the work pieces are dried in an oven, where they are rotated manually or mechanically in order to prevent them from sticking together. This can be the least costly lacquering procedure when protection until use is all that is required. Parts that nest together, or flat pieces, are not adaptable to bulk lacquering.

Centrifuging. The work material in screen baskets is immersed in the clear lacquer and withdrawn; the excess lacquer is allowed to drain back into the container; and then the basket is placed in a centrifuge and whirled for 30 sec in one direction, and for 30 sec in the opposite direction. The pieces are transferred to an oven and dried, after shaking once or twice to prevent sticking.

Barrel Tumbling. Small, lightweight pieces that cannot nest are placed in an oblique, wide-mouth barrel (made of brass, stainless steel or monel) revolving at about 30 rpm. A small quantity of lacquer (for instance, 2 oz) is applied to the inside of the barrel, whence it is transferred to about 25 lb of work, coating only the outside of the shells that have a cup shape. The parts are dried in an oven, with periodic agitation, and are then baked to polymerize the film. One coat of lacquer is not sufficient to give a continuous film, so barrel tumbling is used only with baking finishes that enable the application of several coats.

An orifice type of viscosity cup is desirable for checking the viscosity of the lacquers or enamels in order to maintain uniformity.

Characteristics of the seven methods of application are summarized in Table I.

Table I. Characteristics of Methods of Application for Lacquers or Enamels

Method	Optimum Appearance of Finish	Optimum Durability of Finish	Material Consumption	Relative Labor Cost
Hand brushing	Fair	Fair	Low	High
Hand spraying	Excellent	Excellent	High	High
Automatic machine spraying	Excellent	Excellent	Very high[a]	Very low
Machine dipping	Excellent	Excellent	Low	Low
Basket bulk dipping..	Fair	Fair	Low	Very low
Centrifuging	Good	Good	Low	Very low
Barrel tumbling.....	Good	Excellent	Low	Low

(a) May be reduced by the use of electrostatic equipment.
NOTE. Containers may be made of 18% nickel silver, chromium-plated or silver-plated brass or ceramic.

Enamels. Enamels are essentially clear lacquers, air-drying or baking, in which pigments and plasticizers have been incorporated. They may have a high luster or a dull finish. Because of differences in characteristics of the available pigments, coverage, tendency to "bleed", and light fastness will vary for different colors.

With the use of stencils to blank off areas, enamels of air-drying or baking types are often employed to decorate a brass article with attractive designs. The air-drying types are always soluble in the solvents in which they were originally mixed; after baking, the baking types are not soluble in their original solvents, since baking polymerizes the coating to an insoluble condition. Ingenious mechanical devices have been constructed to apply enamels in patterns, by roller coating, screen stenciling and printing.

Some products are made with depressed designs in the metal, so that after clear lacquering or enameling, these designs can be filled in with colors. The process involves hand painting the parts with a quick-drying oil paint, drying them, and wiping off excess paint with a rag.

For most articles, more than one type of lacquer or enamel will be satisfactory. If ovens that circulate hot air with automatically controlled temperatures or infrared heat, are not available for baking the finish, an air-dry lacquer or enamel should be used. If equipment for baking is available, a baked finish can be the least expensive, because of reduction in the number of coats necessary to obtain the same thickness of film. Baking enamels may be sprayed with a total content of solids of 50%; 25% is high for this content in an air-drying nitrocellulose lacquer enamel.

In the coating of copper alloys, it is not necessary for the first coat of enamel to contain a passivating pigment, as is often desired with steel, in order to prevent rusting. Sometimes it is desirable to use for the first coat an enamel and lacquer with especially good adhering qualities, and in special instances it is desirable to roughen the surface by sandblasting or by dipping in acid to attain superior adhesion.

Tables II and III list factors relating to the lacquer finishes that are used most extensively at present.

All solvents used in lacquers and enamels, are toxic to some extent if breathed in regularly. Therefore, positive ventilation by suction should be provided to protect the operator. All solvents have two fundamental properties that should govern any design for ventilation: (*a*) When *cold*, every solvent is heavier than air and naturally flows downward. (*b*) When solvents are *hot*, convection currents more than offset gravity, so hot solvents rise.

Table II. Air-Drying Lacquers and Enamels (Thermoplastic)

Chief Ingredients	Outstanding Good Characteristics	Important Limitations
Nitrocellulose-resin	Compatibility with resins and solvents; nearly colorless, cheap, quick drying	Temperature, 180 F
Cellulose acetate-resin	Better resistance to heat and light than nitrocellulose	Few solvents available, few resins compatible
Cellulose acetate-butyrate resin	Outdoor durability	Few resins compatible, cost high
Ethyl cellulose-resin	Good resistance to alkalies	Ready solubility in many solvents
Polyvinyl-resin	Resistance to acids and alkalies	Ready solubility in ketones and chlorinated solvents
Natural resins (as shellac)	Excellent adhesion	Easily scratched
Methacrylates	Clarity	High cost

NOTES. The nitrocellulose-resin mixtures are the most widely used. "Blushing" is a term applied to whitening caused in the lacquer film when moisture condenses in the wet coating. This is a result of the cooling effect from the rapid evaporation of the solvents in an atmosphere of high humidity. Blushing may be corrected by the addition of up to 10% of solvents that evaporate slowly. Air-conditioned rooms eliminate this atmospheric problem.

Paste wax of the rubbing type may be used to advantage over a lacquer or enamel. Wax will ordinarily increase substantially the durability of a finish to be used outdoors. It can also be employed to advantage on indoor applications, such as railings that are subjected to considerable perspiration from continual handling. In such instances, regular waxing with a moist rag will remove most of the deleterious perspiration, while maintaining a wax coat that protects the lacquer.

Cleaning and Electroplating

The process of cleaning fabricated parts made of copper and copper alloys, in preparation for electroplating and lacquering, is comparatively simple, presenting fewer difficulties than are found with various other metals and alloys. Adequate cleaning is very important because it is essential that oil, grease, dirt, and buffing composition be entirely removed; otherwise, results of the subsequent operations will be unsatisfactory.

Metals such as gold, silver, nickel and chromium are electrodeposited on copper and copper alloys, primarily for decorative purposes and for preventing tarnish. A light deposit will give satisfactory protection, whereas a much heavier coating is needed on some other metals.

Coloring and Chemical Dipping

Immersion Plating of Copper and Copper Alloys. All articles must be thoroughly cleaned and bright dipped before being treated in the following solutions in order to obtain the desired coatings. A short immersion is all that is required in either the gold or the silver solution. After removal from any of the following baths, articles should be rinsed in cold water, then in hot water, and dried.

Silver

Silver nitrate ..... 1.25 oz per gal
Sodium cyanide ..... 2 oz per gal

Use a stoneware or agateware receptacle. Temperature should be approximately 110 F.

Gold

Sodium gold cyanide ..... 0.5 oz per gal
Sodium cyanide ..... 2.5 oz per gal
Sodium carbonate ..... 2 oz per gal

Use a stoneware or agateware receptacle. Temperature should be approximately 180 F.

Tin

Stannous chloride ..... 4 oz per gal
Caustic soda ..... 8 oz per gal

Use a steel tank and operate the bath at approximately 195 F. The fabricated articles must be spread out on steel mesh and covered with strips or sheets of perforated tin for about 2 hr.

Table III. Baking Lacquers and Enamels (Thermosetting)

Chief Ingredients	Outstanding Good Characteristics	Important Limitations
Urea-formaldehyde	Hard, colorless; resistant to chemicals	Temperature, 300 F
Melamine	Colorless, resistant to alkalies and high temp	High cost
Alkyds (glycerol-phthallic acid)	Outdoor durability, excellent adhesion	Slightly yellow; not so hard as urea-formaldehyde
Phenol-formaldehyde	Resistant to chemicals	Darkens in light
Polyvinyl-resin	Highly resistant to acids and alkalies	High cost

NOTES. The urea-formaldehyde, alkyds and phenol-formaldehyde mixtures are the most extensively used. The different kinds are often combined in order to obtain the required characteristics in the finished product. The baking schedules are for 5 to 60 min at temperatures from 250 to 350 F.

Coloring of Copper or Copper Alloys Containing 85% Cu or More. Yellow brass articles are often copper-plated and treated as copper in the following solutions:

Reddish Bronze to Dark Brown (Statuary Bronze). Either of the following solutions may be used:

Solution A

"Liquid sulfur" ..... 1 oz
or
Potassium sulfuret (liver of sulfur) ..... 2 oz
Aqua ammonia (sp gr 0.89) ..... ¼ oz
Water ..... 1 gal

Use solution at room temperature.

Solution B

Potassium sulfuret (liver of sulfur) ..... 2 oz
Caustic soda ..... 3 oz
Water ..... 1 gal

Use solution at approximately 170 F.

The depth of the shade can be controlled by the strength of the solution and the duration of immersion. After the articles have been removed from the bath they should be rinsed thoroughly in cold water, then in hot water, and dried either in hot sawdust or with an air blast. The desired finish is obtained by dry scratch-brushing on a fine wire wheel, and then finally by lacquering.

Steel Black.

Arsenious oxide (white arsenic) ..... 4 oz
Hydrochloric acid (sp gr 1.16) ..... 8 fluid oz
Water ..... 1 gal

Use solution at approximately 180 F. Immerse the articles in the above solution until a uniform color is obtained. Scratch-brush while wet, then dry and lacquer.

Black. Several proprietary processes are available for producing a satisfactory black finish on copper and copper alloys.

Coloring of Brass. All articles should be cleaned thoroughly and bright dipped before they are placed in the following solutions.

Black. Place a suitable quantity of brass articles in an oblique tumbling barrel made of stainless steel, and cover them with warm water; usually 3 to 5 gal is sufficient. Dissolve 3 oz of copper sulfate and 6 oz of sodium thiosulfate in warm water in a separate container, and add to the contents of the barrel. Tumble the articles for 15 to 30 min to obtain the desired black finish. Drain the solution from the barrel and wash the articles thoroughly with clean water. Remove articles from the barrel, dry them in sawdust or with an air blast, and lacquer them if desired.

Blue Black.

Copper carbonate ..... 1 lb
Ammonium hydroxide (sp gr 0.89) ..... 1 qt
Water ..... 3 qt

Mix the copper carbonate thoroughly with the ammonium hydroxide, and then add the water. This solution should be used at approximately 175 F. It is desirable to have an excess of copper carbonate present. Immerse the work pieces until the proper color is obtained, which should be in about one minute. Remove the pieces, rinse them in warm water, and immerse in a hot cleaning solution made by adding 2 to 4 oz of alkaline cleaner per gal of water. Rinse the articles thoroughly, first in cold water, then in hot water, dry, and lacquer.

Black Anodizing *

Caustic soda ..... 16 oz
Water ..... 1 gal

Use the solution in ■ steel tank, and operate at 180 to 210 F with adequate ventilation. Cathodes may be steel, carbon or graphite, and the brass articles serve as anodes. Anode to cathode ratio, approximately 1:1. Current density, ■ to 10 amp per sq ft at 6 v. Plating cycle, 45 to 225 sec. After the articles have been anodized, wash them in hot and cold water, and then rinse them in clean hot water. Dry, buff lightly with a soft cloth wheel, and lacquer if desired.

*McLean and Young, Metal Finishing, June 1945

Brown

Solution A

Copper sulfate	4 oz
Potassium chlorate	8 oz
Water	1 gal

Solution B

"Liquid sulfur"	1 oz

or

Liver of sulfur	2 oz
Water	1 gal

First immerse the articles in Solution *A* for approximately one minute. Then without rinsing, immerse in Solution *B* for a short time. The articles should then be rinsed in cold water, and the dipping operation should be repeated in both solutions until the desired color is obtained. Finally, rinse the work in hot water, dry in hot sawdust or with an air blast, scratch-brush with a fine wire wheel, and lacquer.

Old English Finish (Light Brown)

Solution A

"Liquid sulfur"	½ oz

or

Liver of sulfur	1 oz
Water	1 gal

Solution B

Copper sulfate	2 oz
Water	1 gal

Immerse the articles in Solution *A* and, without rinsing them, immerse in Solution *B*. Then rinse them in cold water, and repeat the dipping operations until a light color is produced. For a uniform finish, scratch-brush and then repeat the dipping operations, first in Solution *A* and then Solution *B*, until the desired color is obtained. Finally, rinse the pieces thoroughly in cold and hot water, dry them in sawdust, scratch-brush on a fine wire wheel, and lacquer. A great variety of colors can be imparted to the surface of copper and copper alloys by the electrocoloring method.

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The Resistance of Copper and Wrought Copper Alloys to Corrosion

BY THE SUBCOMMITTEE ON CORROSION OF COPPER*

SINCE ancient times, many of the applications of copper and of copper alloys have been based on high resistance to corrosion. Copper is highly resistant to the atmosphere, to naturally occurring waters, both fresh and salt, and to alkaline solutions, except those that are distinctly ammoniacal. The behavior of copper in contact with acids depends largely on oxidizing conditions, which affect it adversely. Copper has good resistance to many saline solutions but offers low resistance to sulfur and sulfur compounds, which produce a corrosion product of copper sulfide. When such solutions as sea water and brine move at high velocities against copper, they can damage it seriously.

The commercial copper alloys cover a wide range of composition and accordingly display considerable variation in resistance to corrosion. Many of these alloys overcome deficiencies of the parent metal and may offer further improvements in physical or mechanical properties. Other alloys may have certain superior characteristics at the expense of some resistance to more aggressive exposures.

Through the years, experience has suggested many uses for which the copper alloys are suitable and superior to other obtainable materials. These uses include:

1 Roofing, insect screen cloth, window frames, hardware, and other products that must withstand atmospheric exposure.
2 Fresh-water supply lines requiring superior resistance to corrosion by various types of water and sometimes to corrosion by soil.
3 Equipment used in contact with sea water—usually water supply lines and heat exchangers, including condensers; also shafting and marine hardware.
4 Heat exchangers and condensers in general, subject to certain limitations at higher temperatures.
5 Equipment for industrial and chemical plants, involving exposure to a wide variety of materials, including acid, alkaline or saline solutions.

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The comprehensive tests conducted under the supervision of the American Society for Testing Materials[1,2] have confirmed the general excellence of copper and copper alloys for atmospheric exposures. Other prolonged tests[3] have indicated that there is little or no difference among the several available brands of copper with regard to behavior in the atmosphere. Copper and many copper alloys are well suited to resist all but the most corrosive soils, a fact that has been demonstrated by experience and by the extensive tests conducted by the National Bureau of Standards.[4,5]

Types and Causes of Corrosion. *General or Uniform Thinning.* Under many conditions of service, exposed surfaces of copper and copper alloys corrode uniformly. In indoor exposures or in contact with outdoor rural, industrial and marine atmospheres, the rate of attack is extremely slow. Duration of service is often measured in hundreds of years. The surface of the metal may be only slightly tarnished in very mildly corrosive environments, or may gradually acquire a thin adherent brown or black coating of corrosion product or, in many instances, a green patina.

Corrosion of copper and many alloys of copper is usually general or uniform when it results from long contact with fresh, brackish or salt waters, many types of soil, neutral, alkaline or acid salts, organic acids, sugar juices or other chemicals. The rate of corrosion will vary in such services, depending not only on the corroding mediums but also on the degree of aeration, the presence of oxidizing materials, temperature, velocity of the mediums flowing over the surfaces, and other factors. It is not unusual to measure the duration of service in such applications in periods of 20 to 30 years or longer.

Copper alloys corrode uniformly but more rapidly in contact with mediums that do not permit the formation of protective films or that continually dissolve any films

that do form over the metal surfaces. Thus, oxidizing salts and acids, or salts and acids in the presence of oxygen or an oxidizing agent generally attack the metal in such a way that uniform thinning of the metal results. Both aqueous ammonia and solutions of cyanides cause uniform thinning also. Copper alloys may be entirely unsuitable for use under certain conditions where the above corrodents are present; but, in other applications, copper or alloys of copper have been employed to a considerable extent when the uniform thinning of the material is sufficiently retarded to assure a reasonably long period of usefulness. The use of the copper alloys under such conditions requires a complete study of all factors affecting each individual application, supplemented in many instances by field and laboratory tests.

Pitting. The copper alloys, in common with all commercial metals and alloys, undergo corrosion of the pitting type when exposed to some conditions of service. Sometimes pitting may be general over the entire exposed area; then the metal has an irregular and roughened appearance. In other instances, the metal may be pitted in relatively few areas. Pitting is usually associated with one of the following basic causes: (1) an incomplete protective film or corrosion product or a nonprotective deposit of scale, corrosion product or both over the metal surface; or (2) extraneous deposits that lodge against metal surfaces for considerable periods of time.

In technical publications, the pitting of copper and copper alloys has been described by various terms, such as "deposit attack", "erosion-corrosion", "impingement attack", and "concentration-cell action". The pitting action may be considered electrochemical in character, resulting from the formation of local cells at the metal surface. The term "deposit attack" is usually limited to a pitting action that occurs, under certain service conditions, in the immediate vicinity of foreign deposits, such as sand, stone, wood or clinkers, on the metal surface. Erosion-corrosion action or impingement attack is generally experienced where gases, vapors or liquids impinge on the metal surfaces at relatively high velocities. The erosive action removes protective films from localized areas at the metal surface, thereby contributing to the formation of differential cells at such areas and to localized pitting of the anodic points of the cells. These specialized examples of pitting, as well as other types of pitting initiated by scales or corrosion products of a porous, friable, unprotective type, may all be classified as forms of concentration-cell or solution-cell action.

The pitting of copper and the copper alloys is not sufficiently serious to interfere with the economical use of these materials in most applications. Probably pitting occurs most frequently when the metal is in contact with mediums that contain lower compounds of sulfur, or in contact with polluted or contaminated waters that are salty and brackish. It is often possible to prevent or minimize severe corrosion of the pitting type by proper choice of alloy, by changes in design, by filtering or screening mediums that contact the metal, by frequent cleaning of metal surfaces or by other methods indicated after an inspection.

Dezincification. Certain copper-zinc alloys and, less frequently, aluminum bronze and cupro-nickel, undergo corrosion of a type that, in the copper-zinc alloy, is termed "dezincification". The initial corrosion in this type of attack is followed by a secondary reaction in which copper, in the corrosion product, is redeposited in a porous, friable and weak mass on the metal surface. Corrosion of a similar nature continues beneath the primary deposit of copper, resulting in the gradual replacement of sound metal by brittle, porous copper. Action of this kind, unless arrested, eventually penetrates the cross section of the metal, weakening it structurally and resulting in leakage through the porous copper layer in conduits for conducting liquids. Dezincification that occurs at localized areas on the metal surface is termed "plug-type dezincification". The dezincification of brasses usually occurs in contact with sea water or with fresh waters that have a high content of oxygen and carbon dioxide. Dezincification is particularly active at elevated temperatures.

At present the dezincification of brasses is not a serious corrosion problem, since copper, red brass or several yellow brasses, containing inhibitors of dezincification, can be used in applications where dezincification has been experienced or is anticipated.

*Stress-Corrosion Cracking (Season Cracking).** Under certain specific corrosive conditions, brasses and some other copper alloys that are stressed as a result of cold working or that are stressed by loads externally applied in service, sometimes fail as a result of stress-corrosion cracking or season cracking. In addition to the primary factors of stress and corrosion that influence failures of this type, time and temperature of exposure are also important controlling factors. Ammonia or some ammonium compounds are the special corrosive agents that contribute to such failures. There is evidence that oxygen, carbon dioxide and moisture also influence the action. Contact with mercury and mercury compounds will induce cracking of susceptible materials. The stresses responsible for cracking are high constant tensile stresses acting at the surface of the metal. Failures from stress-corrosion cracking are primarily intercrystalline; however, cracks may pass through grains if no grain boundaries are suitably oriented.

The stress-corrosion cracking of brasses may be overcome by various means, the most important of which may be listed as follows: (1) selection of alloys known to have high resistance to failures of this type; (2) thermal stress-relieving where stresses are residual or have resulted from cold working operations; (3) the use of protective coatings over the metal surfaces, such as electroplates, lacquering or painting; (4) improvement of the environment.

Corrosion-Fatigue Cracking. The combined action of corrosion, usually of the pitting type, and cycle stressing of copper and copper alloys may result in corrosion-fatigue cracking of the material. Cracking of this type is predominantly transcrystalline and is characterized by the localized nature and abruptness of the failure, with very little distortion of the part as a whole. Cracks generally take a direction at right angles to the maximum tensile stress in the affected region. The combination of alternating stress and corrosion, acting simultaneously, is considerably more damaging than either one acting alone. Besides resisting corrosion effectively, copper and the copper alloys also offer very good resistance to failures of the corrosion-fatigue type in the many applications of copper materials that involve repeated stressing and corrosion. These applications include such parts as springs, switches, diaphragms, bellows of the sylphon type, piping and tubing in gasoline and oil lines of aircraft and automobiles, tubing for condensers and heat exchangers, and Fourdrinier wire in the paper industry. Obviously those alloys of copper that have a high endurance limit and that offer high resistance to corrosion under any specific condition, will be most serviceable in applications involving repeated stress and corrosion. Some of the alloys frequently used for service of this kind include beryllium copper, phosphor bronze, aluminum bronze and cupro-nickel.

Intercrystalline Corrosion. Another manifestation of intercrystalline attack, perhaps allied with stress-corrosion cracking, is best referred to simply as "intercrystalline corrosion or solution". In this type of attack, the metal is penetrated along grain boundaries and mechanical stress is apparently not a factor. The attack may be noted under the microscope to a depth of several grains, distinguishing it from ordinary surface roughening where intercrystalline penetration, one or two grains in depth, is sometimes noted. Apparently only a very few alloy compositions are susceptible to this more serious general intercrystalline corrosion, observed rather infrequently.

Galvanic Corrosion. Copper rarely suffers galvanic corrosion as a result of contact with other metals. The reason for this is apparent from examination of the electromotive series of elements, listed in Table I. Copper is cathodic to the commonly encountered metals—iron, zinc, aluminum, magnesium, lead and tin. Of course there are many conditions in which galvanic corrosion does not proceed in accordance with the common electromotive series. The potential differences between dissimilar metals vary, depending on the nature of the corrosive environment.

*** For a more detailed discussion of the stress corrosion of copper alloys, the reader may refer to the article on page 231 of this Handbook.**

Table II lists the potentials that have been observed between couples of copper and several copper alloys when immersed as freshly abraded specimens in a dilute synthetic solution of sea water. Potential differences observed for couples of copper-base materials with other common metals, under similar conditions, are qualitatively similar to the arrangement of the electromotive series of Table I, in that aluminum, iron, lead, nickel, tin and zinc are anodic to the copper-base materials. Laboratory corrosion tests of couples in this same type of solution have shown

Table I. Electromotive Series of the Common Metals[a]

Metal	Ion	Normal Electrode Potential, volts[b]
Gold	Au^{+++}	+1.36
Platinum	Pt^{+++}	+0.86
Mercury	Hg^{++}	+0.799
Silver	Ag^{+}	+0.798
Copper	Cu^{++}	+0.344
Hydrogen (atm)	H^{+}	0.000
Lead	Pb^{++}	−0.12
Tin	Sn^{++}	−0.14
Nickel	Ni^{++}	−0.23
Cadmium	Cd^{++}	−0.40
Iron	Fe^{++}	−0.44
Chromium	Cr^{++}	−0.56
Zinc	Zn^{++}	−0.762
Aluminum	Al^{+++}	−1.33
Magnesium	Mg^{++}	−1.55

(a) U. R. Evans, "Metallic Corrosion, Passivity and Protection", Edward Arnold & Co., London, 1937, p 264
(b) Potential in salt solution of normal ionic activity relative to the normal hydrogen electrode as an arbitrarily chosen zero point

that the use of steel, wrought iron, aluminum, zinc and lead, in combination with copper alloys in water solutions, is likely to result in severe corrosion of the noncopper alloy. Similar tests have indicated that, despite any contrary expectation based on the measurements of potential, nickel, monel metal, tin and stainless steel may usually be coupled with copper alloys with satisfactory results.

Table II. Potential Differences (in volts) Between Various Copper Alloys in Dilute Synthetic Sea Water[a] [b]

	Red Brass	70–30 Brass	Muntz Metal	Aluminum Bronze	30% Cupro-Nickel	Aluminum Brass
Copper	+0.031	+0.047	+0.086	+0.048	+0.030	+0.053
Red Brass	....	+0.038	+0.043	+0.005	−0.012	+0.013
70–30 Brass	....	....	+0.013	−0.033	−0.011	0.00
Muntz Metal	....	....	....	−0.030	−0.042	−0.016
Aluminum Bronze	....	....	....	....	−0.017	+0.010
30% Cupro-Nickel	....	....	....	....	....	+0.027

(a) H. L. Burghoff, "Corrosion of Metals", American Society for Metals, 1946, p 100
(b) Solution one-sixth the usual strength of sea water

With regard to couples of two different copper-zinc alloys, it will be noted that the more anodic materials are the ones of higher zinc content, although even in such combinations the differences in potential are not great. These data accord with experience that galvanic corrosion of copper alloy couples is uncommon. Laboratory corrosion tests in the same series mentioned above indicated that there was virtually no acceleration of corrosion as a result of contact between any two copper alloys. Occasional examples have been observed of the failure by dezincification of Muntz metal nipples used in red brass (85% Cu, 15% Zn) plumbing lines. Failure in such instances may have been hastened by galvanic action, but this is not certain, because it is known that Muntz metal is far inferior to red brass in resistance to naturally occurring waters and that it dezincifies quite readily even when not in contact with other metals.

LaQue and Cox,[7] who determined the potentials of a number of copper alloys and other alloys in sea water, noted only slight differences among the copper alloys.

Effect of Alloy Composition. *The Brasses.* The copper-zinc alloys or brasses range from 55 to 100% Cu, with the remainder essentially zinc. The alloys that contain 55 to 80% Cu are susceptible to dezincification in many natural fresh waters, sea water and numerous aqueous solutions. An increase in copper content to approximately 85% or more renders the alloys virtually immune to dezincification in these mediums. The 85% Cu—15% Zn alloy, red brass, is considered to have the best general resistance to corrosion among the brasses.

In other mediums, the resistance to corrosion of the copper-zinc alloys may improve with a decrease in copper content. In sulfide-bearing solutions and vapors, the 60% Cu—40% Zn alloy, Muntz metal, may corrode at a rate 1/100 as rapid as that of copper or red brass.

Brasses containing more than 80% Cu are highly resistant to stress-corrosion cracking, but those containing 80% Cu or less are highly susceptible to this type of cracking.

Some elements such as lead, tellurium, selenium, beryllium and manganese, as found in certain common commercial coppers and copper alloys, have no significant effect on resistance to corrosion.

Tin-Bearing Brasses. The addition of ¾% Sn to Muntz metal results in the familiar naval brass, 60% Cu, 39¼% Zn, ¾% Sn. In this alloy tin serves chiefly as an inhibitor that lessens the possibility of dezincification under service conditions. Naval brass, however, does not resist dezincification very effectively. The addition of 1% Sn to the 70% Cu—30% Zn alloy to produce admiralty metal (71% Cu, 28% Zn, 1% Sn) lessens the possibilities of rapid dezincification. The further addition of a dezincification inhibitor, such as arsenic, antimony or phosphorus, reduces still further the possibility of this type of attack.

Aluminum Brass. The addition of aluminum to the copper-zinc alloys leads to a marked increase in resistance to impingement corrosion; that is, the resulting alloy exhibits greatly improved resistance to rapidly flowing, turbulent sea water. For example, 2 to 2.25% Al is added to the 60% Cu—40% Zn alloy in the production of propeller bronze, and to the 75% Cu—25% Zn alloy in the production of aluminum brass tubing for condensers. The aluminum brass, however, is still susceptible to dezincification. This weakness is reduced by the use of an inhibitor of dezincification, such as arsenic, antimony or phosphorus.

Arsenic, Antimony and Phosphorus in Brasses. The addition of such elements as arsenic, antimony and phosphorus has been found to prevent or to minimize dezincification in admiralty metal and aluminum brass under a number of conditions. Concentrations of 0.02 to 0.05% As, Sb or P have been found effective in these alloys. These inhibiting elements are used also in certain other brasses containing less than about 85% Cu; the actual amounts vary with the alloy.

Copper-Tin Alloys. The addition of tin to copper to produce the phosphor bronzes, which may also contain as much as 0.35% P, improves resistance to corrosion from contact with flowing sea water and most acids, except hydrochloric acid. In general, very uniform corrosion takes place in the wrought bronzes that contain from 5 to 10% Sn. This group of alloys is much less susceptible than brass to stress-corrosion cracking.

Copper-Nickel Alloys. The most common copper-nickel alloys are 70% Cu—30% Ni and 80% Cu—20% Ni. The 70% Cu—30% Ni alloy is widely used in the form of condenser tubing for the construction of marine condensers, because of its high resistance to attack by rapidly flowing sea water. The addition of approximately ½% Fe definitely improves the resistance of the 70% Cu—30% Ni alloy to impingement corrosion caused by sea water.

The 70% Cu—30% Ni alloy also resists effectively corrosion caused by alkalies and for this reason is widely used for storing and conveying alkaline solutions in chemical plants. This alloy is generally regarded as the best of the copper alloys now available for such applications.

The resistance of 70% Cu—30% Ni to corrosion by sulfide-bearing solutions and vapors appears approximately equal to that of red brass and, therefore, this alloy is less satisfactory than admiralty metal or Muntz metal. The 70% Cu—30% Ni alloy is apparently immune to the stress-corrosion type of failure.

Copper-Nickel-Zinc Alloys. The two most common nickel silvers contain 65 and 55% Cu, 18% Ni and the remainder zinc. The nickel silvers have good resistance to corrosion by fresh and salt waters. In saline solutions the resist-

Table III. Corrosion Ratings for Copper and Wrought Copper Alloys in Various Corrosive Mediums

This table is intended to serve only as a general guide concerning the behavior of copper and copper alloys in corrosive environments. It is impossible to cover in a simple tabulation the performance of a material for all possible variations of temperature, concentration, velocity, impurities, degree of aeration, and stress. It should be emphasized strongly that the table should be used with caution. The ratings shown in the tabulation are based on general performance.

The letters **a**, **b** and **c** have the following significance:

a The metal should be suitable under most conditions of use.

b Corrosion may be expected but the metal should be suitable under some conditions.

c Corrosion rates will usually be too high for successful use.

Corrosive Medium	Copper Gilding, 95%	Commercial Bronze, Leaded Bronze	Red Brass	Low Brass	Cartridge Brass*	Admiralty Metal	Naval Brass, Manganese Bronze	Aluminum Brass	Phosphor Bronze A 85-5-5-5 Casting	Phosphor Bronze C	Phosphor Bronze D, G & M Bronzes	Phosphor Bronze E	Cupro-Nickel 30%	Nickel Silver 18% Grade A	Nickel Silver 18% Grade B	Silicon Bronze Type A	Silicon Bronze Type B	Aluminum Bronze
Acetate solvents	a	a	a	a	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Acetic acid	a	a	a	b	c	c	c	c	a	a	a	a	a	a	b	a	a	a
Acetone	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Acetylene (1)	c	c	c	c	b	c	b	c	c	c	c	c	c	c	c	c	c	c
Alcohols (2)	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Alumina	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Aluminum chloride	b	b	b	c	c	c	c	c	b	b	b	b	b	b	b	b	b	b
Aluminum hydroxide	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Aluminum sulfate	a	a	a	b	c	c	c	c	a	a	a	a	a	a	a	a	a	a
Ammonia, moisture free	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Ammonia, moist gas	c	c	c	c	c	c	c	c	c	c	c	b	b	c	c	c	c	c
Ammonium hydroxide	c	c	c	c	c	c	c	c	c	c	c	b	c	c	c	c	c	c
Ammonium chloride	c	c	c	c	c	c	c	c	c	c	c	b	c	c	c	c	c	c
Ammonium nitrate	c	c	c	c	c	c	c	c	c	c	c	b	b	c	c	c	c	c
Ammonium sulfate	b	b	b	c	c	c	c	b	b	b	b	b	b	b	b	b	b	b
Aniline and aniline dyes	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b
Asphalt	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Atmosphere, industrial	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
marine	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
rural	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Barium chloride	a	a	a	b	c	a	c	a	a	a	a	a	a	a	a	a	a	a
Barium hydroxide, sulfate	a	a	a	a	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Barium sulfide	b	b	b	b	a	a	a	b	b	b	b	b	b	b	b	b	b	b
Beer (2)	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Beet sugar syrup	a	a	a	a	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Benzol	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Benzine	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Black liquor, sulfate process	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Borax	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Bordeaux Mixture	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Boric acid	a	a	a	b	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Butane	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Calcium bisulfite	a	a	a	b	c	b	c	b	a	a	a	a	a	a	a	a	a	a
Calcium chloride	a	a	a	b	c	a	c	a	a	a	a	a	a	a	a	a	a	a
Calcium hydroxide	a	a	a	a	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Calcium hypochlorite	b	b	b	c	c	c	c	b	b	b	b	b	b	b	b	b	b	b
Cane sugar syrups	a	a	a	a	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Carbon dioxide, dry	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Carbon dioxide, moist (2)	a	a	a	b	c	b	c	b	a	a	a	a	a	a	a	a	a	a
Carbonated beverages (2)	a	a	a	b	c	b	c	b	a	a	a	a	a	a	a	a	a	a
Carbon tetrachloride, dry	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Carbon tetrachloride, moist	b	b	b	c	c	b	c	b	b	b	b	b	a	b	b	b	b	b
Castor oil	a	a	a	a	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Chlorine, dry	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Chlorine, moist	b	b	b	c	c	c	c	c	b	b	b	b	b	b	b	b	b	b
Chloracetic acid	b	b	b	c	c	c	c	c	b	b	b	b	b	b	b	b	b	b
Chromic acid	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Citric acid	a	a	a	b	c	b	c	b	a	a	a	a	a	a	a	a	a	a
Copper sulfate	a	a	a	b	c	b	c	b	a	a	a	a	a	a	a	a	a	a
Copper nitrate	b	b	b	b	c	b	c	b	b	b	b	b	b	b	b	b	b	b
Corn oil (2)	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Cottonseed oil (2)	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Creosote	a	a	a	a	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Ethers	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Ethylene glycol	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Ferric chloride, sulfate	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Ferrous chloride, sulfate	b	b	b	b	c	b	c	b	b	b	b	b	b	b	b	b	b	b
Formaldehyde	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Formic acid	a	a	a	b	c	b	c	b	a	a	a	a	a	a	a	a	a	a
Freon	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Fuel oil	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Furfural	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Gasoline	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Gelatin (2)	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Glucose	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Glue	a	a	a	a	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Glycerin	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Hydrochloric or muriatic acid	b	b	b	c	c	c	c	c	b	b	b	b	b	b	b	b	b	b
Hydrocyanic acid	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c

Corrosive Medium	Copper Gilding, 95%	Commercial Bronze, Leaded Bronze	Red Brass	Low Brass	Cartridge Brass*	Admiralty Metal	Naval Brass, Manganese Bronze	Aluminum Brass	Phosphor Bronze A 85-5-5-5 Casting	Phosphor Bronze C	Phosphor Bronze D, G & M Bronzes	Phosphor Bronze E	Cupro-Nickel 30%	Nickel Silver 18% Grade A	Nickel Silver 18% Grade B	Silicon Bronze Type A	Silicon Bronze Type B	Aluminum Bronze
Hydrofluoric acid	b	b	b	c	c	c	c	c	b	b	b	b	b	b	b	b	b	b
Hydrofluosilicic acid	b	b	b	c	c	c	c	c	b	b	b	b	b	b	b	b	b	b
Hydrogen	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Hydrogen peroxide	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b
Hydrogen sulfide, dry	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Hydrogen sulfide, moist	c	c	c	c	b	b	b	b	c	c	c	c	b	c	b	c	c	c
Lacquers	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Lacquer thinners	a	a	a	a	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Lactic acid	a	a	a	b	c	b	c	b	a	a	a	a	a	a	a	a	a	a
Lime-sulfur mixture	b	b	b	b	a	a	a	a	b	b	b	b	b	b	b	b	b	b
Linseed oil	a	a	a	a	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Magnesium chloride	a	a	a	b	c	b	c	b	a	a	a	a	a	a	a	a	a	a
Magnesium hydroxide	a	a	a	a	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Magnesium sulfate	a	a	a	a	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Mercury, mercury salts	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Milk (2)	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Molasses (2)	a	a	a	a	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Natural gas	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Nitric acid	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Nickel chloride	b	b	b	c	c	c	c	b	b	b	b	b	b	b	b	b	b	b
Nickel sulfate	a	a	a	b	c	b	c	b	a	a	a	a	a	a	a	a	a	a
Oleic acid	a	a	a	b	b	b	b	a	a	a	a	a	a	a	a	a	a	a
Oxalic acid	a	a	a	b	c	b	c	b	a	a	a	a	a	a	a	a	a	a
Phosphoric acid	b	b	b	b	c	b	c	b	b	b	b	b	b	b	b	b	b	b
Picric acid	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Potassium cyanide	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Potassium chloride	a	a	a	b	c	b	c	b	a	a	a	a	a	a	a	a	a	a
Potassium hydroxide	b	b	b	b	c	b	c	b	b	b	b	b	b	b	b	b	b	b
Potassium sulfate	a	a	a	a	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Propane gas	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Rosin	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Sea water	a	a	a	b	b	a	a	a	a	a	a	a	a	a	a	a	a	a
Sewage	a	a	a	b	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Soap solutions	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Sodium bicarbonate	a	a	a	b	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Sodium bisulfate	a	a	a	b	c	b	c	b	a	a	a	a	a	a	a	a	a	a
Sodium carbonate	a	a	a	a	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Sodium chloride	a	a	a	b	c	a	b	a	a	a	a	a	a	a	a	a	a	a
Sodium cyanide	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Sodium hydroxide	b	b	b	b	c	b	c	b	b	b	b	b	a	b	b	b	b	b
Sodium hypochlorite	b	b	b	c	c	c	c	b	b	b	b	b	b	b	b	b	b	b
Sodium nitrate	a	a	a	a	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Sodium peroxide	b	b	b	c	c	b	c	b	b	b	b	b	b	b	b	b	b	b
Sodium phosphate	a	a	a	a	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Sodium sulfate, silicate	a	a	a	a	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Sodium sulfide, thiosulfate	b	b	b	b	a	a	a	a	b	b	b	b	b	b	b	b	b	b
Stearic acid	a	a	a	b	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Sulfur, solid	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b
Sulfur chloride	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b
Sulfur dioxide, dry	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Sulfur dioxide, moist	a	a	a	b	c	b	c	b	a	a	a	a	a	a	a	a	a	a
Sulfur trioxide, dry	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Sulfuric acid 60 to 95%	b	b	b	b	c	b	c	b	b	b	b	b	b	b	b	b	b	b
Sulfuric acid 60%	b	b	b	c	c	c	c	c	b	b	b	b	b	b	b	b	b	b
Sulfurous acid	a	a	a	b	c	b	c	b	a	a	a	a	a	a	a	a	a	a
Tannic acid	a	a	a	b	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Tartaric acid	a	a	a	a	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Toluene	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Trichlorethylene, dry	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Trichlorethylene, moist	a	a	a	b	c	b	b	b	a	a	a	a	a	a	a	a	a	a
Turpentine	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Varnish	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
Vinegar	b	b	b	c	c	b	c	b	b	b	b	b	b	b	b	b	b	b
Water, acid mine	b	b	b	c	c	b	c	b	b	b	b	b	b	b	b	b	b	b
Water, potable	a	a	a	a	c	a	b	a	a	a	a	a	a	a	a	a	a	a
Water, condensate	a	a	a	a	c	a	b	a	a	a	a	a	a	a	a	a	a	a
Whisky (2)	a	a	a	a	b	a	b	a	a	a	a	a	a	a	a	a	a	a
Zinc chloride	b	b	b	c	c	b	c	b	b	b	b	b	b	b	b	b	b	b
Zinc sulfate	a	a	a	b	c	a	c	a	a	a	a	a	a	a	a	a	a	a

* The column includes cartridge brass, yellow brass, Muntz metal, forging brass and architectural bronze.

(1) Containers having more than 65% Cu should not be used for acetylene because of the danger of the formation of explosive acetylides.

(2) When copper or copper alloys are used in contact with foodstuffs or beverages, the metal should be tin-coated or otherwise protected to prevent the pickup of copper ions, which may affect the color or the taste of the food products.

ance to corrosion is usually appreciably higher than that of brasses of the same copper content, because the large amount of nickel inhibits dezincification.

The 80% Cu—20% Ni alloy is sometimes modified by the addition of 5% Zn. The resulting alloy has approximately the same corrosion resistance as the original alloy.

Copper-Silicon Alloys. In general, the resistance to corrosion of the commercial copper-silicon alloys is similar to that of copper. When copper-silicon is chosen by the product designer in preference to copper, selection is usually based on the relatively high mechanical properties of the silicon bronze alloys, in conjunction with their ready weldability. Examples of usage include tanks, bolts, screws, connectors, fastenings, gears, shafts and pinions.

When the alloys containing 3% Si or more are used in contact with steam under pressure, the possibility of intergranular corrosion should be recognized.

Copper-Aluminum Alloys. As with the copper-silicon alloys, selection of the copper-aluminum alloys, rather than copper, is frequently based on properties other than resistance to corrosion, such as superior resistance to wear and oxidation, and superior mechanical properties at room and elevated temperatures. However, aluminum bronze resists corrosion more effectively than copper under a number of environmental conditions. Aluminum bronze condenser tubes, containing 5% Al, have been used successfully with contaminated brackish cooling water. The aluminum bronzes are more resistant than copper to corrosion by sea water moving at high velocity.

Aluminum bronze is used for beater bars and blades of wood-pulping machines because of the ability of the alloy to withstand mechanical abrasion as well as chemical attack by sulfite solutions and other bleaching compounds; it is used also in sewage equipment.

Amounts of aluminum larger than about 5% sometimes induce selective corrosion, in which aluminum is removed by an action similar to the dezincification of brasses.

Nickel, manganese and iron are sometimes added to aluminum bronze. In the small amounts usually added, these elements have no significant effect on resistance to corrosion, although nickel is sometimes credited with increasing this resistance. Similarly, the addition of 2% Si to aluminum bronze has no significant effect on resistance to corrosion.

Protective Coatings. The relatively high resistance to corrosion of copper and copper alloys in many kinds of environment, is a result of the protective coatings developed by converting the surface metal into one or more compounds.

For various uses, this resistance may be increased by the preapplication of protective coatings. For convenience, these coatings may be divided into two groups, metallic and organic. Provided the coating material is able to resist corrosion adequately, success in service may depend on impermeability, continuity, and adhesion to the base metal. In metallic coatings, the electropotential relationship of the metal to the base may be important.

Tin, lead, and solder, used extensively as coatings, are ordinarily applied by hot dipping. Tin-coated copper is used for dairy and refrigeration equipment, as well as for containers and conveyers of foods and beverages. Tin-coated copper tubing is useful for handling natural fresh waters that are very soft or that contain large percentages of dissolved carbon dioxide and oxygen. As a coating on copper conductor wire and cable, tin arrests corrosion caused by sulfur in rubber insulation. Lead-coated copper is used chiefly for roofing, for other construction materials, and for applications requiring contact with flue gases or other products that contain dilute sulfuric acid. Tin or lead coatings are sometimes applied to copper that is intended for atmospheric exposure; however, these coatings serve primarily for architectural effects, since the atmospheric resistance of bare copper is excellent. Likewise, chromium plate is used not for protection from corrosion but for decoration, improvement of wear resistance, or reflectivity. Electroplated nickel is used commonly as protective underplating for chromium. Processes have been developed for coating copper with tin or black cupric oxide by immersion.

Clear lacquer is used to delay tarnish of copper and brass during indoor exposure. For more corrosive conditions, many new synthetic resins have been developed, such as phenolic, vinyl and acrylic. Thermosetting types of coatings have certain advantages over the thermoplastic or air-drying types; for instance, greater stability and a higher limit for temperatures that can be withstood in service.

Selection of Materials. Operating experience, in the form of careful records properly interpreted, is the most reliable guide (although costly and imperfect) in the selection of a suitable alloy. Instead of service data, or in conjunction with them, various considerations or tests aid in the choice of material.

Resistance to corrosion alone is an inadequate criterion for selection. The original cost of material, the costs of installation, maintenance, shutdowns and obsolescence should be considered. On occasion, some resistance to corrosion will have to be sacrificed in order to fulfill minimum requirements for such properties as formability, weldability, yield strength, and electrical conductivity.

Sometimes the economical solution of a corrosion problem will consist in appropriate changes in the design of the product or in treatment of the environment, rather than in a change of alloy.

Laboratory corrosion tests can furnish valuable information concerning the length of service to be expected, but only if the operating conditions can be defined precisely and simulated faithfully in all important respects in the laboratory. In the past, many laboratory tests have been inadequate because investigators have failed to realize the importance of taking into account operating factors such as stress, velocity, effects of galvanic couples and concentration cells, effect of surface condition, size of metal specimen and contamination of the solution. When test conditions are intensified to accelerate the test, there is considerable danger of distorting the results.

Erroneous conclusions based on laboratory tests may be reached not only by making the test improperly but by measuring inaccurately the damage from corrosion. If damage is in the form of pitting, intergranular corrosion, or deposition of metal (for example, dezincification), a measurement of corrosion rate based on loss or gain in weight may be misleading. Other methods of measurement should be used, such as loss of tensile strength, microscopic examination, or measurement of pit depth.

Much valuable information has been obtained from field tests wherein many different metals, alloys and coatings are tested for long periods of time in different types of atmospheres and natural waters. The corrosion testing station at Kure Beach, N. C., is a well-known example. Another type of testing requires the insertion of a group of test specimens of varying alloys, often in the form of tensile specimens, into operating equipment—for example, into the shell of a heat exchanger where major corrosion damage is on the shell side. In some instances, a test specimen is inserted as an integral part of the equipment.

The corrosion ratings of copper and copper alloys as shown in Table III may be helpful in the selection of materials.

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The Metallography of Copper and Copper Alloys

BY THE SUBCOMMITTEE ON METALLOGRAPHY OF COPPER ALLOYS*

THE SELECTION and preparation of a metallographic specimen is fundamental, because improper choice of section, mounting technique or polishing technique can not only destroy a valuable sample, but can result in misleading interpretations of the structure. The paragraphs below include basic principles together with certain precautions.

Mechanical Preparation. *Sectioning.* The following rules are suggested.

1 Castings are sectioned, depending on size and design, adjacent to risers and through extremely heavy or thin sections, to reveal shrinkage voids, porosity and cold shuts.

2 Forgings are sectioned to include all changes in direction of flow. The edges should be kept sharp to reveal cold shuts and other surface defects.

3 Manufactured articles fabricated from wrought mill products should be sectioned longitudinally to reveal, if possible, the original grain size in unworked sections and the degree of deformation in worked sections.

4 Fabricated articles that have failed in service should be sectioned both in the region of failure and adjacent to it, to reveal the maximum information.

5 The determinations of grain size and structure for wrought and annealed wire, rod, tube and other drawn products, should be made on a complete longitudinal section or from the center to the surface.

6 For determinations of average grain size on flat products thicker than about 0.1-in. gage, a longitudinal section is recommended. On lighter gages, an area below and parallel to the surface is acceptable if desired for purposes of convenience.

7 Distribution of defects, such as shrinkage, seams, porosity, pipe, cracks and laminations in wrought products, is revealed best by a transverse section.

8 Thickness of plating on electroplated objects should be determined from the average of at least three transverse sections, after deposition of a protective plate of a different metal.

Normally, small, well-selected, representative longitudinal and transverse sections give the most information.

Mounting, Grinding, Polishing. For a detailed general discussion of mounting, grinding and polishing, the reader may refer to the article on "Metallographic Polishing", page 159 in this Handbook.

The following additional recommendations have been suggested for copper and copper alloys.

1 Multiple mounting of relatively light-gage stock for routine determinations of grain size, can be accomplished in several ways:

(*a*) For examination of longitudinal or transverse sections, specimens of light-gage strip can be stacked and held together with clamps, or mounted in solder or a plastic medium under pressure.
(*b*) Specimens of light-gage strip or wire can be laid on a plate at the bottom of a mold and mounted in a suitable medium. Molten sulfur or plastics molded under pressure are recommended.
(*c*) For heavier gage stock up to about ⅜ in., solder is recommended for method (*b*).

For method (*a*), strip and wire specimens can be held together in a vise. The projecting ends are then bent over and soldered.

2 To avoid tearing the polishing cloths, the edges of the mount or of the unmounted specimen should be beveled.

3 For preservation of edge sharpness, when cloth wheels are used for polishing, the specimen may be nickel-plated or sandwiched between harder material in brass clamps. Hand polishing toward the edge in question, using metallographic papers 0, 00, 000, 0000 on plate glass, is also recommended for preservation of the edge in a mounted sample, and for good flatness. Each successive operation should be carried out at an angle to the preceding operation.

4 To prevent staining, caused by seepage of etchant from a crack, void, or any space subject to capillary action, the specimen can be warmed sufficiently to allow penetration by beeswax before the preliminary facing operation.

5 Grinding on a belt surfacer, using 30-grit, 50-grit and 100-grit successively, has been found to be adequate preparation for polishing. Finer grits may be used if desired.

6 The following polishing cycle has proved adequate for routine preparation of most copper alloys when rotating cloth-covered disks are used at suitable speeds. Other abrasives and cloths are commonly used in different laboratories with equal success.

(*a*) 8 to 12-oz canvas duck.....220-mesh emery
(*b*) felt .....FF Turkish emery
(*c*) wool broadcloth.....SF6X Turkish emery
(*d*) velvet, or "kitten's ear".....levigated alumina (re-levigated as desired)

Step (*d*) is sometimes omitted for rapid routine work.

7 For detailed microexamination and photomicrography, hand polishing on plate glass with metallographic papers 0, 00, 000, and 0000 successively, is recommended. Two or three polishing cycles should follow, using increasingly finer levigated alumina and low wheel speeds (200 to 500 rpm).

8 Preparation of surfaces for macroexamination depends on the size of the section. For as-cast bars, cakes, or billets, a very smooth machined surface (preferably planed by using a single-tooth cutter) is adequate for macroexamination. For sections such as small forgings, cartridge cases or castings, the surface to be etched may be machined smooth or prepared on a belt surfacer using 30-grit, 50-grit and 100-grit successively.

Chemical Etching of Copper and Copper Alloys. *Macrostructures.* Sections that have been cut from castings, cakes, bars, billets, forgings, rod, extrusions, strip or coarse wire, and prepared according to the directions of the preceding section, may be placed in a shallow container, where weight and size permit, and the etchant may be poured over and flowed back and forth by raising and lowering one side of the container. When the structure has developed sufficiently, the section is rinsed first with water, then with alcohol, and is then dried as promptly as possible. On larger units, the etchant may be applied with a large swab, followed immediately by rinsing in water—preferably hot water—and drying rapidly.

To preserve the surface temporarily for photographing, the specimen may be covered with a thin film of colorless mineral oil or glycerin, or, for permanent preservation, with clear thin lacquer.

Etchants that have been used successfully are nitric acid with and without dilution, 20% ferric chloride solution acidified with hydrochloric acid, chromic acid solution, and potassium bichromate solution acidified with sulfuric acid, as listed in Table I. Concentrated nitric acid is desirable for large units because of the speed of reaction. The etching is done customarily at room temperature.

To minimize staining caused by seepage, it may be advisable to freshen the surface with etchant, replace with acidified water or alcohol, and photograph the specimen in the tray under a thin layer of the liquid.

Microstructures. Suitable etchants for microstructures are listed in Tables I and II. The technique of good etching is an art to be learned through a great deal of experience. Metallographers have produced equally good results by techniques that differ in the application of etchants—by swabbing, immersion or agitation. It is frequently advisable to follow the progressive attack of the reagent with the microscope. Not infrequently, even the careful metallographer fails to develop the full measure of structural delineation, and therefore, it is sometimes worth while to overetch experimentally in order to determine the limit of suitable etching.

Specimens finished on 0000 emery paper can often be etched in concentrated nitric acid and chromic anhydride with entirely satisfactory results.

* The members of this subcommittee are F. H. Wilson, *Chairman* (The American Brass Company), W. D. France (Scovill Manufacturing Company), H. B. Pulsifer (Deceased) and P. A. Leichtle (Chase Brass & Copper Co.).

Electrolytic Polishing and Etching. The polishing of metallographic specimens by electrolytic methods, following the introduction and development of the idea by P. Jacquet, has provided a technique for obtaining a highly polished surface, free from mechanical distortion. According to requirements, two major techniques may be applied to copper alloys. The first, where quality of polish is paramount, has been the subject of the greater amount of published information. This technique—an excellent tool for the research metallographer—involves mechanical polishing followed by electrolytic polishing, with rather careful control of current density and voltage. The second technique, where saving time is paramount, has received comparatively little attention in technical publications. Methods of rapid electrolytic polishing have been developed for copper alloys, and polishes adequate for determinations of grain size can be developed from ground surfaces in a minute or less. In this limited space, representative techniques for each purpose are presented on the assumption that every investigator will adapt the most suitable technique to his specific purpose. Various modifications have been described in technical publications.

Table I. Etchants Used in Routine Examination of Copper and Copper Alloys

No.	Etchant			Remarks
1	NH_4OH	5 parts		Fresh solution made up just before use
	H_2O_2 (3%)	2 to 5 parts		
	with or without	5 parts H_2O		
2	NH_4OH	10 ml		KOH prevents oxide film. Fresh solution made up just before use
	H_2O_2 (3%)	4 ml		
	KOH (20%)	1 ml		
	H_2O	▮ ml		
3	Electrolytic			Can also be used following 1 or 5 for coloring copper and high-copper alloys. Circuit includes dry cell, a platinum wire cathode and the specimen as anode. The polished surface is dipped just under the surface.
	$FeSO_4$	30 g		
	NaOH	4 g		
	H_2SO_4 (conc)	100 ml		
	H_2O	1900 ml		
4	CrO_3	40 g		Also used for macrostructure. The degree of contrast can be modified by adding a few drops of HNO_3 or H_2SO_4 to the etching bath as desired.
	NH_4Cl	7.5 g		
	HNO_3 (conc)	50 ml		
	H_2SO_4 (conc)	50 ml		
	H_2O to make 1 liter	900 ml		
5	$K_2Cr_2O_7$	2 g		Also used for macrostructure.
	NaCl	1.5 g		
	H_2SO_4 (conc)	8 ml		
	H_2O	100 ml		
6	HNO_3 (conc)	75 ml		Also used for macrostructure. Fresh solution is made up just before use. Specimen should be dry.
	Glacial acetic acid	25 ml		
		(a)	*(b)*	
7	$FeCl_3$	5 g	10 g	Also used for macrostructure.
	HCl	10 ml	25 ml	
	H_2O	100 ml	100 ml	
8	HNO_3	various conc		For macrostructure. Trace of $AgNO_3$ gives brilliance.
9	$(NH_4)_2S_2O_8$ 10% solution			Follows 8, for improving contrast.

Table II. Etchants Used for Various Copper Alloys

Alloy[a]	Etchant[b]	Remarks
Copper and dilute copper alloys	4 or 5	.....
Brass, alpha, 85 to 100%	4, 5 or 1 then 7	7 follows 1 to develop contrast
Brass, alpha, 65 to 85%	1	.....
Brass, alpha-beta	1 or 1 then 7	7 follows 1 to darken beta
Phosphor (tin) bronze	4, 5 or 1	.....
Tin brass	1	.....
Silicon brass	4 or 1	.....
Silicon bronze	4 or 5	.....
Aluminum bronze, alpha	5 or 4	.....
Aluminum bronze, alpha-beta	1 or 1 then 7	7 follows 1 to darken beta
Aluminum-silicon bronze	2 or 5	.....
Manganese bronze	1 or 1 then 7	7 follows 1 to darken beta
Nickel silver	4, 5 or 6	.....
Cupro-nickel	3, 4 or 5	3 minimizes appearance of coring
Beryllium bronze	5 or 1	1 used for detecting small quantities of beta

(a) For leaded alloys, use the etchant recommended for matrix.
(b) Numbers, given in order of preference, refer to the etchants listed in Table I.
NOTE. These etchants are commonly used for ordinary examination. When other etchants are sought for special purposes, reference can be made to ASTM Tentative Method E 3-46T.

Research Method. The electrolyte consists fundamentally of phosphoric acid. Various concentrations and diluents are employed, according to the alloy to be polished. The specimen, which has been given a preliminary mechanical polish up to 0000 emery paper, serves as the anode, and a cathode of much greater area can consist of copper, lead, stainless steel or such. The freshly made solution is not agitated; the polished surface is held in a horizontal position with the cathode above and about ½ in. from the surface to be polished. A low-voltage d-c source, such as a battery, is adequate and the voltage across the cell is controlled with a rheostat. As the voltage is increased with rheostat adjustment above 1 volt, the current increases with it for a while and then decreases. With the rheostat left stationary, the surface becomes polished, while the voltage increases and the current decreases gradually. After several minutes of polishing, the specimen is transferred to a rinse quickly, and preferably without opening the circuit, if etching is to be avoided; or etching can be accomplished by shifting the rheostat for applying a lower voltage. If slight staining occurs, it can be removed by dipping the specimen in a fresh solution of 5% orthophosphoric acid.

For copper, 1.5 to 1.8 volts, giving a current density of 6 to 8 amp per sq dm, in an electrolyte of 400 to 500 ■ per liter of pyrophosphoric acid, will produce a good polish in 10 to 15 min at 15 to 25 C. Under similar conditions, copper alloys have been polished, and it is probable that modifications of conditions can be found for polishing all single-phase copper alloys. Duplex alloys are more difficult, but alpha-beta brass has been polished adequately for metallographic purposes. P. Jacquet has presented a recent review and bibliography of this field.[1]

Rapid Method. Under some circumstances the use of electrolytic polishing can be adapted so as to accelerate the preparation of metallographic specimens for the determination of grain size. H. E. Brown[2] has reported a rapid method for polishing most copper alloys by the use of an electrolyte that consists of two parts methyl alcohol to one part concentrated nitric acid. The constituents of this electrolyte react exothermally and can develop a violent reaction unless the electrolyte is kept cool. Another rapid method, suggested by DeSy and Haemers for iron and steel specimens, has been adapted to other metals including copper alloys.[3] This method uses high voltage and high current densities with an electrolyte of perchloric acid, water, alcohol and ether. The perchloric acid introduces a serious hazard, since explosive reactions can result from contact with organic substances.

A safer rapid method has been developed that employs relatively dilute phosphoric acid, high voltages and high current densities.[4] It has been found that if the specimen is agitated in the solution, a good polish can be developed by the application of about 30 volts. By this means, roughly ground specimens can be given an adequate polish in one minute. For usual anode areas, ⅛ sq in. or more, the necessary current densities demand voltages as high and resistances in the electrolyte as low as these. Thus a high-capacity source of d-c power is required.

The following specific procedure is described with the realization that numerous modifications can probably give adequate results. The output of an autotransformer attached to the 110-volt a-c line is given full-wave rectification with a copper oxide rectifier. The specimen or specimens, serving as anode, are held in an insulating holder that is rotated by a stirrer motor, giving the specimens a circular path in the electrolyte. The electrolyte, consisting of orthophosphoric acid diluted to a specific gravity of 1.04, is cooled in a bath of running water. Voltage and current are controlled entirely by the autotransformer. For polishing, the voltage is controlled and the current passing may be 10 to 20 amp; for etcning, amperage is controlled.

An initially flat surface is produced on copper and brass specimens by grinding with 180-grit on a belt sander. They are polished electrolytically in one minute, using 30 volts, after which the voltage is decreased for etching purposes. Brass specimens develop a film of copper that disappears

quickly during the etching. Cartridge brass (70% Cu) is etched with a current of 2 amp for 15 sec and copper is etched with 1 amp for 75 sec; for intermediate alloys, intermediate times and currents are used. After etching, the specimens are rinsed quickly and dipped for a few seconds in a solution of copper ammonium sulfate (30 g Cu $SO_4 \cdot 5H_2O$, 70 ml H_2O, and 21 ml conc NH_4OH, filtered); 10% ammonium persulfate, 10% ferric chloride or dilute nitric acid may also be used. These solutions improve the grain contrast. Specimens are then rinsed in water and alcohol and dried.

The chief disadvantage of this method is the necessity for the high-capacity d-c power source. More concentrated electrolytes, with lower voltages and currents, result in longer times for polishing. The method has not yet been extended to alloys other than the brasses, but it is quite probable that it can be applied more widely with proper modifications.

With adequate precautions, the nitric acid–methyl alcohol method may be preferred, since it has been used successfully with other copper alloys, including tin bronzes. Moreover, when the samples polished by this method are small enough, adequate current densities can be obtained by the comparatively simple arrangement of a grid-controlled tube rectifier in conjunction with a small transformer and with resistances.

Because electrolytic polishing affords a distinct improvement over other methods in providing surfaces totally free from scratches and distorted metal, this method has an important place in metallography. The technique is easily mastered. The chief disadvantage of electrolytic polishing is that this method may exaggerate discontinuities. It is ideal for homogeneous structures, but the differences in electrolytic potential between phases of heterogeneous structures lead to uneven or pitted surfaces, although some duplex structures have been polished satisfactorily.

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Factors That Determine the Applications of Copper

By the Subcommittee on Applications of Copper*

COPPER has certain valuable properties that, individually and in combination, determine what fields of application are suitable for the metal. The properties of major significance are electrical conductivity, thermal conductivity, resistance to corrosion, malleability, formability and strength. In addition, copper has a pleasing color, is nonmagnetic and is easily finished by plating or lacquering. Copper can also be welded, brazed and soldered satisfactorily. When it is desirable to improve certain of these basic properties and when such an improvement can be effected with the sacrifice of no other properties except those of limited significance in the intended application, alloying often solves the problem, and such widely used commercial materials as the brasses, bronzes, copper-nickel alloys and nickel silvers have been developed in consequence.

Copper is a moderately expensive metal of high density and, in about 90% of its applications, serves satisfactorily where ferrous materials or the light metals could not, and where lead, zinc and tin would be unsuitable. In possibly 10% of the applications copper products are in direct price competition with other materials.

The greatest single field of use for copper results from the high electrical conductivity of the metal. The reasons for the use of copper for electrical conductors and in the manufacture of all types of electrical equipment are so commonly understood that a detailed discussion is unnecessary. However, it is of interest to note that even in the electrical industry high conductivity alone does not give copper great economic value; it is rather the combination of this property with high resistance to corrosion and ease of formability. Even with very high electrical conductivity, a refractory material, unable to be drawn or fabricated with ease, or subject to rapid corrosion when exposed to normal atmospheric conditions, would not be practical in the electrical industry.

In applications where resistance to corrosion is the primary attribute—for instance, in the use of copper for roofing, sheathing, construction of large vessels and chemical engineering equipment—it is again found that not corrosion resistance alone, but corrosion resistance in conjunction with workability and formability, renders the metal commercially valuable in widespread application.

The same considerations govern when the high thermal conductivity of the material is of prime importance. If this property were not accompanied by high resistance to corrosion, the utility of the metal as a conductor of heat would be decreased or nullified in many instances; for example, copper would be unsuitable for use in the construction of heat-exchange or heat-transfer equipment.

An automobile radiator is typical of a structure with performance depending on many attributes of copper, rather than on a single property. In such a radiator very light gages of metal are used, approximately 0.005 in. thick. Obviously resistance to corrosion must be sufficient to prevent various waters from penetrating the thin sections of metal over a period of many years of service. In addition, moderately high thermal conductivity is desirable in order to dissipate heat, since cooling is the primary function of the radiator. High ductility and formability and ease of joining the material are factors of major importance in manufacturing.

Electrical and thermal conductivities of copper *alloys* are of secondary importance, if significant at all. When alloying elements are added to copper these properties are deliberately sacrificed for the purpose of improving other characteristics that are more important in the articles for which alloys are used.

When copper is alloyed with zinc, the tensile properties are improved without much sacrifice of resistance to corrosion and tarnish. The properties are retained that lead to ease in buffing, finishing and plating, and hence qualify the base metal for a wide variety of stamped, spun, drawn and other formed parts that can be made into highly finished and plated products. By the substitution of nickel for some of the copper in various brasses, a series of alloys is obtained in which the color is changed in order to make a more suitable base for silver-plated flatware and hollow ware, without sacrifice of strength, ductility, formability or ease of finishing.

When high rates of production are desired, as for screw-machine parts, and when resistance to tarnish or corrosion is desirable in the finished part, then lead is added to brass for the purpose of improving machinability—a purpose achieved by this means with no other substantial modification of the properties of the brass.

It is unnecessary to list here the numerous applications of copper; it should suffice to reiterate that some combination of properties frequently suggests the use of copper or copper alloys in sound engineering design.

* The members of this subcommittee are R. A. Wilkins, *Chairman* (Revere Copper and Brass Incorporated), W. M. Baldwin (Chase Brass & Copper Co.), W. B. Price (Scovill Manufacturing Company) and V. P. Weaver (The American Brass Company).

PROPERTIES OF COPPER AND COPPER ALLOYS

Pure Copper*

COMPILED BY J. S. SMART, JR.*

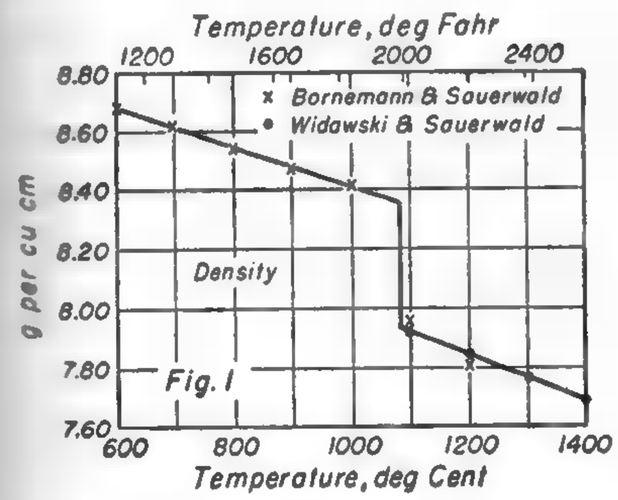
C *1 Density* at 20 C (68 F).[1] 8.96 ■ per cu cm (0.324 lb per cu in.) *Density versus temperature. See* Fig. 1.
4 Density versus percentage deformation.[1] 0.028% decrease in density for a reduction of 50% by drawing
5 Solidification shrinkage. 4.92%

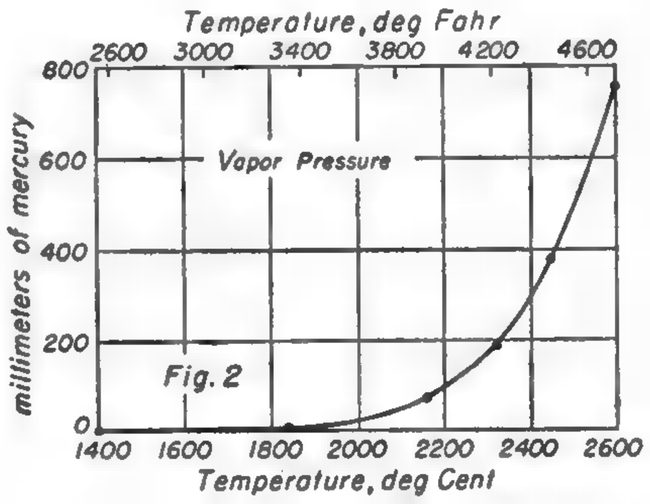
D *1 Melting point.*[5] 1083.0 ± 0.1 C (1981.4 ± 0.2 F)
4 Boiling point.[32] 2595 C (4703 F)
Vapor pressure versus temperature.[32] *See* Fig. 2.
6 Thermal expansion at 20 C.[31] 0.0000165 per °C
[0 to 300 C (32 to 572 F)][7]
$L_t = L_0 [1 + (16.23t + 0.00483t^2) \times 10^{-6}]$
[0 to 1000 C (32 to 1832 F)][8]
$L_t = L_0 [1 + (16.733t + 0.002626t^2 + 0.00000091t^3) \times 10^{-6}]$
For data on instantaneous coefficient of expansion between minus 23 C and minus 223 C, see Fig. 3.[9,10,11]
11 Specific heat at 20 C (68 F).[41] 0.092 cal per ■
12 Specific heat vs temperature.[10,12–14,16–23] *See* Fig. 4 and 5.
13 Latent heat of fusion.[42] 50.6 cal per ■
16 Thermal conductivity at 20 C (68 F).[26] 0.941 ± 0.005 cal/sq cm/cm/°C/sec
17 Thermal conductivity vs temperature. See Fig. 6.[27,35–39]
19 Recrystallization diagram.[1] *See* Fig. 7.

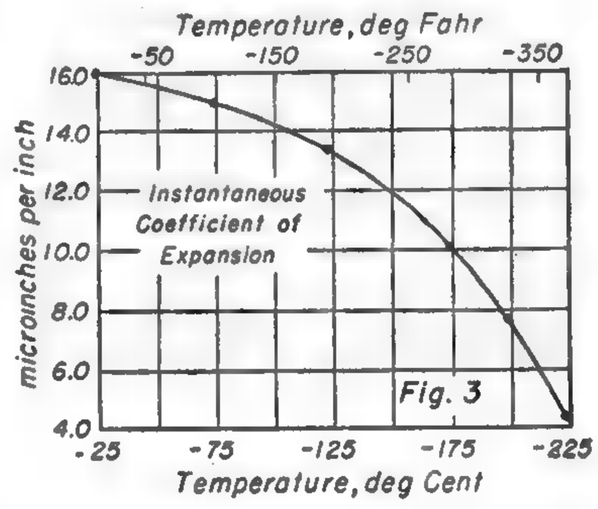
E *1 Volume conductivity* referred to std copper.[1] 103.06%
Mass conductivity referred to std copper. 102.3%
2 Electrical resistivity at 20 C (68 F).[1] 0.14983 ohms per meter-gram or 1.6730 microhm-cm
4 Electrical resistivity (liquid). See Fig. 6.[27,35–39]
5 Temperature coefficient of electrical resistivity at 20 C (68 F).[26] 0.0068 microhm-cm per °C or 0.00060 ohms per meter-gram per °C
Electrical resistivity vs temperature. See Fig. 6.[27,35–39]

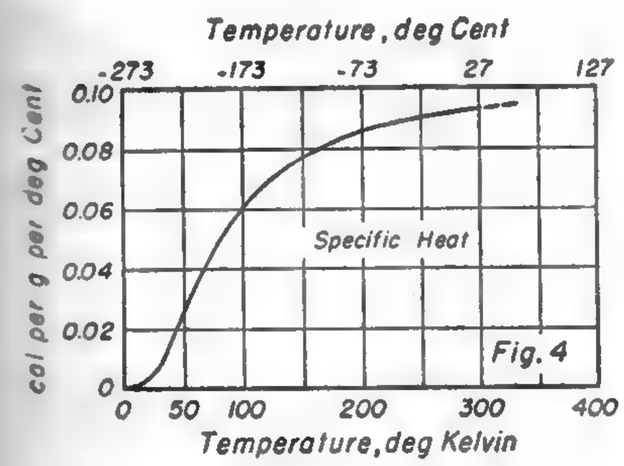
* The properties marked with reference numbers 1, 2, 3, 4 and 5 were determined on spectrographically pure copper, as reported in the cited articles. Other values were measured on various coppers of purity equal to or greater than that of commercial electrolytic copper.

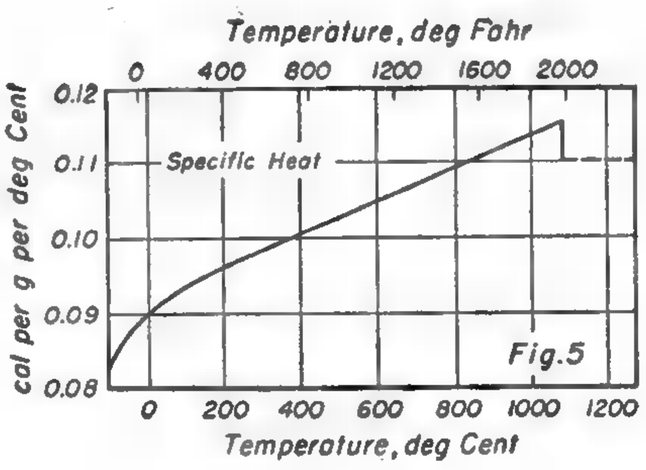
* Research Department, American Smelting and Refining Company, Barber, N. J.

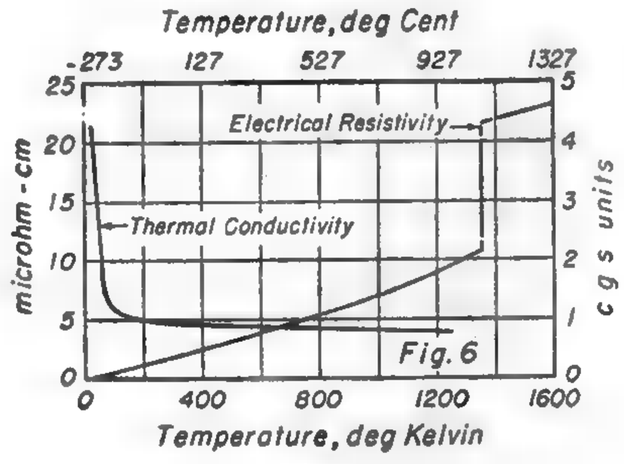


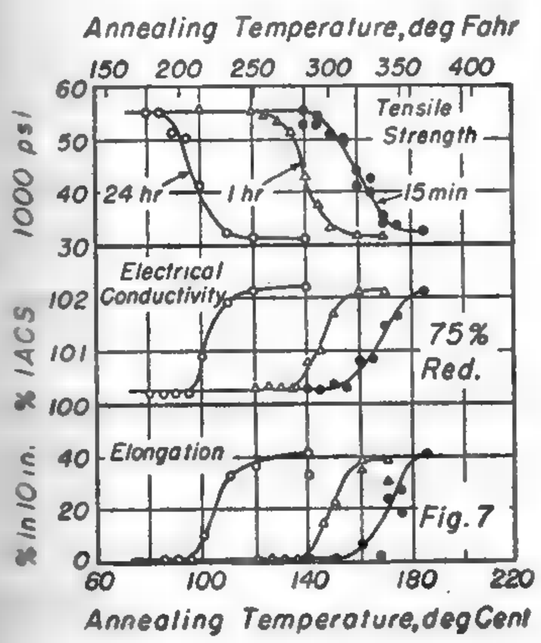


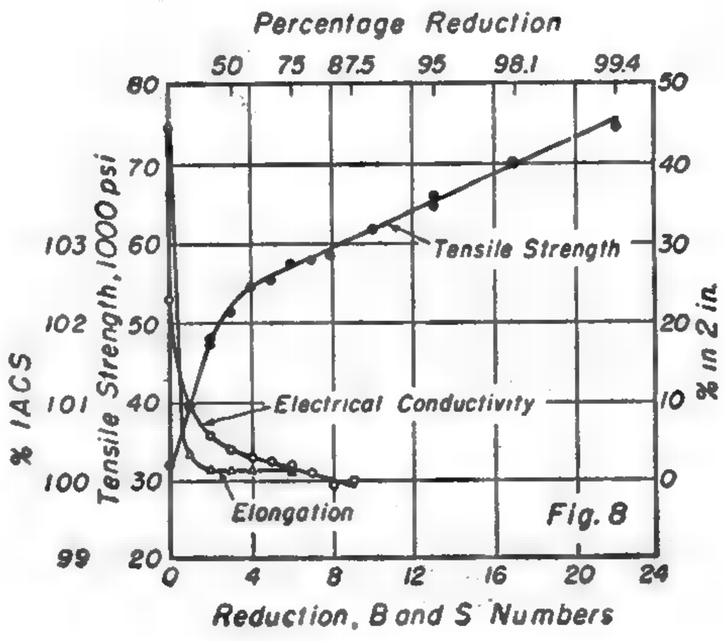


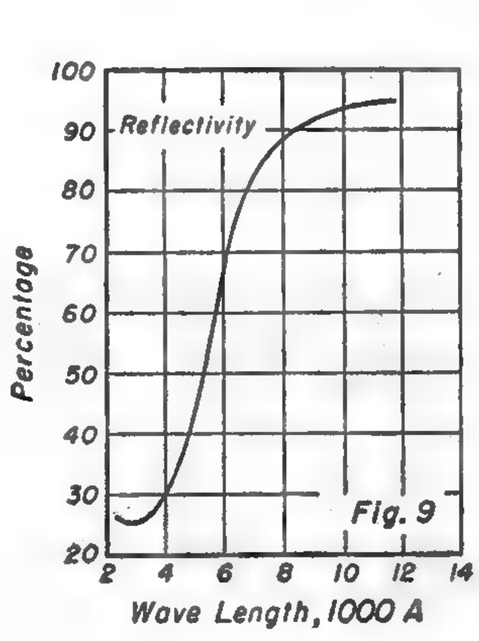












8 Electrical conductivity versus plastic deformation at 20 C (68 F).[1] *See* Fig. 8.

10 Electrochemical equivalent.
0.3294 mg per coulomb for Cu^{++}
0.6588 mg per coulomb for Cu^{+}

15 Hall effect.[34] minus 5.24×10^{-4} volts; 3000 to 8116 gausses

F *1 Reflectivity versus wave length.*[33] *See* Fig. 9.

5 Emissivity.[40]

Wave length, A	7000	6500	6000	5500	5000
% Emissivity at 1000 C (1832 F)	8.7	11.2	18.5	31.3	40.4
% Emissivity at 1125 C (2057 F)	11.8	14.8	20.5	29.3	38.7

G *1 Influence of treatments.* The magnetic susceptibility of copper is determined largely by the quantity of iron present as an impurity. If the copper is free from oxygen, the iron is present in solid solution and has but a small effect. The presence of oxygen results in the precipitation of Fe_3O_4 and a greater effect on magnetic properties. The measurements below were probably made on oxygen-bearing coppers.

2 Magnetic susceptibility.
at 18 C (64 F). minus 0.086×10^{-6} cgs[28,29]
at 1080 C (1976 F). minus 0.077×10^{-6} cgs[30]
at 1090 C (1994 F). minus 0.054×10^{-6} cgs[30]
minus 259 to minus 253 C (−434 to −423 F). minus 0.097×10^{-6} cgs

J *1 Crystal structure.* Face-centered cubic; $a = 3.6080$ kX

2 Slip plane (primary). (111)

3 Twinning plane. (111)

5 Minimum interatomic distance. 2.551 kX

K *Mechanical properties. See* Fig. 7 and 8.

M *Composition limits.* Continuously cast, high-purity copper (⅜-in. rod), *impurities:* 0.0005% Fe max; 0.0001% Sb max; 0.00005% Pb max; 0.00005% Sn max; 0.0001% Ni max; 0.0001% Bi max; 0.00003% Ag max; 0.0001% As max; 0.0001% Te max; 0.0001% Se max; 0.0001% S max; 0.0008% C max; nil O_2.

2 Consequences of exceeding impurity limits. Effects of impurities are discussed in detail in references 3, 4, 5 and 15. *See also* "Electrolytic Tough Pitch Copper".

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99.92 Cu – 0.04 O*

A *1 Common name.* **Electrolytic Tough Pitch Copper***

3 ASTM numbers.
Rolled flat products: B 48; B 124, No. 12; B 133; B 152, type A; B 187; B 11, grade 1
Rod: B 124, No. 12; B 133; B 187
Wire: B 1, B 2, B 3, B 33, B 47, B 49, B 189,
Tube: B 188
Pipe: B 188
Shapes: B 124, No. 12; B 133, B 187

4 Government and other designations.

	SAE	AMS	Federal	Army	Navy	Army-Navy
Sheets, strips and plates	71, type A	4500	QQ-C-501a	Federal	47C2f	.....
Rods, bars and shapes	...	...	QQ-C-501a	Federal	47C2f	.....
Rod for compression cylinders	...	...	.....	57-154-1B	.....	.....
Rod, forging	...	...	QQ-C-501a	Federal	47C2f	.....
Bus bars, rods and shapes	...	...	QQ-C-504	.....	.....	.....
Wire, hard drawn	...	...	QQ-W-336a	Federal	22W3e	.....
Wire, medium hard drawn	...	...	QQ-W-339	.....	Federal	.....
Wire, soft	83	...	QQ-W-341a	Federal	22W9b	.....
Wire, trolley	...	...	.....	.....	22W3e	.....
Wire, magnet	...	...	.....	57-211	.....	.....
Wire, spraying	...	...	.....	.....	.....	AN-W-20
Anodes	...	...	.....	57-226a	.....	.....

B *1 Typical uses.* Architectural: building fronts, downspouts, flashing, gutters, roofing, screening, spouting; automotive: gaskets, radiators; electrical: bus bars, conductivity wire, contacts, radio parts, switches, terminals; hardware: ball floats, burrs, cotter pins, nails, rivets, soldering coppers, tacks; miscellaneous: anodes, chemical process equipment, kettles, pans, printing rolls, rotating bands, road-bed expansion plates, vats.

C *1 Density* at 20 C (68 F). 8.89 to 8.94 ■ per cu cm (0.321 to 0.323 lb per cu in.)
Density at 1083 C (1981 F).[1]
(solid). 8.32 g per cu cm
(liquid). 7.93 ■ per cu cm

3 Density versus pressure (compressibility). Volume compressibility is given by

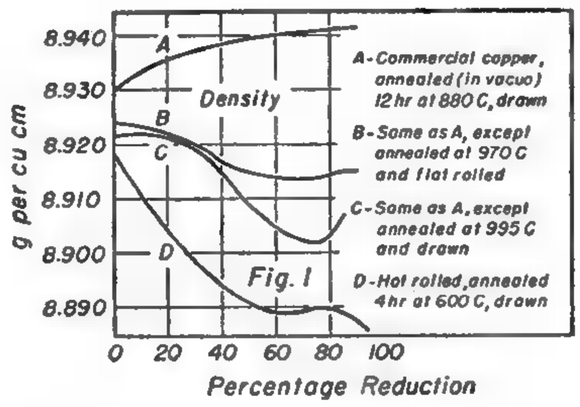
$$\Delta V/V_0 = 10^{-7} P (7.32 - 2.7 \times 10^{-5} P)$$

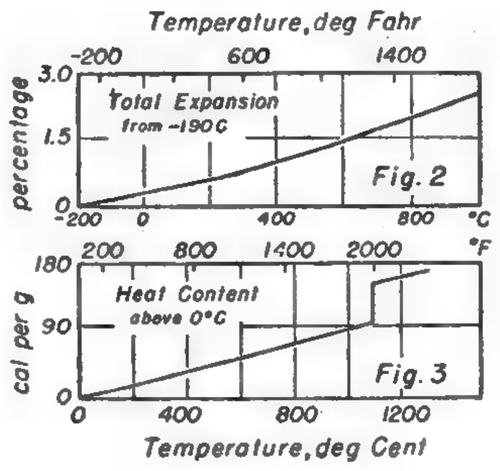
(P = pressure in kg per sq cm). For a pressure of 10,000 atm, this means a volume shrinkage of about 0.7%, or an increase in density of about the same amount.[2,3]

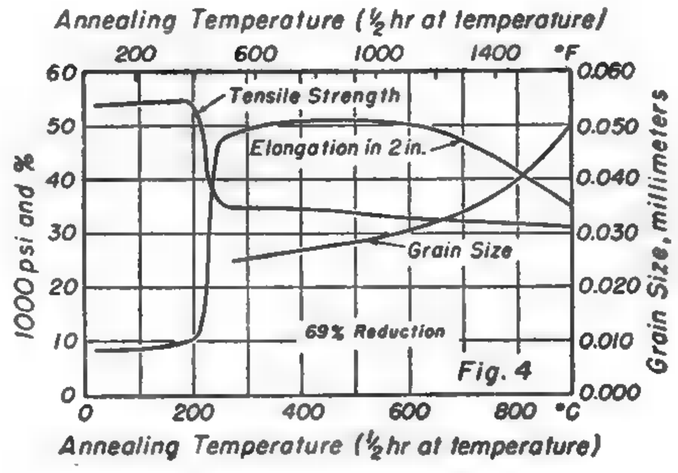
4 Density versus percentage deformation. See Fig. 1. It is generally considered that cold working decreases density. Maier[4] states density changes in cold work

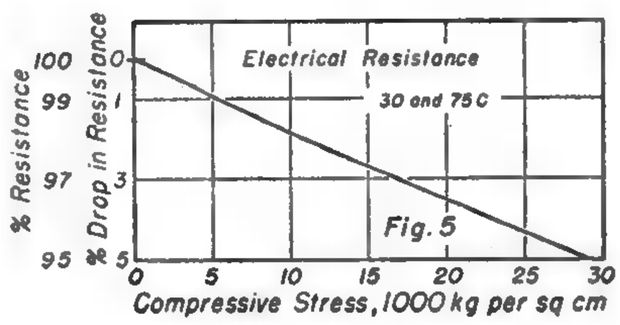
* Compiled by the Copper & Brass Research Association and the American Brass Company

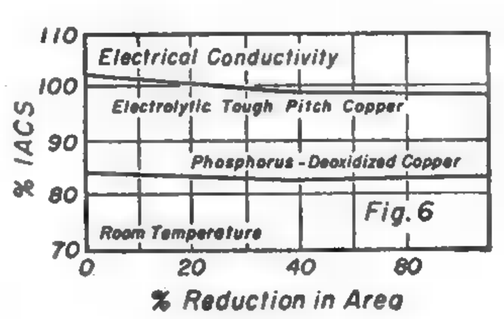
* Most of the physical properties listed here were measured on laboratory coppers that contained various amounts of oxygen. However, the values listed are generally applicable to electrolytic tough pitch copper. For the properties of higher-purity material, see the data sheet on "Pure Copper".

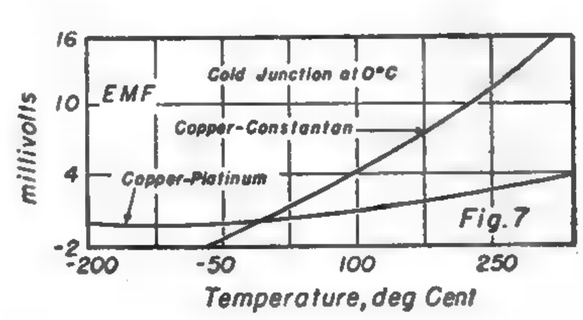


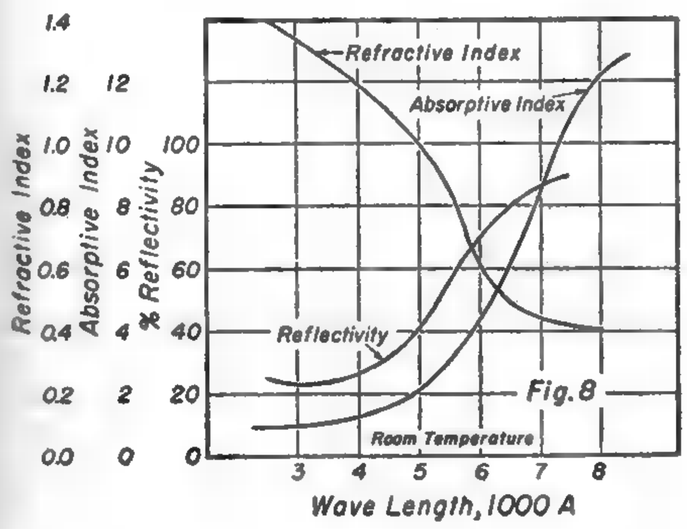


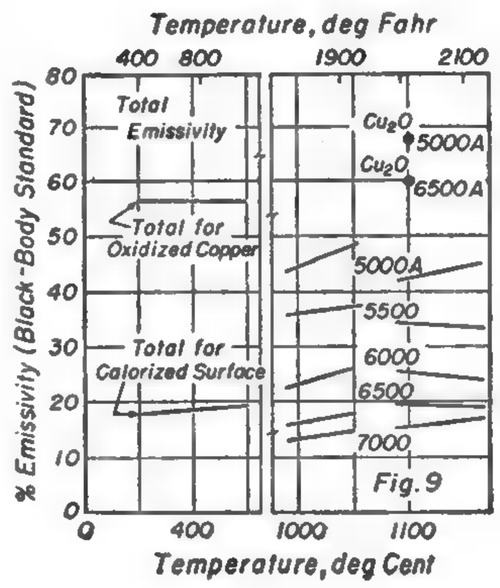


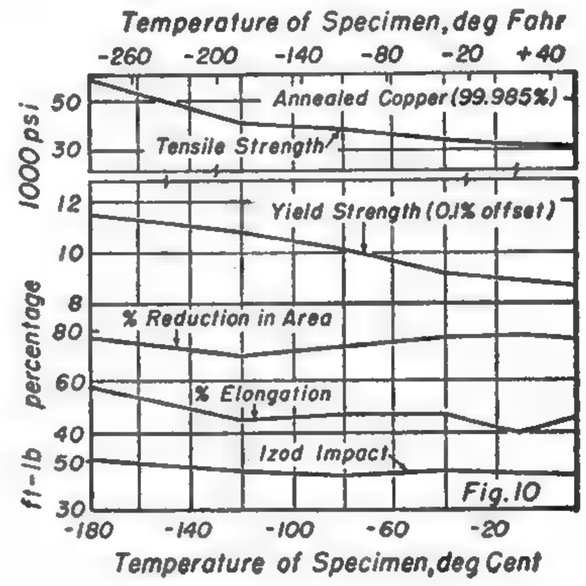












may be positive or negative depending on the type of cold work and the conditions of annealing.

5 *Solidification shrinkage.* Ideal casting condition for tough pitch copper is a "level set", such that liberation of gas counteracts the normal shrinkage.

D 1 *Liquidus temperature.* 1083 C (1981 F)

2 *Solidus temperature.* 1065 C (1949 F)

6 *Thermal expansion* 20 to 300 C (68 to 572 F).[6] 0.0000177 per °C

$L_t = L_0 [1 + (1623 \times 10^{-8}t + 483 \times 10^{-11}t^2)]$ *See* Fig. 2

10 *Volume thermal expansion* (liquid) 1083 to 1295 C (1981 to 2363 F).[12] 0.00019 per °C

11 *Specific heat* at 20 C (68 F). 0.092 cal per g per °C

12 *Specific heat versus temperature. See* Pure Copper. *Heat content versus temperature. See* Fig. 3.

13 *Latent heat of fusion.*[1] 50.6 cal per ■

15 *Latent heat of vaporization.*[12] 1755 cal per ■

16 *Thermal conductivity* at 20 C (68 F). 0.934 cal/sq cm/cm/°C/sec (adjusted to correspond to an electrical conductivity of 101%)

17 *Thermal conductivity versus temperature. See* Pure Copper and Deoxidized Copper.

18 *Heat of combustion.*[13] Cu_2O 279 cal per g
CuO 438 cal per g

19 *Recrystallization temperature.*[14] About 225 C (435 F) for 69% reduction and 0.030-mm initial grain size (nominal 0.5-hr anneal). *See* Fig. 4.
Recrystallization diagram. See Fig. 4.

E 1 *Volume conductivity* referred to standard copper. 101% at 20 C, annealed

2 *Electrical resistivity* at 20 C (68 F). 1.71 microhm-cm, annealed

4 *Electrical resistivity (liquid)* at 1100 C (2012 F). 21.52 microhm-cm

5 *Temperature coefficient of electrical resistivity* at 20 C (68 F). 0.00392 per °C.
Electrical resistivity versus temperature. See Pure Copper and Deoxidized Copper.

7 *Pressure coefficient of electrical resistivity. See* Fig. 5.

8 *Electrical conductivity versus plastic deformation* at 20 C (68 F).[21] *See* Fig. 6.

9 *Contact potential. See* Fig. 7.

10 *Electrochemical equivalent. See* Pure Copper.

11 *Electrolytic solution potential versus hydrogen.*
Cu^{++} minus 0.344 volts
Cu^{+} minus 0.470 volts

13 *Temperature coefficient of solution potential* versus hydrogen, between 20 and 50 C.[45] minus 0.01 millivolts per °C

14 *Hydrogen overvoltage.*[46] 0.23 (dilute H_2SO_4) Varies with current density.

15 *Hall effect.*[24] R = minus 0.52×10^{-12} volt-cm per ampere-gauss. Experimental figures vary from minus 0.428 to minus 0.547×10^{-12}.

F 1 *Reflectivity.*[25]
32.7%, at $\lambda = 4200$ A
43.7%, at $\lambda = 5000$ A
71.8%, at $\lambda = 6000$ A
83.4%, at $\lambda = 7000$ A
Values given here are for polished surfaces, which vary considerably according to polish.
Reflectivity versus wave length. See Fig. 8.

2 *Refractive index. See* Fig. 8.

3 *Absorptive index. See* Fig. 8.

5 *Emissivity versus temperature. See* Fig. 9.

G *Magnetic properties. See* Pure Copper.

H 1 *Velocity of sound.*[28] 12,700 ft per sec at 20 C (68 F)

J *Structure. See* Pure Copper.

Table I. Mechanical Properties of Electrolytic Tough Pitch Copper

Section, in.	Temper	Tensile Strength, psi	Yield Strength,[a] psi	Reduction of Area, percentage	Elongation in 2 in., percentage	Rockwell Hardness F	Rockwell Hardness B	Rockwell Hardness 30-T	Shear Strength, psi	Endurance Strength, psi	Endurance Strength, 10^6 cycles
				Flat Products							
0.040	0.050 mm	32,000	10,000	..	45	40	..	..	22,000	.....	...
0.040	0.025 mm	34,000	11,000	..	45	45	..	..	23,000	11,000	100
0.040	⅛ hard	36,000	28,000	..	30	60	10	25	25,000	.....	...
0.040	¼ hard	38,000	30,000	..	25	70	25	36	25,000	.....	...
0.040	½ hard	42,000	36,000	..	14	84	40	50	26,000	13,000	100
0.040	Hard	50,000	45,000	..	6	90	50	57	28,000	13,000	100
0.040	Spring	55,000	50,000	..	4	94	60	63	29,000	14,000	100
0.040	Extra spring	57,000	53,000	..	4	95	■	64	29,000	.....	...
0.040	As hot rolled	34,000	10,000	..	45	45	..	..	23,000	.....	...
				Flat Products							
0.250	0.050 mm	32,000	10,000	..	50	40	..	..	22,000	.....	...
0.250	⅛ hard	36,000	28,000	..	40	60	10	..	25,000	.....	...
0.250	¼ hard	38,000	30,000	..	35	70	25	..	25,000	.....	...
0.250	Hard	50,000	45,000	..	12	90	50	..	28,000	.....	...
0.250	As hot rolled	32,000	10,000	..	50	40	..	..	22,000	.....	...
1.0	Hard	45,000	40,000	..	20	85	45	..	26,000	.....	...
				Rod							
1.0	0.050 mm	32,000	10,000	70	55	40	..	..	22,000	.....	...
0.250	Hard (40%)	55,000	50,000	..	10	94	60	..	29,000	.....	...
1.0	Hard (35%)	48,000	44,000	55	16	87	47	..	27,000	17,000	300
2.0	Hard (16%)	45,000	40,000	..	20	85	45	..	26,000	.....	...
1.0	As hot rolled	32,000	10,000	70	55	40	..	..	22,000	.....	...
				Wire							
0.080	0.050 mm	35,000	.....	..	35[b]	..	..	..	24,000	.....	...
0.080	Hard	55,000	.....	..	1.5[c]	..	..	..	29,000	.....	...
0.080	Spring	66,000	.....	..	1.5[c]	..	..	..	33,000	.....	...
				Tube (1.0-in. OD by 0.065 in.)							
	0.050 mm	32,000	10,000	..	45	40	..	..	22,000	.....	...
	0.025 mm	34,000	11,000	..	45	45	..	..	23,000	.....	...
	Light drawn (15%)	40,000	32,000	..	25	77	35	45	26,000	.....	...
	Hard drawn (40%)	55,000	50,000	..	8	95	60	63	29,000	.....	...
				Shapes							
0.500	0.050 mm	32,000	10,000	..	50	40	..	..	22,000	.....	...
0.500	Hard (15%)	40,000	32,000	..	30	..	35	..	26,000	.....	...
0.500	As hot rolled	32,000	10,000	..	50	40	..	..	22,000	.....	...
0.500	As extruded	32,000	10,000	..	50	40	..	..	22,000	.....	...

(a) 0.5% extension under load (b) Elongation in 10 inches (c) Elongation in 60 inches

K *Mechanical properties.* *See* Tables I and II, and Fig. 4.

Poisson's ratio.[18] 0.33 ± 0.01

Modulus of elasticity. 17,000,000 psi. This modulus is "directional".[29] It decreases with increasing temperature and is believed to decrease with cold work.[30,31]

Impact values. Impact testing is not routine for copper and the ductile copper alloys. Values here were derived from investigations of a research nature and are not necessarily typical of the material.

Condition	Izod, ft-lb	Charpy, ft-lb
Hot rolled, annealed[36]	..	71 standard V notch
Rod, annealed[14]	..	38 standard key-hole notch
Rod, commercial temper	..	26 standard key-hole notch
Cast[32]	..	8 standard key-hole notch
Cast, hot rolled	..	32 standard key-hole notch
Plate, hot rolled[33]	38	
Rod, annealed, drawn 30%[33]	40	
Rod, drawn 30%	33	
Plate, annealed[33]	39	sample parallel to rolling
Plate, cold rolled 50%	19	sample parallel to rolling
Plate, annealed	29	sample transverse to rolling
Plate, cold rolled 50%	9	sample transverse to rolling

Mechanical properties at low temperatures. All wrought copper alloys are alike in that the effect of temperatures lower than normal is to improve all useful mechanical properties.[34] *See* Fig. 10.

2 *Directional properties.* The most pronounced differences are found with heavy reductions followed by high anneals. Earing generally takes place at angles of 0 and 90 deg to the rolling direction, in contrast to brass. *See* Table II.

6 *Minimum creep rate* at 204 C (400 F). (annealed) (by interpolation)[37]

5000 psi, 0.042% per 1000 hr
6700 psi, 0.10% per 1000 hr
9000 psi, 0.21% per 1000 hr

7 *Viscosity* at 1145 C (2093 F).[1] 0.0341 cgs units

8 *Surface tension* at 1150 C (2102 F).[1] 1104 dynes per cm

9 *Specific damping capacity.* The damping capacity of copper and brasses depends on the amplitude and, under certain conditions, on the frequency of vibration; it is also affected by the condition of the metal. A specific damping capacity of 0.00005 has been recorded for single-crystal, annealed copper.[38] Up to a point damping capacity increases with cold working (increase is reported for reduction as large as 60% for a 70-30 brass).[31] Under torsional stress, brass and copper have relatively high damping capacity.[39] Under the same conditions, copper has a higher damping capacity than alpha brasses (*see* graphs, page 910).

M *Composition limits* (ASTM Specification B 5-43). Electrolytic wire bars, cakes, slabs, billets, ingots and ingot bars. All the following forms specify copper (silver being counted as copper) at 99.9%: chill cast, sheet, wire, extrusions, forgings, and deep drawings. By

Table II. Directional Properties of Tough Pitch Lake Copper[35]
(Within specification purity for electrolytic tough pitch copper)

Treatment	Tensile Strength, psi: Parallel to rolling	Tensile Strength, psi: 45 deg to rolling	Tensile Strength, psi: 90 deg to rolling	Elongation in 2 in., percentage: Parallel to rolling	Elongation in 2 in., percentage: 45 deg to rolling	Elongation in 2 in., percentage: 90 deg to rolling
Cold rolled 50%	51,300	50,100	53,700	6.2	6.2	4.8
Cold rolled 50%, annealed at 600 C	31,375	31,400	31,750	52.5	54.8	57.5
Cold rolled 50%, annealed at 800 C	30,750	30,225	30,750	51.0	57.3	53.6
Cold rolled 89.8%	62,750	60,450	64,600	5.	4.5	4.
Annealed at 600 C	29,900	29,250	29,250	49.3	64.2	48.5
Annealed at 800 C	26,200	26,950	26,250	41.2	76.5	42.

agreement between manufacturer and purchaser, additions of silver up to 30 ounces per ton (0.102%) may be considered within the specification, silver being counted as copper in the chemical analysis.

2 *Consequences of exceeding impurity limits.*

Nominal *oxygen* content about 0.04% (range 0.01 to 0.07%).

Sulfur causes spewing and unsoundness, and is kept below 0.003% in ordinary refinery practice.

Selenium and *tellurium* are usually considered undesirable impurities but may be added to improve machinability.

Bismuth creates brittleness in amounts greater than 0.001%. Bismuth is rarely detected in American copper.

Silver has little effect on mechanical and electrical properties, but does raise the recrystallization temperature and tends to "fine" the grain.[1, 41, 42, 43]

Iron, as present in commercial copper, has no effect on mechanical properties, but even traces of iron may cause ferromagnetism.[47]

Lead should not be present in amounts greater than 0.005% if copper is to be hot rolled.

Cadmium is rarely present; its effect is to toughen copper without much loss in conductivity.

Arsenic decreases the conductivity of copper noticeably, although it is often added intentionally to copper not used in electrical service, because it increases the toughness and heat resistance of the metal.

Antimony is sometimes added to copper when high recrystallization temperature is desired.

N 1 *Melting and casting temperature range.* 1083 to 1150 C (1981 to 2102 F)

5 *Type of flux.* Melt under charcoal.

6 *Precautions in melting.* Pour into dry mold. Oxygen content should be kept within good working limits.

7 *Hot working temperature range.* 750 to 875 C (1400 to 1600 F)

9 *Annealing temperature.* 375 to 650 C (700 to 1200 F)

10 *Maximum cold reduction between anneals* is about 90%. It may be higher in strip.

11 *Suited to forming* by blanking, coining, coppersmithing, drawing, heading and upsetting, hot forging and pressing, impact extrusion, piercing and punching, roll threading and knurling, shearing, spinning, squeezing and swaging, and stamping.

12 *Precautions in forming.* Avoid annealing in a reducing atmosphere.

17 *Joining.*

Rivet composition. Copper

Soft solder with all grades solder; commercial solder fluxes or rosin.

Silver solder with all grades solder; proprietary flux; all types of flame.

Braze with Cu-P or Cu-Zn alloy; commercial brazing flux; all types of flame.

Oxyacetylene welding is not recommended.

Carbon-arc welding is not recommended.

Resistance welding is not satisfactory, except as butt welding of rod and wire.

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99.94 Cu – 0.02 P*

A 1 *Common name.* **Deoxidized Copper** (Phosphorized Copper, High Residual Phosphorus)

3 *ASTM numbers.*
Rolled flat products: B 124, No. 12; B 133; B 152; B 11
Drawn flat products; B 133
Rod: B 124, No. 12; B 133
Tube: B 68, B; B 75, B; B 88; B 111; B 13
Pipe: B 42
Shapes: B 124, No. 12; B 133

4 *Government and other designations.*

	SAE	Federal	Army	Navy
Tubes for general use..	75	....	....	....
Tubes for use with SPS flanged fittings	..	WW-T-797	Federal	44T12c
Tubes, water	..	WW-T-799a	Federal	Federal
Pipe, SPS	..	WW-P-377	Federal	44P2g
Blanks for projectile rotating bands	..	....	50-27-1B, class A	....

B 1 *Typical uses.* Household: gas lines, heater lines and units, oil-burner tubes, plumbing pipe and tube, refrigerators; industrial: condenser, evaporator and heat-exchanger tubes, dairy tubes, distiller tubes, pulp and paper lines, steam and water lines, brewery tubes; transportation: air, gasoline, hydraulic and oil lines, oil coolers; miscellaneous: rotating bands, gage lines.

C 1 *Density* at 20 C (68 F). 8.94 g per cu cm (0.323 lb per cu in.)

D 1 *Liquidus temperature.* 1083 C (1981 F).

6 *Thermal expansion* 20 to 300 C (68 to 572 F). 0.0000177 per °C

10 *Thermal expansion (liquid). See* Electrolytic Copper.

11 *Specific heat* at 20 C (68 F). 0.092 cal per g per °C

12 *Specific heat versus temperature. See* Pure Copper.

13 *Latent heat of fusion.* 50 cal per g

15 *Latent heat of vaporization.* 1755 cal per g

16 *Thermal conductivity* at 20 C (68 F). 0.81 cal/sq cm/cm/°C/sec (196 Btu/sq ft/ft/hr/°F)

17 *Thermal conductivity versus temperature.*[1, 2, 3] *See* Fig. 1.

18 *Heat of combustion. See* Electrolytic Copper.

19 *Recrystallization temperature.*[4] About 300 C (570 F) for 69% reduction and 0.045-mm initial grain size (nominal 0.5-hr anneal). *See* Fig. 2, which is the recrystallization diagram for deoxidized copper.

E 1 *Volume conductivity* referred to standard copper. 85% at 20 C, annealed; 0.493 megmho-cm at 20 C, annealed.

2 *Electrical resistivity* at 20 C (68 F). 2.03 microhm-cm (12.2 ohms per mil-ft), annealed

4 *Electrical resistivity (liquid). See* Electrolytic Copper.

*Compiled by the Copper & Brass Research Association and the American Brass Company

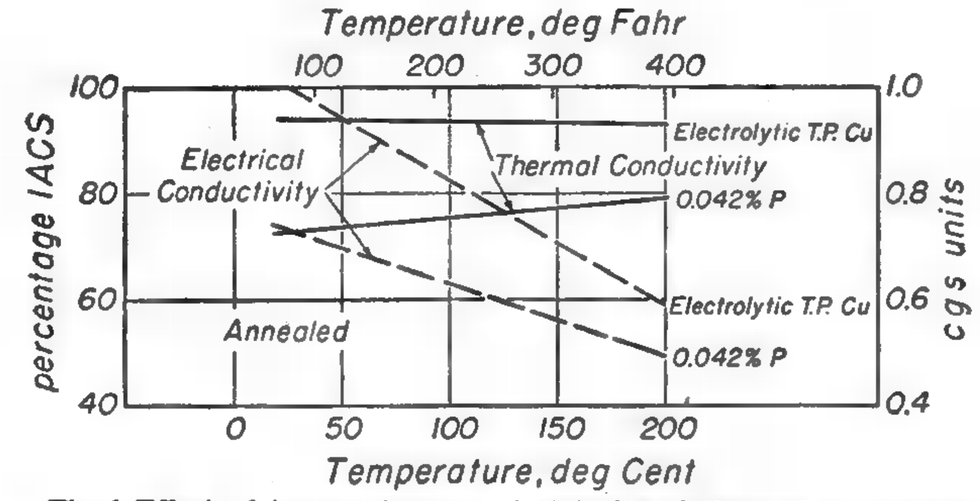

Fig. 1 Effect of temperature on electrical and thermal conductivity of electrolytic and deoxidized coppers (Smith,[1,2] Smith and Palmer[3])

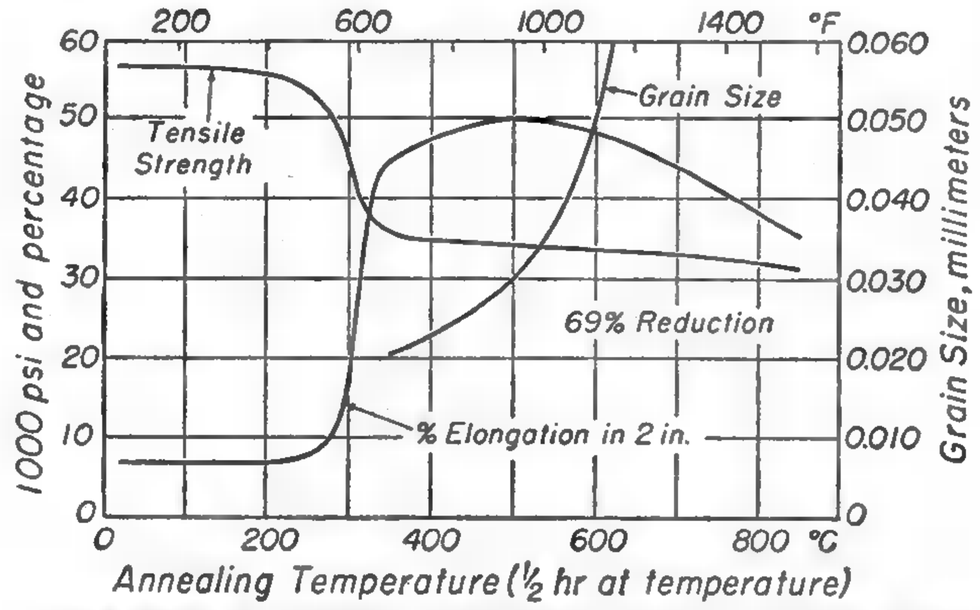

Fig. 2 Effect of annealing temperature on tensile strength, elongation and grain size of deoxidized copper (American Brass Company)

5 Temperature coefficient of electrical resistivity 20 to 200 C (68 to 392 F).
0.042% P, 0.002198 per °C
0.02% P, about 0.003 per °C
See Fig. 1.

8 Electrical resistivity versus plastic deformation at 20 C (68 F). Less than 1% with 84% reduction. *See* Electrolytic Copper.

10 Electrochemical equivalent. See Pure Copper.

F *Optical properties.* The optical properties are probably the same as for electrolytic copper, except possibly for the emissivity of the oxidized surface. *See* Electrolytic Copper.

G *1 Influence of treatments on magnetic properties.* Normally diamagnetic, unless considerable iron is present

2 Magnetic susceptibility. See Pure Copper.

H *1 Velocity of sound.* 12,700 ft per sec at 20 C (68 F).

J *Structure. See* Pure Copper.

K *Mechanical properties. See* Tables I and II, Fig. 2, 3.
Modulus of elasticity (tension) 17,000,000 psi (nominal figure, *see* Electrolytic Copper)
Impact Tests. (*See also* Fig. 3)

Condition	Izod, ft-lb	Charpy, ft-lb
Cold rolled[5]	79[a]	...
Annealed[5]	113[a]	...
No. 939, wrought annealed rod[4]	...	47[a] keyhole
Cast[6]	...	36[b] keyhole
Hot rolled[6]	...	46[b]
Hot rolled plates[7]	46[a]	...
Annealed rod[7]	45[a]	...
Drawn 30%[7]	55[a]	...

(a) Most samples unbroken (b) No data on breaking

2 Directional properties. Values given in Table II are for deoxidized electrolytic copper, 0.0089% P, and 0.005% O, plate thickness 0.102 in.[8]

4 Machinability index (free-cutting brass = 100). 20

6 Minimum creep rate at 204 C (400 F). 0.125-in. wire[12]
2100 psi, 0.01% per 1000 hr (ann, 0.013 mm)
5200 psi, 0.01% per 1000 hr (drawn 84%, slightly recrystallized)

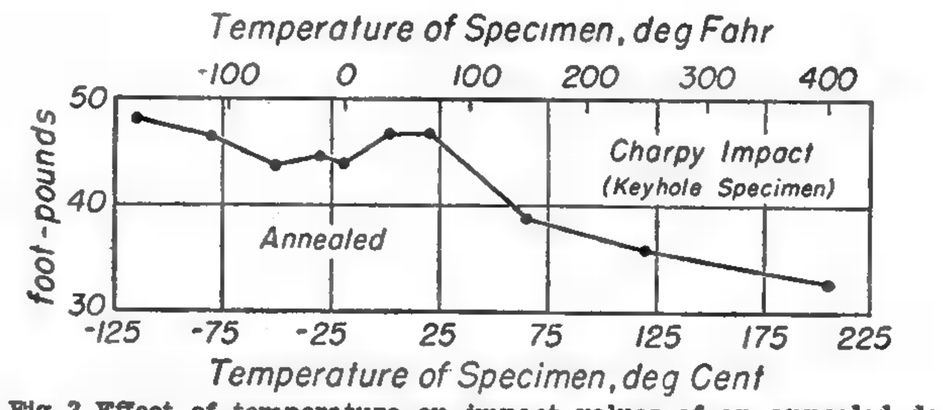

Fig. 3 Effect of temperature on impact values of an annealed deoxidized copper (99.95 Cu – 0.025 P) (American Brass Company data)

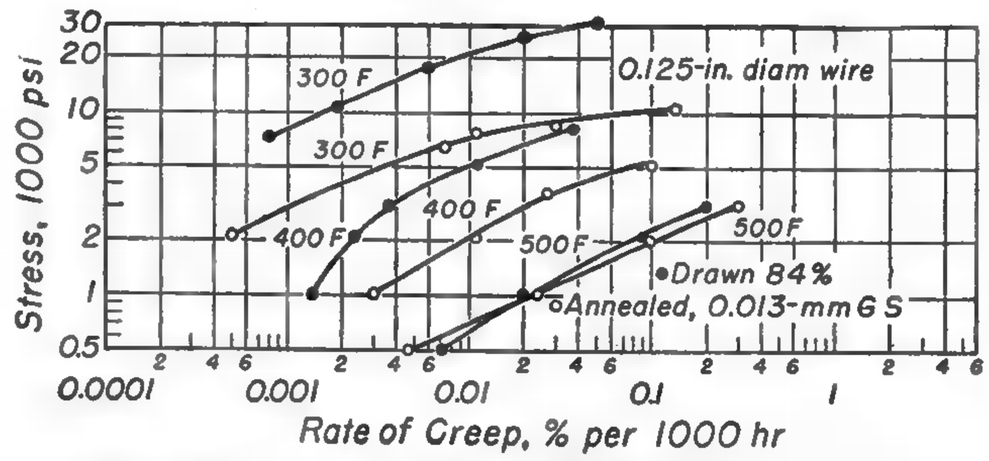

Fig. 4 Rate of creep versus stress for deoxidized copper (Burghoff and Blank[12])

Minimum creep rate at 260 C (500 F)
1950 psi, 0.10% per 1000 hr (ann, 0.013 mm)
2300 psi, 0.10% per 1000 hr (drawn 84%, recrystallization well advanced). *See* Fig. 4.

M *Composition limits* (ASTM Specifications).

Form	Designation	Components: Cu[a] min	Components: P min	Components: P max	Impurities: Others (total) max
Sheet	B 152, B; B 11	99.90	0.015	0.040	....
Tubing	B 75; B 68, B	99.90	0.015	0.040	....
Condenser tubing	B 111	99.90	....	0.035	....
Water tubes	B 88	99.90	....	0.040	....
Boiler tubes	B 13	99.90	....	....	0.100
Pipes	B 42	99.90	....	0.04	....

(a) Silver is counted as copper. *See note* on silver for Electrolytic Copper.

2 Consequences of exceeding impurity limits.

Phosphorus lowers electrical and thermal conductivity; "toughens" the copper.

Remarks on electrolytic copper relative to the harmful effects of bismuth and lead apply to deoxidized copper.

Presence of arsenic in commercial amounts does not appreciably affect the impact strength of deoxidized copper.[7]

N *1 Casting temperature.* 1083 to 1150 C (1981 to 2102 F)

3 Alloying. 15% P-Cu cake is added in the ladle just before pouring.

5 Type of flux. Melt under charcoal.

6 Precautions in melting. Pour into oil-dressed mold.

7 Hot working temperature. 750 to 875 C (1400 to 1600 F)

9 Annealing temperature. 375 to 650 C (700 to 1200 F)

10 Maximum reduction between anneals. 95% is possible.

11 Suited to forming by blanking, coining, coppersmithing, drawing, forming and bending, hot forging and pressing, piercing and punching, shearing, spinning, squeezing and swaging, and stamping. Excellent hot and cold working properties.

17 Joining.
Soft solder with all grades solder; commercial solder fluxes or rosin.
Silver solder with all grades solder; proprietary flux; all types of flame.
Braze with Cu-P or Cu-Zn alloy; commercial brazing flux; all types of flame.
Oxyacetylene welding with special copper rods; commercial brazing flux; oxyacetylene flame.
Carbon-arc welding with phosphor bronze, no flux; or with copper-silicon alloy and a flux.
Resistance welding is not satisfactory, except for butt welding of rod and wire.

Table I. Mechanical Properties of Deoxidized Copper

Temper	Tensile Strength, psi	Yield Strength,(a) psi	Elongation in 2 in., percentage	Rockwell Hardness, F	B	30-T	Shear Strength, psi	Endurance Strength, psi	Endurance Strength, 10^6 cycles
Flat Products (0.040 in. thick)									
0.050 mm	32,000	10,000	45	40	..	..	22,000	.....	..
Tube (1.0-in. OD by 0.065 in.)									
0.050 mm	32,000	10,000	45	40	..	..	22,000	11,000(b)	20
0.025 mm	34,000	11,000	45	45	..	..	23,000	.....	..
Light drawn (15%)	40,000	32,000	25	77	35	45	26,000	14,000(b)	20
Hard drawn (40%)	55,000	50,000	8	95	60	63	29,000	19,000(b)	20
Pipe (0.750-in. SPS)									
Hard (30%)	50,000	45,000	10	90	50	..	28,000	.....	..

(a) 0.5% extension under load (b) Rotating-beam tests on rod

Table II. Directional Properties of Deoxidized Copper

Treatment	Tensile Strength in psi, Parallel to rolling	Tensile Strength in psi, 45 deg to rolling	Tensile Strength in psi, 90 deg to rolling	Elongation in percentage, Parallel to rolling	Elongation in percentage, 45 deg to rolling	Elongation in percentage, 90 deg to rolling
Cold rolled, 50%	53,350	53,400	55,350	6.	5.2	5.7
Annealed at 600 C	33,300	33,075	32,500	57.	53.	56.2
Annealed at 800 C	31,625	31,150	30,000	50.2	52.2	54.5
Cold rolled, 89.8%	64,400	63,000	67,350	5.7	5.	4.
Annealed at 600 C	35,750	33,100	33,100	48.	54.5	56.5
Annealed at 800 C	35,500	29,200	30,750	42.7	55.	59.5

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6 Lorig, Dahle and Roberts, Metals & Alloys, 72, 63 (1938)
7 Cook and Larke, J Inst Metals, 68, 1 (1942)
8 Phillips and Bunn, Trans AIME, Inst Metals Div, 353 (1931)
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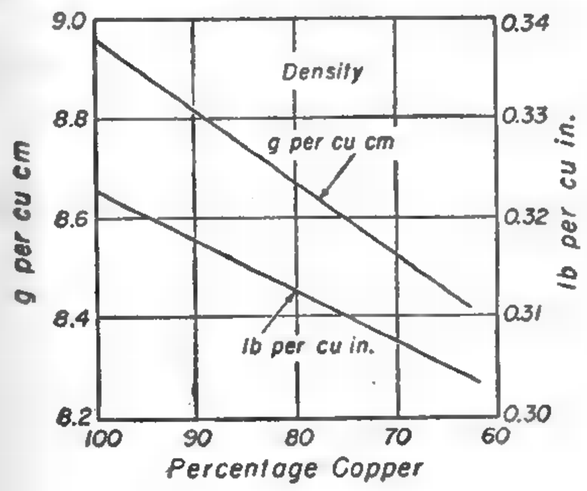
12 Burghoff and Blank, Trans AIME, 161, 420 (1945)

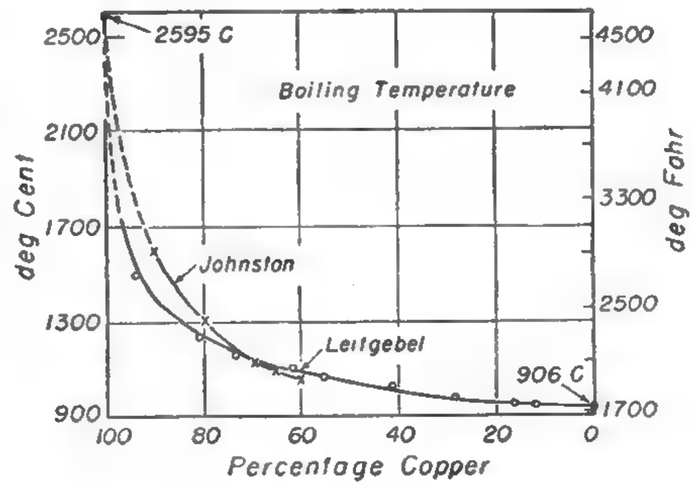
WROUGHT ALLOYS

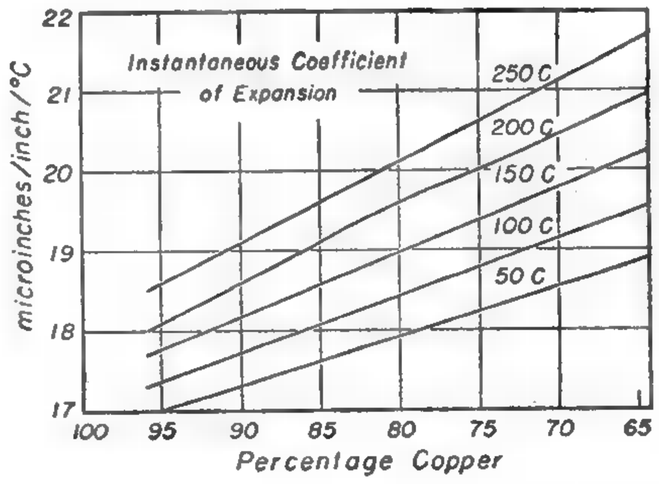
Some Properties of Copper-Zinc Alloys*

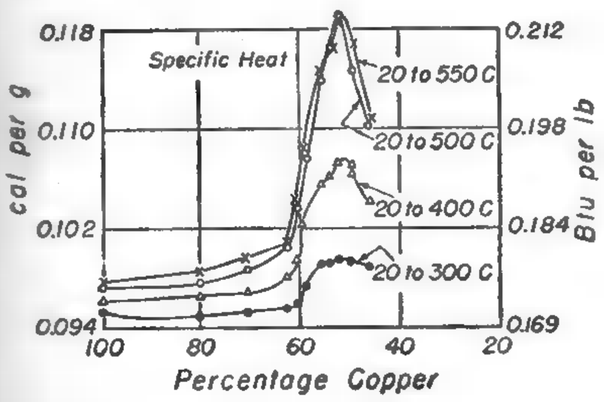
THIS COMPILATION summarizes graphically the effect of composition on some of the physical and mechanical properties of binary copper-zinc alloys. More specific information concerning the properties of particular alloys in this series may be found in the data sheets for the seven standard wrought copper-zinc alloys that contain 95, 90, 85, 80, 70, 65 and 60% Cu. These data sheets are given on pages 910 to 917, immediately following this compilation.

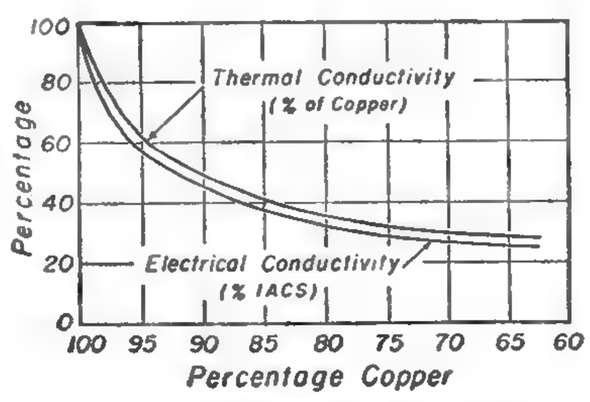
* Compiled by The American Brass Company

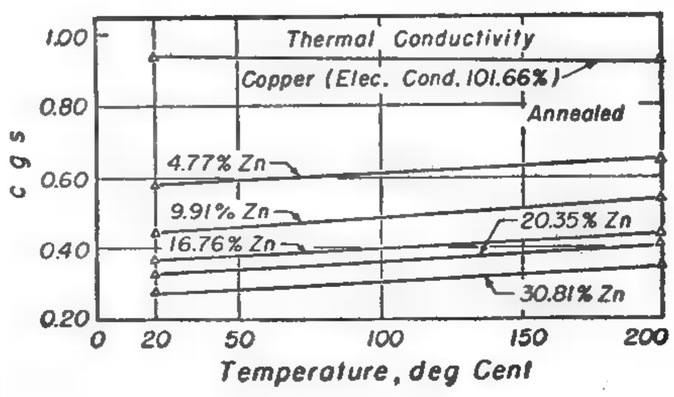












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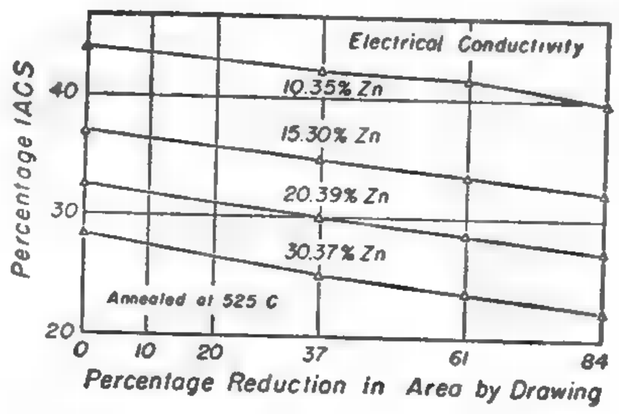
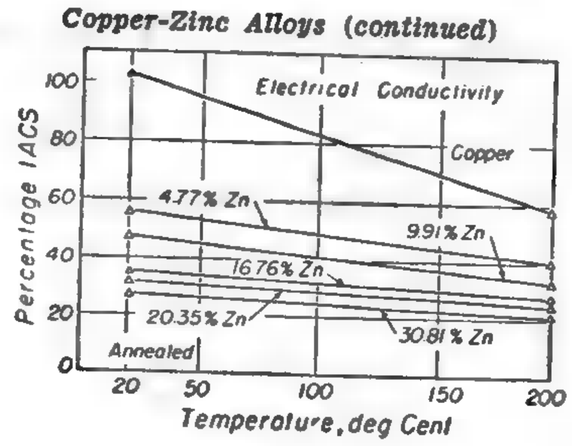
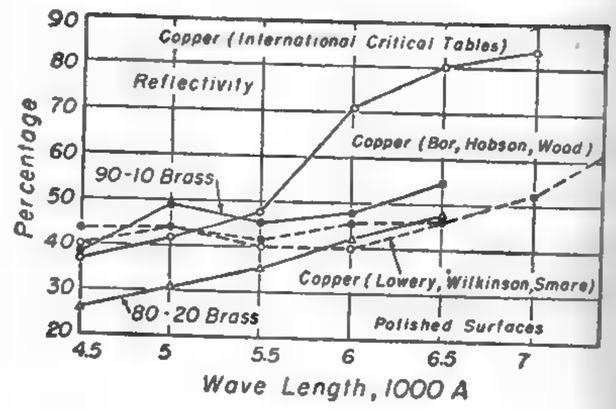
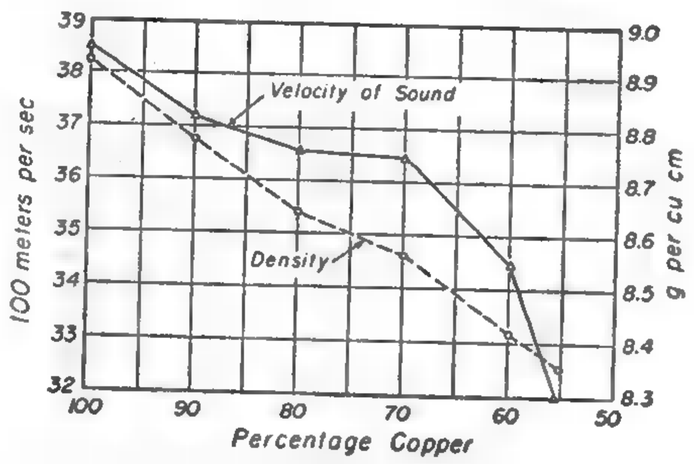
Properties of Gilding Metal

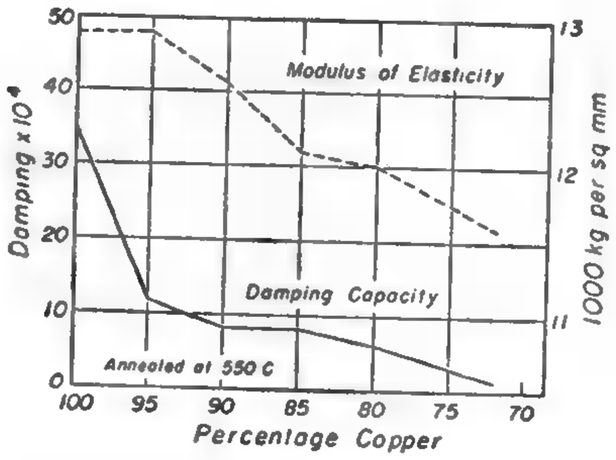


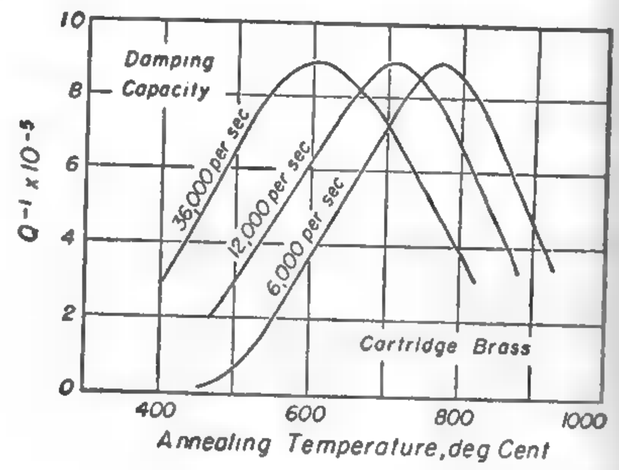
Copper-Zinc Alloys (continued)

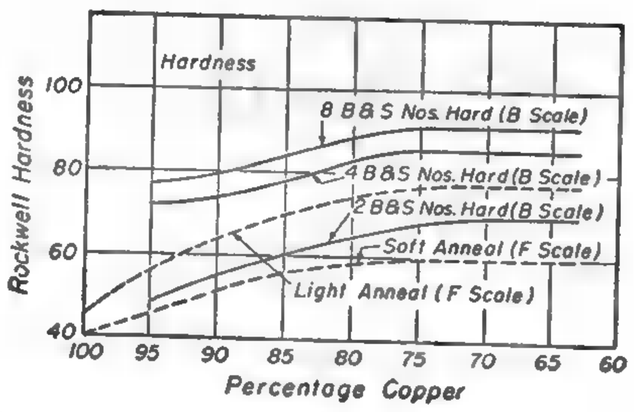


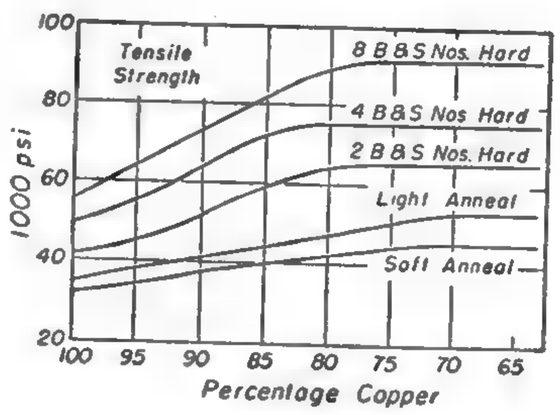


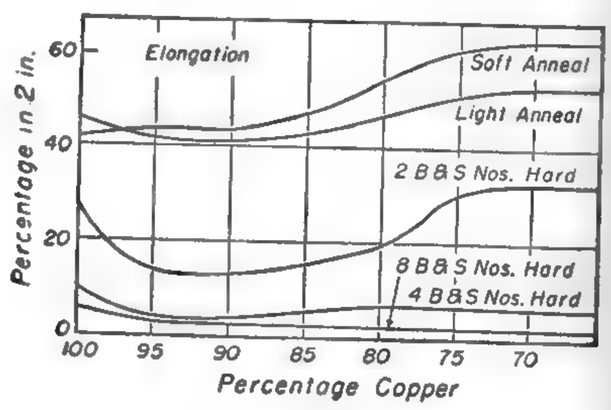












95 Cu – 5 Zn*

A *1 Common name.* **Gilding Metal**

3 ASTM number.
Rolled flat products: B 36, No. 1; B 134, No. 1
Drawn flat products: B 134, No. 1
Wire: B 134, No. 1

4 Government number. Army 57-171-2

B *1 Typical uses.* Coinage: coins, medals and tokens; munitions: bullet jackets, firing-pin supports, shells, fuse caps and primers; novelties: emblems, jewelry, plaques; miscellaneous: base for gold plate, base for vitreous enamel, etched articles.

C *1 Density* at 20 C. 8.86 ■ per cu cm (0.320 lb per cu in.)

D *1 Liquidus temperature.* 1065 C (1950 F)

2 Solidus temperature. 1050 C (1920 F)

4 Boiling point at 760 mm Hg.[1] About 1600 C (2910 F)

6 Thermal expansion 25 to 300 C (77 to 572 F).[2] 0.0000181 per °C (0.0000100 per °F), cold rolled

$L_t = L_0\ [1 + (16.81t + 0.00389t^2) \times 10^{-6}]$ cold rolled

$L_t = L_0\ [1 + (16.87t + 0.00356t^2) \times 10^{-6}]$ cast (avg of 4)

11 Specific heat at 20 C (68 F). 0.09 cal per ■ per °C

16 Thermal conductivity at 20 C (68 F). 0.56 cal/sq cm/cm/°C/sec (135 Btu/sq ft/ft/hr/°F)

17 Thermal conductivity versus temperature. See "Some Properties of Copper-Zinc Alloys".

19 Recrystallization temperature.[4] About 370 C (700 F) for 50% reduction and 0.015 to 0.070-mm initial grain size. *See* Fig. 1.

E *1 Volume conductivity* referred to standard copper. 56% at 20 C (68 F), annealed

2 Electrical resistivity at 20 C (68 F). 3.1 microhm-cm (18.5 ohms per mil-ft), annealed

4 Electrical resistivity (liquid).[5]
at 1100 C (2010 F). 24.4 microhm-cm
at 1300 C (2370 F). 26.6 microhm-cm

5 Temperature coefficient of electrical resistivity at 20 C (68 F).[6] 0.00231 per °C

Electrical resistivity versus temperature. See "Some Properties of Copper-Zinc Alloys".

F *1 Reflectivity.*[7] 90% at $\lambda = 5780$ A

G *2 Magnetic susceptibility.*[8] minus 0.086 $> \chi >$ minus 1.00×10^{-6} cgs

H *1 Velocity of sound.*[9] Approx 12,400 ft per sec at 20 C (68 F) (by interpolation)

J *1 Crystal structure.* Face-centered cubic alpha; lattice parameter. 3.620 kX

5 Minimum interatomic distance. 2.559 kX

K *Mechanical properties.* See Fig. 1.

Temper	Tensile Strength, psi	Yield Strength, psi	Elongation in 2 in., percentage[a]	Rockwell Hardness 30-T	Shear Strength, psi
Rolled strip, 0.040-in. section					
0.050 mm	34,000	10,000	45	F 46	.....
0.035 mm	35,000	11,000	45	F 52	28,000
0.015 mm	38,000	14,000	42	F 60	30,000
¼ hard	42,000	32,000	25	B 38	32,000
½ hard	48,000	40,000	12	B 52	34,000
Hard	56,000	50,000	5	B 64	37,000
Extra hard	61,000	55,000	4	B 70	39,000
Spring	64,000	58,000	4	B 73	40,000

(a) 0.5% extension under load

Modulus of elasticity (tension). 17,000,000 psi

4 Machinability index (free-cutting brass = 100). 20

M *Composition limits.* See Table I.

2 Consequences of exceeding impurity limits. See remarks for 70 Cu – 30 Zn concerning the effects of lead

* Compiled by the Copper & Brass Research Association and the American Brass Company

Table I. Composition Limits of 95 Cu – 5 Zn

Form	ASTM Designation	Components: Cu min	Cu max	Zn min	Zn max	Impurities: Pb max	Fe max
Sheet	B 36	94.0	96.0	remainder		0.03	0.05
Wire	B 134	94.0	96.0	remainder		0.05	0.05

and of iron. Lead in the amounts specified above has little effect on tensile properties.

N 1 *Melting and chill casting temperature range.* 1275 to 1300 C (2327 to 2372 F)

3 *Alloying.* Zinc is added just before pouring.

5 *Type of flux.* Melt under charcoal.

6 *Precautions in melting.* The temperatures above may not be exact. The right pouring temperature is indicated by "zinc shine" on the melt. "Zinc boiling" at higher temperatures is to be avoided. The melt should be poured into an oil-dressed mold.

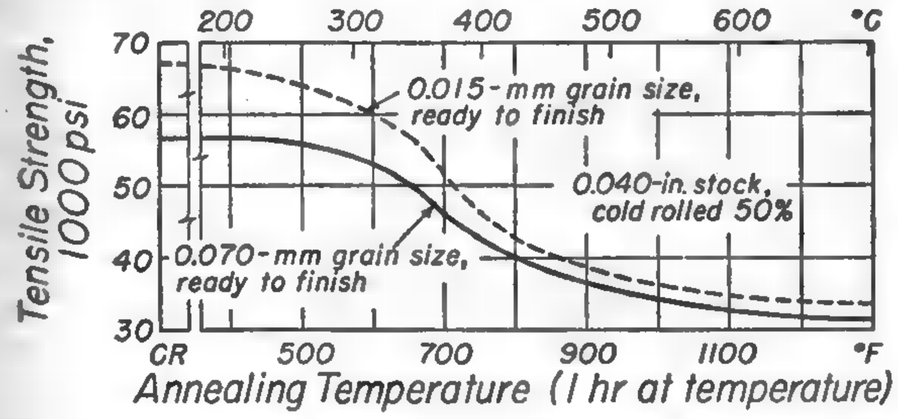


Fig. 1 Recrystallization diagram for gilding metal (Wilkins and Bunn[4])

7 *Hot working temperature.* 750 to 875 C (1400 to 1600 F)

9 *Annealing temperature.* 425 to 800 C (800 to 1450 F)

10 *Maximum reduction between anneals.* Almost as high as copper

11 *Suited to forming* by blanking, coining, drawing, forming and bending, piercing and punching, shearing, spinning, squeezing and swaging, and stamping. Excellent cold working properties, good hot working properties.

17 *Joining.*

Soft solder with all grades solder, commercial solder fluxes or rosin.

Silver solder with all grades solder, proprietary flux, all types of flame.

Braze with P-Cu, or copper-zinc alloy, commercial brazing flux, all types of flame.

Oxyacetylene welding with bronze welding rods, commercial brazing flux, and oxyacetylene flame.

Carbon-arc welding is fair.

Resistance welding is unsatisfactory except for butt welding of rod and wire.

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2 Hidnert, Nat Bur Standards, Sci Paper 410 (1921)
3 Smith, Trans AIME, Inst Metals Div, 89, 84 (1930)
4 Wilkins and Bunn, "Copper and Copper-Base Alloys", McGraw-Hill Book Co., New York, 1943, p 31
5 "International Critical Tables", Vol 6, 1929, p 197
6 Smith and Palmer, Trans AIME, 117, 225 (1935)
7 "International Critical Tables", Vol 5, 1929, p 251
8 "International Critical Tables", Vol 6, 1929, p 365
9 Allen, Phil Mag, 32, 7th ser, 165 (1941)

90 Cu – 10 Zn*

A 1 *Common name.* **Commercial Bronze**

3 *ASTM number.*
Rolled flat products: B 36, No. 2; B 130, B 134, No. 2
Drawn flat products: B 134, No. 2
Wire: B 134, No. 2
Bullet jacket cups: B 131

4 *Government numbers.*
Sheet, strip and coil for small-arms ammunition: Army 57–171–1B
Bullet jacket cups: Army 57–171–3A
Wire, spraying: AN–W–20 (Army-Navy Aeronautical)
Blanks for projectile rotating bands: Army 50–27–1B, class B

B 1 *Typical uses.* Architectural: etching bronze, grillwork, screen cloth, weather stripping; hardware: escutcheons, kick plates, line clamps, marine hardware, rivets, screws, screw shells; munitions: primer caps, rotating bands; miscellaneous: compacts, lipstick cases, costume jewelry, ornamental trim, screen wire, base for vitreous enamel.

C 1 *Density* at 20 C. 8.80 g per cu cm (0.318 lb per cu in.)

D 1 *Liquidus temperature.* 1045 C (1910 F)

2 *Solidus temperature.* 1020 C (1870 F)

4 *Boiling point* at 760 mm Hg. About 1400 C (2550 F)

6 *Thermal expansion* 25 to 300 C (77 to 572 F).[3] 0.0000182 per °C (0.0000101 per °F), cold rolled

$L_t = L_0\ [1 + (17.01t + 0.00379t^2) \times 10^{-6}]$, cold rolled

11 *Specific heat* at 20 C (68 F). 0.09 cal per g per °C

16 *Thermal conductivity* at 20 C (68 F). 0.45 cal/sq cm/cm/°C/sec (109 Btu/sq ft/ft/hr/°F)

17 *Thermal conductivity versus temperature.* See "Some Properties of Copper-Zinc Alloys".

19 *Recrystallization temperature.*[4] About 370 C (700 F) for 37% reduction and 0.050-mm initial grain size. *See* Fig. 1.

E 1 *Volume conductivity* referred to standard copper. 44% at 20 C (68 F), annealed

2 *Electrical resistivity* at 20 C (68 F). 3.9 microhm-cm (23.5 ohms per mil-ft), annealed

4 *Electrical resistivity (liquid)* at 1100 C (2012 F).[5] 27.2 microhm-cm

5 *Temperature coefficient of electrical resistivity* at 20 C (68 F). 0.00186 per °C
Electrical resistivity versus temperature. See "Some Properties of Copper-Zinc Alloys".

8 *Electrical resistivity versus plastic deformation.*[6] See "Some Properties of Copper-Zinc Alloys".

F 1 *Reflectivity.* See "Properties of Copper-Zinc Alloys".

G 2 *Magnetic susceptibility.*[7] minus 0.086 $> \chi >$ minus 1.00×10^{-6} cgs

H 1 *Velocity of sound.* 12,200 ft per sec at 20 C (68 F).

J 1 *Crystal structure.* Face-centered cubic alpha; lattice parameter 3.63 kX

5 *Minimum interatomic distance.* 2.57 kX

K *Mechanical properties.* See Fig. 1 and Table I.
Modulus of elasticity (tension). 17,000,000 psi
Endurance strength. (Spring temper, flat product, 0.040 in. thick) 21,000 psi, 15,000,000 cycles. (Hard wire, 0.080-in. diam) 23,000 psi, 100,000,000 cycles.

4 *Machinability index* (free-cutting brass = 100). 20

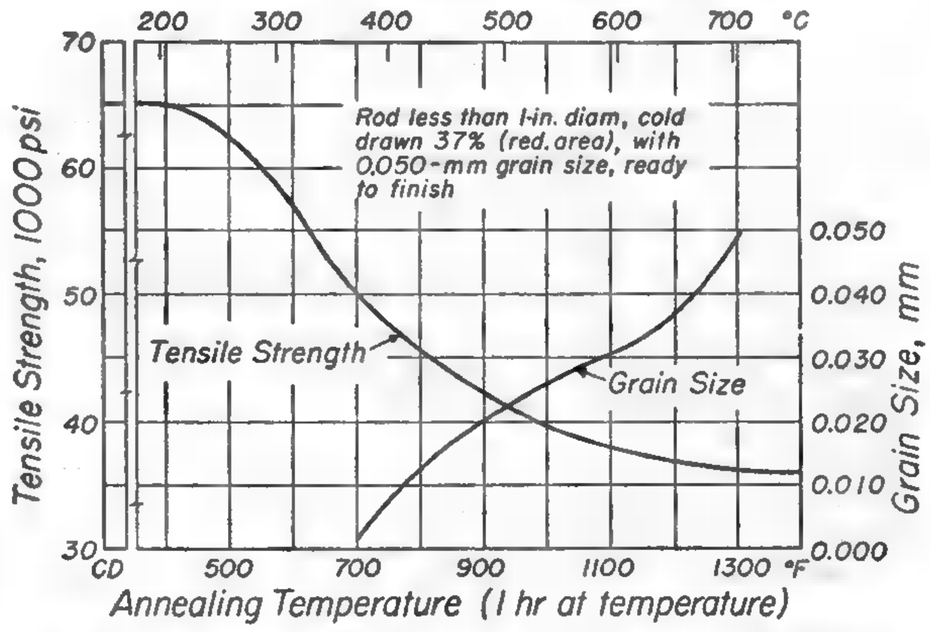

Fig. 1 Recrystallization diagram for commercial bronze (Wilkins and Bunn[4])

* Compiled by the Copper & Brass Research Association and the American Brass Company

Table I. Mechanical Properties of 90 Cu – 10 Zn

Temper	Tensile Strength, psi	Yield Strength,[a] psi	Elongation in 2 in., percentage	Rockwell Hardness	30-T	Shear Strength, psi
Flat Products (0.040-in. section)						
0.050 mm	37,000	10,000	45	F 53	6	28,000
0.035 mm	38,000	12,000	45	F 57	12	30,000
0.025 mm	39,000	14,000	44	F 60	16	31,000
0.015 mm	41,000	15,000	42	F 65	26	32,000
¼ hard	45,000	35,000	25	B 42	44	33,000
½ hard	52,000	45,000	11	B 58	56	35,000
Hard	61,000	54,000	5	B 70	63	38,000
Extra hard	67,000	58,000	4	B 75	67	40,000
Spring	72,000	62,000	3	B 78	69	42,000
As hot rolled	39,000	14,000	44	F 60	..	31,000
Flat Products (0.250-in. section)						
0.035 mm	38,000	12,000	50	F 57	..	30,000
½ hard	52,000	45,000	15	B 58	..	35,000
As hot rolled	37,000	10,000	45	F 53	..	28,000
Wire (0.080-in. diam)						
0.035 mm	40,000	.....	50	....	..	30,000
0.015 mm	42,000	.....	48	....	..	32,000
⅛ hard	44,000	.....	27	....	..	33,000
¼ hard	50,000	.....	13	....	..	34,000
½ hard	60,000	.....	6	....	..	37,000
Hard	74,000	.....	4	....	..	42,000
Extra hard	83,000	.....	3	....	..	.....
Spring	90,000	.....	3	....	..	.....
Tube (1.0-in. OD by 0.065 in.)						
0.035 mm	38,000	12,000	50	F 57	12	.....
Hard drawn (35%)	80,000	53,000	6	B 69	62	.....
Rod (0.500 in.)						
0.035 mm	40,000	.....	50	F 55	..	32,000
⅛ hard	45,000	.....	25	B 42	..	33,000

(a) 0.5% extension under load

M *Composition limits.*

Form	ASTM Designation	Components: Cu min	Cu max	Zn min	Zn max	Impurities: Pb max	Fe max	Others (total) max[a]
Sheet	B 36, No. 2	89.0	91.0	remainder		0.05	0.05	...
Strip	B 130	89.0	91.0	remainder		0.05	0.05	0.13
Bullet jacket cups	B 131	89.0	91.0	remainder		0.05	0.05	0.13
Wire	B 134, No. 2	89.0	91.0	remainder		0.05	0.05	...

(a) Other than copper and zinc

2 Consequences of exceeding impurity limits. See general statement for brasses under 70 Cu – 30 Zn.

N *1 Melting and chill casting temperature ranges.* 1225 to 1250 C (2237 to 2282 F)

3 Alloying. Zinc is added to scrap and copper melt just before pouring.

5 Type of flux. Melt under charcoal.

6 Precautions in melting. See 95 Cu – 5 Zn.

7 Hot working temperature range. 750 to 875 C (1400 to 1600 F)

9 Annealing temperature. 425 to 800 C (800 to 1450 F)

10 Maximum reduction between anneals. 90%

11 Suited to forming by blanking, coining, drawing, forming and bending, heading and upsetting, hot forging and pressing, piercing and punching, roll threading and knurling, shearing, spinning, squeezing and swaging, stamping. Excellent cold working properties, good hot working properties.

17 Joining.

Soft solder with all grades solder, commercial solder fluxes or rosin.

Silver solder with all grades solder, proprietary flux, all types of flame.

Braze with P-Cu or Cu-Zn alloy, commercial brazing flux, all types of flame.

Oxyacetylene welding with bronze welding rods, commercial brazing flux, all types of flame.

Carbon-arc welding is fair.

Resistance welding is unsatisfactory except for butt welding of rod and wire.

References

1 Johnston, J Am Inst Metals, 12, 15 (1918)
2 Leitgebel, Z anorg allgem Chem, 202, 305 (1931)
3 Hidnert, Nat Bur Standards Sci Paper 410 (1921)
4 Wilkins and Bunn, "Copper and Copper-Base Alloys", McGraw-Hill Book Co., 1943, p 39
5 "International Critical Tables", Vol 6, 1929, p 197
6 Crampton, Burghoff and Stacy, Trans AIME, 143, 228 (1941)
7 "International Critical Tables", Vol 6, 1929, p 365
8 Lowery, Wilkinson and Smare, Proc Phys Soc London, 49, 345 (1937)
9 Allen, Phil Mag, 32, 7th ser, 165 (1941)

85 Cu – 15 Zn*

A *1 Common name.* **Red Brass**

3 ASTM number.
Rolled flat products: B 36, No. 3; B 134, No. 3
Drawn flat products: B 134, No. 3
Wire: B 134, No. 3
Tube: B 111, B 135, No. 1
Pipe: B 43

4 Government numbers and other designations.

Form	SAE	Federal	Army	Navy
Sheet and strip	79, grade A	.....	57-160	.....
Tubes	74, alloy D	WW-T-791, grade 1	.....	44T15b, grade 1
Pipe	.....	WW-P-351, grade A	.....	44T16b 44P12c, grade A

B *1 Typical uses.* Architectural: etching parts, trim, weather strip; electrical: conduit, screw shells, sockets; hardware: eyelets, fasteners, fire extinguishers; industrial: condenser and heat-exchanger tubes, flexible hose, pickling crates, plumbing pipe, pump lines, radiator cores; plumbing: J-bends, pipe, service lines, traps; miscellaneous: badges, compacts, costume jewelry, dials, etched articles, lipstick containers, name plates, tags.

C *1 Density* at 20 C. 8.75 g per cu cm (0.316 lb per cu in.)

D *1 Liquidus temperature.* 1025 C (1880 F)

2 Solidus temperature. 990 C (1810 F)

4 Boiling point at 760 mm Hg. About 1300 C (2370 F).

* Compiled by the Copper & Brass Research Association and the American Brass Company

6 Thermal expansion 25 to 300 C (77 to 572 F).[1] 0.0000187 per °C (0.0000104 per °F), cold rolled
Equation for −50 to 300 C (−58 to 572 F), cold rolled:

$$L_t = L_0\,[1 + (17.03t + 0.00512t^2) \times 10^{-6}]$$

11 Specific heat at 20 C (68 F). 0.09 cal per g per °C

16 Thermal conductivity at 20 C (68 F). 0.38 cal/sq cm/cm/°C/sec (92 Btu/sq ft/ft/hr/°F)

17 Thermal conductivity versus temperature. See "Some Properties of Copper-Zinc Alloys".

19 Recrystallization temperature. About 350 C (660 F) for 0.039-in. sheet, rolled 6 B&S numbers hard, 50% reduction and 0.035-mm initial grain size.* *See* Fig. 1.

E *1 Volume conductivity* referred to standard copper. 37% at 20 C (68 F), annealed

2 Electrical resistivity at 20 C (68 F). 4.7 microhm-cm (28 ohms per mil-ft), annealed

4 Electrical resistivity (liquid).[2]
at 1100 C (2012 F). 29.87 microhm-cm
at 1200 C (2192 F). 30.43 microhm-cm

5 Temperature coefficient of electrical resistivity at 20 C (68 F).[3] 0.0016 per °C
Electrical resistivity versus temperature. See "Some Properties of Copper-Zinc Alloys".

8 Electrical resistivity versus plastic deformation. See "Some Properties of Copper-Zinc Alloy".

G *2 Magnetic susceptibility.*[4] Approx minus 1.00×10^{-6} cgs

H *1 Velocity of sound.* 12,000 ft per sec at 20 C (68 F).

J *1 Crystal structure.* Face-centered cubic alpha; lattice parameter 3.643 kX

* American Brass Company data

5 *Minimum interatomic distance.* 2.577 kX

K *Mechanical properties.* See Fig. 1, 2 and 3.

Temper	Tensile Strength, psi	Yield Strength, psi [a]	Elongation in 2 in., percentage	Rockwell Hardness		Shear Strength, psi
					30-T	
Flat Products (0.040-in. thick)						
0.070 mm	39,000	10,000	48	F 56	10	31,000
0.050 mm	40,000	12,000	47	F 59	14	31,000
0.035 mm	41,000	14,000	46	F 63	22	31,000
0.025 mm	43,000	16,000	44	F 66	28	32,000
0.015 mm	45,000	18,000	42	F 71	38	33,000
¼ hard	50,000	39,000	25	B 55	54	35,000
½ hard	57,000	49,000	12	B 65	60	37,000
Hard	70,000	57,000	5	B 77	68	42,000
Extra hard	78,000	61,000	4	B 83	72	44,000
Spring	84,000	63,000	3	B 86	74	46,000
Wire (0.080-in. diam)						
0.035 mm	41,000	.....	48	....	..	31,000
0.025 mm	43,000	.....	..	....	..	32,000
0.015 mm	45,000	.....	..	....	..	33,000
⅛ hard	50,000	.....	25	....	..	35,000
¼ hard	59,000	.....	11	....	..	38,000
½ hard	72,000	.....	8	....	..	43,000
Hard	88,000	.....	6	....	..	48,000
Spring	105,000	.....	..	....	..	54,000
Tube (1.0-in. OD by 0.065 in.)						
0.050 mm	40,000	12,000	55	F 60	15	.....
0.015 mm	44,000	18,000	45	F 71	38	.....
Light drawn (15%)	50,000	40,000	30	B 55	54	.....
Hard drawn (35%)	70,000	58,000	8	B 77	68	.....
Pipe (0.750-in. SPS)						
0.015 mm	44,000	18,000	45	F 71	..	.....

(a) 0.5% extension under load

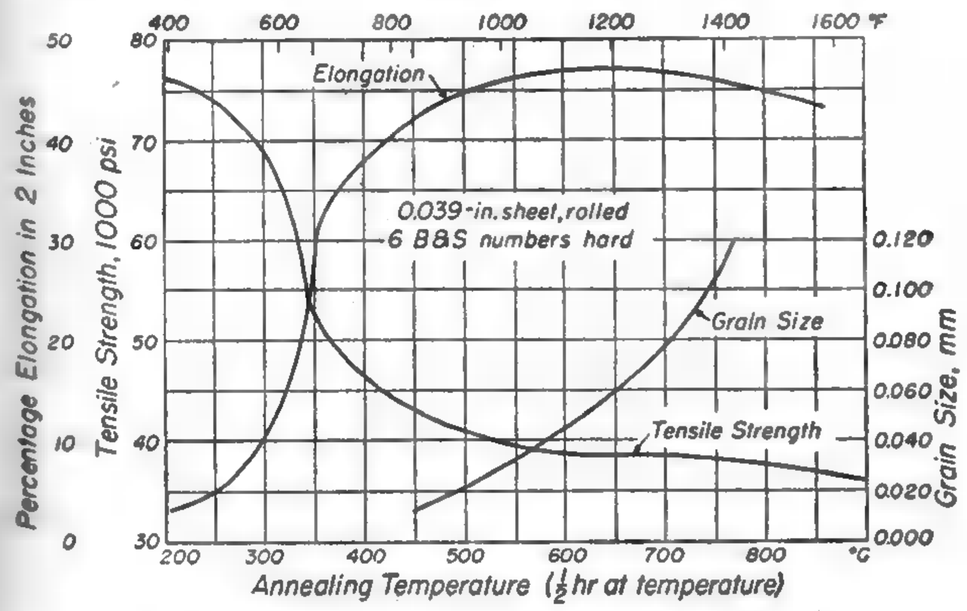

Fig. 1 Recrystallization diagram for red brass

Modulus of elasticity (tension) 17,000,000 psi
Endurance strength. (⅛ hard, rod) 20,000 psi, 300,000,000 cycles
Impact test results.

Condition	Izod Type, ft-lb	Charpy Type, ft-lb
Cast[6]	33	.....
Cast, annealed[7]	32	.....
	(No data on breaking)	
Wrought, annealed rod[a]	.....	50.5 (Not broken—Charpy keyhole)

(a) American Brass Company data

Effect of temperature on impact values. See Fig. 2.
4 *Machinability index* (free-cutting brass = 100). 30
6 *Minimum creep rate.*[5] See Fig. 3.

M *Composition limits.* See Table I.
2 *Consequences of exceeding impurity limits.* See general statement under 70 Cu – 30 Zn.

N 1 *Melting and chill casting temperature range.* 1200 to 1225 C (2192 to 2237 F)
3 *Alloying.* Zinc is added to copper and scrap melt just before pouring.
5 *Type of flux.* Melt under charcoal.
6 *Precautions in melting. See* 95 Cu – 5 Zn.
7 *Hot working temperature.* 800 to 900 C (1450 to 1650 F)

Table I. Composition Limits of 85 Cu – 15 Zn

Form	ASTM Designation	Components: Cu min	Cu max	Zn min	Zn max	Impurities: Pb max	Fe max	Sn max
Sheet	B 36	84.0	86.0	remainder		0.05	0.05	...
Wire	B 134	84.0	86.0	remainder		0.05	0.05	...
Tubes	B 135	83.0	86.0	remainder		0.06	0.05	...
Tubes, Condenser	B 111	84.0	...	remainder		0.075	0.06	...
Pipe	B 43	83.0	86.0	remainder		0.06	0.05	0.15

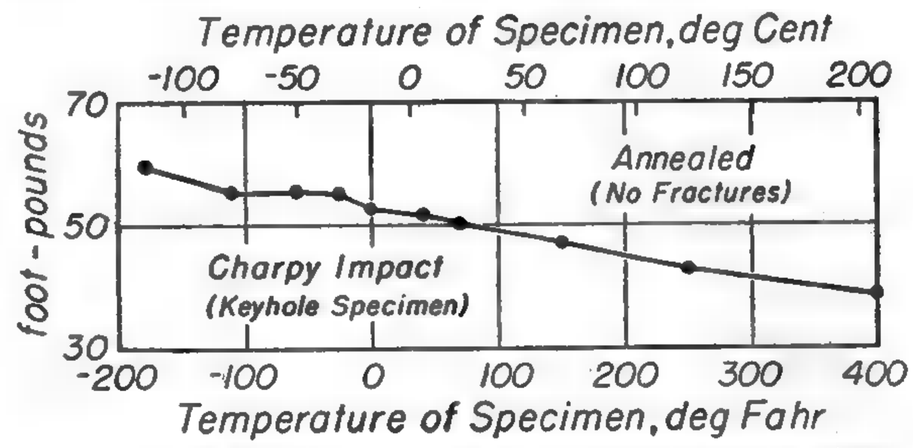

Fig. 2 Effect of temperature on impact values for red brass

9 *Annealing temperature.* 425 to 725 C (800 to 1350 F)
10 *Maximum cold reduction between anneals.* 75%
11 *Suited to forming* by blanking, coining, drawing, forming and bending, heading and upsetting, piercing and punching, roll threading and knurling, shearing, spinning, squeezing and swaging, stamping. Excellent cold working properties, good hot working properties.
17 *Joining.*
Soft solder with all grades solder, commercial solder fluxes or rosin.
Silver solder with all grades solder, proprietary flux, all types of flame.
Braze with P-Cu or Cu-Zn alloy, commercial brazing flux, all types of flame.
Oxyacetylene welding with bronze welding rods, commercial brazing flux, oxyacetylene flame.
Carbon-arc welding is fair.
Resistance welding is unsatisfactory except for butt welding of rod and wire.

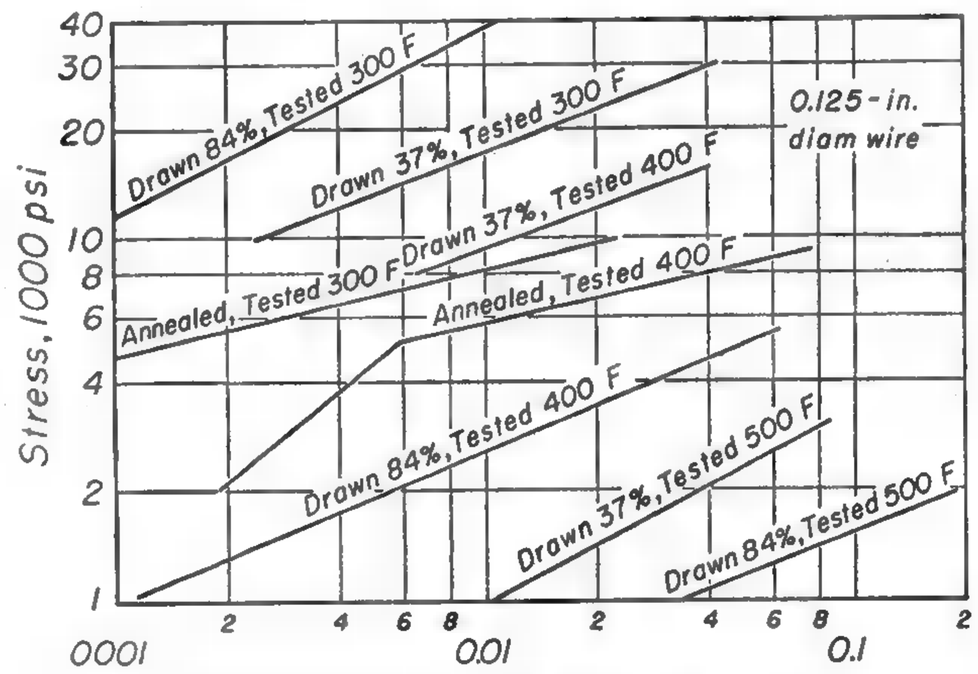

Fig. 3 Minimum creep rate versus stress for red brass (Burghoff, Blank and Maddigan[5])

References

1 Hidnert, Nat Bur Standards Sci Paper 410 (1921)
2 "International Critical Tables", Vol 6, 1929, p 198
3 Smith and Palmer, Trans AIME, 117, 225 (1935)
4 "International Critical Tables", Vol 6, 1929, ■ 365
5 Burghoff, Blank and Maddigan, Proc ASTM, 42, 668 (1942)
6 Northcutt, J Inst Metals, 68, 189 (1942)
7 Bunting, J Inst Metals, 31, 47 (1924)

80 Cu – 20 Zn*

A *1 Common name.* **Low Brass**
3 ASTM number.
Rolled flat products: B 36, No. 4; B 134, No. 4
Drawn flat products: B 134, No. 4
Wire: B 134, No. 4

4 Government numbers and other designations.

Form	SAE	Federal	Army	Navy
Sheet and strip	79, grade B	.....	57-160	.....
Wire	.....	QQ-S-551, composition D	Federal 57-217A	46S15b, grade D
Anodes	.....	.....	57-229A	.....

B *1 Typical uses.* Architectural: ornamental metal work, medallions, spandrels; electrical battery caps; bellows and musical instruments; hardware: clock dials, flexible hose, pump lines, tokens; miscellaneous etched articles.

C *1 Density* at 20 C. 8.67 g per cu cm (0.313 lb per cu in.)
5 Solidification shrinkage. 5 to 6%

D *1 Liquidus temperature.* 1000 C (1830 F)
2 Solidus temperature. 965 C (1770 F)
4 Boiling point at 760 mm Hg. About 1240 C (2270 F).
6 Thermal expansion 25 to 300 C (77 to 572 F).[1] 0.0000191 per °C (0.0000106 per °F), cold rolled

$$L_t = L_0\ [1 + (17.22t + 0.00590t^2) \times 10^{-6}]$$

11 Specific heat at 20 C (68 F). 0.09 cal per g per °C
16 Thermal conductivity at 20 C (68 F). 0.33 cal/sq cm/cm/°C/sec (81 Btu/sq ft/ft/hr/°F)
17 Thermal conductivity versus temperature. See "Some Properties of Copper-Zinc Alloys".
19 Recrystallization temperature. About 400 C (750 F) for 37% reduction and 0.060-mm initial grain size.[2] *See* Fig. 1.

E *1 Volume conductivity* referred to standard copper. 32% at 20 C (68 F), annealed
2 Electrical resistivity at 20 C (68 F). 5.4 microhm-cm (32 ohms per mil-ft), annealed
4 Electrical resistivity (liquid).[3]
at 1000 C (1832 F). 33.03 microhm-cm
at 1200 C (2192 F). 33.83 microhm-cm
5 Temperature coefficient of electrical resistivity at 20 C (68 F).[4] 0.00154 per °C
Electrical resistivity versus temperature. See "Some Properties of Copper-Zinc Alloys".
8 Electrical resistivity versus plastic deformation. See "Some Properties of Copper-Zinc Alloys".
15 Hall effect.[5] minus 0.404×10^{-12} volt-cm per amp-gauss

G *2 Magnetic susceptibility.*[6] Approx minus 1.00×10^{-6} cgs

J *1 Crystal structure.* Face-centered cubic alpha; lattice parameter 3.654 kX
5 Minimum interatomic distance. 2.584 kX

K *Mechanical properties.* See Fig. 1 and Tables I and II.

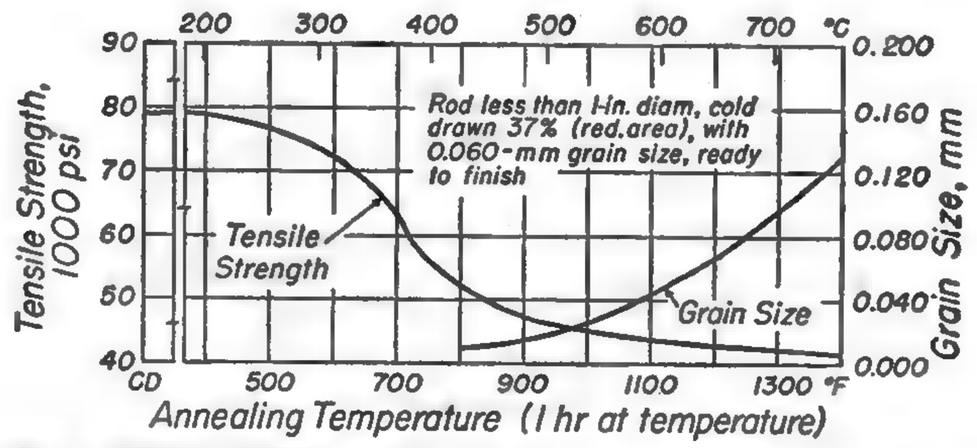

Fig. 1 Recrystallization diagram for low brass (Wilkins and Bunn[2])

Modulus of elasticity (tension). 16,000,000 psi
4 Machinability index (free-cutting brass = 100). 30

* Compiled by the Copper & Brass Research Association and the American Brass Company

Table I. Mechanical Properties of Low Brass

Temper	Tensile Strength, psi	Yield Strength, psi	Elongation in 2 in., percentage (a)	Rockwell Hardness		Shear Strength, psi
					30-T	
Flat Products (0.040 in. thick)						
0.070 mm	42,000	12,000	52	F 57	8	.....
0.050 mm	44,000	14,000	50	F 61	16	32,000
0.035 mm	46,000	15,000	48	F 66	28	.....
0.025 mm	48,000	17,000	47	F 69	32	.....
0.015 mm	50,000	20,000	46	F 75	42	33,000
¼ hard	53,000	40,000	30	B 55	54	36,000
½ hard	61,000	50,000	18	B 70	64	39,000
Hard	74,000	59,000	7	B 82	71	43,000
Spring	91,000	65,000	3	B 91	77	48,000
Wire (0.080-in. diam)						
0.050 mm	44,000	.....	55	....	..	32,000
0.035 mm	46,000	.....	50	....	..	.....
0.015 mm	50,000	.....	47	....	..	33,000
⅛ hard	56,000	.....	27	....	..	37,000
¼ hard	68,000	.....	12	....	..	42,000
½ hard	82,000	.....	8	....	..	47,000
Hard	107,000	.....	5	....	..	53,000
Extra hard	116,000	.....	4	....	..	.....
Spring	125,000	.....	3	....	..	60,000

(a) 0.5% extension under load

Table II. Endurance Strength of Low Brass

Form and Condition	Endurance Strength, psi	Millions of Cycles
0.040-in. flat product, spring temper	24,000	20
0.080-in. diam wire, hard	23,000	100
0.080-in. diam wire, spring	26,000	100

M *Composition limits*

Form	ASTM Designation	Components: Cu min	Cu max	Zn min	Zn max	Impurities: Pb max	Fe max
Sheet and strip	B 36	78.5	81.5	remainder		0.05	0.05
Wire	B 134	78.5	81.5	remainder		0.05	0.05

2 Consequences of exceeding impurity limits. See general statement under 70 Cu – 30 Zn.

N *1 Melting and casting temperature range.* 1175 to 1200 C (2147 to 2192 F)
3 Alloying. Zinc is added to copper and scrap melt just before pouring.
5 Type of flux. Melt under charcoal.
6 Precautions in melting. See 95 Cu – 5 Zn.
7 Hot working temperature range. 825 to 900 C (1500 to 1650 F)
9 Annealing temperature. 425 to 700 C (800 to 1300 F)
10 Maximum reduction between anneals. 75%
11 Suited to forming by blanking, drawing, forming and bending, heading and upsetting, piercing and punching, roll threading and knurling, shearing, spinning, squeezing and swaging, stamping. Excellent cold working properties, fair hot working properties.
17 Joining.
Soft solder with all grades solder, commercial solder fluxes or rosin.
Silver solder with all grades solder, proprietary flux, all types of flame.
Braze with P-Cu or Cu-Zn alloy, commercial brazing flux, all types of flame.
Oxyacetylene welding with bronze welding rod, commercial brazing flux, oxyacetylene flame.
Carbon-arc welding is fair.
Resistance welding is unsatisfactory except for butt welding of rod and wire.

References

1 Hidnert, Nat Bur Standards Sci Paper 410 (1921)
2 Wilkins and Bunn, "Copper and Copper-Base Alloys", McGraw-Hill Book Co., 1943, p 51
3 "International Critical Tables", Vol 6, 1929, p 198
4 Smith and Palmer, Trans AIME, 117, 225 (1935)
5 "International Critical Tables", Vol 6, 1929, p 417
6 "International Critical Tables", Vol 6, 1929, p 365

70 Cu – 30 Zn*

A *1 Common name.* **Cartridge Brass**
3 ASTM number.
Rolled flat products: B 19; B 36, No. 6; B 134, No. 6
Drawn flat products: B 134, No. 6
Disks: B 19
Cups: B 129
Wire: B 134, No. 6
Tube: B 14; B 135, No. 2
4 Government numbers and other designations.

Form	SAE	AMS	Federal	Army	Navy	Army-Navy
Sheet and strip	70, grade A	4505A	QQ-B-611a, composition E	Federal	47B2h	....
Sheet, strip and coil	....	....	....	57-172-1D	47B4	JAN-B-50
Disks	....	....	....	57-173C	47B5	JAN-B-67
Cups	....	....	....	57-172-2C	....	....
Wire	....	....	QQ-S-551, composition C	Federal	46S15b, grade C	....
Tubes	74, alloy C	4555	....	....	....	....

B *1 Typical uses.* Automotive: radiator cores and tanks, reflectors; electrical: bead chain, flashlight shells, lamp fixtures, socket shells, screw shells; hardware: eyelets, fasteners, pins, rivets, springs, stamping, tubes, etched articles; munitions: ammunition components.
C *1 Density* at 20 C. 8.53 g per cu cm (0.308 lb per cu in.)
D *1 Liquidus temperature.* 955 C (1750 F)
2 Solidus temperature. 915 C (1680 F)
4 Boiling point at 760 mm Hg. About 1150 C (2100 F)
6 Thermal expansion 25 to 300 C (77 to 572 F).[1] 0.0000199 per °C (0.0000111 per °F), cold rolled
Equation for 20 to 300 C (68 to 572 F):

$$L_t = L_0\ [1 + (17.75t + 0.00653t^2) \times 10^{-6}]$$

11 Specific heat at 20 C (68 F). 0.09 cal per g per °C
12 Specific heat versus temperature. See "Some Properties of Copper-Zinc Alloys".
16 Thermal conductivity 20 C (68 F). 0.29 cal/sq cm/cm/°C/sec (70 Btu/sq ft/ft/hr/°F)
17 Thermal conductivity versus temperature. See "Some Properties of Copper-Zinc Alloys".

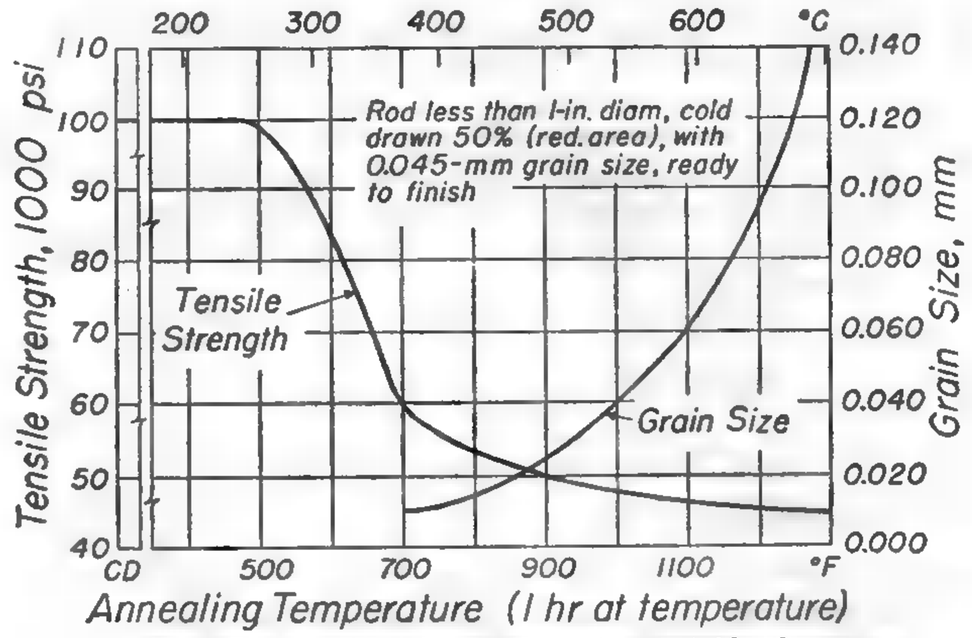

Fig. 1 Recrystallization diagram for cartridge brass (Wilkins and Bunn[2])

19 Recrystallization temperature.[2] About 350 C (660 F) for 50% reduction and 0.045-mm initial grain size. *See* Fig. 1.
E *1 Volume conductivity* referred to standard copper. 28% at 20 C (68 F), annealed
2 Electrical resistivity at 20 C (68 F). 6.2 microhm-cm (37 ohms per mil-ft), annealed
4 Electrical resistivity (liquid) at 1000 C (1832 F).[3] 39 microhm-cm (by extrapolation)
5 Temperature coefficient of electrical resistivity at 20 C (68 F).[4] 0.001484 per °C
Electrical resistivity versus temperature. See "Some Properties of Copper-Zinc Alloys".
7 Pressure coefficient of electrical resistivity.[5] This value for 74 Cu – 26 Zn is negative with increase in temperature.
8 Electrical resistivity versus plastic deformation. See "Some Properties of Copper-Zinc Alloys".
15 Hall effect.[6] minus 0.250×10^{-12} volt-cm per amp-gauss
G *1 Influence of treatments on magnetic properties.*[8] Iron in excess of 0.03% can be precipitated from cartridge brass by suitable low-temperature anneals. Precipitation is slow and occurs chiefly in the nonmagnetic form, which is converted to the ferromagnetic structure on cold working.

* Compiled by the Copper & Brass Research Association and the American Brass Company

Table I. Mechanical Properties of Cartridge Brass

Temper	Tensile Strength, psi	Yield Strength,(a) psi	Elongation in 2 in., percentage	Hardness Rockwell 30-T	Shear Strength, psi	Endurance Strength, psi	Endurance Strength, 10^8 cycles	Reduction of Area, percentage
Flat Products (0.040 in. thick)								
0.100 mm	44,000	11,000	66	F 54	11	.....	13,000	100 ..
0.070 mm	46,000	14,000	65	F 58	15	32,000	13,000	100 ..
0.050 mm	47,000	15,000	[illegible]	F 64	26	.....	.....	... ..
0.035 mm	49,000	17,000	57	F 68	31	34,000	14,000	100 ..
0.025 mm	51,000	19,000	[illegible]	F 72	36	.....	.....	... ..
0.015 mm	53,000	22,000	54	F 78	43	35,000	15,000	100 ..
¼ hard	54,000	40,000	43	B 55	54	36,000	.....	... ..
½ hard	62,000	52,000	23	B 70	65	40,000	18,000	100 ..
Hard	76,000	63,000	8	B 82	73	44,000	21,000	100 ..
Extra hard	86,000	65,000	[illegible]	B 88	76	46,000	.....	... ..
Spring	94,000	65,000	3	B 91	77	48,000	23,000	100 ..
Extra spring	99,000	65,000	3	B 93	78	.....	.....	... ..
Wire (0.080-in. diam)								
0.050 mm	48,000	.....	64	....	..	.....	.....	... ..
0.035 mm	50,000	.....	60	....	..	34,000	.....	... ..
0.025 mm	52,000	.....	58	....	..	.....	.....	... ..
0.015 mm	54,000	.....	56	....	..	.....	.....	... ..
⅛ hard	58,000	.....	35	....	..	38,000	.....	... ..
¼ hard	70,000	.....	20	....	..	.....	.....	... ..
Extra hard	124,000	.....	4	....	..	.....	.....	... ..
Spring	130,000	.....	3	....	..	60,000	22,000	100 ..
Tube (1.0-in. OD by 0.065 in.)								
0.050 mm	47,000	15,000	65	F [illegible]	26	.....	.....	... ..
0.025 mm	52,000	20,000	55	F 75	40	.....	.....	... ..
Hard drawn (35%)	78,000	64,000	8	B 82	73	.....	.....	... ..
Rod (1.0-in. diam)								
0.050 mm	48,000	16,000	65	F 65	..	34,000	.....	... 75
⅛ hard (6%)	55,000	40,000	48	B 60	..	36,000	.....	... 70
½ hard (20%)	70,000	52,000	30	B 80	..	42,000	22,000	50 68

(a) 0.5% extension under load

2 *Magnetic susceptibility.*[9] minus 1 > χ > minus ■ × 10^{-6} cgs. Susceptibility in alpha brasses decreases with increasing zinc content.

H 1 *Velocity of sound.* 12,000 ft per sec at 20 C (68 F).

J 1 *Crystal structure.* Face-centered cubic alpha; lattice parameter 3.677 kX

5 *Minimum interatomic distance.* 2.600 kX

K *Mechanical properties.* See Table I and Fig. 1, ■ and 3.

Modulus of elasticity (tension). 16,000,000 psi

Mechanical properties at low temperature. See Fig. 2.

Impact tests.

Condition	Izod, ft-lb	Charpy, ft-lb
Wrought, annealed[12]	66, notched round specimen, no fractures	....
Cast, annealed[13]	44, no data on breaking	....
Cast[14]	35, no data on breaking	....
Hot rolled[15]	.....	14, V notch
Hot rolled, annealed.....	.....	44, no data on breaking

2 *Directional properties.* Directionality in brass is more readily developed, the higher the zinc content. Earing usually occurs at 45 deg to the direction of rolling, aggravated by heavy final reductions, low ready-to-finish and high finish anneals.[10]

Material with ready-to-finish anneal at 400 C, cold rolled 70%, and annealed for one hour at 575 C

Property	Parallel to rolling	45-deg angle to rolling	90-deg angle to rolling
Tensile strength, psi.....	48,000	44,000	47,000
Elongation in 2 in., percentage	59	66	61

NOTE: Approximate values, taken from graph in reference 10.

4 *Machinability index* (free-cutting brass = 100). 30.

6 *Minimum creep rate.* See Fig. 3.

9 *Specific damping capacity.* See references 17 to 24 and "Some Properties of Copper-Zinc Alloys", also, general statement under Electrolytic Tough Pitch Copper.

M *Composition limits.*

Form	ASTM Designation	Components Cu min	Components Cu max	Components Zn min	Components Zn max	Impurities Pb max	Impurities Fe max	Impurities Others (total) max[a]
Sheet and strip	B 36	68.5	71.5	remainder		0.07	0.05	...
Sheet, strip, etc.	B 19	68.5	71.5	remainder		0.07	0.05	0.15
Cups	B 129	68.5	71.5	remainder		0.07	0.05	0.15
Wire	B 134	68.5	71.5	remainder		0.07	0.05	...
Tubes	B 135	68.5	71.5	remainder		0.075	0.06	...

(a) Other than copper and zinc

2 Consequences of exceeding impurity limits.[25, 26, 27]

Tolerance for bismuth under commercial processing is virtually nil. The worst effect is in hot working. Small additions of phosphorus make brass workable with bismuth present up to 0.05%. Bismuth up to 0.97% has little effect on tensile properties of cartridge brass that has been processed by cold working and careful annealing.

Lead should be kept under 0.01% (possibly under 0.015%) for hot rolling, although additions of lead up to 4% are made to improve machinability in material processed by extrusion and cold working. Lead lowers ductility in brass.

As little as 0.017% Sb impairs the hot working qualities of cartridge brass. The presence of lead aggravates this condition.

Aluminum as high as 2% has no adverse effect on hot or cold working. However, annealing and grain size are affected.

Arsenic does not affect hot or cold working, but tends to "fine" the grain and thus to lower the ductility. Cadmium is doubtful. Some claim as much as 0.10% has little effect, others would keep it under 0.05%. Chromium affects temperature of anneal and grain size. This condition is aggravated when iron is present. Iron chiefly affects annealing. (*See also* Magnetic Properties.) Nickel restrains grain growth. Phosphorus has no adverse effect up to 0.04% but grain growth is restrained; tensile strength is increased; ductility is lowered somewhat.

N 1 *Melting and chill casting temperature range.* 1125 to 1150 C (2057 to 2102 F)

5 *Type of flux.* Melt under charcoal.

6 *Precautions in melting.* See 95 Cu–5 Zn.

7 *Hot working temperature.* 725 to 850 C (1350 to 1550 F)

9 *Annealing temperature.* 425 to 750 C (800 to 1400 F)

10 *Maximum cold reduction between anneals.* 75%

11 *Suited to forming* by blanking, drawing, forming and bending, heading and upsetting, piercing and punching, shearing, spinning, squeezing and swaging, stamp-

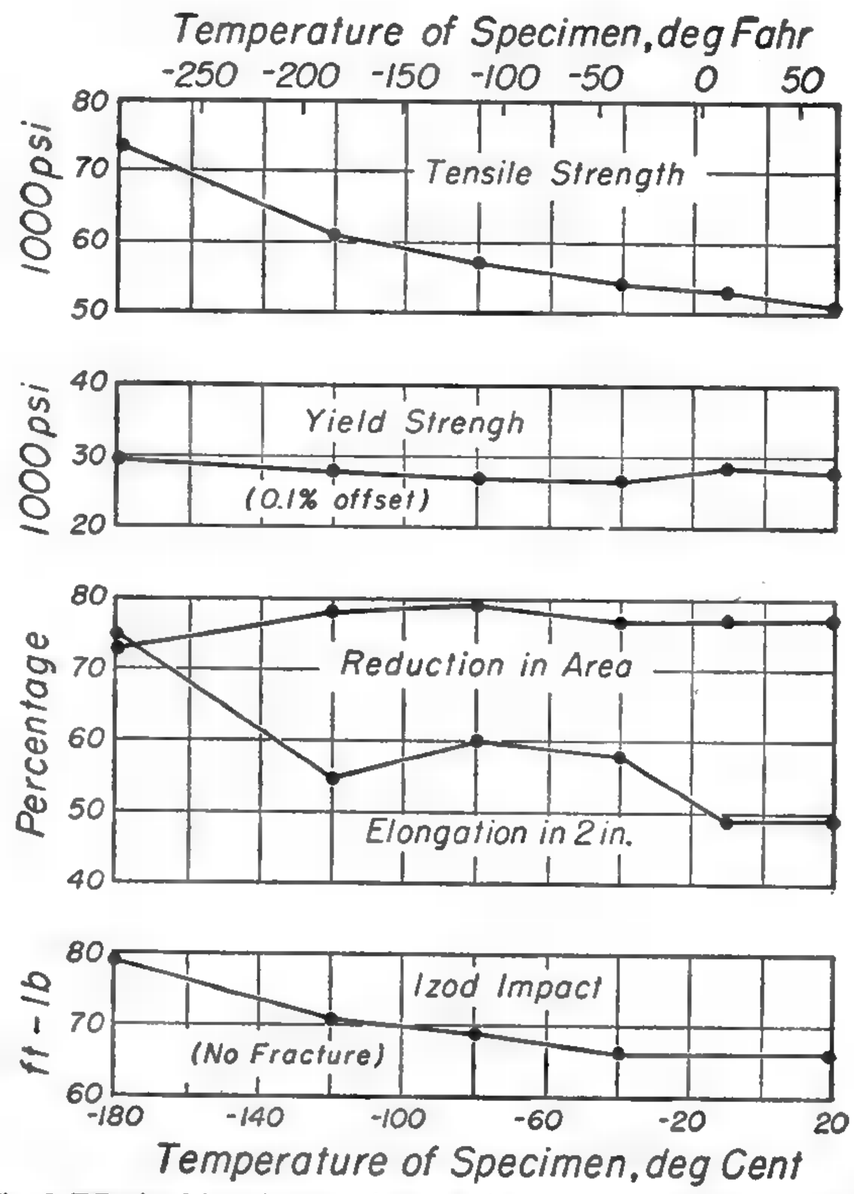

Fig. 2 Effect of low temperature on the mechanical properties of a cartridge brass (69.56% Cu, 30.50% Zn), annealed (Colbeck and MacGillivray[30])

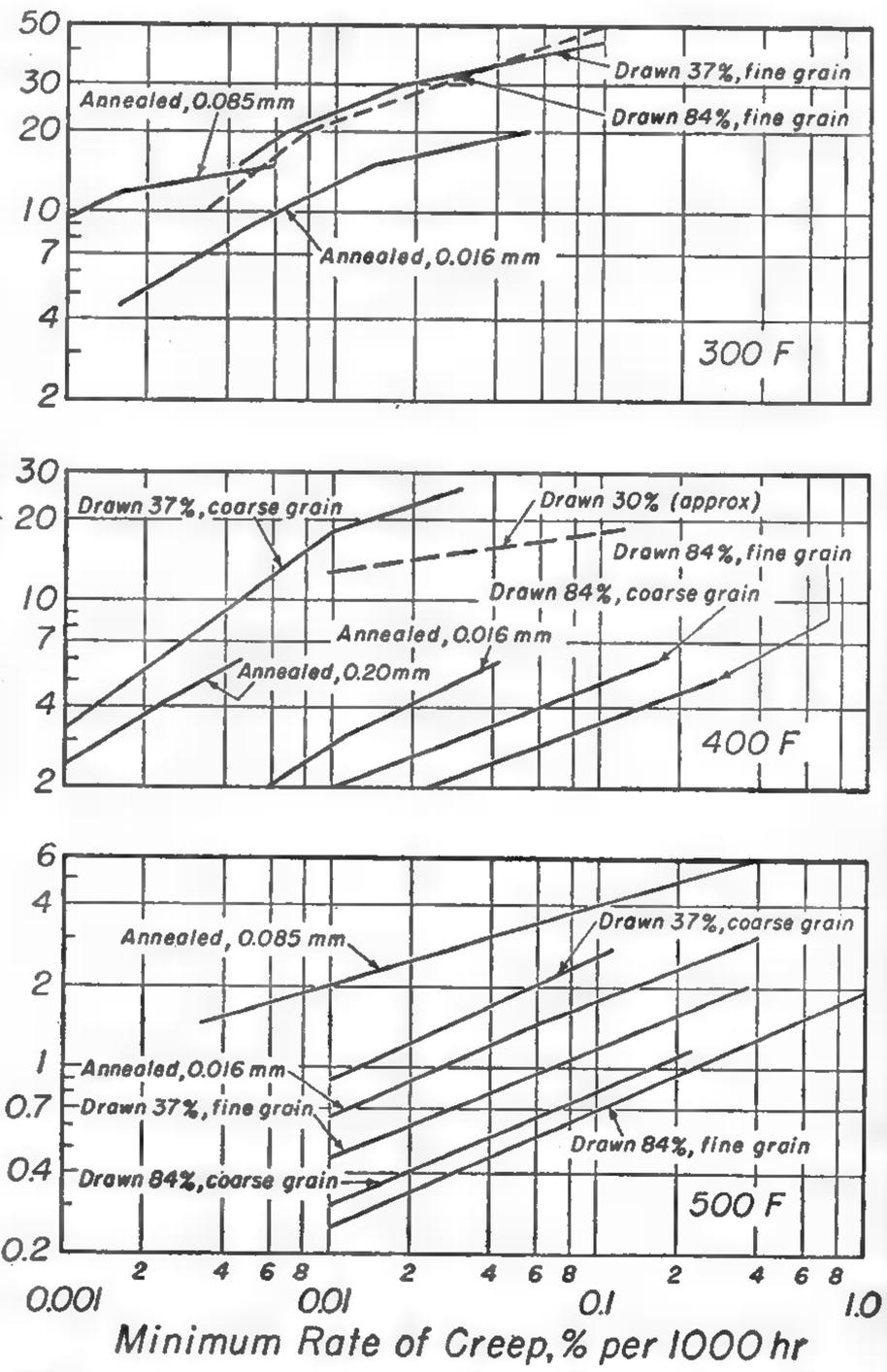

Fig. 3 Minimum rate of creep versus stress for cartridge brass (Burghoff, Blank and Maddigan[16])

ing. Excellent cold working properties, fair hot working properties.

17 Joining.
Soft solder with all grades solder, commercial solder fluxes or rosin.
Silver solder with all grades solder, proprietary flux, all types of flame.
Braze with P-Cu or Cu-Zn alloy, commercial brazing flux, all types of flame.
Oxyacetylene welding with bronze welding rods, commercial brazing flux, oxyacetylene flame.
Carbon-arc welding is fair.
Resistance welding is fair.

References

1 Hidnert, Nat Bur Standards Sci Paper 410 (1921)
2 Wilkins and Bunn, "Copper and Copper-Base Alloys", McGraw-Hill Book Co., 1943, p 63
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6 "International Critical Tables", Vol 6, 1929, p 417
7 Lowery, Wilkinson and Smare, Proc Phys Soc London, 49, 345
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19 Randall, Rose and Zener, Phys Rev, 56, 343 (1939)
20 Zener and Randall, Trans AIME, 137, 41 (1940)
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27 Gibbs, Metal Progress, 44, 243 (1943)
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29 Clark and White, Proc ASTM, 32, 492 (1932)
30 Colbeck and MacGillivray, Trans Inst Chem Engrs (London), 11, 107 (1933)

65 Cu – 35 Zn*

A *1 Common name.* **Yellow Brass**
3 ASTM number. B36, No. 8; B134, No. 7
B *1 Typical uses.* Architectural grillwork; automotive: radiator cores and tanks, reflectors; electrical: flashlight shells, lamp fixtures, screw shells, socket shells; hardware: bead chain, chain, eyelets, fasteners, grommets, kick plates, push plates, stencils; plumbing: accessories, sink strainers; wire; pins; rivets; screws; and springs.
C *1 Density* at 20 C (68 F). 8.47 ■ per cu cm (0.306 lb per cu in.)
D *1 Liquidus temperature.* 930 C (1710 F)
2 Solidus temperature. 905 C (1660 F)
6 Thermal expansion 20 to 300 C (68 to 572 F). 0.0000203 per °C (0.0000113 per °F)
11 Specific heat at 20 C (68 F). 0.09 cal per ■
16 Thermal conductivity at 20 C (68 F). 0.28 cgs
E *1 Volume conductivity* referred to standard copper. 27%, annealed
2 Electrical resistivity at 20 C (68 F). 6.4 microhm-cm (38 ohms per mil-ft), annealed
K *Mechanical properties.* See Table I, and the illustrations in "Annealing and Heat Treating of Copper and Wrought Copper Alloys", page 877.
M *Composition limits.*

		Components			Impurities	
Form	Designation	Cu min	Cu max	Zn	Pb max	Fe max
Sheet ...	B 36, No. 8	64.0	67.5	remainder	0.30	0.05
Wire	B134, No. 7	63.0	67.5	remainder	0.10	0.05

N *9 Annealing temperature.* 425 to 700 C (800 to 1300 F)

Table I. Mechanical Properties of Rolled Flat Products

Temper	Tensile Strength, psi	Yield Strength[a] psi	Elongation in 2 in., percentage	Rockwell Hardness	Modulus of Elasticity, psi	Shear Strength, psi	Eudurance Limit for 10^8 cycles, psi
Annealed	49,000	17,000	57	F 68	15,000,000	34,000	12,000
¼ hard	54,000	40,000	43	B 55	15,000,000	36,000	.....
½ hard	61,000	50,000	23	B 70	15,000,000	40,000	.....
Hard	74,000	60,000	8	B 80	15,000,000	43,000	14,000
Spring	91,000	62,000	3	B 90	15,000,000	47,000	20,000

(a) 0.5% extension under load

60 Cu – 40 Zn*

A *1 Common name.* **Muntz Metal**
3 ASTM number. B 111; B 124; B 135, No. 5
B *1 Typical uses.* Architectural trimming; large nuts and bolts; brazing rod; condenser plates; condenser, evaporator, and heat-exchanger tubing; hot forgings; and valve stems.
C *1 Density* at 20 C (68 F). 8.39 g per cu cm (0.303 lb per cu in.)
D *1 Liquidus temperature.* 905 C (1660 F)
2 Solidus temperature. 900 C (1650 F)
6 Thermal expansion 20 to 300 C (68 to 572 F). 0.0000208 per °C (0.0000116 per °F)
11 Specific heat at 20 C (68 F). 0.09 cal per g
16 Thermal conductivity at 20 C (68 F). 0.29 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 28%, annealed
2 Electrical resistivity at 20 C (68 F). 6.2 microhm-cm (37 ohms per mil-ft), annealed
K *Mechanical Properties.* See Table I.
M *Composition limits.* Sheet: *components,* 59 to 63% Cu; remainder zinc; *impurities,* 0.20% max Pb, 0.15% max Fe.
N *7 Hot working temperature range.* 625 to 800 C (1150 to 1450 F)
9 Annealing temperature. 425 to 600 C (800 to 1100 F)

* Compiled by the Copper & Brass Research Association and the Bridgeport Brass Company

Table I. Mechanical Properties of Rolled Flat Products

Temper	Tensile Strength, psi	Yield Strength,[a] psi	Elongation, percentage	Rockwell Hardness, 30-T	Modulus of Elasticity, psi	Shear Strength, psi
Annealed	54,000	21,000	45	F 80 46	15,000,000	40,000
½ hard	70,000	50,000	10	B 75 67	15,000,000	44,000

(a) 0.5% extension under load

89 Cu – 9.25 Zn – 1.75 Pb*

A *1 Common name.* **Leaded Commercial Bronze**
3 ASTM number. B 140, type B
B *1 Typical uses.* Screws, screw-machine parts, pickling crates
C *1 Density* at 20 C (68 F). 8.83 g per cu cm (0.319 lb per cu in.)
D *1 Liquidus temperature.* 1040 C (1900 F)
2 Solidus temperature. 1010 C (1850 F)
6 Thermal expansion 20 to 300 C (68 to 572 F). 0.0000184 per °C (0.0000102 per °F)
11 Specific heat at 20 C (68 F). 0.09 cal per g
16 Thermal conductivity at 20 C (68 F). 0.43 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 42%, annealed
2 Electrical resistivity at 20 C (68 F). 4.1 microhm-cm (25 ohms per mil-ft), annealed
K *Mechanical properties.* See Table I.
M *Composition limits.* Rod: *components,* 87.50 to 90.50% Cu, 1.25 to 2.25% Pb, remainder zinc; *impurities,* 0.10% max Fe.
N *9 Annealing temperature.* 425 to 650 C (800 to 1200 F)

Table I. Mechanical Properties of Leaded Commercial Bronze Rod

Temper	Tensile Strength, psi	Yield Strength,(a) psi	Elongation percentage	Reduction of Area, percentage	Rockwell Hardness	Modulus of Elasticity, psi	Shear Strength, psi
Annealed	37,000	12,000	45	70	F 55	17,000,000	24,000
½ hard (20%)	52,000	45,000	18	60	B 58	17,000,000	30,000

(a) 0.5% extension under load

64.5 Cu – 35 Zn – 0.5 Pb*

A *1 Common name.* **Low-Leaded Brass**
3 ASTM number. B 121, No. 2
B *1 Typical uses.* Hardware, butts, hinge brass, watch hooks.
C *1 Density* at 20 C (68 F). 8.47 g per cu cm (0.306 lb per cu in.)
D *1 Liquidus temperature.* 925 C (1760 F)
2 Solidus temperature. 900 C (1650 F)
6 Thermal expansion 20 to 300 C (68 to 572 F). 0.0000203 per °C (0.0000113 per °F)
11 Specific heat at 20 C (68 F). 0.09 cal per g
16 Thermal conductivity at 20 C (68 F). 0.28 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 26%, annealed
2 Electrical resistivity at 20 C (68 F). 6.6 microhm-cm (40 ohms per mil-ft), annealed
K *Mechanical properties.* See Table I.
M *Composition limits.* Sheet: *components,* 62.5 to 66.5% Cu, 0.30 to 0.70% Pb, remainder zinc; *impurities,* 0.10% max Fe.
N *9 Annealing temperature.* 425 to 700 C (800 to 1300 F)

Table I. Mechanical Properties of Low-Leaded Brass Rolled Flat Products

Temper	Tensile Strength, psi	Yield Strength,(a) psi	Elongation, percentage	Rockwell Hardness	Modulus of Elasticity, psi	Shear Strength, psi
Annealed	49,000	17,000	57	F 68	15,000,000	34,000
¼ hard	54,000	40,000	43	B 55	15,000,000	36,000
½ hard	61,000	50,000	23	B 70	15,000,000	40,000
Hard	74,000	60,000	8	B 80	15,000,000	43,000

(a) 0.5% extension under load

67 Cu – 32.5 Zn – 0.5 Pb*

A *1 Common name.* **Low-Leaded Brass (Tube)**
3 ASTM number. B 135, No. 3
B *1 Typical uses.* General-purpose use: where some degree of machinability is required together with moderate cold working properties; primers for munitions; plumbing: J-bends, pump lines, trap lines.
C *1 Density* at 20 C (68 F). 8.50 g per cu cm 0.307 lb per cu in.)
D *1 Liquidus temperature.* 940 C (1720 F)
2 Solidus temperature. 905 C (1660 F)
6 Thermal expansion 20 to 300 C (68 to 572 F). 0.0000202 per °C (0.0000112 per °F)
16 Thermal conductivity at 20 C (68 F). 0.28 cgs
E *1 Volume conductivity* referred to standard copper. 26%, annealed
2 Electrical resistivity at 20 C (68 F). 6.6 microhm-cm (40 ohms per mil-ft), annealed
K *Mechanical properties of tube.*

Temper	Tensile Strength, psi	Yield Strength,(a) psi	Elongation, percentage	Rockwell Hardness
Annealed	47,000	15,000	60	F 64
Hard (35%)	75,000	60,000	7	B 80

(a) 0.5% extension under load

M *Composition limits.* Tube: *components,* 65.0 to 68.0% Cu; 0.3 to 0.8% Pb, remainder zinc; *impurities,* 0.07% max Fe.
N *9 Annealing temperature.* 425 to 650 C (800 to 1200 F)

64.5 Cu – 34.5 Zn – 1.0 Pb*

A *1 Common name.* **Medium-Leaded Brass**
3 ASTM number. B 121, No. 3
B *1 Typical uses.* Hardware, butts, gears, nuts, rivets, screws; miscellaneous usage as dials, engravings, instrument plates.
C *1 Density* at 20 C (68 F). 8.47 g per cu cm (0.306 lb per cu in.)
D *1 Liquidus temperature.* 925 C (1700 F)
2 Solidus temperature. 885 C (1630 F)
6 Thermal expansion 20 to 300 C (68 to 572 F). 0.0000203 per °C (0.0000113 per °F)
11 Specific heat at 20 C (68 F). 0.09 cal per g

* Compiled by the Copper & Brass Research Association and the Bridgeport Brass Company

16 *Thermal conductivity* at 20 C (68 F). 0.28 cgs
E 1 *Volume conductivity* referred to standard copper. 26%, annealed
2 *Electrical resistivity* at 20 C (68 F). 6.6 microhm-cm (40 ohms per mil-ft), annealed
K *Mechanical properties.* See Table I.
M *Composition limits.* Sheet: *components,* 62.5 to 66.5% Cu, 0.75 to 1.25% Pb, remainder zinc; *impurities,* 0.10% max Fe.
N 9 *Annealing temperature.* 425 to 650 C (800 to 1200 F)

Table I. Mechanical Properties of Medium-Leaded Brass Rolled Flat Products

Temper	Tensile Strength, psi	Yield Strength,(a) psi	Elongation, percentage	Rockwell Hardness	Modulus of Elasticity, psi	Shear Strength, psi
Annealed	49,000	17,000	54	F 68	15,000,000	34,000
¼ hard	54,000	40,000	41	B 55	15,000,000	36,000
½ hard	61,000	50,000	21	B 70	15,000,000	40,000
Hard	74,000	60,000	7	B 80	15,000,000	43,000

(a) 0.5% extension under load

62.5 Cu – 35.75 Zn – 1.75 Pb*

A 1 *Common name.* **High-Leaded Brass**
2 *Trade names.* Clock Brass, Engraver's Brass, Heavy-Leaded Brass
3 *ASTM number.* B121, No. 4
B 1 *Typical uses.* Hardware: clock plates and nuts, clock and watch backs, gears, wheels.
Industrial uses as channel plate.
C 1 *Density* at 20 C (68 F). 8.47 g per cu cm (0.306 lb per cu in.)
D 1 *Liquidus temperature.* 910 C (1670 F)
2 *Solidus temperature.* 885 C (1630 F)
6 *Thermal expansion* 20 to 300 C (68 to 572 F). 0.0000203 per °C (0.0000113 per °F)
16 *Thermal conductivity* at 20 C (68 F). 0.28 cal/sq cm/cm/°C/sec (67 Btu/sq ft/ft/°F/hr)
E 2 *Electrical resistivity* at 20 C (68 F). 6.6 microhm-cm (40 ohms per mil-ft), annealed
K *Mechanical properties.*

Condition	Tensile Strength, psi	Yield Strength,(b) psi	Elongation in 2 in., percentage	Rockwell Hardness 30-T	Shear Strength, psi
Flat Products					
Annealed	49,000	17,000	52	F 68 31	34,000
¼ hard	54,000	40,000	38	B 55 54	36,000
½ hard	61,000	50,000	20	B 70 65	40,000
Hard(a)	74,000	60,000	7	B 80 69	43,000
Extra hard	85,000	62,000	5	B 87 74	45,000
Rod					
½ hard (20%)	58,000	45,000	25	B 75 ..	.....

(a) *Modulus of elasticity.* (hard) 15,000,000 psi
(b) 0.5% extension under load

62.5 Cu – 35 Zn – 2.5 Pb*

A 1 *Common name.* **Extra-High-Leaded Brass**
3 *ASTM number.* B121, No. 6
5 *Other designations.* Block Brass and Rule Brass.
B 1 *Typical uses.* Hardware: clock plates and nuts, clock and watch backs, clock gears and wheels
Industrial uses as channel plate.
C 1 *Density* at 20 C (68 F). 8.50 ■ per cu cm (0.307 lb per cu in.)
D 1 *Liquidus temperature.* 905 C (1660 F)
2 *Solidus temperature.* 885 C (1630 F)
6 *Thermal expansion* 20 to 300 C (68 to 572 F). 0.0000205 per °C (0.0000114 per °F)
11 *Specific heat* at 20 C (68 F). 0.09 cal per g (0.09 Btu/lb/°F)
16 *Thermal conductivity* at 20 C (68 F). 0.28 cal/sq cm/cm/°C/sec (67 Btu/sq ft/ft/°F/hr)
E 2 *Electrical resistivity* at 20 C (68 F). 6.6 microhm-cm (40 ohms per mil-ft), annealed
K *Mechanical properties of flat products.*

Condition	Tensile Strength, psi	Yield Strength,(b) psi	Elongation in 2 in., percentage	Rockwell Hardness 30-T
Annealed	49,000	17,000	50	F 68 31
¼ hard	54,000	40,000	35	B 55 54
½ hard	61,000	50,000	20	B 70 65
Hard(a)	74,000	60,000	7	B 80 69

(a) *Modulus of elasticity.* (hard) 14,000,000 psi
(b) 0.5% extension under load

61.5 Cu – 35.5 Zn – 3 Pb*

A 1 *Common name.* **Free-Cutting Brass**
2 *Trade names.* Free-Turning Brass, Free-Cutting Yellow Brass
3 *ASTM number.* B16
B 1 *Typical uses.* Hardware, gears and pinions; automatic high-speed screw-machine parts.
C 1 *Density* at 20 C (68 F). 8.50 ■ per cu cm (0.307 lb per cu in.)
D 1 *Liquidus temperature.* 900 C (1650 F)
2 *Solidus temperature.* 885 C (1630 F)
6 *Thermal expansion* 20 to 300 C (68 to 572 F). 0.0000205 per °C (0.0000114 per °F)
16 *Thermal conductivity* at 20 C (68 F). 0.28 cal/sq cm/cm/°C/sec (67 Btu/sq ft/ft/°F/hr)
E 2 *Electrical resistivity* at 20 C (68 F). 6.6 microhm-cm (40 ohms per mil-ft), annealed
K *Mechanical properties.*

Condition	Section, in.	Tensile Strength, psi	Yield Strength,(a) psi	% Elong 2 in.	Hardness, R_B,R_F	Shear Strength, psi
Flat Products						
¼ hard	....	56,000	45,000	20	....	33,000
Rod						
Annealed	....	49,000	18,000	53	F 68	30,000
½ hard	1.0	68,000	52,000	18	B 80	38,000
½ hard	0.25	58,000	45,000	25	B 78	34,000
½ hard	1.0	55,000	44,000	32	B 75	32,000
Shapes						
Extruded	....	49,000	18,000	50	F68	30,000
¼ hard	....	56,000	45,000	20	B62	33,000

Modulus of elasticity. (hard) 14,000,000 psi
(a) 0.5% extension under load

* Compiled by the Copper & Brass Research Association and the Scovill Manufacturing Company

60 Cu – 39.5 Zn – 0.5 Pb*

A *1 Common name.* **Leaded Muntz Metal**
3 ASTM number. B171
B *1 Typical uses.* Condenser-tube plates.
C *1 Density* at 20 C (68 F). 8.41 ■ per cu cm (0.304 lb per cu in.)
D *1 Liquidus temperature.* 900 C (1650 F)
2 Solidus temperature. 885 C (1630 F)
6 Thermal expansion 20 to 300 C (68 to 572 F). 0.0000208 per °C (0.0000116 per °F)
16 Thermal conductivity at 20 C (68 F). 0.29 cal/sq cm/cm/°C/sec (71 Btu/sq ft/ft/°F/hr)
■ *2 Electrical resistivity* at 20 C (68 F). 6.2 microhm-cm (38 ohms per mil-ft), annealed
K *Mechanical properties.* Hot rolled plate (1-in. section): tensile strength 54,000 psi; yield strength 20,000 psi; elongation in ■ in. 45%; Rockwell hardness F 80; shear strength 40,000 psi; modulus of elasticity 15,000,000 psi.
N *7 Hot working temperature.* 625 to 800 C (1150 to 1450 F)
9 Annealing temperature. 425 to 600 C (800 to 1100 F)

60.5 Cu – 38.4 Zn – 1.1 Pb*

A *1 Common name.* **Free-Cutting Muntz Metal**
2 Trade names. Half-Leaded Muntz, Leaded Muntz, Muntz Metal
B *1 Typical uses.* Automatic screw-machine products
C *1 Density* at 20 C (68 F). 8.41 g per cu cm (0.304 lb per cu in.)
D *1 Liquidus temperature.* 900 C (1650 F)
2 Solidus temperature. 885 C (1630 F)
6 Thermal expansion 20 to 300 C (68 to 572 F). 0.0000208 per °C (0.0000116 per °F)
16 Thermal conductivity at 20 C (68 F). 0.28 cal/sq cm/cm/°C/sec (69 Btu/sq ft/ft/°F/hr)
E *2 Electrical resistivity* at 20 C (68 F). 6.4 microhm-cm (38 ohms per mil-ft), annealed
K *Mechanical properties of tubing.*

Condition	Section, in.	Tensile Strength, psi	Yield Strength, psi	Elongation in 2 in., percentage	Rockwell Hardness	30-T
Light anneal ...	1.5 OD	54,000	20,000	40	F 80	43
Hard (35%)(a)..	1.0	80,000	60,000	6	B 85	74
Hard (25%)	2.0	70,000	45,000	10	B 75	67

(a) *Modulus of elasticity,* (hard drawn) 15,000,000 psi

4 Machinability index (free-cutting brass = 100). 70
N *7 Hot working temperature range.* 625 to 800 C (1150 to 1450 F)
9 Annealing temperature. 425 to 600 C (800 to 1100 F)

60 Cu – 38 Zn – 2 Pb*

A *1 Common name.* **Forging Brass**
3 ASTM number. B124, No. 2
B *1 Typical uses.* Forgings and pressings of all kinds
C *1 Density* at 20 C (68 F). 8.44 ■ per cu cm (0.305 lb per cu in.)
D *1 Liquidus temperature.* 895 C (1640 F)
2 Solidus temperature. 880 C (1620 F)
6 Thermal expansion 20 to 300 C (68 to 572 F). 0.0000207 per °C (0.0000115 per °F)
16 Thermal conductivity at 20 C (68 F). 0.28 cal/sq cm/cm/°C/sec (69 Btu/sq ft/ft/°F/hr)
E *2 Electrical resistivity* at 20 C (68 F). 6.4 microhm-cm (38 ohms per mil-ft), annealed
K *Mechanical properties.* Rods and shapes, as extruded (1.0-in. section): tensile strength 52,000 psi; yield strength 20,000 psi; elongation in 2 in. 45%; Rockwell hardness F 78; modulus of elasticity 15,000,000 psi.
N *7 Hot working temperature.* 650 to 825 C (1200 to 1500 F)
9 Annealing temperature. 425 to 600 C (800 to 1100 F)

57 Cu – 40 Zn – 3 Pb*

A *1 Common name.* **Architectural Bronze**
B *1 Typical uses.* Architectural trim; hardware items as butts, hinges and lock bodies; and industrial forgings.
C *1 Density* at 20 C (68 F). 8.47 g per cu cm (0.306 lb per cu in.)
D *1 Liquidus temperature.* 890 C (1630 F)
2 Solidus temperature. 875 C (1610 F)
6 Thermal expansion 20 to 300 C (68 to 572 F). 0.0000209 per °C (0.0000116 per °F)
16 Thermal conductivity at 20 C (68 F). 0.29 cal/sq cm/cm/°C/sec (71 Btu/sq ft/ft/°F/hr)
E *2 Electrical resistivity* at 20 C (68 F). 6.2 microhm-cm (37 ohms per mil-ft), annealed
K *Mechanical properties.* As extruded (1-in. section): tensile strength 60,000 psi; yield strength 20,000 psi; elongation in 2 in. 30%; Rockwell hardness B 65; shear strength 35,000 psi.
Sand cast: modulus of elasticity 14,000,000 psi.
4 Machinability index (free-cutting brass = 100). 90
N *7 Hot working temperature range.* 625 to 725 C (1150 to 1350 F)
9 Annealing temperature. 425 to 600 C (800 to 1100 F)

71 Cu – 28 Zn – 1 Sn*

A *1 Common name.* **Admiralty Metal**
2 Trade name. Admiralty
3 ASTM numbers. B 111 (condenser tubes); B 171 (condenser-tube plates)
4 Government numbers. Navy 44T7g (condenser tubes); Navy 47B3 (brass plates); Federal WW-T-756a (condenser-tube plates).
B *1 Typical uses.* Condenser, evaporator and heat-exchanger tubes, condenser-tube plates, distiller tubes and ferrules.
C *1 Density* at 20 C (68 F). 8.53 g per cu cm (0.308 lb per cu in.)
D *1 Liquidus temperature.* 935 C (1720 F)
2 Solidus temperature. 900 C (1650 F)
6 Thermal expansion 20 to 300 C (68 to 572 F). 0.0000202 per °C (0.0000112 per °F)
11 Specific heat at 20 C (68 F). 0.09 cal per g per °C
16 Thermal conductivity at 20 C (68 F). 0.26 cal/sq

* Compiled by the Copper & Brass Research Association and the Scovill Manufacturing Company

* Compiled by the Copper & Brass Research Association and Revere Copper and Brass Incorporated

cm/cm/°C/sec (64 Btu/sq ft/ft/°F/hr)

E *1 Volume conductivity* referred to standard copper, 20 C (68 F). 24.65%, annealed

2 Electrical resistivity at 20 C (68 F). 42 ohms per cir mil-ft, annealed

K *Mechanical properties.* See Tables I and II.

Temper	Tensile Strength, psi	Yield Strength,[a] psi	Elongation in 2 in., percentage	Rockwell Hardness
Tube (1-in. OD, 0.065-in. wall)				
Annealed (0.025-mm grain)	53,000	22,000	65	F 75
Plate (1 in. thick)				
As hot rolled.....	48,000	18,000	65	F 70
Wire (0.080 in. in diam.)				
Annealed (0.015-mm grain)	55,000	.....	60	.....

(a) 0.5% extension under load

Modulus of elasticity. 15,000,000 psi

Apparent elastic limit. 18,000 psi (tube)

4 Machinability index (free-cutting brass = 100). 30

M *Composition limits* (ASTM spec). *See* Table III.

N *7 Hot working temperature.* 650 to 800 C (1200 to 1450 F)

9 Annealing temperature. 425 to 600 C (800 to 1100 F)

11 Suited to forming by cold rolling, cold drawing, hot extrusion and hot rolling.

Table I. Fatigue Properties of Admiralty Metal
(Results of tests on annealed rod, 0.035-mm grain)

Composition, percentage Cu	Sn	Zn	Other	Endurance Strength for 10^7 cycles, psi
70.88	1.07	rem	....	19,000
70.11	1.08	rem	0.03 As	17,000
71.04	1.07	rem	0.033 Sb	18,000
70.25	1.05	rem	0.034 P	17,000

Table II. Creep Data for Admiralty Metal
(Rod, hot rolled to 0.875 in., cold drawn to 0.750 in.)

Temperature deg Cent	deg Fahr	No Measurable Flow	Stress, psi, required to produce designated creep per 1000 hr 0.01%	0.10%	1.00%
204	400	10,000	13,000	19,000	27,000
316	600	Approaching zero	1,000	1,950	3,800
427	800	Approaching zero	54	160	500

References

S. L. Hoyt, "Metals and Alloys Data Book", Reinhold Publishing Corp., New York, 1943

Wilkins and Bunn, "Copper and Copper-Base Alloys", McGraw-Hill Book Co., New York, 1943

Table III. Composition Limits of Admiralty Metal

Form	ASTM Designation	Components Cu min	Cu max	Sn min	Sn max	Zn	Impurities Fe max	Pb max	Additive Agents As, Sb, or P[a] max
Tube	B 111	70.00	73.00	0.90	1.20	remainder	0.06	0.075	0.10
Plate	B 171	70.00	73.00	0.75	1.20	remainder	0.06	0.075	0.10

(a) Addition for purpose of inhibiting dezincification

60 Cu – 39.25 Zn – 0.75 Sn*

A *1 Common name.* **Naval Brass**

2 Trade name. Naval Brass (Grade A)

3 ASTM numbers.
B 21, Grade A (rod and bar); B 124, Alloy 3 (forging rod); B 171 (condenser-tube plates)

4 Government numbers. Federal QQ-B-636a, Class A (bars, plates, rods, shapes, sheet and strip); QQ-R-571, Type B (welding rods for gas welding); Army-Navy Aeronautical AN-QQ-B-646 (rolled brass) (bar, and rods for turnbuckle barrels); Navy 46B6k (bars, forgings, plates, rods, wire, shapes, sheet and strip); Bureau of Ships 46B6 (INT) (bars, forgings, plates, rods, wire, shapes, sheet and strip); Navy 46R1b, Type B (welding rods for gas welding); Bureau of Ships 46B6 (INT) (welding rods for carbon-arc and gas welding).

B *1 Typical uses.* Condenser plates, welding rod, marine hardware, propeller shafts, piston rod and valve stems, airplane turnbuckle barrels.

C *1 Density* at 20 C (68 F). 8.41 g per cu cm (0.304 lb per cu in.)

D *1 Liquidus temperature.* 900 C (1650 F)

2 Solidus temperature. 885 C (1630 F)

6 Thermal expansion 20 to 300 C (68 to 572 F). 0.0000212 per °C (0.0000118 per °F)

11 Specific heat at 20 C (68 F). 0.09 cal per g per °C

16 Thermal conductivity at 20 C (68 F). 0.28 cal/sq cm/cm/°C/sec (67 Btu/sq ft/ft/°F/hr)

E *1 Volume conductivity* referred to standard copper, 20 C (68 F). 26%, annealed

2 Electrical resistivity at 20 C (68 F). 42 ohms per cir mil-ft, annealed

K *Mechanical properties.* See Tables I and II.
Fatigue properties (rod form, cold worked 11.5%).
Modulus of elasticity. 15,000,000 psi

4 Machinability index (free-cutting brass = 100). 30

M *Composition limits* (ASTM specifications). *See* Table III.

* Compiled by the Copper & Brass Research Association and Revere Copper and Brass Incorporated

Table I. Mechanical Properties of Naval Brass

Section, in.	Temper	Tensile Strength, psi	Yield Strength,[a] psi	% Elong 2 in.	R_B Hardness	Shear Strength, psi
	Flat Products					
0.040	Light anneal ..	62,000	30,000	40	60	41,000
0.040	¼ hard	70,000	58,000	17	75	43,000
0.250	Soft anneal....	58,000	25,000	49	56	40,000
0.250	Light anneal ..	60,000	28,000	45	58	41,000
1.0	As hot rolled.	55,000	25,000	50	55	40,000
	Rod					
0.250	Soft anneal....	58,000	27,000	45	56	40,000
0.250	Light anneal ..	63,000	30,000	40	60	42,000
0.250	¼ hard (10%).	70,000	48,000	25	80	43,000
0.250	½ hard (20%).	80,000	57,000	20	85	45,000
1.0	Soft anneal....	57,000	25,000	47	55	40,000
1.0	Light anneal ..	63,000	30,000	40	60	42,000
1.0	¼ hard (8%)..	69,000	46,000	27	78	43,000
1.0	½ hard (20%).	75,000	53,000	20	82	44,000
2.0	Soft anneal....	56,000	25,000	47	55	40,000
2.0	Light anneal ..	62,000	28,000	43	60	42,000
2.0	¼ hard (8%)..	67,000	40,000	35	75	43,000
	Tube (0.375-in. OD, 0.097-in. wall)					
	Hd drawn (35%)	88,000	66,000	18	95	.....

(a) 0.5% extension under load

Table II. Fatigue Properties of Naval Brass
(Rod form, cold worked 11.5%)

Composition, percentage Cu	Sn	Zn	Other	Endurance Limit, psi	10^6 cycles
60.00	0.82	39.13	0.04 Pb	15,000	300
60.05	0.87	39.02	0.04 Pb	15,000	300

N *7 Hot working temperature.* 650 to 825 C (1200 to 1500 F)

9 Annealing temperatures. 425 to 600 C (800 to 1100 F)

11 Suited to forming by cold rolling, forging, hot rolling, hot extrusion and cold drawing

References. Same as for Admiralty Metal, above.

Table III. Composition Limits of Naval Brass

Form	Designation	Components: Cu min	Cu max	Sn min	Sn max	Zn min max	Impurities: Fe max	Pb max	Others max
Rod and Bar...	B 21, Grade A	59.00	62.00	0.50	1.00	remainder	0.10	0.20	0.10
Forgings	B 124, Alloy 3	59.00	61.00	0.50	1.00	remainder	0.10	0.20	....
Tube Plates.....	B 171	59.00	61.00	0.50	1.00	remainder	0.10	0.20	0.10

60 Cu – 37.5 Zn – 1.75 Pb – 0.75 Sn*

A *1 Common name.* **Leaded Naval Brass**
2 Trade name. Leaded Naval Brass, Grade C
3 ASTM number. B 21, Grade C (rod and bar)
4 Government number. Federal QQ-B-636a, Class B; (bars, plates, rods, shapes, sheet and strip)

B *1 Typical uses.* Marine hardware, screw-machine products

C *1 Density* at 20 C (68 F). 8.44 g per cu cm (0.305 lb per cu in.)

D *1 Liquidus temperature.* 900 C (1650 F)
2 Solidus temperature. 885 C (1630 F)
6 Thermal expansion 20 to 300 C (68 to 572 F). 0.0000214 per °C (0.0000118 per °F)
11 Specific heat at 20 C (68 F). 0.09 cal per g per °C
16 Thermal conductivity. 0.28 cal/sq cm/cm/°C/sec (67 Btu/sq ft/ft/°F/hr)

E *1 Volume conductivity* referred to standard copper, 20 C (68 F). 26% annealed
2 Electrical resistivity at 20 C (68 F). 40 ohms per cir mil-ft, annealed

K *Mechanical properties.* See Table I.
Modulus of elasticity. 15,000,000 psi
4 Machinability index (free-cutting brass = 100). 70%

M *Composition limits.* Rod and bar, ASTM B 21, Grade C, *components*: 59 to 62% Cu; 0.5 to 1.0% Sn; 1.25 to 2.25% Pb; remainder zinc; *impurities*: 0.10% max Fe; others 0.10% max.

N *7 Hot working temperature range.* 650 to 750 C (1200 to 1400 F)
9 Annealing temperatures. 425 to 600 C (800 to 1100 F)
11 Suited to forming by hot extrusion, hot forging, pressing and machining.

Table I. Mechanical Properties of Leaded Naval Brass

Temper	Tensile Strength, psi	Yield Strength,(a) psi	Elongation in 2 in., percentage	Rockwell Hardness	Shear Strength, psi
		Rod (1.0 in. in diam)			
Soft anneal...	57,000	25,000	40	B 55	36,000
¼ hard (8%).	69,000	46,000	20	B 78	39,000
½ hard (20%)	75,000	53,000	15	B 82	40,000

(a) 0.5% extension under load

Reference

Wilkins and Bunn, "Copper and Copper-Base Alloys", McGraw-Hill Book Co., New York, 1943

58.5 Cu – 39 Zn – 1.4 Fe – 1 Sn – 0.1 Mn*

A *1 Common name.* **Manganese Bronze**
2 Trade name. Manganese Bronze, Type A
3 ASTM number. B 138, Type A (rod and bar); B 124, Alloy No. 4 (forging rod)
4 Government number. Federal QQ-B-721a, Class A (bars, forging, plates, rods and shapes); Navy 46B15e, Grade A (bars, forgings, plates, rods, sheet and strip).

B *1 Typical uses.* Clutch disks, pump rods, shafting rod, valve stems, welding rod

C *1 Density* at 20 C (68 F). 8.53 g per cu cm (0.308 lb per cu in.)

D *1 Liquidus temperature.* 890 C (1630 F)
2 Solidus temperature. 865 C (1590 F)
6 Thermal expansion 20 to 300 C (68 to 572 F). 0.0000212 per °C (0.0000118 per °F)
11 Specific heat at 20 C (68 F). 0.09 cal per g per °C
16 Thermal conductivity at 20 C (68 F). 0.26 cal/sq cm/cm/°C/sec (61 Btu/sq ft/ft/°F/hr)

E *1 Volume conductivity* referred to standard copper, 20 C (68 F). 24%, annealed
2 Electrical resistivity at 20 C (68 F). 43 ohms per cir mil-ft, annealed

K *Mechanical properties.* See Table I.
Modulus of elasticity. 15,000,000 psi
4 Machinability index (free-cutting brass = 100). 30%

M *Composition limits* (ASTM spec). *See* Table II.

N *7 Hot working temperature range.* 625 to 750 C (1150 to 1450 F)
9 Annealing temperatures. 425 to 600 C (800 to 1100 F)
11 Suited to forming by hot forging, pressing, hot heading, upsetting.

Table I. Mechanical Properties of Manganese Bronze

Temper	Tensile Strength, psi	Yield Strength,(a) psi	Elongation in 2 in., percentage	Rockwell Hardness	Shear Strength, psi
		Rod (1.0 in. in diam)			
Soft anneal...	65,000	30,000	33	B 65	42,000
¼ hard (10%)	77,000	45,000	23	B 83	47,000
½ hard (20%)	84,000	60,000	19	B 90	48,000
		Rod (2.0 in. in diam)			
¼ hard (10%)	72,000	42,000	27	B 77	44,000

(a) 0.5% extension under load

Reference

Wilkins and Bunn, "Copper and Copper Base Alloys", McGraw-Hill Book Co., New York, 1943

* Compiled by the Copper & Brass Research Association and Revere Copper and Brass Incorporated

Table II. Composition Limits of Manganese Bronze

Form	Designation	Components: Cu min	Cu max	Fe min	Fe max	Sn min	Sn max	Mn max	Zn min	Zn max	Impurities: Pb max	Al max
Rod	B 138, Type A	57.00	60.00	0.80	2.00	0.50	1.50	0.5	remainder		0.20	....
Forging rod	B 124, Alloy 4	57.00	60.00	0.80	2.00	0.50	1.50	0.5	remainder		0.20	0.25

76 Cu – 22 Zn – 2 Al*

A *1 Common name.* **Aluminum Brass**
3 ASTM number. B 111 (condenser tubes)
B *1 Typical uses.* Condenser, evaporator and heat-exchanger tubes; distiller tubes; ferrules
C *1 Density* at 20 C (68 F). 8.33 g per cu cm (0.301 lb per cu in.)
D *1 Liquidus temperature.* 975 C (1780 F)
2 Solidus temperature. 935 C (1710 F)
6 Thermal expansion 20 to 300 C (68 to 572 F). 0.0000185 per °C (0.0000103 per °F)
11 Specific heat at 20 C (68 F). 0.09 cal per g per °C
16 Thermal conductivity at 20 C (68 F). 0.24 cal/sq cm/cm/°C/sec (58 Btu/sq ft/ft/°F/hr)
E *1 Volume conductivity* referred to standard copper, 20 C (68 F). 23%, annealed
2 Electrical resistivity at 20 C (68 F). 45 ohms per cir mil-ft, annealed
K *Mechanical properties.* Tube (1.0-in. OD, 0.065-in. wall, 0.025-mm grain size): tensile strength 60,000 psi; yield strength (0.5% extension under load) 27,000 psi; elongation in 2 in. 55%; Rockwell hardness F 77; apparent elastic limit 16,000 psi.
4 Machinability index. (free-cutting brass = 100). 30
M *Composition limits.* Tube (ASTM B 111), *components*: 76.00% min Cu; 1.75 to 2.50% Al; remainder zinc; *impurities*: 0.075% max Pb; 0.06% max Fe; and others 0.10% max. Arsenic, phosphorus or antimony are the other additions, made for the purpose of preventing dezincification.
N *7 Hot working temperature range.* 750 to 875 C (1400 to 1600 F)
9 Annealing temperatures. 425 to 600 C (800 to 1100 F)
11 Suited to forming by hot extrusion, cold drawing, cold rolling.

* Compiled by the Copper & Brass Research Association and Revere Copper and Brass Incorporated

Reference

Wilkins and Bunn, "Copper and Copper Base Alloys", McGraw-Hill Book Co., New York, 1943

95 Cu – 5 Sn*

A *1 Common name.* **Phosphor Bronze, 5%—Grade A**
3 ASTM number. B103-A; B139-A; B159-A
B *1 Typical uses.* Beater bars, bridge bearing-plates, bellows, Bourdon tubing, clutch disks, cotter pins, diaphragms, fuse clips, fasteners, lock washers, sleeve bushings, springs, switch parts, truss wire, wire brushes, chemical hardware, perforated sheets, textile machinery, welding rods.
C *1 Density* at 20 C (68 F). 8.86 g per cu cm (0.320 lb per cu in.)
D *1 Liquidus temperature.* 1050 C (1920 F)
2 Solidus temperature. 950 C (1750 F)
6 Thermal expansion 20 to 300 C (68 to 572 F). 0.0000178 per °C
11 Specific heat at 20 C (68 F). 0.09 cal per g
16 Thermal conductivity at 20 C (68 F). 0.19 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 18%
2 Electrical resistivity at 20 C (68 F). 9.6 microhm-cm
K *Mechanical properties.* See Table I.
4 Machinability index (free-cutting brass=100). 20
M *Composition limits.* See Table II.
N *1 Melting temperature range.* 950 to 1050 C (1750 to 1920 F)
9 Annealing temperature. 475 to 675 (900 to 1250 F)

Table I. Mechanical Properties of Phosphor Bronze (5% Sn)

Condition	Section, in.	Tensile Strength, psi	Yield Strength, psi	Elongation, percentage	Rockwell Hardness
		Flat Products			
Annealed[a]	0.040	47,000	19,000	64	B 26
½ hard[a]	0.040	68,000	55,000	28	B 78
Hard	0.040	81,000	75,000	10	B 87
Spring	0.040	100,000	80,000	4	B 95
Extra spring ...	0.040	107,000	80,000	3	B 97
		Wire			
Annealed	0.080	50,000	20,000	58	....
¼ hard	0.080	68,000	60,000	24	....
½ hard	0.080	85,000	80,000	8	....
Hard	0.080	110,000	.....	5	....
Spring	0.080	140,000	.....	2	....
		Rod			
½ hard	0.500	75,000	65,000	25	B 80
½ hard	1.0	70,000	58,000	25	B 78

(a) *Modulus of elasticity.* 16,000,000 psi

11 Suited to forming by blanking, drawing, forming, bending, upsetting, roll threading and knurling, shearing, stamping.
16 Precautions in forming. Material is hot short.
17 Joining. This alloy can be soft soldered, silver soldered, brazed, oxyacetylene welded, carbon-arc welded and resistance welded.

Table II. Composition Limits of Phosphor Bronze (5% Sn)

Form	ASTM Specification	Components: Cu min	Cu max	Sn min	Sn max	P min	P max	Impurities: Pb max	Fe max	Zn max	Sb max
Sheet	B 103-A	remainder		3.5	5.8	0.03	0.35	0.05	0.10	0.30	0.01
Wire	B 159-A	remainder		3.5	5.8	0.03	0.35	0.05	0.10	0.30	...
Rod	B 139-A	remainder		3.5	5.8	0.03	0.35	0.05	0.10	0.30	...

92 Cu – 8 Sn*

A *1 Common name.* **Phosphor Bronze, 8%—Grade C**
3 ASTM number. B103-C; B139-C; B159-C
B *1 Typical uses.* Bridge bearing-plates, beater bars, bellows, Bourdon tubing, clutch disks, cotter pins, diaphragms, fuse clips, fasteners, lock washers, sleeve bushings, springs, switch parts, truss wire, wire brushes, chemical hardeners, perforated sheets, textile machinery and welding rods.
C *1 Density* at 20 C (68 F). 8.80 g per cu cm (0.318 lb per cu in.)
D *1 Liquidus temperature.* 1020 C (1880 F)
2 Solidus temperature. 880 C (1620 F)
6 Thermal expansion 20 to 300 C (68 to 572 F). 0.0000182 per °C
11 Specific heat at 20 C (68 F). 0.09 cal per g

* Compiled by the Copper & Brass Research Association and the Chase Brass & Copper Co.

16 *Thermal conductivity* at 20 C (68 F). 0.15 cal/sq cm/cm/°C/sec

E 1 *Volume conductivity* referred to standard copper. 13%

2 *Electrical resistivity* at 20 C (68 F). 13 microhm-cm

K *Mechanical properties.* See Table I.

4 *Machinability index* (free-cutting brass=100). 20

M *Composition limits.* See Table II.

N 1 *Melting temperature range.* 880 to 1020 C (1620 to 1880 F)

9 *Annealing temperature.* 475 to 675 C (900 to 1250 F)

11 *Suited to forming* by blanking, drawing, forming, bending, shearing, stamping.

12 *Precautions in forming.* Material is hot short.

17 *Joining.* This alloy can be soft soldered, silver soldered, brazed, oxyacetylene welded, carbon-arc welded and resistance welded.

Table I. Mechanical Properties of Phosphor Bronze (8% Sn)

Condition	Section in.	Tensile Strength, psi	Yield Strength, psi	Elongation, percentage	Rockwell Hardness
		Flat Products			
Annealed[a]	0.040	55,000	.....	70	F 75
½ hard[a]	0.040	76,000	55,000	32	B 84
Hard[b]	0.040	93,000	72,000	10	B 93
Spring	0.040	112,000	.....	3	B 98
Extra Spring	0.040	120,000	.....	2	B 100
		Wire			
Annealed	0.080	60,000	24,000	65	....
¼ hard	0.080	81,000	.....	..	....
½ hard	0.080	105,000	.....	..	....
Hard	0.080	130,000	.....	..	....
Spring	0.080	140,000	.....	..	....
		Rod			
½ hard	0.500	80,000	65,000	33	B 85

(a) *Modulus of elasticity.* 16,000,000 psi
(b) *Endurance limit* for 10^8 cycles of stress. 22,000 psi

Table II. Composition Limits of Phosphor Bronze (8% Sn)

Form	ASTM Specification	Components: Cu min	Cu max	Sn min	Sn max	P min	P max	Impurities: Pb max	Fe max	Zn max	Sb max
Sheet	B 103–C	remainder		7.0	9.0	0.03	0.25	0.05	0.10	0.20	0.01
Wire	B 159–C	remainder		7.0	9.0	0.03	0.35	0.05	0.10	0.20	...
Rod	B 139–C	remainder		7.0	9.0	0.03	0.35	0.05	0.10	0.20	...

90 Cu – 10 Sn*

A 1 *Common name.* **Phosphor Bronze, 10%—Grade D**

3 *ASTM number.* B 103-D; B 139-D; B 159-D

B 1 *Typical uses.* Heavy bars and plates for severe compression, good resistance to wear and to corrosion; bridge and expansion plates and fittings; articles requiring extra spring qualities, greatest resiliency, particularly in fatigue.

C 1 *Density* at 20 C (68 F). 8.78 g per cu cm (0.317 lb per cu in.)

D 1 *Liquidus temperature.* 1000 C (1830 F)

2 *Solidus temperature.* 845 C (1550 F)

6 *Thermal expansion* 20 to 300 C (68 to 572 F). 0.0000184 per °C

11 *Specific heat* at 20 C (68 F). 0.09 cal per ▮

16 *Thermal conductivity* at 20 C (68 F). 0.12 cal/sq cm/cm/°C/sec

E 1 *Volume conductivity* referred to standard copper. 11%

2 *Electrical resistivity* at 20 C (68 F). 16 microhm-cm

K *Mechanical properties.* See Table I.

4 *Machinability index* (free-cutting brass=100). 20

M *Composition limits.* See Table II.

N 1 *Melting temperature.* 845 to 1000 C (1550 to 1830 F)

9 *Annealing temperature.* 475 to 675 C (900 to 1250 F)

Table I. Mechanical Properties of Phosphor Bronze (10% Sn)

Condition	Section, in.	Tensile Strength, psi	Elongation, percentage	Rockwell Hardness
		Flat Products		
Annealed[a] [b]	0.040	66,000	68	B 55
½ hard[b]	0.040	83,000	32	B 92
Hard	0.040	100,000	13	B 97
Spring	0.040	122,000	4	B 101
Extra Spring	0.040	128,000	3	B 103
		Wire		
Annealed	0.080	66,000	70	.....
¼ hard	0.080	93,000	..	.....
½ hard	0.080	118,000	..	.....
Hard	0.080	147,000	..	.....

(a) *Yield strength.* 28,000 psi
(b) *Modulus of elasticity.* 16,000,000 psi

11 *Suited to forming* by blanking, forming, bending and shearing.

12 *Precautions in forming.* This material is hot short.

17 *Joining.* This alloy can be soft soldered, silver soldered, brazed, oxyacetylene welded, carbon-arc welded and resistance welded.

Table II. Composition Limits of Phosphor Bronze (10% Sn)

Form	ASTM Specification	Components: Cu min	Cu max	Sn min	Sn max	P min	P max	Impurities: Pb max	Fe max	Zn max	Sb max
Sheet	B 103–D	remainder		9.0	11.0	0.03	0.25	0.05	0.10	0.20	0.01
Wire	B 159–D	remainder		9.0	11.0	0.03	0.25	0.05	0.10	0.20	...
Rod	B 139–D	remainder		9.0	11.0	0.03	0.25	0.05	0.10	0.20	...

98.75 Cu – 1.25 Sn*

A 1 *Common name.* **Phosphor Bronze, 1.25%—Grade E**

3 *ASTM number.* B 105-40

B 1 *Typical uses.* Electrical contacts, flexible hose, pole-line hardware, trolley wire.

C 1 *Density* at 20 C (68 F). 8.89 g per cu cm (0.321 lb per cu in.)

D 1 *Liquidus temperature.* 1075 C (1970 F)

2 *Solidus temperature.* 1035 C (1900 F)

6 *Thermal expansion* 20 to 300 C (68 to 572 F). 0.0000178 per °C

11 *Specific heat* at 20 C (68 F). 0.09 cal per g

16 *Thermal conductivity* at 20 C (68 F). 0.49 cal/sq cm/cm/°C/sec

E 1 *Volume conductivity* referred to standard copper. 48%

2 *Electrical resistivity* at 20 C (68 F). 3.6 microhm-cm

K *Mechanical properties.* See Table I.

* Compiled by the Copper & Brass Research Association and the Chase Brass & Copper Co.

4 *Machinability index* (free-cutting brass=100). 20
M *Composition limits.* Commercial grade: 98.5% min Cu; 1.0 to 1.5% Sn; trace P.
N 1 *Melting temperature range.* 1035 to 1075 C (1900 to 1970 F)
7 *Hot working temperature range.* 800 to 875 C (1450 to 1600 F)
9 *Annealing temperature.* 475 to 650 C (900 to 1200 F)
11 *Suited to forming* by blanking, forming, bending, heading, upsetting, shearing, squeezing, and swaging.
17 *Joining.* This alloy can be soft soldered, silver soldered, brazed, oxyacetylene welded, carbon-arc welded, and resistance welded.

Table I. Mechanical Properties of Phosphor Bronze (1.25% Sn)

Condition	Tensile Strength, psi	Yield Strength, psi	Elongation, percentage	Rockwell Hardness
Flat Products (0.040-in. section)				
Annealed[a]	40,000	14,000	48	F 60
½ hard[a]	55,000	45,000	16	B 64
Hard	65,000	50,000	8	B 75
Spring	75,000	.....	4	B 79
Wire				
Hard (0.08 in.)[b]	79,000	.....	..	.....
Hard (0.46 in.)	72,000	.....	..	.....

(a) *Modulus of elasticity.* 17,000,000 psi
(b) *Endurance limit* at 10^8 cycles. 32,000 psi

70 Cu – 30 Ni*

A 1 *Common name.* **Cupro-Nickel, 30%**
3 *ASTM number.* B111; B122, No. 5; B171
B 1 *Typical uses.* Condensers, condenser plates, distiller tubes, evaporator and heat-exchanger tubes, ferrules.
C 1 *Density* at 20 C (68 F). 8.94 g per cu cm (0.323 lb per cu in.)
D 1 *Liquidus temperature.* 1240 C (2260 F)
2 *Solidus temperature.* 1170 C (2140 F)
6 *Thermal expansion* 20 to 300 C (68 to 572 F). 0.0000162 per °C
11 *Specific heat* at 20 C (68 F). 0.09 cal per g
16 *Thermal conductivity* at 20 C (68 F). 0.07 cal/sq cm/cm/°C/sec
E 1 *Volume conductivity* referred to standard copper. 4.6%.
2 *Electrical resistivity* at 20 C (68 F). 37 microhm-cm
F 4 *Color.* White
K *Mechanical properties.* See Table I.
4 *Machinability index* (free-cutting brass=100). 20
M *Composition limits.* See Table II.
N 1 *Melting temperature.* 1170 to 1240 C (2140 to 2260 F)

Table I. Mechanical Properties of 70 Cu – 30 Ni

Condition	Section, in.	Tensile Strength, psi	Yield Strength, psi	Elongation, percentage	Rockwell Hardness
Flat Products					
Hot rolled	1.0	55,000	20,000	45	B 35
Tubes					
Annealed	1.0 OD by 0.065	60,000	25,000	45 (2 in.)	B 36
Rod					
½ hard	1.0	75,000	70,000	15 (2 in.)	B 80

(a) *Modulus of elasticity.* 22,000,000 psi

7 *Hot working temperature.* 925 to 1050 C (1700 to 1900 F)
9 *Annealing temperature.* 650 to 825 C (1200 to 1500 F)
11 *Suited to* forming and bending.
17 *Joining.* This alloy can be soft soldered, silver soldered, brazed, oxyacetylene welded, carbon-arc welded, and resistance welded.

Table II. Composition Limits of 70 Cu – 30 Ni

Form	ASTM Specification	Components: Cu Min	Components: Cu max	Components: Ni min	Components: Ni max	Impurities: Fe max	Impurities: Mn max	Impurities: Zn max	Impurities: Sn max	Impurities: Pb max
Sheet	B 122, No. 5 B 171	remainder		29.0	33.0	0.6	1.0	1.0	1.50	0.05
Tube	B 111	remainder		29.0	33.0	0.6	1.0	1.0	1.50	0.05

65 Cu – 18 Ni – 17 Zn*

A 1 *Common name.* **Nickel Silver, 18%—Alloy A**
3 *ASTM number.* B 122, No. 2; B 151-A; B 206-A
B 1 *Typical uses.* Rivets, screws, table flatware, truss wire, zippers, optical goods, base for silver plate, costume jewelry, etching stock, hollow ware, name plates, radio dials.
C 1 *Density* at 20 C (68 F). 8.73 g per cu cm (0.316 lb per cu in.)
D 1 *Liquidus temperature.* 1110 C (2030 F)
2 *Solidus temperature.* 1070 C (1960 F)
6 *Thermal expansion* 20 to 300 C (68 to 572 F). 0.0000162 per °C
11 *Specific heat* at 20 C (68 F). 0.09 cal per g
16 *Thermal conductivity* at 20 C (68 F). 0.08 cal/sq cm/cm/°C/sec
E 1 *Volume conductivity* referred to standard copper. 6%
2 *Electrical resistivity* at 20 C (68 F). 29 microhm-cm
F 4 *Color.* White
K *Mechanical properties.* See Table I.
4 *Machinability index* (free-cutting brass=100). 20
M *Composition limits.* See Table II.
N 1 *Melting temperature range.* 1070 to 1110 C (1960 to 2030 F)

Table I. Mechanical Properties of 65 Cu – 18 Ni – 17 Zn

Condition	Section, in.	Strength, Tensile psi	Strength, Yield psi	Elongation, percentage	Rockwell Hardness
Flat Products					
Annealed[a]	0.040	58,000	25,000	40	B 40
¼ hard	0.040	65,000	50,000	20	B 73
½ hard[a]	0.040	74,000	62,000	8	B 83
Hard	0.040	85,000	74,000	3	B 87
Rod					
Annealed	0.500	56,000	25,000	42	....
Hard	0.500	70,000	60,000	20	B 78
Wire					
Annealed	0.080	58,000	25,000	45	....
¼ hard	0.080	73,000	65,000	16	....
½ hard	0.080	86,000	80,000	7	....
Hard	0.080	103,000	90,000	3	....

(a) *Modulus of elasticity.* 18,000,000 psi

9 *Annealing temperature.* 600 to 825 C (1100 to 1500 F)
11 *Suited to forming* by blanking, drawing, etching, forming, bending, heading, upsetting, roll threading, knurling, shearing, spinning, squeezing, and swaging.
17 *Joining.* This alloy can be soft soldered, silver soldered, brazed, oxyacetylene welded, carbon-arc welded, and resistance welded.

* Compiled by the Copper & Brass Research Association and the Chase Brass & Copper Co.

Table II. Composition Limits of 65 Cu–18 Ni–17 Zn

Form	ASTM Specification	Components: Cu min	Cu max	Ni min	Ni max	Zn min	Zn max	Impurities: Pb max	Fe max	Mn max
Sheet	B 122, No. 2	63.0	66.5	17.0	19.5	remainder		0.10	0.25	0.50
Wire, rod, bar	B 151-A	63.0	66.5	17.0	19.5	remainder		0.05	0.25	0.50
Wire	B 206-A	63.0	66.5	16.5	19.5	remainder		0.10	0.25	0.50

55 Cu – 27 Zn – 18 Ni*

A *1 Common name.* **Nickel Silver, 18%—Alloy B**
3 ASTM number. B 122, No. 4; B 151-B; B 206-B
B *1 Typical uses.* Optical goods, springs, resistance wire.
C *1 Density* at 20 C (68 F). 8.70 g per cu cm (0.314 lb per cu in.)
D *1 Liquidus temperature.* 1055 C (1930 F)
6 Thermal expansion 20 to 300 C (68 to 572 F). 0.0000167 per °C
11 Specific heat at 20 C (68 F). 0.09 cal per g
16 Thermal conductivity at 20 C (68 F). 0.07 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 5.5%
2 Electrical resistivity at 20 C (68 F). 31 microhm-cm
F *4 Color.* White
K *Mechanical properties.* See Table I.
4 Machinability index (free-cutting brass=100). 30
M *Composition limits.* See Table II.

* Compiled by the Copper & Brass Research Association and the Chase Brass & Copper Co.

Table I. Mechanical Properties of 55 Cu–27 Zn–18 Ni

Condition	Section, in.	Tensile Strength, psi	Yield Strength, psi	Elongation, percentage	Rockwell Hardness
		Flat Products			
Annealed[a]	0.040	60,000	27,000	40	B 55
Hard[a]	0.040	100,000	85,000	3	B 91
Spring	0.040	115,000	93,000	2.5	B 99
		Wire			
Annealed	0.080	60,000	.....	40	....
Spring	0.080	145,000	.....	2	....

(a) *Modulus of elasticity.* 18,000,000 psi

N *1 Melting temperature range* near 1055 C (1939 F)
9 Annealing temperature. 600 to 825 C (1100 to 1500 F)
11 Suited to forming by blanking, forming, bending, and shearing.
17 Joining. This alloy can be soft soldered, silver soldered, brazed, oxyacetylene welded, carbon-arc welded, and resistance welded.

Table II. Composition Limits of 55 Cu–27 Zn–18 Ni

Form	ASTM Specification	Components: Cu min	Cu max	Ni min	Ni max	Zn min	Zn max	Impurities: Pb max	Fe max	Mn max
Sheet	B 122, No. 4	53.5	56.5	16.5	19.5	remainder		0.10	0.25	0.50
Wire	B 206-B	53.5	56.5	16.5	19.5	remainder		0.10	0.25	0.50
Rod, bar, wire	B 151-B	53.5	56.5	17.0	19.5	remainder		0.05	0.25	0.50

Cu – 3 Si*†

A *1 Common name.* **Silicon Bronze, Type A**
2 Trade name. Copper-Silicon Alloy; High-Silicon Bronze A
3 ASTM number. B 96, Type A (plate and sheet for pressure vessels); B 97, Type A (sheet); B 98, Type A (rod and bar); B 99, Type A (wire); B 100, Type B (plate); B 124, Alloy No. 7 (forging rod)
4 Government number. Federal QQ-C-591a, Class A (bars, plates, rods, shapes, sheet and strip); Bureau of Ships 46R1 (INT), Grade II, Class B (welding rod); Navy 46B27a (bars, forgings, plates, rods, shapes, sheet and strip).
B *1 Typical uses.* Hydraulic pressure lines, marine hardware, pole-line hardware, nails, screws, nuts, rivets and burrs, hot water tanks, bearing plates, shafting rod, bushings, channels, heat-exchanger tubes, Fourdrinier wire and cloth, kettles, screen cloth and wire, piston rings, chemical equipment.
C *1 Density* at 20 C (68 F). 8.53 g per cu cm (0.308 lb per cu in.)
D *1 Liquidus temperature.* 1025 C (1880 F)
2 Solidus temperature. 970 C (1780 F)
6 Thermal expansion 20 to 300 C (68 to 572 F). 0.0000180 per °C (0.0000100 per °F)
11 Specific heat at 20 C (68 F). 0.09 cal per g per °C
16 Thermal conductivity at 20 C (68 F). 0.09 cal/sq cm/cm/°C/sec (21 Btu/sq ft/ft/°F/hr)
E *1 Volume conductivity* referred to standard copper, 20 C (68 F). 7%, annealed
2 Electrical resistivity at 20 C (68 F). 150 ohms per cir mil-ft, annealed
K *Mechanical properties.* See Tables I and II.

* Compiled by the Copper & Brass Research Association and Revere Copper and Brass Incorporated

† One or more of the elements tin, manganese, iron and zinc, or a combination of iron and nickel may be present also. *See* Table III.

Table I. Mechanical Properties of Silicon Bronze, Type A

Temper	Tensile Strength, psi	Yield Strength,[a] psi	Elongation in 2 in., percentage	Rockwell Hardness B	Rockwell Hardness 30-T	Shear Strength, psi
		Flat Products (0.040 in. thick)				
0.070 mm	56,000	21,000	63	40	..	42,000
0.035 mm	60,000	25,000	60	62	..	43,000
0.015 mm	63,000	30,000	55	66	..	45,000
¼ hard	68,000	35,000	30	75	67	47,000
½ hard	78,000	45,000	17	87	75	50,000
Hard	94,000	58,000	8	93	78	57,000
Extra hard	104,000	60,000	6	96	80	60,000
Spring	110,000	62,000	4	97	81	63,000
		Rod (1 in. in diam)				
0.050 mm	58,000	22,000	60	60	..	43,000
½ hard (20%)	78,000	45,000	35	85	..	52,000
Hard (36%)	92,000	55,000	22	90	..	58,000
Extra hard (50%)	108,000	60,000	13	95	..	62,000
		Wire (0.080 in. in diam)				
0.035 mm	60,000	25,000	60	..	..	43,000
⅛ hard	70,000	40,000	35	..	..	48,000
¼ hard	80,000	48,000	20	..	..	52,000
½ hard	98,000	57,000	8	..	..	58,000
Hard[b]	125,000	65,000	5	..	..	65,000
Spring (80%)[c]	145,000	70,000	3	..	..	70,000
		Tube (1.0-in. OD, 0.065-in. wall)				
0.050 mm	57,000	.....	70	45	..	.....
Hard (35%)	93,000	.....	22	[redacted]	78	.....

(a) 0.5% extension under load
(b) Endurance strength: 29,000 psi for 100,000,000 cycles
(c) Endurance strength: 30,000 psi for 100,000,000 cycles

Modulus of elasticity. 15,000,000 psi

4 Machinability index (free-cutting brass = 100). 30
6 Creep data.

Temperature, deg Cent	Temperature, deg Fahr	Condition	Stress, psi, required to produce designated creep per 1000 hr: 0.01%	0.10%
204	400	I(a)	8,100	14,900
288	550	I(a)	3,750	6,400
204	400	II(b)	10,500	22,500

(a) Cold drawn 0.750-in. round bar; annealed at 842 F; Brinell hardness 119; tensile strength 70,300 psi; elongation in 2 in. 52%; reduction of area 46%.
(b) Fully annealed

M *Composition limits* (ASTM specifications). *See* Table III.
N *7 Hot working temperature.* 700 to 875 C (1300 to 1600 F)
9 Annealing temperatures. 475 to 700 C (900 to 1300 F)
11 Suited to forming by hot extrusion, hot forging, pressing, hot rolling, cold heading, cold drawing, blanking, forming, roll threading, knurling, shearing, squeezing and swaging.

Reference

Wilkins and Bunn, "Copper and Copper Base Alloys", McGraw-Hill Book Co., New York, 1943

Table II. Fatigue Properties of Silicon Bronze, Type A

Condition	Composition, percentage: Cu	Si	Mn	Sn	Fe	Endurance Strength: 1000 psi	10^6 cycles
Strip							
Cold rolled 6 B&S Nos. hard, 50% reduction of area	96.42	3.12	....	....	0.16	29	50
Annealed	95.89	3.00	1.00	....	....	16	100
Cold rolled 4 B&S Nos. hard, 37% reduction of area	95.89	3.00	1.00	....	....	23	100
Cold rolled 8 B&S Nos. hard, 60% reduction of area	95.89	3.00	1.00	....	....	20.5	100
Rod							
Cold drawn, 39% reduction of area, ready-to-finish grain size 0.125 mm	95.49	3.20	1.07	....	0.15	33.6	300
Cold drawn, 20% reduction of area, ready-to-finish grain size 0.065 mm	96.13	2.91	0.95	....	0.16	30.5	300
Cold drawn, 8% reduction of area, ready-to-finish grain size 0.085 mm	96.13	2.91	0.95	....	0.16	31.5	300
Annealed 1300 F for ½ hr ready-to-finish grain size 0.085 mm	95.49	3.20	1.07	....	0.15	18.8	300
Cold drawn, 20% reduction of area, ready-to-finish grain size 0.100 mm	96.29	3.19	....	0.42	0.10	30	100
Annealed at 1300 F for 1 hr	96.29	3.19	....	0.42	0.10	18	100

Table III. Composition Limits of Silicon Bronze, Type A

Form	Designation	Components: Cu min	Si min	Si max	Optional elements (one or more): Mn max	Zn max	Fe max	Sn max	Ni max	Impurity: Pb max
Plate and Sheet	B 96	94.80	2.75	3.50	1.50	1.50	1.60	0.75	0.60	0.05
Sheet and Strip	B 97	94.80	2.75	3.50	1.50	1.50	1.60	0.75	0.60	0.05
Rod and Bar	B 98	94.80	2.75	3.50	1.50	1.50	1.60	0.75	0.60	0.05
Wire	B 99	94.80	2.75	3.50	1.50	1.50	1.60	0.75	....	0.05
Plate	B 100	94.80	2.70	3.75	1.50	1.50	1.60	0.75	....	0.05
Forging Rod	B 124	94.80	2.70	3.75	1.50	1.75	1.60	0.75	....	0.05
					1.50	1.75	1.60	0.75	....	0.05

Cu – 1.5 Si*†

A *1 Common name.* **Silicon Bronze, Type B**
3 ASTM number.
B 97, Type B (sheet and strip); B 98, Type B (rod and bar); B 99, Type B (wire); B 124, Alloy No. 8 (forging rod).
4 Government number. Federal QQ-C-591a, Class B (bars, plates, rods, shapes, sheet and strip); Bureau of Ships 46R1 (INT), Grade II, Class A (welding rods); Navy 46B27a (bars, forgings, plates, rods, shapes, sheet and strip).
B *1 Typical uses.* Hydraulic pressure lines, marine hardware, bolts, nuts, rivets, V bolts; cap screws, machine screws, cable lamps, pole-line hardware, electrical conduit, heat-exchanger tube, welding rod.
C *1 Density* at 20 C (68 F). 8.75 g per cu cm (0.316 lb per cu in.)
D *1 Liquidus temperature.* 1060 C (1940 F)
2 Solidus temperature. 1030 C (1890 F)
6 Thermal expansion 20 to 300 C (68 to 572 F). 0.0000179 per °C (0.0000099 per °F)
11 Specific heat at 20 C (68 F). 0.09 cal per g per °C
16 Thermal conductivity at 20 C (68 F). 0.14 cal/sq cm/cm/°C/sec (33 Btu/sq ft/ft/°F/hr)
E *1 Volume conductivity* referred to standard copper, 20 C (68 F). 12%, annealed
2 Electrical resistivity at 20 C (68 F). 86 ohms per cir mil-ft, annealed
K *Mechanical properties.* See Tables I and II.
Modulus of elasticity. 15,000,000 psi
Machinability index (free-cutting brass = 100). 30
M *Composition limits* (ASTM specifications B 97, 98 and 99). *Components:* 96% Cu min, 0.75 to 2.00% Si; *Optional elements* (one or more), max: 0.75% Mn, 1.50% Zn, 0.80% Fe, 1.60% Sn; *Impurity:* 0.05% Pb max.

* Compiled by the Copper & Brass Research Association and Revere Copper and Brass Incorporated

† One or more of the elements tin, manganese, iron and zinc may be present also. *See* item M for maximum contents of these elements.

N *7 Hot working temperature.* 700 to 875 C (1300 to 1600 F)
9 Annealing temperatures. 475 to 675 C (900 to 1250 F)
11 Forming. See previous data sheet.

Reference. Wilkins and Bunn, "Copper and Copper Base Alloys", McGraw-Hill Book Co., New York, 1943

Table I. Mechanical Properties of Silicon Bronze, Type B

Temper	Tensile Strength, psi	Yield Strength,(a) psi	Elongation in 2 in., percentage	Rockwell Hardness	Shear Strength, psi
Rod (1 in. in diam)					
0.035 mm	40,000	15,000	50	F 55	.....
Hard (36%)	70,000	55,000	15	B 80	45,000
Extra hard (50%)	90,000	67,000	12	B 90	50,000
Wire (0.080 in. in diam)					
⅛ hard	50,000	35,000	40	....	36,000
¼ hard	57,000	45,000	25	....	40,000
½ hard	70,000	55,000	15	....	45,000
Hard(b)	90,000	67,000	12	....	50,000
Extra hard(c)	95,000	69,000	11	....	53,000
Wire (0.440 in. in diam)					
¼ hard (21%)	53,000	.....	30	....	.....
½ hard (37%)	63,000	.....	20	....	.....
Hard (60%)	80,000	.....	12	....	.....
Tube (1-in. OD, 0.065-in. wall)					
0.015 mm	45,000	20,000	55	F 68	.....
Hard drawn (35%)	65,000	40,000	20	B 75	.....

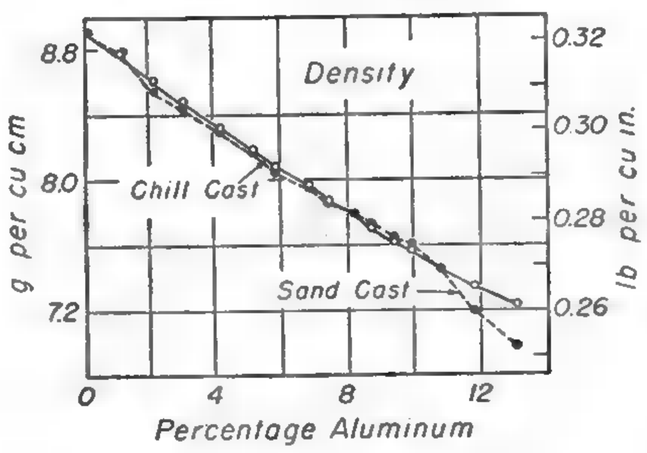
(a) 0.5% extension under load
(b) Endurance strength: 25,000 psi for 100,000,000 cycles
(c) Endurance strength: 28,000 psi for 100,000,000 cycles

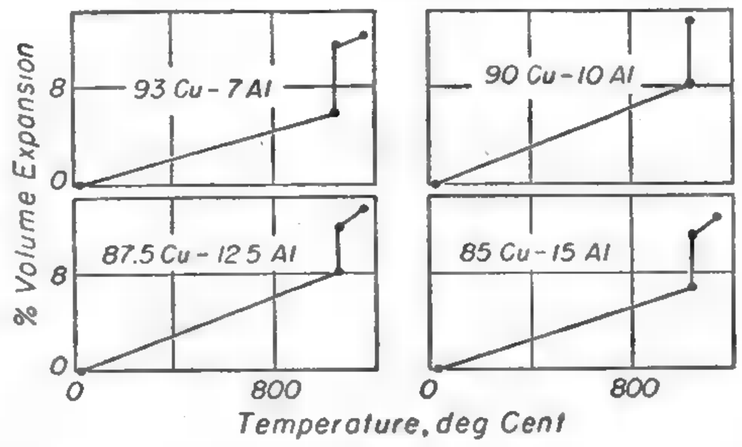
Table II. Fatigue Properties of Silicon Bronze, Type B

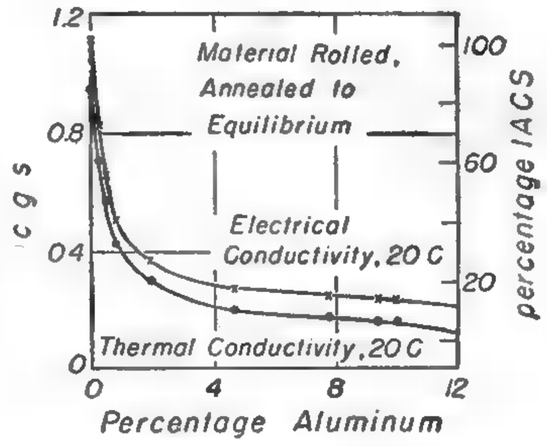
Condition	Composition, percentage: Cu	Si	Mn	Sn	Fe	Endurance Strength: 1000 psi	10^6 cycles
Rod							
Cold drawn, 72% reduction of area	98.17	1.41	0.21	....	0.06	30.4	300
Extruded	97.97	1.74	....	0.21	0.08	19	50
Extruded	97.97	1.74	....	0.21	0.08	20	50
Hot rolled	98.06	1.70	....	0.18	0.06	16	50
Hot rolled	98.06	1.70	....	0.18	0.06	19	60

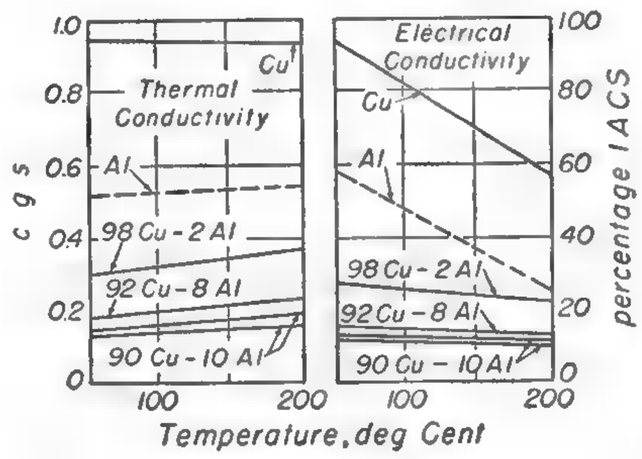
Some Properties of Aluminum Bronzes*

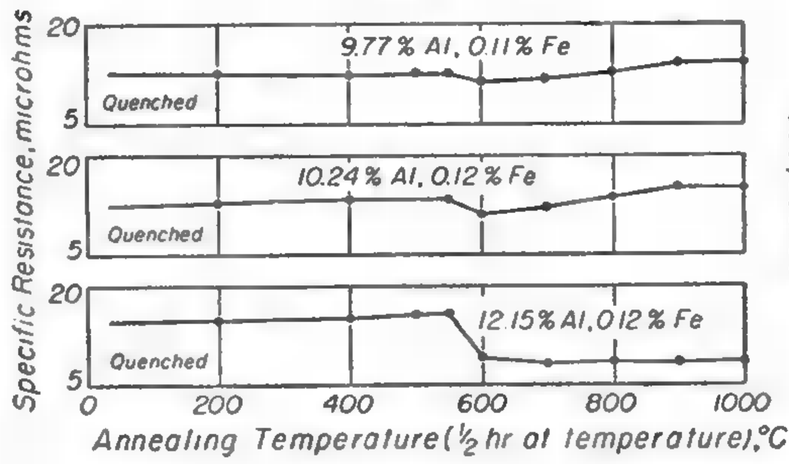
THIS COMPILATION summarizes graphically the effect of composition on some of the physical and mechanical properties of aluminum bronzes. Additional information concerning the properties of both cast and wrought alloys may be found in the data sheets for particular commercial aluminum bronzes, pages 929 to 933 and 941, 942.

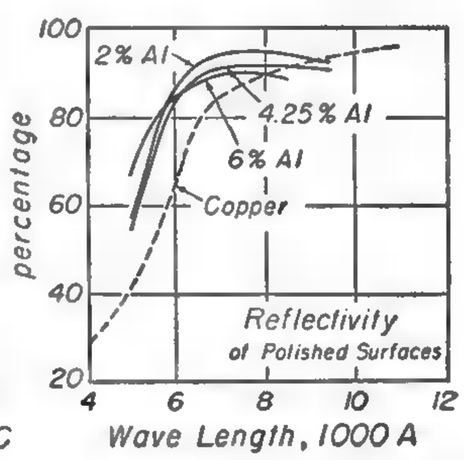


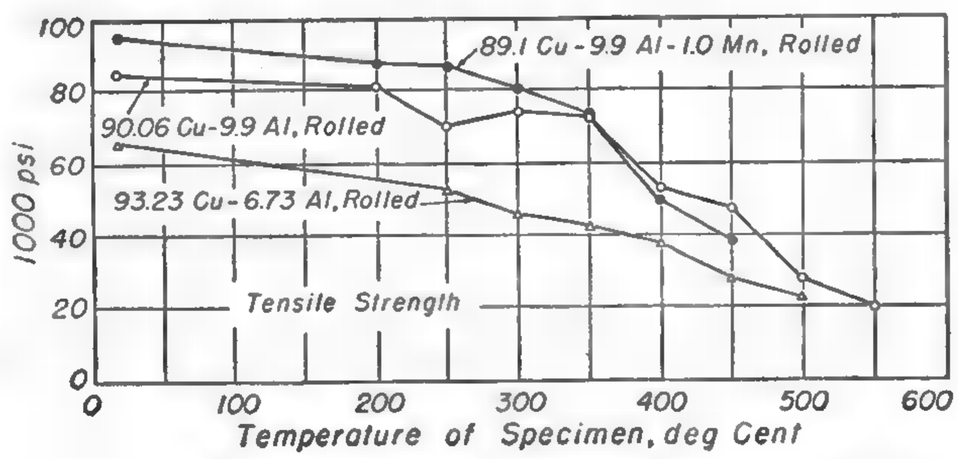


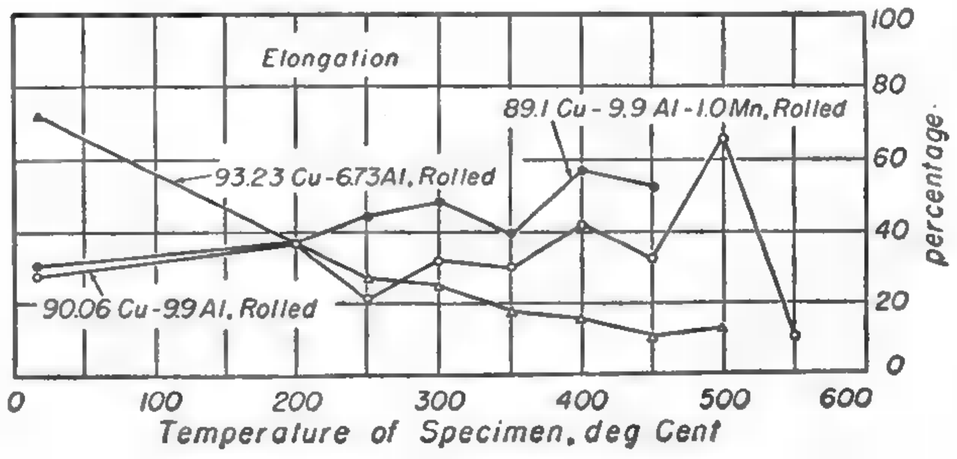












95 Cu – 5 Al*

A *2 Trade name.* **5% Aluminum Bronze**
3 ASTM numbers, government and other designations.

Form	ASTM	SAE	Federal	Army	Navy
Sheet, strip, plates.....	B 169 Alloy A	.....	QQ-B-666, Grade A	Federal	46B17c, Grade A
Rods, bars, shapes.....	.....	701A	.....	.....	.....
Rods for forging.....	B 124 Alloy 10	.....	.....	.....	.....
Tubes for condensers...	B 111	.....	.....	.....	.....

B *1 Typical uses. See* Cu – 10 Al. The low-alloy alpha-type aluminum bronzes, while suitable for both hot and cold working, are especially adapted to such cold worked forms as sheet, strip, wire, and tubing. Aluminum bronzes for "gold" decoration are usually of the 95% Cu, 5% Al type.

C *1 Density* at 20 C (68 F). 8.17 g per cu cm (0.295 lb per cu in.)

D *1 Liquidus temperature.* 1060 C (1940 F)
2 Solidus temperature. 1050 C (1920 F)
16 Thermal conductivity at 20 C (68 F).[6] 0.198 cgs
17 Thermal conductivity versus temperature. See "Some Properties of Aluminum Bronzes", top of this page.
19 Recrystallization temperature. Approx 350 C (660 F) at 44% reduction and 0.075-mm initial grain size.

E *1 Volume conductivity* referred to standard copper. 17.5%, annealed
2 Electrical resistivity at 20 C. 9.8 microhm-cm
4 Electrical resistivity (liquid) at 1100 C (2012 F).[38] 43.18 microhm-cm
5 Temperature coefficient of electrical resistivity 20 to 200 C. 0.00160 per °C. *See also* graphs at top of page.
8 Electrical resistivity versus plastic deformation at 20 C (68 F).[1] An increase from 15.6 to 17.5% IACS on annealing a sheet previously reduced 44%.
11 Slightly electropositive to copper.[39]

F *1 Reflectivity. See* graphs at the top of this page.

G *1 Influence of treatments on magnetic properties. See* Cu – 10 Al.

K *Mechanical properties. See* Table I and Fig. 1.
Fatigue tests on rod (reversed stress). Composition: 94.85% Cu, 5.62% Al, 0.07% Fe, rolled; tensile strength 72,000 psi; elongation 43%; endurance strength 19,000 psi for 10^8 cycles
4 Machinability index (free-cutting brass = 100). 20.

M *Composition limits* (ASTM spec). See Table II.
2 Consequences of exceeding impurity limits. See Cu – 10 Al.

N *Working Data. See* Cu – 10 Al.
7 Hot working temperature. 815 to 870 C (1500 to 1600 F)
9 Annealing temperatures. 425 to 750 C (800 to 1400 F)
11 Suited to forming by both hot and cold working; not

* Compiled by The American Brass Company

Table I. Mechanical Properties of 5% Aluminum Bronze

Composition, percentage Cu	Al	Fe	Ni	Zn	Condition	Tensile Strength, psi	Yield Strength,(a) psi	Elongation in 2 in., percentage	Rockwell Hardness, B scale	Brinell Hardness (500-kg load)
94.88	5.02	0.04	....	0.06	0.041-in. sheet, cold rolled, 44% reduction	100,000	63,900	8.0	93.5	...
					0.041-in. sheet, annealed at 500 C	60,300	25,600	65.8	48.5	...
94.79	4.97	0.06	0.03	0.15	0.015-in. sheet, cold rolled, 37% reduction	80,500	62,500	8.0	...	...
					0.015-in. sheet, annealed at 400 C	65,200	34,100	41.8	...	...
94.83	4.80	0.07	0.05	0.25	0.020-in. sheet, cold rolled, 37% reduction	88,900	66,500	6.8	...	...
					0.020-in. sheet, annealed at 400 C	65,000	32,500	50.0	...	...
95.19	4.66	....	....	....	Rod less than 1 in., drawn, 50% reduction	110,000	65,000	15.0	92	163
					Rod less than 1 in., annealed at 650 C	55,000	20,000	60.0	45	79
94.62	4.69	....	Trace Pb	....	Tube, ¾ in. OD, 0.049 in. wall, cold drawn	71,000	.....	30	85	...
					Same tube, annealed at 705 C	55,000	.....	65	...	...
95	5	....	....	....	Hot rolled	57,000	.....	69	...	124

(a) 0.5% extension under load.

Table II. Composition Limits of Aluminum Bronze

Form	ASTM Designation	Cu min	Cu max	Al min	Al max	Fe max
Sheets, strips, plates(a)	B 169, Alloy A	92	96	4.0	7.0	0.50
Rods, forging(a).	B 124, Alloy 10	92	96	4.0	7.0	0.50
Tubes, condenser(b)	B 111	remainder		5.0	6.5	0.10

(a) Total Cu plus Al plus Fe, 99.50% min
(b) Arsenic, 0.35% max; lead, 0.10% max.

generally used, however, for severe drawing or stamping operations.

17 Joining. See Cu – 10 Al.

References

The superscript numbers refer to the list of publications at the end of the data sheet for Cu – 10 Al.

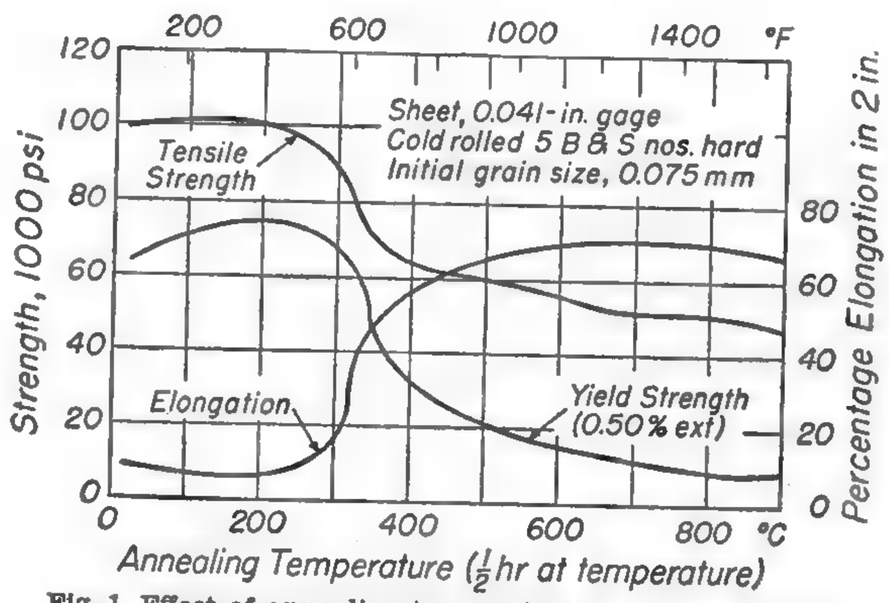


Fig. 1 Effect of annealing temperature on the mechanical properties of 5% aluminum bronze

92 Cu – 8 Al*

A *2 Trade name.* **8% Aluminum Bronze**

3 ASTM numbers.
Flat rolled products: B 169, Alloy C; B 124, Alloy 11.
Rods, bars, shapes: B 124, Alloy 11; B 150, Type I.

4 Other designations (rods, bars, shapes).
SAE 701B; Federal QQ-B-666, Grade B; Army, Federal; Navy 46B 17c, Grade B.

C *5 Solidification shrinkage.* Approx 4.6% for 93 Cu – 7 Al.

D *6 Thermal expansion.*[21]
20 to 100 C (68 to 212 F). 0.0000166 per °C
20 to 200 C (68 to 392 F). 0.0000174 per °C
20 to 300 C (68 to 572 F). 0.0000182 per °C
7.34% Al, 0.40% Zn, 0.09% Si, hot rolled.

E *8 Electrical resistivity versus plastic deformation.*[41] A decrease from 15.9 to 11.5% IACS for a 75% reduction in a 7.5% aluminum bronze.

K *Mechanical properties. See* Table I and Fig. 1.
Fatigue strength. An endurance limit of 14,000 psi for 300,000,000 cycles has been reported for an alloy with 91.96% Cu, 7.98% Al, 0.05% Fe, hard, 11.5% reduction (rod form). *See* Cu – 10 Al for table of fatigue values.

6 Creep rate
at 295 C (560 F). 10,000 psi, 1% per 10,000 hr
at 450 C (840 F). 3,000 psi, 1% per 10,000 hr
Reference 15 (91.5% Cu, 7.5% Al, die cast)
at 315 C (600 F). 10,000 psi, 0.54% per 1,000 hr
at 425 C (800 F). 3,000 psi, 0.038% per 1,000 hr
at 480 C (900 F). 3,000 psi, 0.35% per 1,000 hr
Reference 26 for cast bronze (91.47% Cu, 7.68% Al, 0.08% Sn, 0.66% Fe, 0.01% P)

References. Superscript numbers refer to Cu – 10 Al.

* Compiled by The American Brass Company

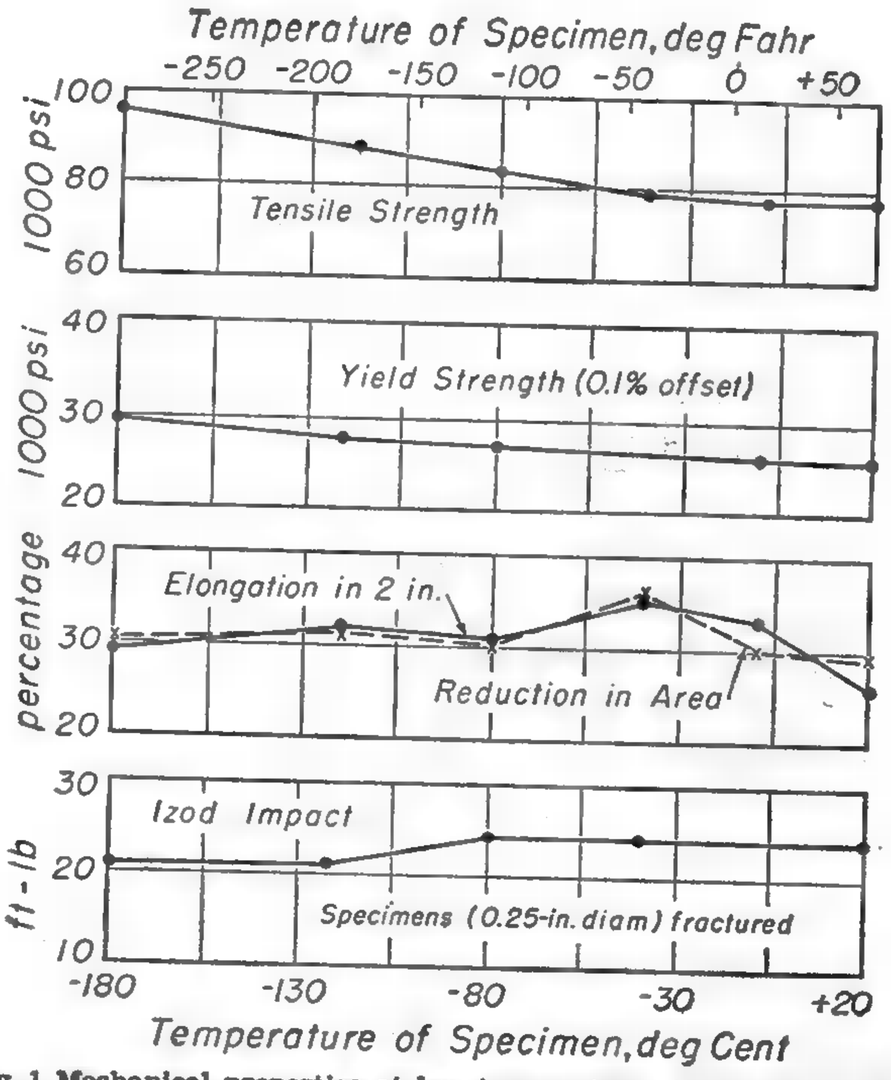


Fig. 1 Mechanical properties at low temperature, for an alloy containing 91.1% Cu, 7.31% Al, 1.02% Zn, 0.44% Mn. (Reference 16)

Table I. Mechanical Properties of Aluminum Bronzes Containing from 7 to 8% Al

Composition, percentage					Condition	Tensile Strength, 1000 psi	Yield Strength,[a] psi	Elongation in 2 in., %	Rockwell Hardness, B scale	Bhn (500-kg load)
Cu	Al	Fe	Ni	Zn						
91.74	8.10	0.04	0.02	0.10	0.020 in. sheet, cold rolled, 37% reduction	91.0	65,700	12.8	...	...
					Same sheet, annealed at 400 C	78.2	42,200	41.8	...	...
91.73	8.01	Traces of Pb and Fe.....			Rod under 1 in., cold rolled, 50% reduction	140.0	65,000	10	89	154
					Same rod, annealed 705 C	60.0	15,000	70	33	69
					Rod, hot forged	60 to 70	.....	60–70	33–48	69–81
					Rod, annealed, cold forged	70 to 80	.....	40–50	67–76	106–122
					Rod, cold drawn, 10% reduction, cold forged	85.0	.....	30	...	...
92.65	7.35	...	...	.....	Hot rolled	63.0	.....	73	...	134
92	7	1	...	.....	Hard sheet	126.1	.....	7.5	...	...
					Annealed 705 C	81.2	.....	45.3	...	...
92	7	...	1	.....	Cold rolled, annealed	124.0	.....	4.5	...	...
					Cold rolled, annealed at 650 C	66.2	.....	62.3	...	...
92	7	...	...	1% Mn	Cold rolled, annealed at 315 C	112.5	.....	8.5	...	...
					Cold rolled, annealed at 650 C	66.4	.....	60.8	...	...

(a) 0.5% extension under load

Cu – 10 Al*†

A *2 Trade name.* **10% Aluminum Bronze†**
3 ASTM number (rods, bars and shapes). B 150, Type I; B 124, Alloy 11.
4 Government and other designations.

Form	SAE	AMS	Federal	Army	Navy
Rods, bars, shapes....	701B	4630A 4632	QQ-B-666, grade B	Federal	46B17c, grade B
Rods for forging	....	....	QQ-B-666, grade B	Federal	46B17c, grade B
Forgings	....	4630A	.....	.....	46B17c, grade ■

B *1 Typical uses.* Corrosion-resistant parts: marine pumps, shafts, propellers, trim, valves, nuts, and the like; pickling crates, chains, hooks, impeller blades in the chemical industry; beater bars and blades in the paper-making industry; also corrosion-resistant tubing of the alpha alloys. Heat-resistant parts: applications requiring strength and resistance to corrosion at high temperatures, as parts for internal-combustion engines; jaws and clamps for electric-welding equipment; gas-stove grill plates; and searchlight components. Usage where toughness, wearability, low coefficient of friction, and damping capacity are important: spindle bearings, bushings, gear wheels, pinions, worm wheels, roller-bearing cages; bearing material; wear and aligning plates for machines and for bridges; cam rollers, locking nuts, cam supports, damping bushings in airplanes. Applications where hardness and low friction (high aluminum) are desirable, as in dies for the forming and drawing of stainless steel and other metal strip and sheet, for instance, zinc and aluminum. Decorative usage (resistant to tarnish), as in coins, medallions, plaques, statues, grills, fireplace fittings, vanity sets, imitation jewelry; and as a "gold" pigment in paints.

C *1 Density* at 20 C (68 F). 7.58 g per cu cm (0.274 lb per cu in.)
5 Solidification shrinkage. 3.8 to 4.1% at the solidus. *See also* page 928.

* Compiled by The American Brass Company

† Iron, nickel and tin are usually present in amounts less than 1%. A typical composition for this alloy is: 89.25% Cu, 9.25% Al, 0.60% Fe, 0.50% Ni, 0.40% Sn.

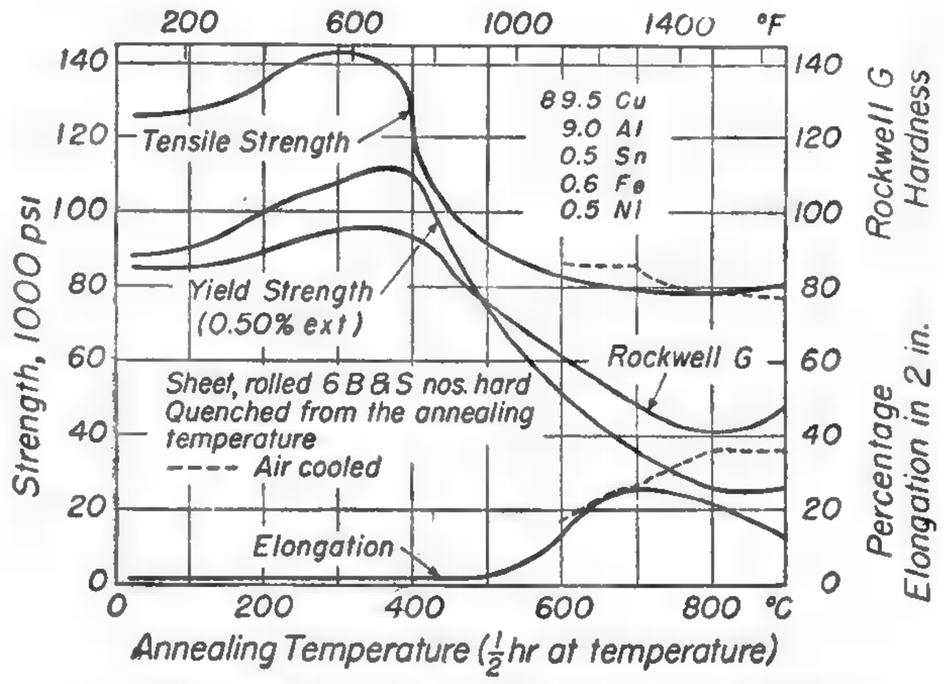


Fig. 1 Effect of annealing temperature on the mechanical properties of 10% aluminum bronze

D *1 Liquidus temperature.* 1042 C (1905 F)
2 Solidus temperature. Approx 1030 C (1890 F)
5 Transformation temperature (cooling). 570 C (1060 F)
6 Thermal expansion. See Table I.
11 Specific heat 20 to 100 C (68 to 212 F).[37] 0.104 cal per g for 11.3% aluminum bronze, soft
16 Thermal conductivity at 20 C (68 F).[6] 0.144 cal/sq cm/cm/°C/sec, soft annealed
17 Thermal conductivity versus temperature. See "Some Properties of Aluminum Bronzes", page 928.
19 Recrystallization diagram. See Fig. 1.

E *1 Volume conductivity* referred to standard copper.[6] 12.6%, annealed
2 Electrical resistivity at 20 C (68 F).[6] 13.67 microhm-cm *See also* page 928.
4 Electrical resistivity (liquid) at 1100 C (2012 F).[38] 58.22 microhm-cm
5 Temperature coefficient of electrical resistivity at 20 C (68 F).[6] 0.000829 per °C
Electrical resistivity versus temperature. See "Some Properties of Aluminum Bronzes", page 928.
11 Slightly electropositive to copper.[39]

Table I. Coefficients of Linear Thermal Expansion for Various Aluminum Bronzes

Composition, %	Condition	Coefficient of Expansion, in. per in. per °C (× 10⁶) 20 to 100 C	20 to 200 C	20 to 300 C	20 to 500 C	20 to 700 C
7.34 Al, 0.40 Zn, 0.09 Si[27]	Hot rolled	16.6	17.4	18.2	...	...
9.29 Al, 0.44 Fe, 0.38 Sn, 0.18 Ni[28]	Hard drawn rod	16.2	16.3	16.8	18.5	18.9
10.8 Al, 6.0 Fe, 3.5 Mn[36]	As cast	17.6	17.9	19.2	...	...
10.0 Al, 1.0 Fe[36]	As cast	16.5	17.3	18.5	...	...

Table II. Mechanical Properties of Aluminum Bronzes Containing from 85 to 90% Cu
(References 1, 2, 10, 11, 12, 13)

Composition, percentage					Condition	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 in., percentage	Rockwell Hardness	Brinell Hardness (3000-kg load)
Cu	Al	Fe	Ni	Other						
89.25	9.25	0.6	0.5	Sn 0.4	Annealed rod	80	40[b]	22	.....	...
					Comml temper	95	55[b]	16	.....	...
87.45	5.62	..	6.93	.....	Hot rolled	109.9	103.3	20.0	.....	241[a]
					C R, annealed 300 C	117.6	116.8	12.0	.....	...
					C R, annealed 900 C	65.4	19.3	73.0	.....	...
88.75	8.5	2.75	..	.....	Sand cast	75	28[b]	40	.....	126
					Extruded	82	37.5[b]	25	.....	140
85.75	10.75	3.50	..	.....	Sand cast	90	37[b]	14	.....	175
					Extruded	95	47[b]	12	.....	195
88.5	8.6	2.9	..	.....	Forged	82 to 90	32 to 38	25 to 30	.....	143 to 156
					Extruded	88 to 94	48 to 55	25 to 30	.....	179 to 187
					Hot rolled	95 to 105	55 to 65	18 to 22	.....	170 to 187
90	10	..	..	.....	Cast	65 to 70	24 to 28[c]	25 to 30	B 71 to 73	...
86.2	10.2	3.3	..	Mn 0.30	Cast	70 to 80	32 to 37[c]	18 to 22	B 71 to 82	...
89.0	10–11	1	..	.....	Heat treated	90 to 100	70 to 80[c]	2 to 6	C 20 to 25	...
85	11	3.7	..	Mn 0.30	Heat treated	95 to 105	43 to 50	10 to 15	.....	179 to 207

(a) Brinell, 500-kg load (b) 0.5% extension under load (c) 0.01% extension under load

G *1 Influence of treatment.* Commercial aluminum bronzes (without large additives) are virtually nonmagnetic. Appreciable additions of iron or nickel may make the alloys slightly magnetic. Certain alloys in the Cu-Al-Mn series, containing more than 5% Mn, are definitely magnetic (Heusler alloys).[3,8,33]

J *6 Microstructure. See* Reference 11.

K *Mechanical properties. See* Tables II, III and IV, Fig. 1.

Modulus of elasticity

12,000,000 to 18,000,000 psi for cast aluminum bronze of duplex type[12]

17,500,000 to 19,000,000 for "commercial aluminum bronzes"[3]

12,000,000 to 19,000,000 psi for aluminum bronzes in general[33]

Properties at elevated temperature. See page 928.

4 Machinability index. The aluminum bronzes are difficult to machine, but with high speed steel tools that have lower rake angles than for steel, they are machined in production without serious difficulty.

M *Composition limits* (ASTM). *See* Table V.

2 Consequences of exceeding impurity limits.

Iron greatly increases the strength and hardness of the alloy and refines the grain; in large quantities helps prevent "self annealing" (formation of coarse, brittle, cast structure).[1,3,5,11,33,25]

Nickel increases hardness and tensile strength but to a less extent than iron; increases resistance to corrosion in sea water and alkaline solutions, but not in fresh water or acids.[1,3,33]

Manganese affects the hardness and strength similarly to nickel; grain refiner; helps to incorporate lead into molten bronze (leaded aluminum bronze); in small amounts used for deoxidizing copper.[1,3,4,33]

Silicon, when carefully balanced, imparts great strength to certain aluminum bronzes; likely to have an embrittling effect in alpha-beta compositions; improves fluidity for certain casting alloys.[3,4,33,31]

Zinc and *iron* together are said to help prevent "self annealing"; zinc has a hardening effect on alpha alloys, but elongation decreases.[33]

Tin is said to be effective in preventing "self annealing"; not harmful up to 0.50%, but produces brittleness in amounts of 1.00% or more.[33]

Phosphorus addition of 0.05% is said to diminish hydrogen solubility; residual phosphorus should not exceed 0.05% because of the embrittling effect and the danger of hot shortness.[3]

Magnesium, like phosphorus, may have an embrittling effect.[33]

Cobalt increases hardness with little effect on grain size.[4]

Lead is used in bearing and machining alloys; as in brasses, however, it prevents hot rolling.[3,33]

Bismuth has a bad effect on hot working properties, as for brasses.

Antimony and *arsenic* are said to have bad effects.[33]

Table III. Results of Fatigue Tests on Aluminum Bronze Rods
(References 12, 20 and 40)

Composition, percentage					Condition	Tensile Strength, 1000 psi	Elongation in 2 in.	Endurance Limit, psi	Number of Cycles, 10^6
Cu	Al	Ni	Fe	Other					
89.71	8.74	0.51	0.64	Sn 0.38	Hard, 11.5% reduction	97.5	14.5	22,000	300
89.5	8.89	...	0.15	Zn 1.40	Extruded, light draw	80	37.0[a]	31,360	52.5[b]
89.91	10.06	...	0.13	.....	Extruded, H T	77.5	36	34,000	70
90.52	10.01	...	trace	.....	Annealed	83.5	38	28,000	80

(a) Elongation in $4\sqrt{\text{area}}$ (b) Specimens unbroken, level curve

Table IV. Impact Values for Aluminum Bronze Containing from 85 to 91% Cu
(References 3, 28, 29, 30)

Composition, percentage						Condition	Impact values, ft-lb		
							Izod		
Cu	Al	Fe	Mn	Ni	Zn		Range	Average	Charpy
90	10	...	...	..	.....	Cast	21 to 34	28	...
90	10	...	...	..	.....	Hot rolled, quenched from 600 C	...	38	...
90	10	...	...	..	.....	Heat treated	...	11	...
90	10	...	...	..	.....	Forged and heat treated	...	14	...
91	9	...	...	..	.....	Drawn rod	...	30	...
89.5	8.9	0.15	...	..	1.40	Extruded, slight draw	19 to 43	30	...
88	9	3.	...	..	.....	Forged	...	35	...
88	9	3.	...	..	.....	Forged and heat treated	...	30	...
86.5	10.3	3.2	...	..	.....	Quenched from 900 C	...	15	...
86.5	10.3	3.2	...	..	.....	Quenched and tempered	...	13	...
85	10	...	...	5	.....	Forged	...	19	...
85	10	...	...	5	.....	Forged and annealed	...	25	...
85	10	...	...	5	.....	Forged and heat treated	...	8	...
88.5 to 89.5	9.5 to 10.5	1	...	..	.....	Sand cast	...	..	20 to 30
86	10	3.3	...	..	.....	Sand cast	...	..	26
89	5	3	0.33	2	.....	Forged	...	66	...

Table V. Composition Limits for 10% Aluminum Bronze

Form	ASTM Designation	Cu min	Cu max	Al min	Al max	Fe max	Ni[a] max	Si[a] max	Mn max	Sn max	Zn max	Te max	Others max
Rods, bars, shapes.....	B 150, type I	80	93	6.50	11	4	1	2.25	1.50	0.60	1	0.65	0.50[b]
Rods, forgings	B 124	78	93	6.50	11	4	5.50	2.25	2	0.60	..	...	...

(a) When Ni and Si are present together, only one shall be in excess of 0.25%. (b) See note under 82.5 Cu – 10 Al – 5 Ni – 2.5 Fe.

N *1 Melting practice.* General precautions are:

1 Use of high-purity metal and scrap.
2 Melting and pouring without too great turbulence (to avoid excessive formation and entrapment of oxide and gas).
3 Melting and pouring at temperatures not too high above the liquidus, in order to prevent excessive oxidation and gas absorption. Temperatures from 50 to 100 °C above the liquidus have been used successfully.

Aluminum is usually added in the form of a high-aluminum Cu-Al alloy. Fluxes may or may not be used. The charge is sometimes remelted in order to avoid "woody" structure. Strauss[33] reports that furnace atmospheres should not be reducing. Melting under carbon is advised by some, but commercial castings can be made without a cover. To minimize turbulence, Genders and Bailey[34] favor the Durville process. Bottom casting is sometimes employed. Vertical casting is used successfully for large castings.

The rate of pouring is important. Volume shrinkage is great, but it is stated that shrinkage difficulties may be caused primarily by the short solidification range.[3] A fairly rapid rate of cooling is essential to avoid "self-annealed" structure. Special precautions in regard to sand, precision and centrifugal casting are considered in reference 3. Aluminum bronzes are not generally suitable for die-casting.

7 Hot working temperature range. Varies with alloy and condition. 800 to 925 C (1470 to 1695 F) is a suitable range, with forging and extrusion temperatures near the upper limit.

11 Forming. Alpha-beta alloys are suitable for most hot working processes. They will stand a little cold work such as light drawing and rolling.

15 Heat treatment. Most references to hardening by heat treatment are concerned with alpha alloys, usually those with a high nickel content. The properties of alpha-beta alloys, however, can be varied by heat treatment. For optimum properties of a 10% aluminum bronze, Grard recommends quenching from 900 C (1652 F) and re-annealing at 675 to 700 C (1247 to 1292 F). For most commercial purposes, the alloy can be annealed at 650 C (1202 F), and then quenched. In general it is advisable to avoid annealing below 570 C (1058 F) and cooling too slowly from the annealing temperature. Forgings should be quenched. For precipitation hardening of alpha-type alloys, *see* references 9, 14, 17, 23, 19, 21.

17 Joining of aluminum bronzes in general. *Soft soldering* is not applicable. *Silver soldering* with all grades of solder; special flux; all types of flame. *Brazing* is not applicable. *Oxyacetylene welding and carbon-arc welding* are difficult, but possible with special fluxes and rods.[3] *Resistance welding* is possible with reasonably clean materials. *Metal-arc welding* is used with flux-coated electrodes.

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82.5 Cu – 10 Al – 5 Ni – 2.5 Fe*

A *3 ASTM number.* Condenser-tube plates: B 171. Rods: B 150, Type II.

B *1 Typical uses.* Especially adapted to hot rolled plates, rods, bars, forgings and marine shafting. *See also* Cu – 10 Al.

C *1 Density* at 20 C (68 F). 7.58 g per cu cm (0.274 lb per cu in.)

5 Solidification shrinkage. Approx 4%

D *1 Liquidus temperature.* 1055 C (1930 F)

2 Solidus temperature.[42] Approx 1035 C (1895 F)

5 Transformation temperature (cooling). Between 750 and 800 C (1380 and 1470 F)

6 Thermal expansion. See Cu – 10 Al.

11 Specific heat at 20 C (68 F). Approx 0.104 cal per

16 Thermal conductivity at 20 C (68 F).[1] 0.091 cal/sq cm/cm/°C/sec (22 Btu/sq ft/ft/°F/hr)

17 Thermal conductivity versus temperature. See "Some Properties of Aluminum Bronzes", page 928.

19 Recrystallization temperature. Approximately 750+ C (1380 + F) for an extruded and light drawn rod.

Recrystallization diagram. See Fig. 1.

E *1 Volume conductivity* referred to standard copper. 7.5% annealed

2 Electrical resistivity at 20 C (68 F). 22.9 microhm-cm

G *Magnetic properties. See* Cu – 10 Al.

K *Mechanical properties. See* Tables I and III and Fig. 1. *Fatigue properties.* (*1*) *Composition:* 81.86% Cu, 9.5% Al, 2.47% Fe, 4.93% Ni, 0.94% Mn, others 0.30%; rod, cold reduction of 11.5%; modulus of elasticity 16,190,000 psi; tensile strength 124,800 psi; elongation in 2 in. 14.2%; endurance strength for 300,000,000 cycles 32,000 psi. (*2*) *Composition:* 79.83% Cu, 9.73% Al, 4.97% Ni, 5.42% Fe; forged rod; tensile strength

* Compiled by The American Brass Company

Table I. Mechanical Properties of Aluminum Bronze Containing Less Than 85% Cu
(References 1, 2, 3, 11)

Composition, percentage					Condition	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 in., percentage	Rockwell Hardness	Brinell Hardness (3000-kg load)
Cu	Al	Fe	Ni	Others						
82.0	9.50	2.50	5.0	Mn 1.00	"Soft" plate	90	...	12	....	.....
					"Hard" rod	105	60[a]	12	B 105	.....
81.7	13.4	4.4	...	Mn 0.5	Cast	85 to 100	37 to 45[b]	1 to 4	C 35 to 38	.....
81.8	9.1	...	...	Pb 9.1	Cast	45 to 50	18 to 20[b]	32 to 35	B 36 to 39	.....
81.1	9.78	3.74	5.38		Forged, annealed 845 C	104.8	61.6	17.3	B 96.5	.....
78.66	8.17	3.39	...	Mn 9.78	Forged, annealed 815 C	100.2	45.0	26.2	B 92.7	.....
					Forged, annealed 815 C, and quenched, annealed at 425 C	118.8	67.5	6.3	B 104.2	.....
82.9	7.15	...	8.12	Mn 1.83	Forged, annealed 845 C	94.5	60.1	28.0	B 90	.....
81.3	10.7	4.0	4.0		Forged and heat treated	96 to 102	55 to 60	10 to 15	....	190 to 217

(a) 0.50% extension under load. (b) 0.01% extension under load

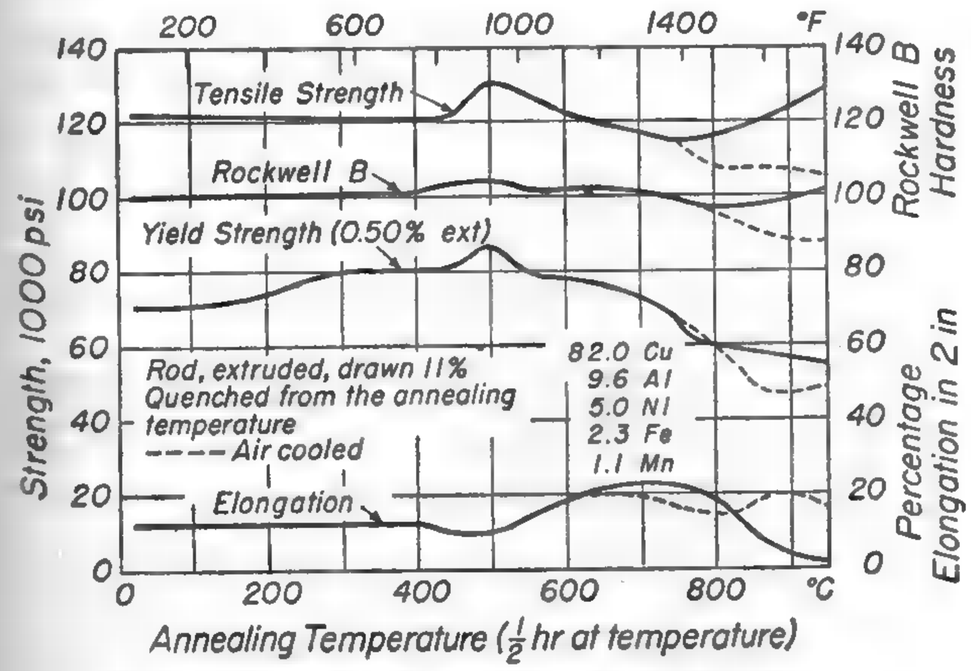

Fig. 1 Effect of annealing temperature on the mechanical properties of 82 Cu – 9.6 Al – 5 Ni – 2.3 Fe

115,800 psi; elongation in 4 $\sqrt{\text{area}}$ 10.8%; endurance strength for 56,800,000 cycles, 50,400 psi

Impact values for various aluminum bronzes are listed in the data sheet for Cu – 10 Al. (*1*) *Composition:* 82% Cu, 10.7% Al, 4% Fe, 4% Ni; forged and heat treated; Charpy 25 to 30 ft-lb. (*2*) *Composition:* 80% Cu, 10% Al, 5% Fe, 5% Ni; forged; Izod 10 ft-lb.

4 Machinability index. See Cu – 10 Al.

M *Composition limits* (ASTM spec). *See* Table II.

N *1 Melting practice. See* Cu – 10 Al.

7 Hot working temperature. 800 to 950 C (1470 to 1740 F)

11 Suited to forming primarily by hot working, but will stand slight cold reductions.

15 Heat treatment. See also Cu – 10 Al.
Grard[8] advises annealing at 900 C (1650 F) for similar compositions. Alloys of this type can be treated in several ways. Table III shows the variation in properties with heat treatment for hot rolled material.

17 Joining. See Cu – 10 Al.

References. The superscript numbers refer to the list of publications at the end of the data sheet for Cu – 10 Al.

Table II. Composition Limits for 10% Aluminum Bronzes Containing Nickel and Iron as Components

Form	ASTM Designation	Components								Impurities			
		Cu min	Cu max	Al min	Al max	Fe min	Fe max	Ni min	Ni max	Si max	Mn max	Sn max	Others max
Condenser-tube plates	B 171	remainder		8.0	11.0	1.5	3.5	4.0	7.0	...	0.5 to 2.0	...	0.50
Rods, bars, shapes	B 150, Type II	78	85	9	11	2	4	4	5.50	0.25	1.50	0.20	0.50[b]
Forging rods, bars, shapes	B 124	78	93	6.5	11	..	4	..	5.50[a]	2.25[a]	2.0	0.60	0.50

(a) B 124 and B 150. When nickel is present, silicon shall not exceed 0.25; conversely when silicon is present, nickel shall not exceed 0.25.
(b) B 150. Analysis made only for elements specified. If other elements are suspected or indicated, further analysis shall be made to determine that the total of these other elements is not in excess of 0.50%.

Table III. Effects of Heat Treatment on the Mechanical Properties of 82.5 Cu – 10 Al – 5 Ni – 2.5 Fe

Heat treatment No.	deg Cent	Tensile Strength, psi	Yield Strength (0.50% extension), psi	Elongation in 2 in., percentage	Rockwell Hardness, C scale	General Results
1	Quenched from 850, reheated to 600	109,000	63,000	25	76	High yield point with good ductility
2	Air cooled from 850	107,000	57,000	21	76	Fair qualities
3	Furnace cooled from 850 to 550, held 2 hr, then quenched	101,000	48,000	30	67	High ductility
4	Quenched from 950, reheated to 450	132,000	80,000	1.5	98	Maximum hardness and strength without cold work
5	Quenched from 850, cold drawn 23%, reheated to 450	151,000	94,100	0.5	100	Maximum hardness and strength

NOTE. Apparently there is a size factor for aluminum bronzes that limits the effectiveness of heat treatment. See page 257 of Reference 33.

55 Cu – 45 Ni

(Constantan)

See PROPERTIES OF NICKEL ALLOYS, page 1062.

Cu – 2 Be – 0.25 Co (or 0.35 Ni)

COMPILED BY PAUL A. BECK*

A *1 Common name.* **Beryllium Copper**
3 ASTM number. B 194–46aT (strip); B 195–46T (strip, special grade); B 196-46aT (rod and bar); B 197-46aT (wire)
4 Government number. Navy, Bureau of Aeronautics M 328; Navy 46C10 (INT); Army Air Forces 11070A

B *1 Typical uses.* Parts in which it is important to have a combination of excellent formability in the soft condition with high proportional limit, high fatigue strength, and great creep resistance in the hardened condition (for example, a great variety of springs); parts in which it is necessary to have corrosion resistance and relatively high electrical conductivity, or nonmagnetic behavior, coupled with high strength (springs, diaphragms, contact bridges, surgical instruments, bolts and screws); hard parts that will wear well against hardened steel (firing pins, dies, aircraft-engine counterweight bushings, small tools).

C *1 Density* at room temperature. 8.23 ± 0.02 g per cu cm (0.297 ± 0.01 lb per cu in.)
5 Solidification shrinkage. ⅛ in. per ft
6 (a) Dilation during aging (linear). minus 0.2%
(b) Increase in density during aging. 0.6%

D *1 Liquidus temperature.* 955 C (1750 F)
2 Solidus temperature. 864 C (1587 F)
6 Thermal expansion
20 to 100 C (68 to 212 F). 0.0000166 per °C
100 to 200 C (212 to 392 F). 0.0000172 per °C
200 to 300 C (392 to 572 F). 0.000019 per °C
11 Specific heat 30 to 100 C. 0.1 cal per ■
16 Thermal conductivity at 20 C (68 F).
0.20 cal/sq cm/cm/°C/sec, condition A;*
0.25 cal/sq cm/cm/°C/sec, condition AT;*
0.18, condition H;* 0.20, condition HT.*
19 Recrystallization temperature (minimum temperature for complete recrystallization in 1 hr). For 50% reduction, 480 C (900 F); 75% reduction, 430 C (810 F); 90% reduction, 370 C (700 F).
20 Grain size versus solution treatment temperature. *See* Fig. 1.

E *1 Volume conductivity* referred to standard copper. 17%, condition A;* 21%, condition AT.*
2 Electrical resistivity at 20 C (68 F). 10 microhm-cm, condition A;* 6.8 to 9.8 microhm-cm, condition AT.*

* Associate Professor of Metallurgy, University of Notre Dame, Notre Dame, Ind.

* See footnotes to table of Mechanical Properties.

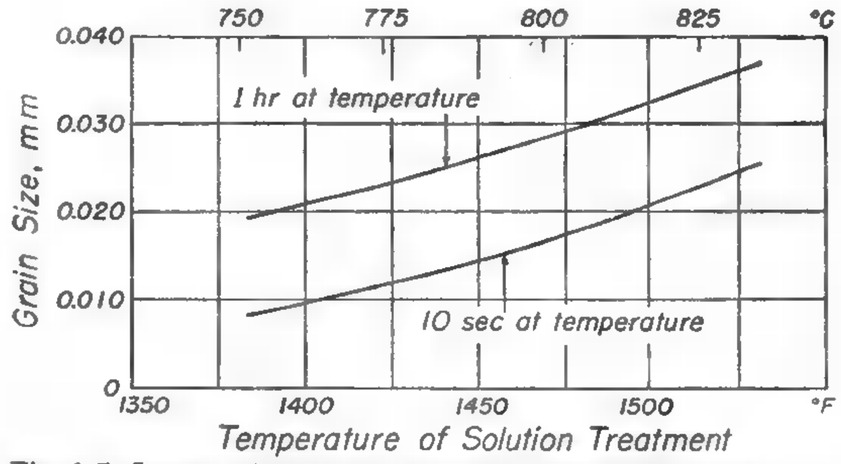

Fig. 1 Influence of solution treatment temperature and time on the grain size of beryllium copper

G *2 Magnetic susceptibility.* minus 0.45 × 10^{-6} cgs, conditions A or H; minus 0.62 × 10^{-6} cgs, conditions AT and HT.

I *1 General resistance to corrosion.* Similar to that of pure copper. It may be markedly reduced in some instances by the presence of oxidizing agents.
2 Specific resistance to corrosive agents.

Atmospheres: Excellent in industrial, marine and rural atmospheres
Natural fresh waters: Good resistance to all types
Sea water: Somewhat more resistant to sea water than is copper
Acids: Beryllium copper has good resistance to most organic acids, and may be used in contact with hot or cold dilute sulfuric acid, cold concentrated sulfuric, and cold dilute hydrochloric acid.
Alkalies: Good resistance to cold concentrated alkalies and to hot or cold dilute alkalies
Salts: Good resistance to most sulfates and chlorides. The chlorides are more corrosive than sulfates, and the salts of the heavy metals are more corrosive than the salts of the light metals.
Sulfides: Like pure copper, this alloy does not have good resistance to corrosion by sulfides, especially at high temperatures.
Organic chemicals: Excellent resistance to organic chemicals, such as alcohols, aldehydes, ketones, esters, and hydrocarbons.

CAUTION: Beryllium copper is not suitable for handling mercury or solutions of mercury compounds, ammonium hydroxide, nitric acid, ferric chloride, ferric sulfate, or acid chromates. It should not be exposed to halogen gases (fluorine, chlorine, bromine, and iodine) at elevated temperatures.

J *1 Crystal structure* of alpha. Face-centered cubic; $a = 3.565$ kX, solution treated, 2.1% Be in solid solution; and $a = 3.604$ kX, after precipitation at 300 C.

K *Mechanical Properties.* See Table I and Fig. 2.
Temperature coefficient of modulus of elasticity at 0 C (32 F). minus 35.0 × 10^{-5} per °C

Table I. Mechanical Properties of Beryllium Copper

Form	Condition*	Section, in.	Tensile Strength, 1000 psi	Yield Strength (0.01% offset), 1000 psi	Proportional Limit, 1000 psi	Elongation, percentage	Brinell Hardness Number	Rockwell Hardness Number	Modulus of Elasticity, 10^6 psi	Fatigue Strength for 10^8 cycles, 1000 psi
Strip	A	0.032	72	25	17	50	...	B 60	17	32.5(d)
Strip	½ H	0.032	95	62	50	12	...	B 93	17	35.6(d)
Strip	H	0.032	107	70	58	6	...	B 97.5	17	36.8(d)
Strip	AT	0.032	175	80	75(a)	5	...	C 41	19.5	35.2(d)
Strip	½ HT	0.032	188	105	90(a)	4	...	C 42	20	39.1(d)
Strip	HT	0.032	195	110	88(a)	3	...	C 42.5	20	40.7(d)
Strip	½ HT(f)	0.020	188.1	126	107(a)	2.5	...	30T 90.8	18.3	....
Strip	(78% red) T(f)	0.020	196.5	139	113.7(a)	1.4	...	30T 91.3	18.4	....
Rod	AT	0.75	190	140(e)	55(b)	3.7	380	....	18.4	....
Rod	HT	0.75	200	171(e)	100(b)	2.8	400	....	18.4	47 to 61.5(c)

* *Designation of tempers:*
A solution treated, quenched
AT solution treated, quenched and precipitation hardened
½ H solution treated, quenched, cold rolled 20.7% (if strip) or cold drawn 37.1% (if wire)
½ HT same as ½ H and precipitation hardened
■ solution treated, quenched, cold rolled 37.1% (if strip) or cold drawn 60.5% (if wire)
HT same as H and precipitation hardened

(a) Not corrected for true stress and strain. The traditional method for determining the proportional limit may lead to considerable error when applied to heat treated beryllium-copper alloys.
(b) Corrected for true stress and strain according to reference 4
(c) Polished specimens tested in the rotating-beam machine
(d) Cross-milled specimens tested in flexure-type machine
(e) True stress for 0.1% offset
(f) The data in these two lines were obtained under identical conditions (including identical heat treatment for minimum drift) except for the difference in the amount of cold work before heat treatment.

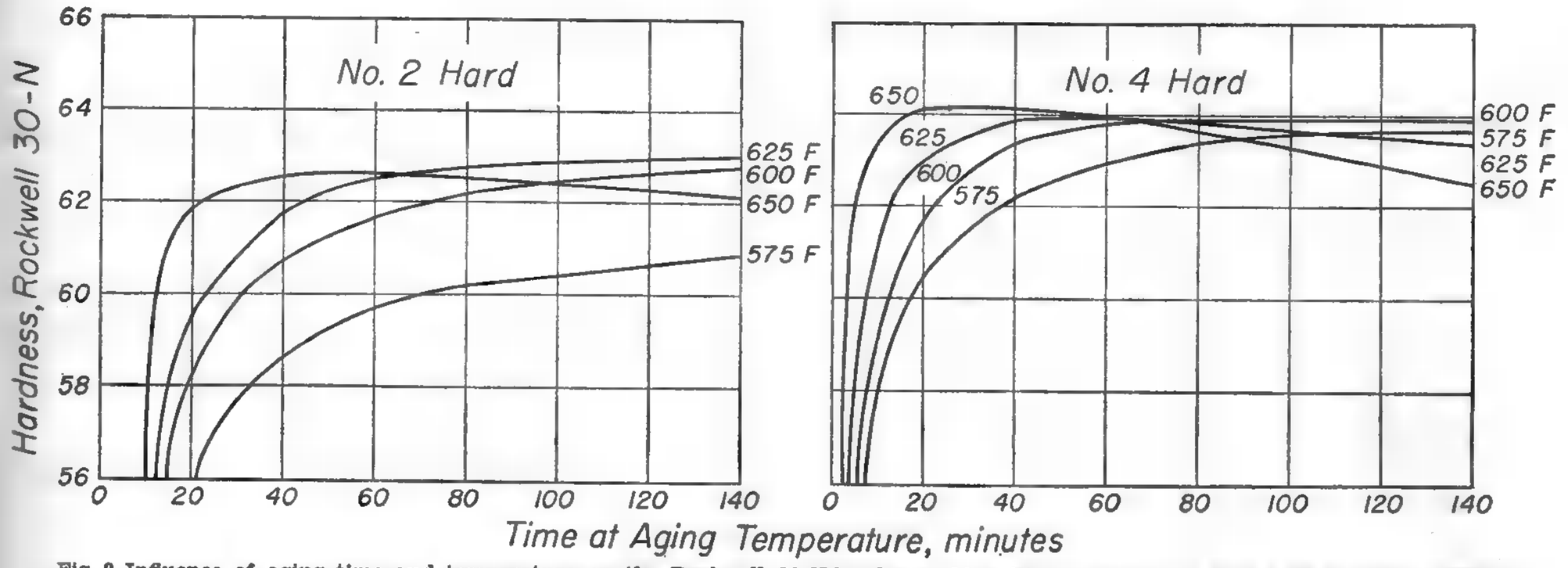

Fig. 2 Influence of aging time and temperature on the Rockwell 30-N hardness of beryllium copper alloy strip 0.028 in. thick. "Number 2 Hard" means "rolled 2 B&S numbers after solution treatment", before reheating for precipitation

M *Composition Limits* (ASTM specification for strip and wire). *Components*: 1.90 to 2.15% Be; 0.15% min Ni, Co plus Fe to 0.50% max Ni, Co plus Fe; *total impurities*, 0.50% max.

N *15 Heat Treatment. Solution treatment* at 756 to 788 C (1392 to 1450 F). In determining the total furnace time, allowance should be made for the time to reach the solution treatment temperature. This time will depend on such factors as furnace load and the thickness of the stock. The time for the stock at the actual temperature of solution treatment does not need to be longer than a few seconds. However, periods of several hours duration are often required if re-solution of the beta segregation is intended.

Precipitation hardening (aging) treatment.

From A temper, total furnace time 3 hr at 316 ± 3 C (600 ± 5 F)

From ½ H temper, total furnace time, 2 hr at 316 ± 3 C (600 ± 5 F)

From H temper, total furnace time, 2 hr at 316 ± 3 C (600 ± 5 F), up to a thickness of 0.75 in. For thicker stock, allow an additional hour for ½ H and H tempers. For accurate springs, higher aging temperatures are often used with correspondingly shorter aging time, in order to obtain minimum drift.

References

Wayne Martin, Heat Treating Beryllium Copper, Iron Age, 153, Part 1, 66 (Feb 24, 1944)

H. G. Williams, Predicting Spring Performance of Beryllium Copper Wire and Strip, Iron Age, 152, 62 (July 8, 1943)

G. R. Gohn and S. M. Arnold, The Fatigue Properties of Beryllium Copper Strip and Their Relation to Other Physical Properties, Proc ASTM, 46, 741 (1946)

Cyril S. Smith and R. W. Van Wagner, The Tensile Properties of Some Copper Alloys, Proc ASTM, 41, 825 (1941)

CASTING ALLOYS

COMPILED BY G. P. HALLIWELL*

88 Cu – 6 Sn – 1.5 Pb – 4.5 Zn

A *1 Common name.* **Leaded Tin Bronze**
2 Trade name. Navy M, Steam or Valve Bronze
3 ASTM number. B 30-45T, No. 2A (ingot)
4 Government number. QQ-B-691b, No. 1 (castings); Navy 46B8i, (castings)
5 Other designations. NFIMI-2A

B *1 Typical uses.* Steam or valve bronze bodies; high-grade steam or valve metal for use at temperatures as high as 550 F; valve bodies subject to medium pressure; oil pumps; gears; bushings; high-duty bearings; backing for babbitt-lined bearings.

* H. Kramer & Co., Chicago

Many of the data on mechanical properties have been obtained from ⅞-in. Webbert bars (*see* Fig. 3 in G. H. Clamer's 1946 AFA Foundation Lecture). For cast manganese bronzes, data are from a paper by G. P. Halliwell, Trans AFA, 51, 839 (1943)

C *1 Density* at 20 C (68 F). 8.7 ■ per cu cm (0.315 lb per cu in.)
7 Patternmaker's shrinkage. 3/16 to 7/32 in. per ft

D *2 Solidus temperature.* 982 to 999 C (1800 to 1830 F)
6 Thermal expansion 21 to 260 C (70 to 500 F). 0.0000185 per °C (0.0000103 per °F)

E *1 Volume conductivity* referred to standard copper. 14%

K *Mechanical properties.* Sand cast (0.505 in. section): tensile strength 38,000 psi; yield strength (0.5% elongation under load) 16,000 psi; elongation 35%; reduction of area 35%; Brinell hardness number (500 kg load) 66; Izod 14 ft-lb; compressive strength (0.001 in. set) 13,000 psi, (0.1 in. set) 34,000 psi; modulus of elasticity 13,000,000 psi.

M *Composition limits.* See Table I.

N *Melting.* See data sheet for 80 Cu – 10 Sn – 10 Pb.

Table I. Composition Limits of 88 Cu – 6 Sn – 1.5 Pb – 4.5 Zn

Form	Components								Impurities					
	Cu min	Cu max	Sn min	Sn max	Pb min	Pb max	Zn min	Zn max	Ni max	Fe max	Sb max	S max	Si max	P max
Sand cast.....	86.00	90.00	5.50	6.50	1.00	2.00	3.0	5.0	1.00	0.25	...	...	....	0.05
Ingot	86.00	89.00	5.75	6.50	1.00	1.75	3.5	5.0	0.75	0.20	0.25	0.05	0.005	0.03

87 Cu – 8 Sn – 1 Pb – 4 Zn

A *1 Common name.* **Leaded Tin Bearing Bronze**
3 ASTM number. B30-45T, No. 2B; B 143-46T, No. 2B
4 Government number. QQ - B - 701a, No. 6 (ingot); QQ - B - 691b, No. ▮ and No. 6X (castings); 46B5j(I,II)
5 Other designations. NFIMI-2B
B *1 Typical uses.* Wear-resistant high-duty bearings; strong, general-utility structural bronze for use under severe conditions; bolts; nuts; gears; high-pressure bearings and bushings to use against hardened steel; valves; expansion points; pump pistons; electrical work; automobile bushings.
C *1 Density* at 20 C (68 F). 8.80 ▮ per cu cm (0.318 lb per cu in.)
7 Patternmaker's shrinkage. 3/16 to 7/32 in. per ft
D *1 Liquidus temperature.* 1000 C (1830 F)
2 Solidus temperature. 854 C (1570 F)
6 Thermal expansion 21 to 177 C (70 to 350 F). 0.000018 per °C (0.00001 per °F)
16 Thermal conductivity. 12% that of copper
E *1 Volume conductivity* referred to standard copper. 11%
K *Mechanical properties.* Sand cast (0.505 in. section): tensile strength 36,000 psi; yield strength (0.5% elongation under load), 18,000 psi; elongation 30%; reduction of area 25%; Brinell hardness number (500 kg load) 68; modulus of elasticity 14,000,000 psi; Izod 9 ft-lb; compressive strength (0.001 in. set) 13,000 psi, (0.1 in. set) 43,000 psi.
M *Composition limits.* See table below.

Form	Components: Cu min	Cu max	Sn min	Sn max	Pb max	Zn min	Zn max	Impurities: Ni max	Fe max	Sb max	S max	Si max	P max
Sand cast	85.00	89.00	7.50	9.0	1.0	3.0	5.0	1.00	0.25	...	...	...	0.05
Ingot	85.00	89.00	7.75	9.0	0.9	3.5	5.0	0.75	0.20	0.25	0.05	0.005	0.03

85 Cu – 5 Sn – 9 Pb – 1 Zn

A *1 Common name.* **High-Leaded Tin Bronze**
3 ASTM number. B 30-45T, No. 3C; B 144-46T, No. 3C
5 Other designations. Similar to SAE 66
B *1 Typical uses.* Small bearings and bushings; bronze back for babbitt-lined automobile bearings.
C *1 Density* at 20 C (68 F). 8.87 ▮ per cu cm (0.320 lb per cu in.)
D *2 Solidus temperature.* 954 C (1750 F) minimum
K *Mechanical properties.* Sand cast: tensile strength 30,000 psi; yield strength (0.5% elongation under load) 15,000 psi; elongation 15%; reduction of area 16%; Brinell hardness number 60; Izod 8 ft-lb; compressive strength (0.001 in. set) 13,000 psi.
M *Composition limits.* See table below.

Form	Components: Cu[a] min	Cu max	Sn min	Sn max	Pb min	Pb max	Zn min	Zn max	Impurities: Ni[a] max	Fe max	Sb max	S max	Si max	P max
Sand cast	83.0	86.0	4.50	6.0	8.00	10.00	0.00	2.00	0.50	0.20	0.30	...	...	...
Ingot	83.0	85.0	4.50	5.5	8.5	9.75	0.5	1.50	0.50	0.15	0.25	0.08	0.003	0.02

(a) Copper (min) may be calculated as copper plus nickel.

83 Cu – 7 Sn – 7 Pb – 3 Zn

A *1 Common name.* **High-Leaded Tin Bronze**
3 ASTM number. B 30-45T, No. 3B; B 144-46T, No. 3B
5 Other designations. Similar to SAE 660
B *1 Typical uses.* General-utility bearings, bushings, automobile fittings
C *1 Density* at 20 C (68 F). 8.93 ▮ per cu cm (0.322 lb per cu in.)
7 Patternmaker's shrinkage. 3/16 to 7/32 in. per ft
D *2 Solidus temperature.* 954 C (1750 F)
6 Thermal expansion —1 to 93 C (30 to 200 F). 0.000018 per °C (0.00001 per °F)
K *Mechanical properties.* Sand cast (0.505 in. section): tensile strength 34,000 psi; yield strength (0.5% elongation under load) 17,000 psi; elongation 20%; reduction of area 18%; Brinell hardness number 60; modulus of elasticity 14,500,000 psi.
M *Composition limits.* See table below.
N *Melting.* See next data sheet.

Form	Components: Cu[a] min	Cu max	Sn min	Sn max	Pb min	Pb max	Zn min	Zn max	Impurities: Ni[a] max	Fe max	Sb max	S max	Si max	P max
Sand cast	81.0	85.0	6.25	7.50	6.00	8.00	2.00	4.00	0.50	0.20	0.35	...	...	...
Ingot	82.0	84.0	6.50	7.50	6.50	7.75	2.50	4.00	0.50	0.15	0.30	0.08	0.003	0.02

(a) Copper (min) may be calculated as copper plus nickel.

80 Cu – 10 Sn – 10 Pb

A *1 Common name.* **High-Leaded Tin Bronze**
2 Trade name. Bushing and Bearing Bronze
3 ASTM number. Similar to ASTM B 30-45T, No. 3A
5 Other designations. NFIMI-3A, SAE 64
B *1 Typical uses.* Bearings for high speed and heavy pressures; roll-neck bearings; lathe bearings; babbitt-lined armature bearings for electric locomotives; bearings in contact with mineral waters or paper-mill sulfite liquor.
C *1 Density* at 21 C (70 F). 8.80 g per cu cm (0.320 lb per cu in.)
7 Patternmaker's shrinkage. ⅛ to 3/16 in. per ft
D *6 Thermal expansion* 21 to 204 C. 0.0000184 per °C
16 Thermal conductivity at 21 C (70 F). 12% that of copper
F *4 Color.* Bronze
K *Mechanical properties.* Sand cast: tensile strength 32,000 psi; yield strength (0.5% elongation under load) 17,000 psi; elongation 12%; reduction of area 10%; Brinell hardness number (500 kg load) 65; modulus of elasticity 11,000,000 psi; Izod ▮ ft-lb; compressive strength (0.001 in. set) 14,500 psi, (0.1 in. set) 43,000 psi.
M *Composition limits.* See table at the top of page 937.
N *4 Preferred deoxidizers.* 15% P-Cu
6 Precautions in melting. Oxidizing atmosphere

Form	Components: Cu[a] min	Cu max	Sn min	Sn max	Pb min	Pb max	Impurities: Zn max	Ni[a] max	Fe max	Sb max	S max	Si max	P max
Sand cast.....	78.00	82.00	9.00	11.00	8.00	11.00	0.75	0.50	0.15	0.55	...	.....	...
Ingot	78.00	81.00	9.25	10.75	8.25	10.75	0.75	0.50	0.10	0.50	0.08	0.003	0.03

(a) Copper (min) may be calculated as copper plus nickel.

78 Cu – 7 Sn – 15 Pb

A *1 Common name.* **High-Leaded Tin Bronze**
2 Trade name. Anti-Acid Bronze
3 ASTM number. B 30-45T, No. 3D; B 144-46T, No. 3D
4 Government number. QQ-B-701a, No. 7 (ingots); QQ-B-691b, No. 7
5 Other designations. SAE 67

B *1 Typical uses.* Locomotive-engine castings and general-service bearings for moderate pressure; general-purpose wearing metal for rod bushings, shoes and wedges; freight and streetcar bearings; backs for lined journal bearings for locomotive tenders and passenger cars.

C *1 Density* at 20 C (68 F). 9.25 g per cu cm (0.334 lb per cu in.)

D *2 Solidus temperature.* 927 C (1700 F)

F *4 Color.* Gray bronze

K *Mechanical properties.* Sand cast: tensile strength 30,000 psi; yield strength (0.5% elongation under load) 16,000 psi; elongation 15%; reduction of area 15%; Brinell hardness number (500 kg load) 55; modulus of elasticity 10,500,000 psi; Izod 5 ft-lb; compressive strength (0.001 in. set) 15,000 psi. (0.1 in. set) 42,000 psi.

M *Composition limits.* See table below.

N *4 Preferred deoxidizers.* 15% P-Cu
5 Type of flux. None
6 Precautions in melting. Oxidizing atmosphere. Pour at lowest temperature possible without misruns.

Form	Components: Cu[a] min	Cu max	Sn min	Sn max	Pb min	Pb max	Impurities: Zn max	Ni[a] max	Fe max	Sb max	S max	Si max	P max
Sand cast.....	75.0	79.0	6.25	7.50	13.0	16.0	0.75	0.75	0.15	0.75	0 05	....	0.05
Ingot	76.0	79.0	6.5	7.5	14.0	16.0	0.75	0.50	0.10	0.75	0.08	0.003	0.03

(a) Copper (min) may be calculated as copper plus nickel.

70 Cu – 5 Sn – 25 Pb

A *1 Common name.* **High-Leaded Tin Bronze**
2 Trade name. Semi-Plastic Bronze
3 ASTM number. B 30-45T, No. 3E; B 144-46T. No. 3E
4 Government number. Navy 46B22f, No. 5 (castings)

B *1 Typical uses.* Bearings under light loads and high speed, driving boxes, railroad bearings

C *1 Density* at 20 C (68 F). 9.30 ■ per cu cm (0.336 lb per cu in.)

D *2 Solidus temperature.* 899 C (1650 F)

F *4 Color.* Dull bronze

K *Mechanical properties.* Sand cast: tensile strength 21,000 psi; elongation 10%; reduction of area 8%; Brinell hardness number (500 kg load) 48; modulus of elasticity 10,000,000 psi; Izod 5 ft-lb; compressive strength (0.001 in. set) 13,000 psi, (0.1 in. set) 23,000 psi.

M *Composition limits.* See table below.

N *Melting.* Same as previous alloy

Form	Components: Cu[a] min	Cu max	Sn min	Sn max	Pb min	Pb max	Impurities: Zn max	Ni[a] max	Fe max	Sb max	S max	P max
Sand cast.....	68.5	73.5	4.50	6.0	22.00	25.00	0.5	0.5	0.15	0.75	...	0.05
Ingot	69.0	73.0	4.50	5.75	22.00	24.50	0.5	0.5	0.10	0.75	0.08	0.03

(a) Copper (min) may be calculated as copper plus nickel.

85 Cu – 5 Sn – 5 Pb – 5 Zn

A *1 Common name.* 85-5-5-5
2 Trade name. Ounce Metal or Composition Metal
3 ASTM number. B 30-45T, No. 4A; B 145-46T, No. 4A
4 Government number. QQ-B-701a, No. 2; QQ-B-691b, No. 2
5 Other designations. SAE 40

B *1 Typical uses.* General castings requiring fair strength, soundness and good machining properties. Low-pressure valves, pipe fittings, gasoline-line and oil-line fittings, small gears, fire equipment fittings, small pump castings, ornamental fixtures.

C *1 Density* at 20 C (68 F). 8.80 ■ per cu cm (0.318 lb per cu in.)

D *2 Solidus temperature.* 988 to 1004 C (1810 to 1840 F)

6 Thermal expansion 21 to 204 C (70 to 400 F). 0.0000191 per °C (0.0000109 per °F)

E *1 Volume conductivity* referred to standard copper. 15%

F *4 Color.* Reddish bronze

K *Mechanical properties.* Sand cast: tensile strength 34,000 psi; yield strength (0.5% elongation under load) 17,000 psi; elongation 25%; reduction of area 25%; Brinell hardness number 60; modulus of elasticity 13,-500,000 psi; Izod 9 ft-lb; compressive strength (0.001 in. set) 11,000 psi; (0.1 in. set) 31,000 psi.

M *Composition limits.* See table below.

N *4 Preferred deoxidizers.* 15% P-Cu
5 Type of flux. None
6 Precautions in melting. Oxidizing atmosphere

Form	Components: Cu[a] min	Cu max	Sn min	Sn max	Pb min	Pb max	Zn min	Zn max	Impurities: Ni[a] max	Fe max	Sb max	■ max	Si max	P max
Sand cast.....	84.00	86.00	4.0	6.0	4.0	6.0	4.00	6.00	1.0	0.3	...	...	.....	0.05
Ingot	84.00	86.00	4.25	6.0	4.0	5.75	4.50	6.00	0.75	0.25	0.25	0.08	0.003	0.03

(a) Copper (min) may be calculated as copper plus nickel.

83 Cu – 4 Sn – 6 Pb – 7 Zn

A *1 Common name.* **Leaded Red Brass**
2 Trade name. Hydraulic Bronze
3 ASTM. B 30-45T, No. 4B; B 145-46T, No. 4B
B *1 Typical uses.* General-purpose free-machining air, gas, and water fittings; plumbing supplies and fittings; pumps and pump bodies; hardware; carburetors; injectors; railroad catenary and overhead fittings.
C *1 Density* at 20 C (68 F). 8.6 ■ per cu cm (0.312 lb per cu in.)
D *2 Solidus temperature.* 982 C (1800 F)
K *Mechanical properties.* Sand cast: tensile strength 32,000 psi; yield strength (0.5% elongation under load) 15,000 psi; elongation 24%; reduction of area 20%; Brinell hardness number (500 kg load) 55; compressive strength (0.001 in. set) 11,500 psi (0.1 in. set) 29,000 psi.
M *Composition limits.* See table below.
N *4 Preferred deoxidizers.* 15% P-Cu
6 Precautions in melting. Oxidizing atmosphere

Form	Components: Cu[a] min	Cu max	Sn min	Sn max	Pb min	Pb max	Zn min	Zn max	Impurities: Ni[a] max	Fe max	Sb max	S max	Si max	P max
Sand cast	82.0	83.75	3.25	4.25	5.00	7.00	5.00	8.00	1.00	0.30	...	...	...	...
Ingot	82.0	83.5	3.5	4.25	5.25	6.75	5.50	8.00	0.75	0.25	0.25	0.08	0.003	0.01

(a) Copper (min) may be calculated as copper plus nickel.

81 Cu – 3 Sn – 7 Pb – 9 Zn

A *1 Common name.* **Leaded Semi-Red Brass**
2 Trade name. Valve Metal
3 ASTM number. B 30-45T, No. 5A; B 145-46T, No. 5A
4 Government number. QQ–B–691b, No. 4 (castings); QQ–B–701a, No. 4 (ingots)
B *1 Typical uses.* Low-pressure valves and fittings, general hardware fittings, plumbing supplies and fixtures, ornamental fixtures.
C *1 Density* at 20 C (68 F). 8.70 ■ per cu cm (0.314 lb per cu in.)
D *2 Solidus temperature.* 954 C (1750 F)
E *1 Volume conductivity* referred to standard copper. 18%
K *Mechanical properties.* Sand cast: tensile strength 32,000 psi; yield strength (0.5% elongation under load) 15,000 psi; elongation 22%; reduction of area 20%; Brinell hardness number (500 kg load) 55; modulus of elasticity 13,000,000 psi; Izod 8 ft-lb.
M *Composition limits.* See table below.
N *4 Preferred deoxidizers.* 15% P–Cu
6 Precautions in melting. Oxidizing atmosphere

Form	Components: Cu[a] min	Cu max	Sn min	Sn max	Pb min	Pb max	Zn min	Zn max	Impurities: Ni[a] max	Fe max	S max	Si max	P max	Sb max
Sand cast	78.00	82.00	2.25	3.5	6.00	8.00	7.00	10.00	1.00	0.40	...	...	0.02	...
Ingot	78.00	82.00	2.5	3.5	6.25	7.75	7.50	10.00	0.75	0.35	0.08	0.003	0.01	0.20

(a) Copper (min) may be calculated as copper plus nickel.

76 Cu – 3 Sn – 6 Pb – 15 Zn

A *1 Common name.* **Leaded Semi-Red Brass**
2 Trade name. Plumbing Goods Brass
3 ASTM number. B 30-45T, No. 5B; B 145-46T, No. 5B
B *1 Typical uses.* Plumbing fixtures, cocks, faucets, stops, wastes, air and gas fittings, general hardware fittings, low-pressure valves and fittings.
C *1 Density* at 20 C (68 F). 8.6 g per cu cm (0.310 lb per cu in.)
D *2 Solidus temperature.* 941 C (1725 F)
K *Mechanical properties.* Sand cast: tensile strength 32,000 psi; yield strength (0.5% elongation under load) 15,000 psi; elongation 30%; reduction of area 30%; Brinell hardness number (500 kg load) 55; modulus of elasticity 12,000,000 psi; compressive strength (0.001 in. set) 9,000 psi, (0.1 in. set) 31,000 psi.
M *Composition limits.* See table below.
N *4 Preferred deoxidizers.* 15% P-Cu
6 Precautions in melting. Oxidizing atmosphere

Form	Components: Cu[a] min	Cu max	Sn min	Sn max	Pb min	Pb max	Zn min	Zn max	Impurities: Ni[a] max	Fe max	Sb max	S max	P max	Si max
Sand cast	75.00	76.75	2.50	3.50	5.25	6.75	13.00	17.00	1.00	0.4	...	...	0.02	...
Ingot	75.00	76.75	2.75	3.25	5.50	6.50	14.00	17.00	0.50	0.35	0.20	0.07	0.01	0.005

(a) Copper (min) may be calculated as copper plus nickel.

71 Cu – 1 Sn – 3 Pb – 25 Zn

A *1 Common name.* **Leaded Yellow Brass**
2 Trade name. High-Copper Yellow Brass
3 ASTM number. B 30-45T, No. 6A; B 146-46T, No. 6A
B *1 Typical uses.* Yellow brass alloy plumbing fixtures, fittings and trimmings; valves; chandeliers; andirons; general hardware; ornamental work.
C *1 Density* at 20 C (68 F). 8.50 g per cu cm (0.307 lb per cu in.)
D *2 Solidus temperature.* 927 C (1700 F)
6 Thermal expansion 21 to 93 C (70 to 200 F). 0.0000207 per °C (0.0000115 per °F)
E *1 Volume conductivity* referred to standard copper. 25%
F *4 Color.* Yellow
K *Mechanical properties.* Sand cast (0.505 in. section: tensile strength 35,000 psi; yield strength (0.5% elongation under load) 12,000 psi; elongation 35%; reduction of area 30%; Brinell hardness number (500 kg load) 48; modulus of elasticity 13,000,000 psi; compressive strength (0.001 in. set) 9,000 psi (0.1 in. set) 30,000 psi.
M *Composition limits.* See table at the top of page 939.
N *4 Preferred deoxidizer.* None
5 Type of flux. None
6 Precautions in melting. Oxidizing atmosphere

Form	Components								Impurities					
	Cu min	Cu max	Sn min	Sn max	Pb min	Pb max	Zn min	Zn max	Ni max	Fe max	Sb max	S max	Si max	P max
Sand cast	70.00	74.00	0.75	2.00	1.5	3.75	remainder		...	0.6	...	...	...	...
Ingot	70.00	73.00	0.75	1.75	1.5	3.50	remainder		0.5	0.5	0.1	0.05	0.05	0.01

66 Cu – 1 Sn – 3 Pb – 30 Zn

A *1 Common name.* **Leaded Yellow Brass**
2 Trade name. No. 1 Yellow Brass
3 ASTM number B 30-45T, No. 6B (ingot); B 146-46T, No. 6B (castings)
4 Government number. QQ-B-621a, grade B; Navy 46B11h, No. 1
5 Other designations. SAE 41
B *1 Typical uses.* General-purpose yellow castings; light castings not subject to high internal pressure; furniture hardware; ornamental castings; radiator fittings; ship trimmings; gas cocks and light fixtures.
C *1 Density* at 20 C (68 F). 8.4 g per cu cm (0.303 lb per cu in.)
D *2 Solidus temperature.* 927 C (1700 F)
6 Thermal expansion 21 to 93 C (70 to 200 F). 0.0000202 per °C (0.0000112 per °F)
E *1 Volume conductivity* referred to standard copper. 18 to 25%
K *Mechanical properties.* Sand cast (0.505 in. section): tensile strength 34,000 psi; yield strength (0.5% elongation under load) 13,000 psi; elongation 35%; reduction of area 30%; Brinell hardness number 50; modulus of elasticity 13,000,000 psi; compressive strength (0.001 in. set) 9,000 psi, (0.1 in. set) 30,000 psi.
M *Composition limits.* See table below.
N *4 Deoxidizer.* None
6 Precautions in melting. Oxidizing atmosphere

Form	Components							Impurities						
	Cu min	Cu max	Sn max	Pb min	Pb max	Zn min	Zn max	Ni max	Fe max	Sb max	[illegible] max	Al max	Si max	P max
Sand cast	65.00	70.00	1.50	1.50	3.75	remainder		...	0.75	0.10	0.05	0.30	...	0.01
Ingot	65.00	69.00	1.50	1.50	3.50	remainder		0.5	0.5	...	...	none	0.05	...

60 Cu – 1 Sn – 1 Pb – 38 Zn

A *1 Common name.* **Leaded Yellow Brass**
2 Trade name. Die-Cast Brass
3 ASTM number. B 30-45T, No. 6C; B 146-46T, No. 6C
4 Government number. QQ-B-621a, "A"; Navy 46B10h
B *1 Typical uses.* Spring bushing alloy; hardware fittings; ornamental castings; ship trimmings.
C *1 Density.* 8.40 g per cu cm (0.304 lb per cu in.)
D *2 Solidus temperature.* 913 to 940 C (1675 to 1725 F)
6 Thermal expansion 21 to 260 C (70 to 500 F). 0.0000216 per °C (0.000012 per °F)
E *1 Volume conductivity* referred to standard copper. 20 to 26%
F *4 Color.* Yellow
K *Mechanical properties.* Sand cast: tensile strength 40,000 psi; yield strength (0.5% elongation under load) 14,000 psi; elongation 25%; reduction of area, 25%; Brinell hardness number (500 kg load) 65; modulus of elasticity 14,000,000 psi.
M *Composition limits.* See table below.
N *Melting.* See preceding data sheet.

Form	Components								Impurities			
	Cu min	Cu max	Sn min	Sn max	Pb min	Pb max	Zn min	Zn max	Ni max	Fe max	Al min	Al max
Sand cast	60.00	65.00	0.5	1.50	0.75	1.50	remainder		...	0.75	...	0.50
Ingot	59.00	63.00	0.5	1.50	0.75	1.25	remainder		0.5	0.5	0.1	0.5

62 Cu – 26 Zn – 3 Fe – 5.5 Al – 3.5 Mn

A *1 Common name.* **High-Strength Yellow Brass**
2 Trade name. High-Strength Manganese Bronze
3 ASTM number. B 30-45T, No. 8C; B 147-46T, No. 8C
4 Government number. Navy 46B29(INT)-1, A and B
B *1 Typical uses.* Extra heavy-duty, high-strength alloy for large valve stems, gears, cams; bearings (slow-speed, heavy-load type); screw-down nuts; bridge parts; hydraulic cylinder parts.
C *1 Density* at 20 C (68 F). 7.9 g per cu cm (0.285 lb per cu in.)
D *1 Liquidus temperature.* 899 C (1650 F)
6 Thermal expansion 21 to 260 C (70 to 500 F). 0.0000198 per °C (0.000011 per °F)
16 Thermal conductivity. 13% that of copper
E *1 Volume conductivity* referred to standard copper. 12%
F *4 Color.* Yellow
K *Mechanical properties.* Sand cast: tensile strength 115,000 psi; yield strength (0.5% elongation under load) 70,000 psi; elongation 15%; reduction of area 15%; Brinell hardness number (3000 kg load) 210; modulus of elasticity 15,500,000 psi; Izod 12 ft-lb; compressive strength (0.001 in. set) 60,000 psi (0.1 in. set) 100,000 psi
M *Composition limits.* See table below.
2 Consequences of exceeding impurity limits. Excessive tin causes brittleness; excessive lead decreases the elongation; and excessive nickel decreases both tensile strength and elongation.

Form	Components										Impurities		
	Cu min	Cu max	Fe min	Fe max	Al min	Al max	Mn min	Mn max	Zn min	Zn max	Pb max	Sn max	Ni max
Sand cast.....	60.00	68.00	2.00	4.00	3.00	7.50	2.50	5.00	remainder		0.2	0.5	...
Ingot	60.00	68.00	2.00	4.00	3.00	7.50	2.50	5.00	remainder		0.1	0.5	1.00

58 Cu – 39.25 Zn – 1.25 Fe – 1.25 Al – 0.25 Mn

A *1 Common name.* **High-Strength Yellow Brass**
2 Trade name. Manganese Bronze
3 ASTM number. B 30-45T, No. 8A; B 147-46T, No. 8A
4 Government number. QQ-B-731b, Class A (ingot); QQ-B-726c, Class A (castings)
5 Other designations. SAE 43
B *1 Typical uses.* Propeller hubs, blades and other parts in contact with salt water and fresh water; gears; liners; valve stems; complicated lever arms where both strength and toughness are required.
C *1 Density* at 20 C (68 F). 8.2 g per cu cm (0.296 lb per cu in.)
D *1 Liquidus temperature.* 904 C (1660 F)
6 Thermal expansion 21 to 93 C (70 to 200 F). 0.0000216 per °C (0.000012 per °F)
E *1 Volume conductivity* referred to standard copper. 18%
K *Mechanical properties.* Sand cast: tensile strength 70,000 psi; yield strength (0.5% elongation under load) 28,000 psi; elongation 30%; reduction of area 30%; Brinell hardness number (500 kg load) 125; modulus of elasticity, 15,000,000 psi. Compressive strength (0.001 in. set) 24,000 psi; (0.1 in. set) 87,000 psi.
M *Composition limits.* See table below.
N *4 Deoxidizer.* None
5 Type of flux. None
6 Precautions in melting. Slightly oxidizing atmosphere

Form	Components									Impurities		
	Cu min	Cu max	Fe min	Fe max	Al min	Al max	Mn max	Zn min	Zn max	Sn max	Pb max	Ni max
Sand cast	55.00	60.00	0.4	2.00	0.50	1.50	1.50	remainder		1.00	0.40	0.50
Ingot	55.00	60.00	0.4	2.00	0.50	1.50	1.50	remainder		1.00	0.30	0.50

59 Cu – 0.75 Sn – 0.75 Pb – 37 Zn – 1.25 Fe – 0.75 Al – 0.5 Mn

A *1 Common name.* **Leaded Manganese Bronze**
2 Trade name. Stem Manganese Bronze
3 ASTM number. B 30-45T, No. 7A; B 147-46T, No. 7A
4 Government number. QQ-B-726c, Class D
B *1 Typical uses.* Free-machining manganese bronze for valve stems, marine castings and fittings, pump bodies, gas-engine bases, lever arms, brackets, gears
C *1 Density.* 8.2 g per cu cm (0.296 lb per cu in.)
D *2 Solidus temperature.* 914 to 940 C (1675 to 1725 F)
6 Thermal expansion 21 to 204 C (70 to 400 F). 0.0000205 per °C (0.0000114 per °F)
F *4 Color.* Yellow
K *Mechanical properties.* Sand cast: tensile strength 65,000 psi; yield strength (0.5% elongation under load) 30,000 psi; elongation 18%; reduction of area 20%; Brinell hardness number (500 kg load) 85; modulus of elasticity 15,000,000 psi; compressive strength (0.001 in. set) 23,000 psi, (0.1 in. set) 87,000 psi; Izod 20 to 40 ft-lb.
M *Composition limits.* See table below.

Form	Cu min	Cu max	Sn min	Sn max	Pb min	Pb max	Fe min	Fe max	Al min	Al max	Mn min	Mn max	Ni max	Zn
Sand cast	56.00	62.00	...	1.50	0.50	1.50	...	2.00	...	1.50	...	1.5	...	remainder
Ingot	56.00	62.0	0.5	1.00	0.5	1.00	0.75	1.50	0.25	1.00	0.10	0.50	0.5	remainder

66 Cu – 5 Sn – 1.5 Pb – 2 Zn – 25 Ni

A *1 Common name.* **Nickel Silver**
2 Trade name. Leaded Nickel Bronze
3 ASTM number. B 30-45T, No. 11B; B 149-46T, No. 11B
B *1 Typical uses.* Dairy and soda fountain equipment, valves and valve seats for elevated temperatures, hardware, musical instruments, keys.
C *1 Density* at 20 C (68 F). 8.8 to 8.9 g per cu cm (0.318 to 0.322 lb per cu in.)
D *16 Thermal conductivity.* 6.5% that of copper.
E *1 Volume conductivity* referred to standard copper. 4 to 5%
F *4 Color.* Silvery white
K *Mechanical properties.* Sand cast: tensile strength 50,000 psi; yield strength (0.5% elongation under load) 24,000 psi; elongation 15%; reduction of area 15%; Brinell hardness number (500 kg load) 130.
M *Composition limits.* See table below.
N *Melting.* See the next data sheet.

Form	Components										Impurities				
	Cu min	Cu max	Sn min	Sn max	Pb min	Pb max	Zn min	Zn max	Ni min	Ni max	Fe max	Sb max	S max	Si max	P max
Sand cast	64.00	67.00	4.00	5.50	1.00	2.50	remainder		24.00	27.00	1.50	...	...	...	1.00
Ingot	64.00	67.00	4.50	5.50	1.00	2.00	remainder		24.00	26.00	1.00	0.25	0.05	0.10	1.00

64 Cu – 4 Sn – 4 Pb – 8 Zn – 20 Ni

A *1 Common name.* **Nickel Silver**
2 Trade name. Dairy Bronze
3 ASTM number. B 30-45T, No. 11A; B 149-46T
4 Government number. FF–H–106, FF–H–136, FF–H–121a, FF–H–116a, FF–H–111, and WW–P–541 (castings)
B *1 Typical uses.* Marine castings, ship trimmings, furniture trim, hardware, valves, ornamental castings.
C *1 Density* at 20 C (68 F). 8.85 g per cu cm (0.320 lb per cu in.)
D *16 Thermal conductivity.* 6% that of copper
E *1 Volume conductivity* referred to standard copper. 5%
F *4 Color.* Silvery
K *Mechanical properties.* Sand cast: tensile strength 40,000 psi; yield strength (0.5% elongation under load) 25,000 psi; elongation 15%; reduction of area, 14%; Brinell hardness number (500 kg load) 105.
M *Composition limits.* See table at the top of page 941.
N *4 Preferred deoxidizers.* Mg–Cu and Mn–Cu
5 Type of flux. Neutral
6 Precautions in melting. Oxidizing atmosphere

Form	Components: Cu min	Cu max	Sn min	Sn max	Pb min	Pb max	Ni min	Ni max	Zn min	Zn max	Impurities: Fe max	Sb max	S max	Si max	Mn max
Sand cast	63.00	67.00	3.5	4.50	3.00	5.00	19.50	21.50	remainder		1.50	...	...	...	1.00
Ingot	63.00	65.00	3.50	4.50	3.50	5.00	19.50	21.00	remainder		1.00	0.25	0.05	0.05	1.00

57 Cu – 2 Sn – 9 Pb – 20 Zn – 12 Ni

A *1 Common name.* **Nickel Silver**
2 Trade name. Benedict Metal
3 ASTM number. B 30-45T, No. 10A; B 149-46T, No. 10A
B *1 Typical uses.* Hardware fittings, valves, valve trimmings, plumbing fixtures, statuary, ornamental castings, free-machining work.
C *1 Density* at 20 C (68 F). 8.95 g per cu cm (0.323 lb per cu in.)
K *Mechanical properties.* Sand cast: tensile strength 34,000 psi; yield strength (0.5% elongation under load) 15,000 psi; elongation 20%; reduction of area 20%; Brinell hardness number (500 kg load) 60.
M *Composition limits.* See table below.
N *4 Preferred deoxidizers.* Mg–Cu and Mn–Cu
5 Type of flux. Neutral
6 Precautions in melting. Oxidizing atmosphere

Form	Components: Cu min	Cu max	Sn min	Sn max	Pb min	Pb max	Ni min	Ni max	Zn min	Zn max	Impurities: Fe max	Mn max	Sb max	■ max
Sand cast	53.00	58.00	1.50	3.00	8.00	11.00	11.00	14.00	remainder		1.50	0.50	...	...
Ingot	53.00	58.00	1.50	3.00	8.00	11.00	11.00	14.00	remainder		1.00	0.5	0.25	0.05

60 Cu – 3 Sn – 5 Pb – 16 Zn – 16 Ni

A *1 Common name.* **Leaded Nickel Brass**
2 Trade name. Nickel Silver
B *1 Typical uses.* Free-machining brass for valves, hardware, boat and railroad-car fittings, pipe fittings.
C *1 Density* at 20 C (68 F). 8.95 ■ per cu cm (0.320 lb per cu in.)
D *16 Thermal conductivity.* 7% that of copper
E *1 Volume conductivity* referred to standard copper. 5 to 6%
F *4 Color.* Nickel, silvery
K *Mechanical properties.* Sand cast: tensile strength 38,000 psi; yield strength (0.5% elongation under load) 17,000 psi; elongation 25%; reduction of area 25%; Brinell hardness number (500 kg load) 75.
M *Composition limits.* Sand cast: *components,* 58.00 to 61.00% Cu, 2.5 to 3.5% Sn, 4.50 to 5.50% Pb, 15.5 to 17.0% Ni, the remainder zinc; *impurities,* 1.00% max Fe, 0.25% max Sb, 0.05% max S, and 0.50% max Mn.
N *4 Preferred deoxidizers.* Mg–Cu and Mn–Cu
5 Type of flux. Neutral
6 Precautions in melting. Oxidizing atmosphere

89 Cu – 1 Fe – 10 Al

A *1 Common name.* **Aluminum Bronze**
2 Trade name. Aluminum Bronze or 89–1–10 Aluminum Bronze
3 ASTM number. B 148-46T, grade 9B; B 30-45T, 9B
4 Government number. AAF 11076 (castings); QQ–B–671a, grade B
5 Other designations. SAE 68B
B *1 Typical uses.* General-purpose aluminum bronze for pickling baskets, steel-mill slippers, nuts, internal gears, and marine equipment welding jaws. This alloy is subject to heat treatment
D *6 Thermal expansion* at 21 to 260 C (70 to 500 F) 0.0000171 per °C (0.0000095 per °F)
16 Thermal conductivity. 14% that of copper
E *1 Volume conductivity* referred to standard copper. 14%
F *4 Color.* Yellow
K *Mechanical properties.* See table below.
M *Composition limits.* Sand cast: *components,* 86.9% min Cu, 0.75 to 1.50% Fe, 9.0 to 11.0% Al.
N *2 Casting temperature range.* 1120 to 1200 C (2048 to 2200 F)
4 Deoxidizer. None.
5 Type of flux. None
6 Precautions in melting. Oxidizing or neutral atmosphere and minimum agitation
15 Heat treatment.
A Solution treatment at 870 to 900 C (1600 to 1650 F), quenched in water and agitated rapidly; aged at 595 to 650 C (1100 to 1150 F) for 1 hr, quenched in water.
B Solution treatment, same as *A;* aged at 540 C (1000 F) for 1 hr, quenched in water.

Condition[c]	Aluminum, percentage	Tensile Strength, psi	Yield Strength,[a] psi	Elongation, percentage	Reduction of Area, percentage	Brinell Hardness Number [b]
SC, cooled in sand	9.5	62,000	26,000	25	25	122
SC, shaken out of mold in 0.5 hr	9.5	70,000	25,000	32	30	120
Heat treatment *A*	9.5	80,000	32,000	25	25	145
Heat treatment *B*	9.5	82,000	40,000	22	20	160
SC, cooled in sand	10.00	67,000	32,000	15	15	140
SC, shaken out of mold in 0.5 hr	10.00	76,000	28,000	22	20	135
Heat treatment *A*	10.00	90,000	40,000	15	15	180
Heat treatment *B*	10.00	92,000	50,000	9	8	195
SC, cooled in sand	10.75	65,000	32,000	15	15	165
SC, shaken out of mold in 0.5 hr	10.75	72,000	28,000	10	10	160
Heat treatment *A*	10.75	85,000	38,000	8	6	180
Heat treatment *B*	10.75	90,000	55,000	5	4	240

(a) 0.5% elongation in 2 in. under load. (b) 3000-kg load. (c) For definitions of heat treatments *A* and *B,* see item N*15* above.

87.5 Cu – 3.5 Fe – 9 Al

A *1 Common name.* **Aluminum Bronze**
3 ASTM number. B 148-46T, No. 9A; B 30-45T, No. 9A
4 Government number. QQ–B–671a, Class A
5 Other designations. SAE 68, grade A
B *1 Typical uses.* Acid-resisting mine pumps (resistant to mild but not strong alkalies), valve seats, guides, stems, propellers, worm wheels, bearings, bushings.
C *1 Density* at 20 C (68 F). 7.4 g per cu cm (0.267 lb per cu in.)
D *6 Thermal expansion.* 0.0000171 per °C (0.0000095 per °F)
16 Thermal conductivity. 15% that of copper
E *1 Volume conductivity* referred to standard copper. 13%.
F *4 Color.* Yellow
K *Mechanical properties.* Sand cast (tests made on sand-cast test bars, shaken out of sand at end of 0.5 hr): tensile strength 75,000 psi; yield strength (0.5% elongation in 2 in. under load) 27,000 psi; elongation 35%; reduction of area 32%; Brinell hardness number (3000 kg load) 120; modulus of elasticity 17,000,000 psi; Izod 40 ft-lb; compressive strength (0.001 in. set) 29,000 psi, (0.1 in. set) 67,000 psi.
M *Composition limits.*

Form	Components Cu min	Fe min	Fe max	Al min	Al max
Sand cast	86.00	2.50	4.00	8.50	9.50
Ingot	86.00	2.50	4.00	8.50	9.50

N *4 Deoxidizer.* None
6 Precautions in melting. Oxidizing atmosphere and minimum stirring

86 Cu – 4 Fe – 10 Al

A *1 Common name.* **Aluminum Bronze**
2 Trade name. Aluminum Bronze or 86–4–10
3 ASTM number. B 148-46T, No. 9C and 9C-HT; B 30-45T, No. 9C and 9C-HT (sand castings)
B *1 Typical uses.* Bearings, gears, worm gears, bushings; or any application where strength, ductility, and resistance to shrinkage are required.
C *1 Density* at 20 C (68 F). 7.5 ■ per cu cm (0.271 lb per cu in.)
D *6 Thermal expansion.* 0.0000162 per °C (0.000009 per °F)
16 Thermal conductivity. 15% that of copper
E *1 Volume conductivity* referred to standard copper. 13%
F *4 Color.* Yellow
K *Mechanical properties.* See Table I.
M *Composition limits.*

Form	Components Cu min	Fe min	Fe max	Al min	Al max	Impurities Mn max	Ni max
Sand cast	83.00	3.0	5.0	10.0	11.5	0.5	2.5

N *4 Deoxidizer.* None
6 Precautions in melting. Oxidizing atmosphere and minimum stirring
15 Heat treatment.
A Solution treatment at 870 to 900 C (1600 to 1650 F), quenched in oil or water.
B Solution treatment as in *A;* aged at 540 C (1000 F) for 1 hr, quenched in water.

Table I. Mechanical Properties of 86 Cu – 4 Fe – 10 Al

Condition[c]	Aluminum, percentage	Tensile Strength, psi	Yield Strength,[a] psi	Elongation, percentage	Reduction of area, percentage	Brinell Hardness Number [b]	Modulus of Elasticity, psi
SC, cooled in sand	10	75,000	35,000	18	15	155	18,000,000
SC, shaken out of mold in 0.5 hr	10	85,000	29,000	25	22	150	18,000,000
Heat treatment A	10	100,000	40,000	15	13	190	15,000,000
Heat treatment ■	10	105,000	52,000	10	8	230	15,000,000
SC, cooled in sand	10.75	80,000	37,000	10	8	170	15,000,000
SC, shaken out of mold in 0.5 hr	10.75	90,000	32,000	15	14	160	15,000,000
Heat treatment A	10.75	105,000	45,000	10	10	200	17,000,000
Heat treatment B	10.75	110,000	65,000	5	4	250	18,000,000

(a) 0.5% elongation in 2 in. under load. (b) 3000-kg load. (c) For definitions of heat treatments *A* and *B*, see item N*15* above.

79 Cu – 5 Fe – 11 Al – 5 Ni

A *1 Common name.* **Aluminum Bronze**
2 Trade name. Aluminum Bronze or 79–5–11–5 Aluminum Bronze
3 ASTM number. B 148-46T, No. 9D and 9D-HT; B 30-45T, No. 9D and 9D-HT
4 Government number. QQ–B–671a, grade D
B *1 Typical uses.* Valves guides, valve seats in airplane engines, bearing plates under heavy loads, corrosion-resistant parts, gun mounts and slides.
F *4 Color.* Yellow
K *Mechanical properties.* See Table I.
M *Composition limits.* Sand cast: *components,* 78.0% min Cu, 3.0 to 5.0% Fe, 10.0 to 11.5% Al, 3.5% max Mn, 3.0 to 5.5% Ni.
N*15 Heat treatment A.* Solution treatment at 870 to 900 C (1600 to 1650 F), quenched in water; aged at 595 to 650 C (1100 to 1200 F) for 1 hr, quenched in water.

Table I. Mechanical Properties of 79 Cu – 5 Fe – 11 Al – 5 Ni

Condition[c]	Tensile Strength, psi	Yield Strength,[a] psi	Elongation, percentage	Reduction of Area, percentage	Brinell Hardness Number [b]	Modulus of Elasticity, psi
Sand cast	95,000	45,000	7	7	195	17,000,000
Heat treatment *A*[c]	115,000	70,000	5	■	235	17,000,000

(a) 0.5% elongation in 2 in. under load. (b) 3000-kg load. (c) For definition of heat treatment *A*, see item N*15* above.

LEAD AND LEAD ALLOYS

Prepared under the chairmanship of

A. A. SMITH, JR.
American Smelting and Refining Company

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Properties of Lead and Lead Alloys

Lead (99.90+ Pb) (Chemical Lead)	960	80 Pb–20 Sn (20-80 Soft Solder)	964
Lead (99.73+ Pb) (Corroding Lead)	961	50 Pb–50 Sn (50-50 Soft Solder)	964
Pb–0.028 Ca	962	85 Pb–10 Sb–5 Sn (Lead-Base Babbitt)	965
99 Pb–1 Sb (1% Antimonial Lead)	962	80 Pb–15 Sb–5 Sn (Lead-Base Babbitt)	965
96 Pb–4 Sb (Hard Lead)	962	75 Pb–15 Sb–10 Sn (Lead-Base Babbitt)	965
94 Pb–6 Sb (Hard Lead)	963	83 Pb–15 Sb–1 Sn–1 As (Arsenical Lead-Base Babbitt)	966
92 Pb–8 Sb (8% Antimonial Lead)	963	83.5 Pb–12.75 Sb–3 As–0.75 Sn (Arsenical Lead-Base Babbitt)	966
91 Pb–9 Sb (Grid Metal)	963	Electrotype, Stereotype, Foundry Type Metal, *see*	957
97.5 Pb–1.5 Ag–1 Sn (Silver Lead Solder)	964		
95 Pb–5 Sn (5-95 Soft Solder)	964		

The Lead Industry

BY F. E. WORMSER* AND R. L. ZIEGFELD*

LEAD is one of the oldest metals known to man. Probably the earliest specimen is a figure from about 3000 BC found in the Temple of Osiris at Abydos and preserved in the British Museum. The Pharaohs, Assyrians and Babylonians had many uses for lead in ornamental objects and for structural purposes. About 2000 years BC the Chinese made their first money of lead. In ancient Greece and Rome, bronze coinage contained 3 to 30% Pb.

Perhaps the most interesting historical application of lead was its general use by the Roman people for water pipes. The pipe was made in 15 standard sizes and regular 10-ft lengths. Many of these lead pipes, in an almost perfect state of preservation, have been dug up in modern times from the ruins of Pompeii and Rome, and in England where the Romans penetrated during invasions. The old Roman baths at Bath, England, use the same lead pipe that was installed by the Romans 1900 years ago. Roman lead pipe was made by folding heavy sheets of cast lead and fusing the seams together.

Many magnificent buildings, erected in the fifteenth and sixteenth centuries, still stand under their original lead roofs. Leaden ornaments, statues, leader heads and cisterns—many of them architectural treasures—have come down to us in a perfect state of preservation.

Lead Minerals. Although at least 60 minerals containing lead are known to science, the lead of commerce is derived almost exclusively from one mineral, galena, the sulfide of lead. The oxides and other salts of lead are comparatively unimportant sources of supply. Common lead minerals include galena, PbS; cerussite, $PbCO_3$; anglesite, $PbSO_4$; crocoite, $PbCrO_4$; wulfenite, $PbMoO_4$; vanadinite, $3Pb_3(VO_4)_2 \cdot PbCl_2$; and pyromorphite, $3Pb_3(AsO_4)_2 \cdot PbCl_2$.

Lead Mining. Lead ore is mined in many countries, frequently in association with zinc ore. The United States is the most important source, followed by Australia, Canada and Mexico. Other important producing areas are Silesia, Burma, Spain, North Africa, Peru and Argentina, although production in all but the last two was badly affected by World War II.

With the development of the flotation process for the treatment of complex lead-zinc ores, many mines are now productive where formerly it was impossible, or extremely difficult, to separate the lead and zinc from each other. The flotation process has revolutionized the concentration of lead ores, both simple and complex. Lead sulfide or galena, the principal lead mineral found all over the world, is especially well suited to treatment by flotation.

Smelting and Refining. When they leave the concentrating mill, lead concentrates contain more than 40% Pb, generally 60%. The concentrates are roasted to remove the sulfur and to agglomerate the fine flotation product, which is not physically desirable in a blast furnace. The roasted sinter is charged into the top of a heated blast furnace

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Table I. Chemical Compositions of Commercial Lead

Element	Corroding Lead[a]	Chemical Lead[b]	Acid Lead[c]	Copper Lead[d]	Common Desilverized Lead A[e]	Common Desilverized Lead B[e]	Soft Undesilverized Lead[f]
Silver, max, per cent	0.0015	0.020	0.002	0.020	0.002	0.002	0.002
Silver, min, per cent	.....	0.002	....	....	....	....	....
Copper, max, per cent	0.0015	0.080	0.080	0.080	0.0025	0.0025	0.04
Copper, min, per cent	.....	0.040	0.040	0.040	....	....	....
Silver and copper together, max, per cent	0.0025	....	....	....	....	....	....
Arsenic, max, per cent	0.0015	....	....	....	....	....	....
Antimony and tin together, max, per cent	0.0095	....	....	....	....	....	....
Arsenic, antimony and tin together, max, per cent	.....	0.002	0.002	0.015	0.015	0.015	0.015
Zinc, max, per cent	0.0015	0.001	0.001	0.002	0.002	0.002	0.002
Iron, max, per cent	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Bismuth, max, per cent	0.05	0.005	0.025	0.10	0.15	0.25	0.005
Lead (by difference), min, per cent	99.94	99.90	99.90	99.85	99.85	99.73	99.93

(a) "Corroding lead" is a designation that has been used for many years in the trade to describe lead refined to a high degree of purity.
(b) "Chemical lead" has been used for many years to describe the undesilverized lead produced from southeastern Missouri ores.
(c) Acid lead is made by adding copper to fully refined lead.
(d) Copper lead is made by adding copper to fully refined lead.
(e) "Common desilverized lead A and B" are designations that are used to describe fully refined desilverized lead.
(f) "Soft undesilverized lead" is used in the trade to describe the type of lead produced from ores of the Joplin, Mo., district.

along with suitable fluxes and coke; the resulting impure lead-base bullion, containing silver, gold and various impurities, is shipped to the refinery for further treatment before the metal is suitable for use in industry.

In the United States, the Parkes process is widely used for lead refining. Electrolytic refining is also practiced, as well as the Betterton process, a development of recent years that depends on chlorination.

In the Parkes process the impure lead is melted and allowed to cool below the freezing point of copper, which crystallizes and is removed by skimming. The lead then passes to a reverberatory or softening furnace. Here the temperature is raised, and a blast of air oxidizes any antimony or arsenic present, thus forming a skin, which must be removed. The lead then goes to desilverizing kettles where small amounts of zinc are added. Since gold and silver have a greater affinity for zinc than for lead, these precious metals immediately leave the lead and combine with the zinc. The zinc-rich compound, lighter than lead, rises to the surface and when the temperature is lowered, solidifies in a skin, which is readily skimmed and treated to recover the precious metals.

Refined commercial lead of a purity of 99.99% Pb is common. Pig lead is generally cast in bars weighing about 100 lb each. The ores of southeastern Missouri contain too little silver for profitable desilverizing. Some of this ore contains a minute amount of copper, from 0.04 to 0.08%, which makes the pig lead derived from it particularly desirable in the chemical industries; hence its designation "chemical lead".

Secondary Lead.* The production of lead from scrap has become increasingly important in recent years, amounting to as much as 50% of total domestic production. The principal source of lead scrap is old storage batteries; sheet, pipe, cable sheathing and other lead products are also used. Large amounts of antimonial lead and some soft lead are thus produced. Considerable tonnages of scrap solder, bearing metals and type metal are recovered and used again, generally after the addition of sufficient new metal to rectify the composition.

Grades of Lead. The commercial grades of pig lead available to the consumer under ASTM Specification B 29-43 are given in Table I.

Antimonial lead is also available, containing from 1 to 25% Sb and averaging about 6 to 7%. Its principal use is in the manufacture of storage batteries.

Lead Industries. The following are the sellers of primary pig lead in the United States: American Metal Co. Ltd., American Smelting & Refining Co., Anaconda Sales Co., Bunker Hill & Sullivan Mining & Concentrating Co., Eagle-Picher Co., National Lead Co., St. Joseph Lead Co., C. Tennants Sons Co., and United States Smelting, Refining & Mining Co., Inc.

Uses of Lead. Before 1929 lead was used principally in electrical applications, as in the manufacture of lead-sheathed power and telephone cable and in the manufacture of storage batteries, but the use of lead for the manufacture of white lead was also extremely important. During the depression, the production of white lead and other pigments became more important than the electrical uses as an outlet for newly mined pig lead; more recently the electrical uses have assumed their old importance. Table II shows a tonnage comparison of the uses of lead in 1929, 1937 and 1944.

* *See also* the article "Secondary Metals", page 741.

Table II. Uses of Lead in the United States[a]

(In Short Tons)

	1929	1937	1944
White lead	119,700	86,000	60,000
Red lead and litharge[b]	30,000	57,000	80,000
Storage batteries	210,000	192,000	307,000
Cable covering	220,000	90,000	131,000
Building[c]	96,000	45,000	70,000
Tetraethyl	(d)	21,400	85,200
Automobiles	18,000	12,000	1,000
Ammunition	41,100	39,500	63,000
Terneplate	4,200	6,400	6,000
Foil	39,800	21,700	20,000
Bearing metal	33,000	15,000	41,000
Solder	37,000	22,000	41,000
Type metal	18,000	17,000	25,000
Calking	31,500	15,000	32,000
Other uses	74,000	38,700	127,800
Total	972,300	678,700	1,090,000

(a) American Bureau of Metal Statistics. Includes primary and secondary lead. (b) Exclusive of oxides for storage batteries. (c) Includes lead used in chemical construction. (d) Among "Other uses"

The market for lead may be classified conveniently into those applications where lead is used as a chemical compound and those where it is used in the metallic form, either alone or alloyed with some other metal.

The chemical compounds most important commercially are the hydrated basic lead carbonate, commonly known as white lead, basic lead sulfate (white and blue), litharge, red lead, the lead chromates, tetraethyl lead, and lead arsenate.

In the metallic form lead finds an important application in building construction as both pipe and sheet, and in solder. Lead is used also in important alloys, such as type metal, antimonial lead for storage batteries, bearing alloys, foil and collapsible tubes, as a coating for other materials, as lead weights, calking lead, gaskets, seals, cable sheathing, bullets and shot.

Basic Lead Carbonate. Basic lead carbonate is the most widely used of the lead pigments and forms the basis of the highest grade paint.

Basic Lead Sulfate. Basic lead sulfate is made directly from pig lead by a volatilization process in which the molten lead is fed through an atomizing flame in the presence of sulfur gases and air. The resulting fumed pigment is collected in baghouses.

Litharge. Litharge is a monoxide of lead (PbO) produced in powder and flake forms and containing approximately 93% Pb and 7% O.

Red Lead. Red lead, an oxide having the formula Pb_3O_4, is made by heating powdered litharge at carefully controlled temperature, lower than for making litharge.

Tetraethyl Lead. This liquid is the antiknock ingredient in virtually all modern high-test gasoline.

Sheet Lead. This useful metallic lead product is rolled in widths up to 11¾ ft, with standard widths of 8 ft, and in any thicknesses desired. Sheet lead is widely used in equipment for the chemical industry, where its resistance to attack from sulfuric acid makes it valuable in many industrial processes. Sheet lead is used also in building construction as a roofing material, for flashing, for shower pans, for X-ray-proofing and soundproofing.

Lead Pipe. Lead pipe has had a long career in transporting water and chemicals. In the plumbing industry, lead is highly favored for pipes and traps.

Soldering Alloys. One of the commonest of the lead alloys is solder, containing 50% Pb and 50% Sn by weight —the half and half grade. Other solders, with many compositions that include between 0 and 60% Sn, are widely used industrially. Plumbers' wiping solder contains 38 to 42% Sn, 0 to 2% Sb, with the remainder lead.

Hard Lead (Lead-Antimony Alloys). Hard lead contains from 1 to 12% Sb. Manufacturers of storage batteries use great quantities of antimonial lead containing approximately 7 to 12% Sb and frequently ¼% Sn. Antimonial lead sheet (6% Sb) is used widely in the United States for building construction also. Hard lead is used in shrapnel and collapsible tubes.

Bearing Alloys. Lead-base ("white metal") bearing alloys vary widely in composition. A common composition for a lead-base bearing used in railroad cars is 86% Pb, 5% Sn and 9% Sb. Copper-lead alloys for bearings contain as much as 40% Pb. Leaded bronzes contain smaller amounts of lead and are essentially mixtures of lead, copper and tin, with a lead content of 4 to 25%. Numerous alloys of lead and alkaline earth metals such as calcium and sodium are used as bearing materials. *See also* page 745.

Type Metals. These alloys are made from lead, tin and antimony. For typical compositions, see page 957.

Fusible Lead Alloys. Many lead alloys melt at low temperatures and are used for electric fuses, automatic sprinkler systems and boiler plugs. Compositions will be found on page 744 of this Handbook.

Terneplate. Terne metal, an alloy of lead and tin, is used to coat steel sheets. Terne alloy contains from 10 to 25% Sn with the remainder lead. Lead alloy coatings that contain as little as 2 to 2.5% Sn are increasingly popular.

Lead Foil. Lead foil is generally known as composition metal foil and is usually made by rolling a sandwich of lead between two sheets of tin, producing a tight union of the metals. Thicknesses of 0.0005 in. or less are common.

Ammunition. Large quantities of lead are used in ammunition for both military and sporting purposes. The alloy used may contain up to 1% As, for shot, and up to 2% Sb, for bullet cores.

Lead Storage Batteries. The production of lead storage batteries requires large quantities of metallic lead and lead pigments. These batteries consist of a series of plates made from antimonial lead and pasted with a mixture of litharge and red lead. The electrolyte is sulfuric acid. The lead used for this purpose is generally reclaimed after the battery has finished its useful life. During the depression and since, lead reclaimed from old batteries has become an important source of the metal, at times furnishing an amount of lead almost equivalent to that recovered from mining operations.

Cable Sheathing. To provide durable protection against moisture, lead sheaths are extruded around electrical power and communications cables. Chemical lead and 1% antimonial lead are most commonly employed for this purpose. Lead alloyed with 0.03% Ca has also been used.

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The Melting and Casting of Lead and Lead Alloys

By E. J. Minarcik*

LEAD and lead alloys were among the earliest metals used by man. The ease of handling lead is well known; and the casting characteristics are excellent, producing sound dense castings rapidly. The low melting points (650 F and less) result in low fuel costs, low maintenance and low losses in dross. The reclamation value of scrap from castings is almost 100% of the original alloy.

The beauty and fidelity of modern high-speed printing methods, particularly of multicolor printing, attest to the quality and precision of lead alloy castings (type metals).

Fuels and Heating. The low melting points allow the use of any type of fuel that is available or most economical. The plumber's lead-pot is heated by gasoline torch and contains only a few pounds of solder. The large plant units may be heated with oil, coal or gas and may contain 500,000 pounds of lead or alloy. Electric immersion heaters are used successfully on medium-sized installations.

Melting Pots. Cast-iron, cast steel, welded steel or spun steel melting pots are used. Cast steel pots serve the longest, although the others are entirely satisfactory. Normally no special coating is necessary to protect the pot from solution by the molten metal. However, the use of fluxes on the surface of the metal may cause attack on the pot at the flux level.

Fluxes. The use of cover slags or fluxes is generally not necessary, but may be useful for certain work. Molten mixtures of halides of alkali and alkaline earth metals may be used over lead or lead alloys without danger of metallic contamination of the lead alloy. A small quantity of granular sal ammoniac (ammonium chloride) sprinkled on the surface of the molten metal, reduces the metal content of the dross. A fume hood should be provided if sal ammoniac is to be used as fluxing agent.

Methods of Casting. Lead alloys are suited to a variety of casting methods; the simplest is hand casting with wrought iron or cast-iron hand ladles. Certain lead alloys are easily die-cast. In plants producing large castings, the metal may be pumped out or drawn through a valve in a bottom-pouring pot.

The pouring temperature for most lead alloys is not critical, and may vary from 50 to 150 F above the liquidus temperature of the alloy. In automatic casting equipment, such as the type-casting machine, the temperature is controlled thermostatically.

Molds. Almost any type of mold may be used that is suitable for the job—permanent, semipermanent, plaster, special paper, rubber, wood or sand. Permanent molds may be used for high production of intricate castings, for instance, storage-battery grids. Plaster molds may be used as semipermanent molds or as single-casting molds. Rubber molds are used most often on a centrifugal casting wheel to produce intricate castings that can be released from the mold by the plasticity of the rubber. In the production of stereotypes, a matte of papier-mâché is used as a mold to produce castings of remarkable fidelity in the form of type-face replicas from which printing is actually done. Built-up wood molds are used for casting boat keels.

Sand molds are occasionally used, with care that the mold is hard enough to withstand the erosive effects of the molten metal of high density.

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Storage-Battery Grid Metal. The casting qualities of lead alloys containing 6 to 12% Sb are markedly improved by the addition of ¼ to ½% Sn. These Pb-Sb-Sn alloys are gravity cast in intricate steel permanent molds, with a thin layer of carbon or other material as a dressing for the mold face. The antimonial lead grid serves as a framework to carry the active ingredients of the storage-battery cell and also to conduct the electrical current to or from the terminals.

Other Lead Alloy Castings. Monotype, Linotype and Intertype are all cast automatically in a machine operated like a typewriter. The operator brings segments of the type mold into position, and as one line is finished, type metal is pressure-cast against the type-mold face and, when solid, is ejected as a finished type-mold unit. Newspaper stereotype metal is cast in curved plates, producing a replica from a paper or composition matrix. Electroplated coatings of nickel, copper or chromium have been used to prolong the useful life of the printing face of the type metal. Telephone books and short runs of printed matter are generally printed directly from the type-metal face.

Electrotype metal is used for backing thin electrotypes (copper replicas) of type or illustrations. It is cast adherently on the reverse side of the thin electrotype, with the aid of solder foil and flux or of a paste containing powdered solder with flux incorporated.

Lead and lead alloys are cast in all types of standard pipe fittings, such as els, tees, valves and the like, for use in the chemical industry. Valves are available either made completely of lead, except for the stem and handle, or made of iron completely lined with lead.

Lead-base die castings are produced for uses where either weight or resistance to corrosion is a factor. These generally lack the strength of other die castings, but they have a definite field of use.

Lead alloys have proved useful in the metal-stamping industry. Antimonial lead punches have been used widely in conjunction with the hard zinc-base dies. Low-melting lead alloys are used to hold various components of jigs and fixtures during stamping, bending or machining.

Lead alloy cast molds are used for making rubber and plastic articles. Lead alloy cast embossing plates are used for surfacing leather or plastic objects.

Lead and lead alloy gravity castings are used to produce a wide variety of products; for example, ornaments, toys, boat keels, sash weights, sinkers, wedges, groutings and packings.

The slush casting of lead alloys is discussed on page 741.

The Production of Lead Sheet and Foil

By Ray C. Skow* and Don E. Campbell*

THIS ARTICLE describes the casting of lead slabs or billets for working and the subsequent rolling of the slabs to sheet or foil.

Sheet Lead. Sheet lead is produced in a variety of thicknesses, widths and lengths, as well as from several grades of lead and lead alloys. The thickness of sheet lead in general use ranges from 1/64 in. (1 lb per sq ft) to ½ in. (30 lb per sq ft). In the trade, sheets are generally referred to according to the number of pounds per square foot—as 2 lb, 4 lb, 6 lb, 8 lb, 16 lb, and so on—rather than in fractional inches of thickness; each pound is approximately equal to 1/64-in. thickness.

A standard roll of sheet lead is 8 ft wide and 20 ft long; however, most sheet lead is ordered cut to the size that will be used ultimately by the consumer. Labor and scrap involved in cutting are thus kept at a minimum at the job site. Widths are available up to 11¾ ft and lengths are limited to about 75 ft, depending on the thickness.

The grades of lead and lead alloys used in the fabrication of sheet lead are usually specified by the consumer. The selection is based on the physical or chemical properties required in the material for its intended use.

Machinery and Equipment. The machinery and equipment in general use for the rolling of sheet lead consist essentially of the kettle, the slab-casting pan, the rolling mill and roller tables, and the cutting table. Extensive equipment for handling is necessary, in the form of an overhead crane and auxiliary devices.

The kettle may be either a gas-heated or an oil-heated cast-iron or steel vessel supported by a steel-jacketed brick-lined pit. The kettle is usually elevated sufficiently for gravity discharge of the molten lead through a controlled opening at the bottom. The capacity may be three to four times the weight of lead used for the casting of an individual slab. In larger installations, kettles are used that will hold 25 to 40 tons, and large pumps of special design are used for moving the molten lead to the pans.

The slab-casting pan is a heavy, open-top steel casting, well supported and anchored to the floor. The sides are tapered sufficiently to facilitate removal of the frozen slab and recesses are provided into which lifting clamps are inserted before the slab is cast. Larger installations cast slabs that weigh approximately eight tons each.

The measurements of the slab pan are determined by the width of the mill as well as by the size of other facilities. Generally, a mill producing sheet lead in widths of 8 ft will use a pan 8½ ft in length. Slabs are normally cast 4 to 6 in. thick. Large slabs are usually cast in a horizontal position, but slabs have been cast on end in a vertical position. Vertical slab molds are generally employed only in conjunction with small mills.

Rolling mills used for the production of sheet lead are of the reversible type and may have either a single-roll or a double-roll drive. The rolls are mounted one above the other; the lower roll has a fixed elevation, whereas the upper roll can be raised or lowered several inches to accommodate the thickness of full slabs. Larger mills for rolling lead sheets have rolls 30 in. in diam by 12 ft in effective length. These rolls have a slight crown to compensate for deflection when wide sheets are rolled.

Roller tables extend about 45 ft on either side of the main mill rolls and are at the same elevation as the top of the lower roll. The sections adjacent to the large rolls consist of closely spaced, power-driven, heavy-duty live rollers. The remainder of the roller table consists of lighter-duty idle rollers. One of the roller tables may be equipped with an elevating section in which power-driven cutters are incorporated, for cutting the broken-down slabs to length. This cutting may be done also with portable power-driven saws.

The cutting table consists of a hardwood-covered extension to one of the roller tables. The size is usually identical with that of the roller table, for it should accommodate the entire sheet and clear the roller tables for further rolling.

The drawknife used for cutting sheet lead is a sharp tool fastened to a handle so that a pull-rope can be attached. The knife is guided manually along the marked sheet. Power is applied to the pull-rope by the use of an elongated winch located at the end of the cutting table. Movable sheaves that can be placed quickly in position provide directional pull for the knife.

Operation. First, the kettle is charged with pig lead, selected according to grade or specification required. The charge is melted and alloying elements are added, if required. After a chemical analysis of the melt, the dross is removed. Slabs are then cast rapidly to prevent premature freezing while the pan is being filled, and are skimmed to remove any oxides before cooling. During the freezing, care is taken to prevent the formation of internal voids or cavities because such imperfections often carry through to the finished sheet.

Slabs are broken down while still hot (300 to 350 F)

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by being rolled across the width until the metal is about 1 in. thick. The breakdown of a hot slab requires less power and the operation is less likely to injure the equipment than when a cold slab is used. After the breakdown, it is important that the thickness of the metal remain constant since a definite relationship exists between the lengths of subsequent sections and the thickness of the finished sheets of uniform size. About 3 in. must be allowed for final trimming of the finished sheets. Accordingly, the rolled slab, still 8½ ft wide, is cut into sections of suitable length. These are subsequently rolled individually to sheets about 41 ft long. Sections are rolled at room temperature and no annealing is required between passes. Although some heat is generated in the metal during the rolling operation, it is not a factor that requires control in the production of either soft lead or antimonial lead sheet. Lead, unlike most other metals, will recrystallize at room temperature. Micrometer readings indicate when the desired thickness has been reached, although experienced workmen need to use the micrometer only as a check after the sheet is finished.

Occasionally sheets 10 ft wide are required. It is then necessary to alter the above procedure by cutting sections 8½ by 10½ ft, turning them 90 deg and rolling them to the desired thickness.

After the rolling has been completed, the long sheet is pulled over the cutting table by means of a winch. It is marked, squared, trimmed and cut to the sizes required. Finally individual sheets are rolled tightly, weighed and packed for shipment.

Lead Foil. In casting the lead billet or slab to be rolled into foil the technique is important. The relation between the temperature of the molten metal and that of the molds, as well as the rate of flow of the metal must be maintained to assure solid casts, free from excessive shrinkage spots and cold shuts. Ordinarily, a metal temperature of 775 F to 800 F and a mold temperature of 200 F are satisfactory. The rate of flow can be determined best by experience and will depend on conditions in the individual foundry. Obviously it is desirable to cast the slab as thin and as long as possible (the width is limited by the width of the rolling equipment) in order to save labor, time in the breakdown mill, and power. Probably the thinnest slab cast in actual production is ½ in. thick by 40 in. long. Continuous casting of lead ⅛ in. thick has been attempted, but the properties of the product were not suitable for the purposes of foil.

The cold rolling and heavy reductions on the breakdown mills soon reveal any defects that may be present in the cast slab. An excessive number of shrinkage spots result in the splitting of the slab down the pouring line; cold shuts cause the slab to crack at the edges. The higher the antimony content, the lighter the reduction that can be taken. Hot rolling is recommended for lead slabs that contain from 2 to 4% Sb. The product generally referred to as "lead foil" contains tin, most of which is a surface coating or "casing". This casing is a prepared sheet—100% Sn on the surface, with a tin-lead alloy backing—which is placed on either side of the slab, with the tin surface outward. Frictional heat and the pressure of the rolls are sufficient to weld the sheets and slab into a unit. The tin surface of the lead foil maintains a brighter more durable luster and prevents the ready oxidation of the lead when subjected to weather conditions. Producers of lead foil usually coil the metal at the end of the breakdown line, at ■ gage between 0.016 and 0.035 in.

One pass on the finishing mill is sufficient to reduce the coil to the gage for the finished foil. The procedure in most plants is to maintain the same gage of coil from the breakdown, regardless of the gage required for the finished foil. Different thicknesses of foil are obtained by suitable crowning of the finishing mill rolls. Foil gages may be changed slightly by modifying the lubricant used in rolling, which may be either a soap-and-water solution or an emulsified oil. However, in any rolling operation for lead foil, the success depends on the experience and technique of the finishing mill operator. The operator's attention is constantly required when rolling lead to 0.00035 or 0.0006 in., because the thin sheet of lead will be affected by the slightest change of temperature in the rolls. Such a change may cause a "belly" in the foil, making it wrinkle when coiled, or may cause a "tight spot", which can result in the breaking of the sheet. The operator must constantly adjust the application of the lubricant on the rolls. The lubricant serves as a cooling medium at the same time. Also, as the heat varies within the rolls, the gage of the foil changes; cooler rolls produce heavier foil and hotter rolls, lighter foil. On 0.00035-in. foil, the permissible tolerance is plus or minus 10%; therefore the operator must be constantly alert in order to make the necessary adjustments for keeping within the tolerance of thirty-five one-millionths of an inch. This care is particularly necessary in rolling lead foil because, having a low melting point, lead is much more readily affected by temperature variations than are metals such as aluminum, copper and steel.

The Extrusion of Lead and Lead Alloys

LEAD and lead alloys can be extruded in a variety of shapes and by methods that differ considerably, one from another. The following discussions concern the processes of extrusion used in the manufacture of shapes such as bar, wire and pipe; the processes used in producing cable sheath; and impact extrusion as employed in the manufacture of collapsible tubes.

Extrusion of Lead Bar, Pipe and Wire

By D. J. Doan*

THE HISTORY and technical aspects of the extrusion of lead and lead alloys have been summarized elsewhere.[1, 2] The earliest development of extrusion for any metal was that of plumbers' lead pipe in 1797; since then cored and solid wire solders, special shapes and bars, plumbers' lead traps and bends, and glaziers' or came lead have been added, as well as other forms.

Equipment. Vertical hydraulic presses of 400 to 1500 tons capacity are used extensively. Figure 1 shows a section of such a press, including the cylinder and ram setup. The die, fixed on the lower face of a stationary ram *D*, defines the outside diameter of the pipe. The cylinder *C* (avg diam, 8 in.) is mounted on a movable table supported by four columns. This table, in turn, is fixed to the hydraulic ram of the press. To produce lead pipe, an exchangeable core rod *B*, ⅜ to 12 in. in diam is mounted in the center of the cylinder. The charge of molten lead is run in and allowed to freeze before extrusion; the weight of the charge (650 lb avg) depends on the sizes of pipe and cylinder. The pipe is coiled before it is fully cooled, or is cut in lengths for the larger sizes. Precast billets, 2½ to 4 in. in diam and 8 to 16 in. long, are used for extrusion of solid shapes, such as bar lead or solder, and wire solder. The general setup of the press is the same as for lead pipe except that the core rod is removed. Multiple-opening dies are utilized that contain as many as 12 openings. Flux-cored solders are produced from ¼-in. tubing that has been filled with flux through an opening in the core rod during extrusion. The wire is then drawn down to size. Lead traps and bends or angles are produced on horizontal double-acting hydraulic presses, a section of which is shown in Fig. 2. The pipe *E* is extruded vertically through an exchangeable die mounted on the upper side of the cylinder *H*. The two rams *G* operate inwardly on either side from two hydraulic rams. The

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core rod is attached to the center portion of the cylinder and is exchangeable for producing different sizes. When the ram pressures are regulated differentially, more lead is forced into one side than into the other, forming a bend *F* of uniform wall thickness. The nose of the cylinder or die holder is designed to permit production of 180-deg bends *F*, and when the process is reversed, the familiar S-trap *E* is formed. The bend *F* forms the outward end of the S-trap *E*. Maintaining equal pressures on the two rams results in the production of straight pipe. Various sizes are made by exchanging dies and cores, and bends of any angle may be formed.

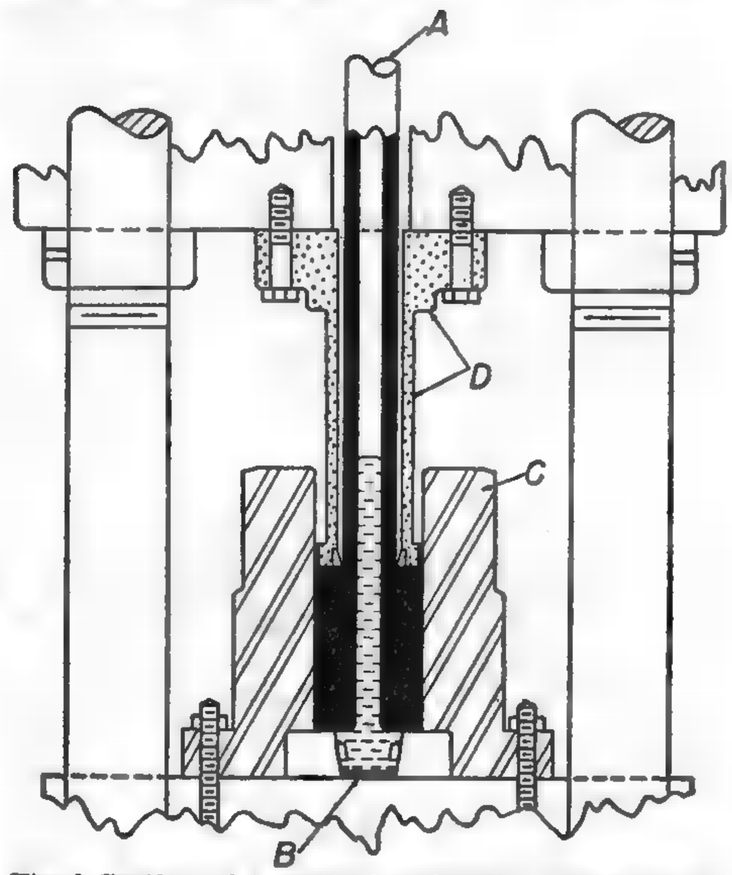

Fig. 1 Section of a vertical hydraulic press used for the extrusion of lead pipe and solder

Pressure. Lead pipe and other soft lead shapes are ordinarily extruded at 8000 to 15,000 psi on the billet area, but the pressure depends on the "extrusion ratio" (the billet area to the die aperture); and temperature, shape of die, composition of lead, and other factors are varied considerably to obtain a rate of extrusion and a product that are satisfactory. Antimonial lead (6% Sb) requires approximately twice the pressure that lead requires at the same speed and temperature. Tin-lead solders require

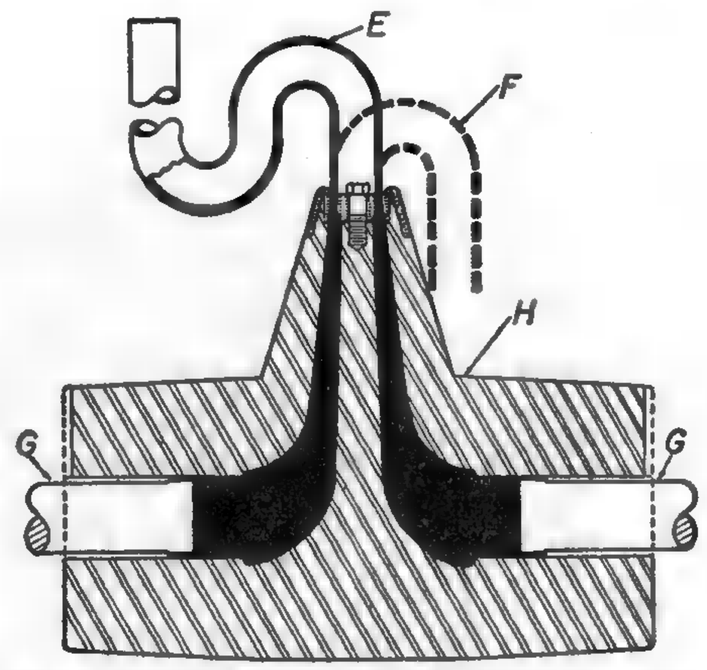

Fig. 2 Cylinder used for the extrusion of lead traps and bends or angled pipe

40,000 to 100,000 psi, depending on the same variables. Cylinders of different billet cross section are exchanged to vary the unit pressure and thus to secure the most satisfactory production.

Speed. Maximum possible speeds are always used but these are subject to wide variations that result from difficulty in handling heavy sections from the press, insufficient pump capacity at times, and susceptibility to surface cracking or "feathering" caused by incipient melting in the die. Speeds of 50 to 60 fpm for lead and about half as much for solders are not unusual.

Temperature. Lead and lead alloys may be extruded when cold, but to decrease pressures and increase speed, lead is extruded at about 400 to 500 F. Little advantage is gained by using higher temperatures.[3] Solder billets are generally preheated to approximately 200 F and the temperature of the cylinder is controlled.

Defects and Precautions. Eccentricity occurs in pipe when the core rod is not centered in relation to the die. Because of faulty casting, inclusions may be introduced in both lead and solder. In pipe, invisible longitudinal welds caused by the "spider" holding the core in a bridge die, will never knit satisfactorily.[4] Consequently these dies are seldom used. Segregation is prevented in solder wire and bar by proper casting of the billets; the molds for this purpose should be cooled by water and the temperature of the metal should be controlled. Thickness of pipe[5] and size of solder wire are measured frequently and dies are changed when worn beyond permitted tolerances.

Extrusion of Lead Cable Sheath

By G. M. Bouton* and Earle E. Schumacher*

SHEATHING of cable with lead or lead alloys consists basically in forcing solid lead, heated to a plastic condition, through the annular space between a die and the outside surface of a concentrically located tube through which the core passes.

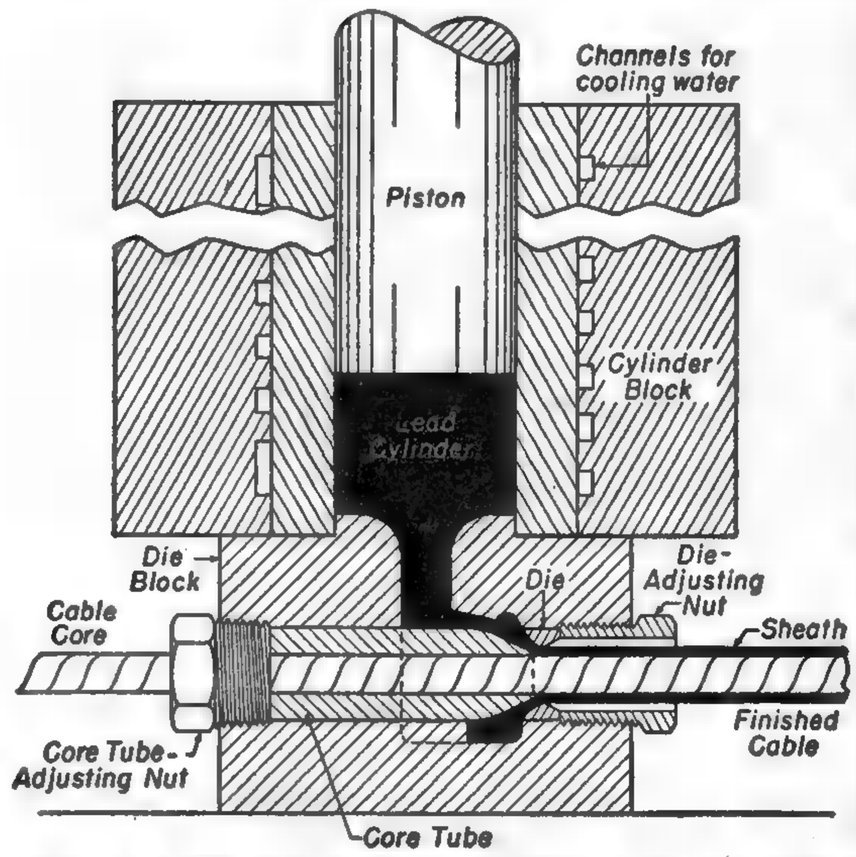

Fig. 3 Cross-sectional view of the assembly employed in the usual type of hydraulic press for the manufacture of lead cable sheath

Press. Figure 3 is a cross-sectional view of the assembly in the usual vertical type of hydraulic press used in the manufacture of cable. Commercial presses are capable of exerting forces of 1000 to 3000 tons and may extrude 600 to 2000 lb of lead in a single stroke. The die block contains a core tube through which the unsheathed cable core passes, and a sizing die to control the outside diameter of the sheath.

Operation. To begin an extrusion, molten lead or lead alloy is poured into the lead cylinder and the piston is brought to bear on the upper surface of the lead, either by raising the cylinder or by lowering the piston hydraulically. Light pressure is applied during solidification, to prevent piping and the formation of voids. Solidification is hastened by circulating water through the cooling channels in the cylinder block. After solidification, pressures of approximately 40,000 to 60,000 psi are applied to the lead, thereby forcing it through the extrusion orifice and onto the cable core. The die block is usually maintained

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at temperatures from 180 to 260 C by means of gas burners or electric heaters.

Various types of die-block cavities are used in the extrusion of cable sheath, since the contour and dimensions of the cavity have considerable bearing on the extrusion pressure required and on the uniformity of sheath thickness. For example, a longitudinal supporting web is often placed below the core tube to prevent it from bending under the pressure applied during extrusion. In the large majority of presses, the lead stream divides as it passes around opposite sides of the core tube, and reunites at the lower portion of the die-block cavity, forming a seam weld (Fig. 4) that runs along the entire length of the cable. This seam weld is nearly always visible microscopically in the sheath and is sometimes a source of weakness. Certain designs of die blocks have a bridge above the core tube, which is said to produce more uniform flow of the lead. However, this construction results in seam welds at both top and bottom of the sheath.

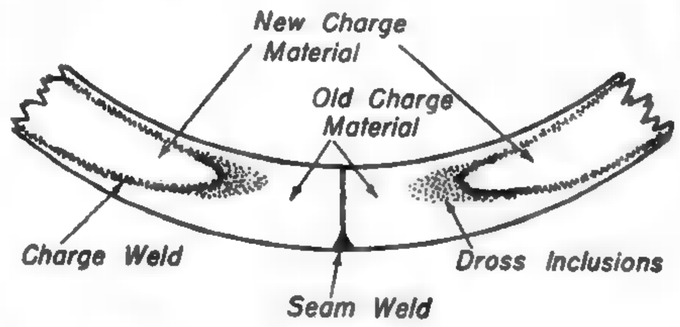

Fig. 4 Cross section of cable sheath a short distance after the start of a press cycle

Charge Weld. The intermittent filling required to sheath long cables results in another type of weld, called the "charge weld". During the introduction of the molten lead into the press, some oxide and dross are generally formed, which have a tendency to rise to the top of the charge. Subsequent extrusion of the charge pushes this layer of dross into the bottom of the lead cylinder, and when the next charge is poured into the cylinder, the layer forms a discontinuity between the old and new charges. After extrusion of the new charge, this discontinuity appears in the extruded sheath as tonguelike charge welds, which are demarcations between the material of old and new charges. The charge weld is most prominent when several feet of cable have been extruded after the charging operation, and becomes less distinct as more and more of the old charge material is expelled from the die block.

Dross. In the past few years considerable effort has been directed toward reducing the amount of dross inclusions in sheath and thus improving the strength of the welds. The following methods are among those used to reduce oxidation during pouring: (1) Pouring through a closed tube that extends nearly to the surface of the old charge at the bottom of the lead cylinder. This method minimizes splashing and also promotes better welding of the new and old charges, particularly if the bottom of the tube is moved continually around the circumference of the cylinder during pouring, or is equipped with deflectors that impart a swirling motion to the incoming lead. (2) Pouring through inert or reducing atmospheres, such as carbon dioxide or burning hydrogen or water gas. (3) Sealing the space between the cylinder and piston and pouring the lead in vacuum.

The following methods are among those used for removing dross or oxides once they are formed: (1) Skimming the top of the charge manually after pouring. (2) Slicing or cropping the dross-bearing portion of the charge by means of mechanically or hydraulically operated skimmer plates that are fitted to the top of the cylinder block. (3) Floating the dross away from the path of the piston. (4) Pushing the dross aside by special contours of the bottom of the piston as the piston is brought to bear on the surface of the molten lead. Some of these methods are used in combination.

Equipment. Other types of presses are used to a minor extent in this country. One type has a concentrically located core tube and a hollow piston that operates in a horizontal position. Molten lead is charged into the space between the wall of the lead cylinder and the core tube. This type of press eliminates the seam welds in the sheath. Another type of horizontal press operates on the "meat-grinder" principle. Molten lead is introduced at the rear of a rotating screw member through a closed tube, solidifies as it passes forward, and develops sufficient pressure to extrude between the sizing die and core tube at the front of the press. The cable core passes through a tube at the axis of the press. This type of press eliminates both charge welds and seam welds, although for the larger diameters of sheath a centering spider, frequently used for positioning the die and core tube, may introduce radial welds. Since there is little likelihood of dross being formed when this type of press is used, radial welds are not likely to be troublesome. This press has the advantage of continuous operation, thereby eliminating the physical and structural discontinuities found, between charges, in sheath made by intermittent processes. Operational difficulties have occurred more frequently with this type of press than with the intermittent type—a fact that has probably deterred manufacturers in this country from employing the continuous process more extensively.

Impact Extrusion of Lead

By John H. Fridén*

THE METHOD of producing collapsible tubes and other containers by impact extrusion has been known for approximately a century. Important industrial uses of this process, however, are less than 30 years old. Increased use of collapsible tubes for packaging in the cosmetic, food and medicine industries has required an increased production of tube, which in 1946 amounted to between 5,000,000 and 6,000,000 gross per year in the United States. This corresponds to approximately 20,000 tons annual lead consumption in this industry.

The Process. This process involves plastic deformation of soft metal, usually in the cold condition, by forcing the metal through an orifice under hydrostatic pressure. In the impact extrusion process, this pressure is exerted by a mechanical power press and the extrusion takes place in about 1/20 sec. The average speed of the press is about 60 strokes per minute. Since one finished product per stroke is the usual output, it follows that the production is 60 extrusions per minute.

A typical example of impact extrusion is an ordinary toothpaste tube. The necessary manufacturing operations follow: First a sheet is rolled and then blanked by conventional means, producing the blank shown in Fig. 5*a*. After this blank has been lubricated by tumbling, it is placed in an extrusion die, Fig. 5*b*, having an inside diameter D equal to the outside diameter of the tube to be extruded. Above the die a punch is arranged concentrically with the die, as illustrated. This punch has an outside diameter d equal to the inside diameter of the tube. Descending by action of the press, the punch first deforms the slug, as shown in Fig. 5*c*, until all the void below the punch and die has been filled and the metal is completely trapped. As the punch descends further, an annular orifice between the punch and die will be formed. The distance t in Fig. 5*c* equals the desired thickness of the wall of the tube, conventionally 0.004 to 0.005 in. The punch descends still further, displacing the metal as in an ordinary squirt gun, and since the annular opening between the punch and the die is the only place through which the metal can escape, the metal is forced to climb up the punch, as shown in Fig. 5*d*. The tube is completed when the punch has descended to the desired depth, leaving the predetermined bottom thickness, as illustrated. After the first part of the cycle has been completed, the punch withdraws, the knock-out pushes the tube out of the die, and the tube stays on the punch until removed by hand or by automatic means. The tube is thus extruded in one stroke of the press. Trimming and threading, if required, can be accomplished in one more operation.

Versatility. Caps and stoppers used in collapsible tubes

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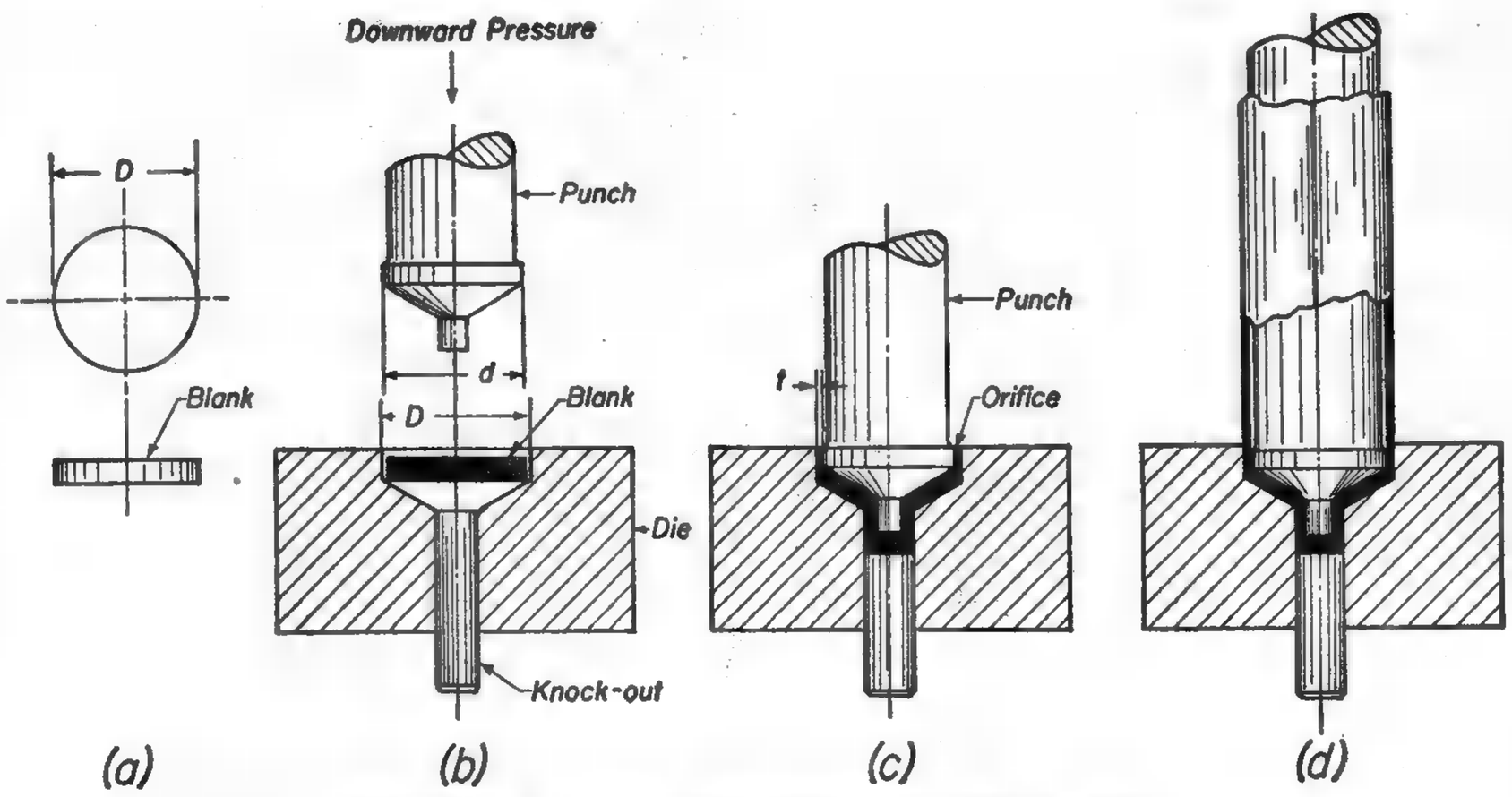

Fig. 5 Steps in producing a collapsible tube by impact extrusion

are also produced by impact extrusion. A threaded cap for collapsible tubes can be completed by impact extrusion in one operation at a speed of 80 to 90 strokes per minute. Many other articles that have lettering, protrusions, slots, depressions and such on the bottom, can be produced in one operation by impact extrusion.

Types of Presses. Ordinary straight-sided presses of the crank or eccentric type are preferred. In mass production it is necessary to equip these presses with automatic feeds, strippers, and devices for safety and removal of tubes. The size of the press is determined by the extrusion pressures involved. Between 30,000 and 50,000 psi is required, depending on the composition of the lead alloy.

Lead Alloys Used in Impact Extrusion. Although it is possible and feasible to extrude pure lead, it is frequently necessary to add some alloying element, such as antimony, copper, tellurium, tin or silver, in order to obtain the required stiffness. Alloying with elements such as tin, which improves the chemical resistivity, is often indicated. For practical purposes, a common alloy for use in the manufacture of collapsible tubes contains 97 to 98% Pb and 2 to 3% Sb. The addition of less than 1% Ag improves the appearance of the alloy.

Duplex Metal. Under some circumstances tin-coated lead tubes are desirable. In order to produce these by conventional extrusion methods, it is necessary to prepare the slug in a special manner. The method used is to wrap a previously rolled, thin sheet of tin around a lead slab and then to roll them down together in a standard rolling mill by conventional procedure. Because of the difference in the cost of tin and of lead, it is customary to use only 3 to 7% Sn. Slugs prepared in this manner extrude as readily as pure lead slugs and the tin is distributed evenly over the entire surface of the lead core.

Other metals and alloys can be extruded with lead in the same manner.

Waxing. For packaging certain materials, it is sometimes necessary to coat the inside of the tube with either wax or some synthetic material. Ordinarily a spray nozzle is used for flushing the coating through the inside of the tube, which is then drained, dried and cooled.

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Joining Lead by Soldering and Welding

By Homer S. Yetman* and David M. Borcina*

SOLDERING and welding are the two methods most commonly used for joining lead. Both methods are effective with lead and, when properly performed, result in joints stronger than the metal itself. Successful joints must fit tightly and all surfaces of the lead forming the joint must be thoroughly cleaned mechanically, by shaving or by using a wire brush or scratch cloth. The outer surface of the lead should be cleaned only over the area that will become part of the joint.

Soldering. Soldered joints in lead are usually made with a soldering copper, or "iron" as it is more often called, or by "wiping", used in joining cable and in the plumbing industry. Wiping consists of pouring the just-molten solder repeatedly over the surfaces to be joined, and working the solder to shape while it is in a semimolten condition. Whether soldering is done by a soldering copper or by wiping, only mild noncorrosive fluxes are needed, affording a distinct advantage. The flux can be either salt-free mutton tallow or rosin. If a liquid flux is desired, rosin may be dissolved in alcohol. Immediately after cleaning, the flux is applied to all surfaces in contact, so that the solder will sweat between layers of lead, and to the outside as well. The lead does not have to be tinned, except in particularly difficult soldering operations.

Soldering coppers weighing about 2 lb each (4 lb per pair) are satisfactory for most work. Only the heaviest lead requires the use of heavier coppers. The soldering copper used most frequently with lead is four-sided and pyramid-tipped. The pyramid, which is the working surface, should be kept clean and well tinned with 50–50 solder. In overhead soldering operations, better control of the solder is imperative, and for this reason only the

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working side of the copper should be tinned. For all soldering operations involving the use of a soldering copper, the solder preferred has a composition of 50% Sn, 50% Pb. The solders with a high melting point, such as lead-silver solder, cannot be used successfully with lead because the melting point is too close to that of lead itself.

The most effective wiped solder joints in lead are made with solder containing from 37 to 40% Sn and the remainder lead, with or without a small percentage of antimony. Solder of this composition is preferred because of its adequate plastic range, good general working qualities, and the density of the finished joint metal, although a tin content as low as 32.5% is successful where the joints will not be under pressure. In wiping, it is the practice to apply a coating of plumbers' soil, library paste, paper or any material that will prevent the solder from adhering to the lead where it is not needed or wanted—for example, beyond the ends of the joint.

Soldered joints in lead sheet and pipe can be made by using a soldering copper or by wiping. The two joints used most commonly on sheet lead are lap joints and butt joints. Either is satisfactory with lead that weighs 6 lb or less. For heavier weights of lead, the butt joint is preferred and the edges forming the joint should be beveled. On all weights of lead pipe, the wiped lap joint is preferred wherever possible. Wiped flanged joints are sometimes used both to join and to support the pipe. Cup joints made with a soldering copper are satisfactory when the pipe is in a vertical position, and overcast or beaded joints may be made where it is possible to roll the pipe. To provide auxiliary heat, a torch is sometimes employed both in wiping and in sweating operations.

Welding. Lead welding, often referred to as "lead burning", fuses the parts of the joint together without flux or recourse to any other metal, although additional lead is frequently added to build up the joint to approximately 1½ times the thickness of the lead that is being joined. A torch with a nonoxidizing flame is used to fuse the metal; a combination of two gases is generally employed. The most popular gases are oxygen and hydrogen, although oxygen and acetylene or other hydrocarbon gases are also used. Oxygen and city gas are sometimes combined for use in shop work. Single gases, such as propane, are used satisfactorily on light weights of lead when the joint is to be welded in a horizontal position.

The flame temperature required in lead welding is low compared with that needed in other types of welding. Only the smallest tips on the torch are used. For lead weighing less than 6 lb, tip sizes 00, 0 and 1 are satisfactory; for lead weighing from 6 lb to 10 lb, tip sizes 2 and 3 are satisfactory, and above that weight, larger tip sizes can be used. These selections will vary somewhat, depending on the mechanic. On vertical and overhead work, where better control of the fused metal is necessary, torch tips as small as possible should be employed.

The preparation of the lead for welding is much the same as for soldering. The metal that will become part of the joint must be kept scrupulously clean; however, no flux is employed. Lap joints are preferred except in very heavy lead. A lead welding rod of the same composition as the lead being joined is used as a filler. The rod is usually ⅛ to ⅜ in. in diam, depending on the thickness of the lead.

The principal precaution to take in lead welding is to avoid burning through or reducing the thickness of the lead, but care should be taken to make sure that fusion occurs through the entire thickness of the joint and not merely on the surface.

When lead is joined to other metals by either soldering or welding, the other metal should first be well tinned.

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The Resistance of Lead and Lead Alloys to Corrosion

By G. O. Hiers*

CENTURIES ago, sheets of lead were placed between the blocks of stone used in the construction of large stone buildings in Rome. Nearly 2000 years ago the Pantheon was built with a lead roof. Such buildings and monuments still stand with these original materials intact.

With the passage of time the property of resistance to corrosion has resulted in a growing variety of uses for lead. When sulfuric acid first became commercially significant, the manufacture of this important product was made possible on a large scale by the use of lead chemical equipment—lead chambers and pans.

About 60 years ago, extruded lead tubing was first applied as protective sheathing on electric cables used for communication and also for the transmission of power.[2]

Storage batteries, which have increased constantly in importance since they were invented, depend largely on lead. In fact, one of the major uses of lead at present is for the grids in battery plates, for the connectors, and for the active material of the plates.

Lead in the Building Industry. *Sheet Lead.* Many skyscrapers have the bases of their columns set on lead for absorption of sound and vibration. These absorption mats consist of 20-gage sheet steel at the center, with ⅜-in. thicknesses of hard asbestos sheet on both sides and, on the outside, a soft lead sheet about ⅛ in. thick. The lead casing is closed by soldering the edges, thus making a durable building element[3] that resists corrosion and effectively absorbs sound and mechanical vibration.

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In many buildings and homes, sheet lead is used for drain pans under shower-bath stalls. The stall flooring is usually concrete, and sheet lead, covered with tar paper or painted with asphaltum, is placed beneath. The protection is necessary for a year or so because oxygenated lime water is corrosive to lead. The free lime in "green" concrete becomes carbonated in the course of time and subsequently water that seeps through the concrete will no longer corrode the lead.[4]

Sheet lead is used extensively for roofing and otherwise weatherproofing buildings. The lead sheet used at present is about 3/64 in. thick (3 lb per sq ft). A 6% antimonial lead alloy is employed in some instances, because of its superior strength.

Recently, the ASTM[5] reported the following rates of corrosion of lead exposed outdoors for ten years:

Test Site	Corrosion Penetration (After 10-yr Exposure to the Atmosphere), 0.0001 inch[(a)]	
	Chemical Lead	1% Antimonial Lead
Altoona, Pa.	2.67	2.14
New York, N. Y.	1.67	1.13
Key West, Fla.	2.16	2.05
La Jolla, Calif.	1.62	2.36
State College, Pa.	1.88	1.29
Phoenix, Ariz.	0.94	1.09

(a) Measured from loss in weight after chemical cleaning

These values indicate that it would take 40 to 100 years

for corrosion to penetrate lead to a depth of 0.001 in. From the standpoint of durability, atmospheric corrosion of lead is fairly insignificant.

Sheet lead for roofing and gutters should be installed only by experienced workers. Changes in temperature cause changes in length of the metal and, to avoid buckling, wrinkling and cracking,[1] the resultant movements should not be restricted. Lead is used also for flashings, spandrels, drain pipes and such. Architects choose lead for its permanence, resistance to weather, and decorative value.

Lead Pipe. Modern lead pipe is made by extrusion. (*See* page 947.) For the conveyance of water, commercial lead of about 99.7% purity is frequently used. With ordinary hard water, a protective coating (probably a calcium plumbite) forms as a thin film on the wall of the pipe, and the water flows through without contamination. Distilled water or very soft water, if untreated, is not recommended for use in lead pipe because of the possibility of lead pickup or contamination. However, soft drinking water treated with lime or sodium silicate can be used safely after flowing through lead pipe.

Ordinary lead pipe having walls of substantial thickness is used underground and bare, generally without protection. During reconstruction work in various cities, lead pipes have been dug up and found in good condition, still giving good service after 50 years submersion and more. Commercial lead pipe is designed in different calibers or thickness of wall, chiefly to withstand 50, 75 or 100 psi water pressure at 70 F.

Cable Sheathing. Insulated copper wires are fed through a die in a hydraulic press and a lead sheathing is extruded over the assembled wires as a waterproof protective covering. (*See* page 948.) Chemical lead, common lead and 1% antimonial lead alloy are ordinarily used for such covering.

Lead-sheathed aerial cables last many years. Although occasional failures of the sheathing do occur, the principal cause is mechanical. As a result of dimensional changes from alternate heating and cooling, cracks develop that resemble transverse fatigue cracks. An alloy of 0.03% Ca with the remainder lead, has a higher endurance limit than lead, and is expected to give better service for aerial lead-sheathed cables. Careful supporting of the cables has minimized the cracking trouble by preventing localization of the stresses that result from movements accompanying thermal changes.

Underground lead-sheathed cables for telephone and telegraph systems are usually contained in wooden tubular covers or conduits. These in turn are usually surrounded by concrete. Similar constructions are frequently used for underground lead-sheathed electric-power cables.

Where corrosion of lead has occurred because of the presence of oxygen and the seepage of water through "green" concrete, the trouble has been corrected by diffusing gaseous carbon dioxide through the concrete conduits to kill the free lime. ($CaO + H_2O \rightarrow Ca(OH)_2$ and $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$).

J. M. Handring[6] states: "It is estimated that in the Bell System more than 50% of all underground sheath failures due to corrosion are the result of nonstray current phenomena." R. M. Burns[2] of the same organization has conducted exhaustive studies of the underground corrosion of lead. Such studies have shown that the several varieties of lead mentioned for cable sheath have about the same resistance to corrosion in the environments to which they are subjected. Some types of soils are known to be more corrosive than others toward lead. Particle size of soil, aeration factors and the like have also been found influential. Underground corrosion tests of various metals including lead have been conducted under the auspices of the National Bureau of Standards.[7]

Storage Batteries, Pickling and Electrolytic Processes. For many years, the largest single market for lead has been the storage battery industry. Briefly, lead storage batteries function as follows: A charged battery has an anode of lead peroxide (PbO_2), a cathode of sponge lead (Pb) and an electrolyte of sulfuric acid in a concentration of about 35%. It delivers an amperage that depends on the area of the plates and the number of plates per cell. The voltage per cell varies from about 2.0 or less at the beginning of discharge to about 1.8 or less at the end of discharge. At the end of discharge the electrolyte has weakened and a coating of lead sulfate has formed on the surfaces of the plates.

In some large stationary batteries of the Planté type, the plates are usually of comparatively pure sheet lead, such as ASTM corroding lead, and have surfaces serrated to provide greater surface area. In other types of large batteries, and also in smaller batteries such as are provided in automobiles for starting, lighting and ignition, antimonial lead alloys are used for the grids, posts and connector lugs.

Repeated charging and discharging of a battery can cause prohibitive corrosion of the grids, if the alloy is of inadequate purity. Typical specifications for battery grid metal are indicated in the following:

Antimony	7 to 12%
Tin	0.10 to 0.50
Arsenic	0.05 max
Copper	0.05 max
Bismuth	0.05 max
Nickel	0.005 max
Zinc	0.005 max
Silver	0.002 max
Iron	0.01 max
Manganese	0.001 max
Lead	Remainder

Metals to be electroplated or coated by the hot dip process are frequently pickled in hot dilute sulfuric acid, in lead-lined tanks. The sheet lead thus used is frequently about ⅛ in. thick or more and is generally chemical lead or tellurium chemical lead. Lead pipes of the same composition carry the steam for heating the pickling baths.

In the production of copper and zinc by electrolytic refining, many tons of sheet made of 6% antimonial lead are used for tank linings and for insoluble anodes. For chromium plating, tank linings of antimonial lead sheet are frequently used with insoluble anodes. Lead is similarly employed for copper plating, nickel plating, zinc plating and with various other plating solutions. An insoluble anode of 99% Pb, 1% Ag is frequently employed in the electrolytic refining of zinc.

Lead Equipment in the Chemical Industry. Lead and some of its alloys are extensively employed in the construction of equipment for the production, transportation, storage and use of many corrosive chemicals. Following is a list of some more or less common chemicals in contact with which lead or its alloys have been used successfully:

Aluminum sulfate	Sodium bisulfate
Ammonia vapor	Sodium chloride solution, or sea water
Ammonium sulfate	Sodium hydrosulfite
Antimony trichloride	Sodium hyposulfite
Bleaching solutions	Sodium sulfate
Brown acid solutions	Sodium sulfide
Carbonate, soluble	Sodium sulfite
Chlorine gas	Sulfonations
Hydrofluoric acid	Sulfur chloride
Koch's acid	Sulfur dioxide
Mixed acids	Sulfuric acid
Nitration mixture of H-acid	Sulfurous acid
Paranitrophenol	Sulfuryl chloride
Phosphoric acid	Zinc chloride
Phosphorous chloride	

This is by no means a complete list of chemicals with which lead may be or has been used, nor does it signify that the behavior of lead is necessarily satisfactory with all the listed chemicals under every circumstance. More detailed information on the performance of lead in contact with various chemicals is given in the list at the end of this article. Because conditions vary so widely from plant to plant and process to process, it is wise to judge each installation on its own merits and, if possible, to make tests under actual operating conditions. The many variables determining the suitability of lead may include temperature, concentration, grade of lead or type of alloy, rate of flow, presence of oxygen, degree of abrasion and presence of impurities.

In selecting lead for equipment that must withstand corrosion, it is important to determine the correct grade or alloy for the purpose. When unalloyed lead is used, it is ordinarily the ASTM grade known as "chemical lead". This grade differs from corroding and common lead mainly in the copper content, which ranges between 0.040 and 0.080%.

There are installations where still greater strength and rigidity are needed than are supplied by chemical lead or chemical tellurium lead. In such installations an alloy may be used. The alloys may also have better corrosion resistance under some operating conditions.

One of the most common lead alloys thus employed is antimonial lead, containing as much as 12% Sb, but since this alloy loses strength rapidly at elevated temperatures, its principal use is at temperatures ranging from 210 to 250 F. For high temperatures, an alloy of lead with 0.035 to 0.050% Te has been employed quite extensively in the last few years because of high resistance to fatigue failure. This alloy work hardens and is said to have good resistance to corrosion, particularly by hot sulfuric acid.

Joints in lead used for corrosion-resistant equipment are made by fusion welding, a method of joining that is commonly known by a somewhat misleading term, "lead burning". This method is used so that no metal other than lead will be exposed to corrosive attack. Likewise, it is necessary to see that the lead exposed to attack is homogeneous in composition, in order that all exposed metal may resist attack uniformly. Therefore, if metal has to be added through the use of a filler or so-called "burning bar", in making joints, the bar should have the same composition as the lead being joined. Thus, chemical lead should be joined by the use of a chemical lead filler bar, 6% antimonial lead by the use of a 6% antimonial lead filler bar, and so on. Oxygen and hydrogen are the gases most generally preferred for lead welding, but others, such as oxygen and acetylene, and oxygen and city gas, are also used. See "Joining Lead and Lead Alloys", the preceding article.

Forms of Equipment. Because of its low strength, lead is usually supported by some other stronger material, such as steel, wood or concrete. (Occasionally chemical equipment is made of cast lead alloy, but then the walls are unusually thick to gain the necessary strength; valves, pumps and fittings are also frequently made of cast lead alloy.) Sometimes the supporting structure may be merely a framework of steel, but more often the entire outer shell is made of strong material and lined with lead that is applied in various ways. Small tanks may simply have the sheet-lead lining hung in them by turning the lead over the upper edge.

For better support, the lining is often held by 2-in. half-round steel straps fastened at frequent intervals inside the lead and through it to the outer steel shell. These straps are covered with strips of lead welded to the lead lining on either side. Vertical strips are usually about 24 to 30 in. apart, and tanks with high walls—for example, 10 ft or more—also have horizontal supports.

For another method of support, lead rivets, welded to the back of the lead lining, extend through holes in the shell and can be riveted on the outside; or the lead rivets may extend through holes in both lining and shell, so that the rivet head on the inside can be welded all around to the lead lining.

The strap method of support is invariably used for lining the top of closed equipment. Both for support and for protection against abrasion, brick linings are often used inside lead linings, particularly where high temperatures are involved.

When the transfer of heat is important, lead linings may be bonded to the supporting shell. In equipment operating under a vacuum or requiring the greatest strength, the lining is always bonded. If temperatures are not high, tin or solder may be used to bond the lead to the steel, but some processes employ a nonmetallic flux to form a bond* that can hold its strength at temperatures nearly as high as the melting point of lead.

Pipe. Horizontal runs of pipe made of lead or lead alloy are usually supported continuously in steel or wooden troughs, or in specially constructed shells of sheet metal. Vertical runs are supported at frequent intervals, for example, every 18 in.; long runs are provided with expansion bends if they operate at high temperatures. When greatest strength is essential, lead-lined steel pipe may be used; the inside of the steel pipe is coated with a bonding agent, such as solder, and extruded lead pipe is inserted. The lead is expanded under steam pressure against the warmed steel and is thus "sweated" to the steel pipe.

Pipe made of lead or lead alloy may be joined by direct welding or by welded flanges and bolts. Lead flanges are usually backed by loose steel flanges. Flanged joints are generally used for lead-lined steel pipe.

Heating or cooling coils made of lead pipe are important items in many pieces of chemical apparatus. Usually they are helical in shape but may take other forms. For support, lead spacers are welded at intervals, ordinarily not more than 18 in. apart, around the coil between the turns. Where greater strength is needed, the coils may be made of copper tube, completely covered with lead.

Commercial Products. Below is a list of stock or standard manufactured lead items for use in industry or generally available at short notice in various parts of the United States: angles, anodes, bars, bends, electrodes, evaporators (cast lead), exhaust fans (cast regulus metal), filters, gaskets (cast, stamped or asbestos filled), grids for filters, laboratory equipment—dishes, bottles, fume ducts and the like, perforated sheets, pipe and fittings (lead, lead-lined steel, steel-reinforced) and lead-covered copper tubing, rotary and centrifugal pumps, rings, sheets, spacer blocks, spray nozzles, traps, valves (compression, gate, diaphragm check), washers, wedges and wire.

The thickness of sheet-lead linings depends largely on the extent of corrosive attack. Sheet lead lighter than 8 lb (⅛ in. thick) is rarely used in chemical equipment. Frequently, different thicknesses are used for different parts of equipment; for example, tank bottoms are often lined with heavier lead than the sides because of greater wear. Abrasion may also be a factor in determining the correct thickness.

Sheet lead is designated by its weight per square foot; 1 sq ft of sheet lead weighs 1 lb for each $\frac{1}{64}$ in. of thickness. This relationship holds true up to 16-lb sheet lead, which is ¼ in. thick. Sheet lead ½ in. thick is designated as 30-lb sheet, and 1 in. thick as 60-lb.

The thickness of lead pipe depends on several factors, including corrosive attack, abrasion, and the pressure to be withstood. For instance, if wall thickness is calculated in the usual manner to accommodate a given pressure, additional wall thickness is allowed to compensate for loss through corrosion or abrasion. Pipe 1½ in. in diam with ½-in. walls is commonly used with steam pressures as high as 45 psi. The formula commonly used to calculate wall thickness is

$$P = \frac{2ST}{D}$$

where P is constant working pressure in psi; S is allowable fiber stress taken as 200 psi for chemical lead at room temperature, and decreasing to 80 psi at 300 F; T is wall thickness in inches; and D is inside diameter in inches.

To the wall thickness thus calculated must be added allowances for corrosion and abrasion. If the pipe is not used under pressure, then corrosion or abrasion is the principal factor. The lightest weight of pipe generally selected under such conditions is the class known as "B" or "M" weight in sizes as large as 2 in. in diam and with walls as thick as ¼ in. in the larger sizes. Standard weights of lead pipe are designated by the actual inside diameter and by a letter showing the wall thicknesses or weight per foot.

Resistance of Lead to Chemical Corrosion. The following list is a general guide to the performance of lead in contact with various chemicals:

Acetic Acid. Moderately corrosive to lead, but corrosion is greatly accelerated by high concentrations and temperatures. Acetic anhydride and glacial acetic acid are handled in lead.

Acetone. Lead is used satisfactorily.

Acetylene. Little effect on lead.

Alcohol, Ethyl. Almost no effect on lead. When used in beverages, only a minute amount of lead contamination is tolerable.

Alcohol, Methyl. No effect on lead.

Aluminum Sulfate or Alum. Lead can be used satisfactorily.

Ammonia. Lead is not affected by the dry gas, and also not by the liquid unless sodium or potassium is dissolved in it.

Ammonium Azide. No effect on lead.

Ammonium Chloride. Lead may be used at ordinary temperatures with concentrations up to 10%.

Ammonium Hydroxide. Lead is satisfactory with liquid or gas at virtually all temperatures and concentrations.

* Such coverings are known to the trade as "homogeneous" lead linings or coverings.

Ammonium Phosphate. Lead can be used satisfactorily.
Ammonium Sulfate. Lead may be used freely.
Antimony Chloride. Lead is somewhat corroded, but is used with comparative economy for chlorinating the trichloride to pentachloride.
Benzyl Chloride. Lead can be used satisfactorily.
Boric Acid. Lead can be used satisfactorily.
Brine. (See *sodium chloride.*)
Bromine. Lead may be used when the bromine is cold and acid-free.
Calcium Carbonate. This compound that is found in natural waters forms a good protective coating on lead, and is added to water to reduce plumbo-solvency.
Calcium Hydroxide. This compound, present in green cement, corrodes lead in the presence of moisture and oxygen. However, added to soft water, it reduces plumbo-solvency.
Carbonates, Soluble. These act as a protection to lead by formation of lead carbonate coating.
Carbon Dioxide. This acts as a protection to lead in natural waters unless carbon dioxide is present in excess, when it increases solubility. Lead is used in acid-carbonate systems for generating CO_2.
Chlorinated Hydrocarbons. Action on lead varies from slight to severe, depending on breakdown to HCl and presence of organic acids.
Chlorination Process. Lead is slowly corroded at temperatures ordinarily used, but length of service is satisfactory compared with that of other common metals and the use of lead permits greater economy.
Chlorine. Dry chlorine does not affect lead and lead may be used with moist chlorine at about 110 C or less with slight corrosion. Amounts of chlorine used in water treatment do not affect lead.
Chromic Acid. Since chromates form a good protective coating on lead, lead may be used with fairly high concentrations of this acid. Antimonial lead is widely used in electroplating.
Cinders. Lead embedded in cinders should be protected.
Coal Tar. Lead is used in refining and recovery of many by-products.
Concrete, Cement or Mortar. When green, the free lime present attacks lead. Aging to carbonate lime or applying asphalt coating on lead is recommended to prevent such corrosion.
Copper Sulfate. Lead is used for anodes and tank linings in electroplating.
Ether. Little or no effect on lead. Lead is used in the manufacture of ether.
Ferric Sulfate. Lead is used in dissolving pots.
Ferrous Sulfate. Lead is used for tank linings and coils in production and service.
Formaldehyde (Formic Acid). Action on lead is similar to that of acetic acid.
Hydrochloric Acid. Use of lead is not generally recommended, but it has been used with some corrosion in concentrations as high as 30% at normal temperatures and 20% at 100 C. Antimonial lead shows better resistance than ordinary lead.
Hydrofluoric Acid. Lead is commonly used since it has fair resistance to the dilute acid.
Hydrogen Chloride (Anhydrous Hydrochloric Acid). Very little effect on lead.
Hydrogen Peroxide. When alone this compound is not likely to affect lead, but it accelerates corrosion when acid is present.
Koch Acid Reduction Mass. Lead may be used safely.
Magnesium Chloride. Corrosive to lead as well as to other metals.
Malachita Green Solution. No appreciable effect on lead at 80 C.
Mixed Acids. Mixtures of sulfuric and nitric acids can be used with lead at ordinary temperatures if water present is less than 30%.
Naphthalene. Lead may be used.
Nitration Mixture of H-Acid. Lead is used with rather high corrosion.
Nitric Acid. Lead is not generally recommended with this acid, but is used with little corrosion when concentrations are higher than 80% at normal temperature.
Nitrobenzol and Nitrochlorbenzol. Corrosive to lead.
Nitrocellulose. Lead is widely used as in all rayon manufacturing processes.
Nitroglycerine. Lead is used to handle spent acid.
Nitrosyl-Sulfuric Acid. Action on lead is least at specific gravity of about 1.5 to 1.6. Close control minimizes corrosion.
Organic Acids. In general, these accelerate the corrosion of lead, but their presence in solutions does not always preclude the use of lead.
Oxygen. Dry gas merely tarnishes lead. In presence of water, initial attack is usually followed by formation of protective coating by salts such as carbonates, sulfates and silicates in water. In absence of these salts, aeration may be employed to remove oxygen, because of its action on all metals.
Oxy-L Acid. Lead is corroded to some extent but is almost the only economical metal that can be used with satisfaction.
Phenol. Lead is used satisfactorily.
Phosphoric Acid. Lead may be used with concentrations as high as 80% at temperatures lower than 200 C. Impure acid has even less effect on lead and can be used in concentrations as high as 85%.
Photographic Solutions. Lead is generally satisfactory.
Potassium Permanganate. This compound attacks lead.
Pyridene. No effect on lead.
Silicates. These form protective coatings on lead and thus can be recommended for treating natural waters if necessary.
Sodium Bisulfate. When highly concentrated, this can be handled in lead.
Sodium Carbonate. Dilute solutions do not affect lead; in natural waters this forms a protective coating on lead.
Sodium Chloride. Lead is satisfactory for dilute solutions at ordinary temperatures. Sea water or brine is commonly handled in lead or antimonial lead.
Sodium Hydrosulfite. Lead can be used satisfactorily.
Sodium Hydroxide. Lead can be used with concentrations up to 25% and temperatures to 80 C.
Sodium Hyposulfite. Lead can be used satisfactorily.
Sodium Hypochlorite. This compound attacks lead.
Sodium Sulfate. Lead can be used satisfactorily with solutions as strong as 10% concentration boiling.
Sodium Sulfide. Lead can be used satisfactorily with these solutions at temperatures as high as 100 C.
Sodium Sulfite. Lead can be used with solutions as high as 20% in concentration at 25 C.
Sulfur Chloride. Little effect on lead.
Sulfur Dioxide. This has little effect on lead when dry and can be used moist at about 200 C or less.
Sulfuric Acid. Lead is the standard material for handling this acid. Lead can be used with concentrations as high as 96% at room temperature and 85% at temperatures as high as 220 C. Lead is sometimes used satisfactorily even at temperatures as high as 250 C.
Sulfurous Acid. Lead is satisfactory at about 220 C or less.
Tannic Acid. Somewhat similar to acetic acid.
Tartaric Acid. Somewhat similar to acetic acid.
Thionyl Chloride. Lead is used satisfactorily as high as 220 C and sometimes higher.
Titanium Sulfate. These solutions can be handled satisfactorily in lead.
Victoria Green Solution. Lead may be used satisfactorily as high as 80 C.
Water, Distilled. Lead is dissolved very slowly in proportion to amount of dissolved oxygen.
Water, Natural. Usually no effect on lead because of the protective coating formed from dissolved salts. Very soft waters or those of peaty origin may dissolve lead slightly, as they do other metals. In some localities, such action is prevented by treatment of the waters with lime or sodium silicate. The generally suggested tolerance limit for lead in drinking water is 0.10 parts per million.
Wood. Most wood has little or no corrosive effect on lead. A few instances of corrosion by wood that contains organic acids, such as green oak, have been reported. Wood to be lined with lead should be inspected for the presence of borers.
Zinc Chloride. Lead can be used satisfactorily.

The section of the foregoing article dealing with Lead Equipment in the Chemical Industry is adapted from a paper by F. E. Wormser, which appeared under the title "Lead Equipment Used in Industry" in Metal Progress, February 1943.

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The Metallography of Lead and Lead Alloys

By J. R. Vilella*

Because of the softness of lead and lead alloys, the preparation of specimens for microscopic examination has always been difficult. Two hindrances are encountered: (1) The finished surface is usually scratched too heavily. (2) The surface metal flows, forming a layer of cold worked metal that masks the true structure.

The usual way of overcoming these difficulties has been to etch deeply so as to get below the surface imperfections. However, a deep chemical attack roughens, blackens and obliterates the fine details of the structure. It is therefore desirable to finish the samples with a minimum of scratches and flowed metal so as to permit light etching.

Two basic methods have been described,[1,2] as well as several modifications thereof, intended to overcome these surface difficulties. One method is based on the use of a strong, rigid microtome, equipped with a specially sharpened knife capable of producing a smooth cut surface suitable for etching and microscopic examination without further polishing. The other method, requiring no special equipment, is based on the fact that scratches and flowed metal can be eliminated by a series of alternate light polishings and etchings.

Microtome Method. The success of this method depends on three factors.

1 *A Microtome Sufficiently Rigid for the Service.* Lucas, who originated the method, employs a Jung microtome, type K, originally designed for wood sectioning;* but he states that given a solid, substantial instrument, good results are largely a matter of personal skill in sharpening the knife and manipulating the apparatus. Schumacher and Bouton[3] have successfully employed an inexpensive biological microtome. They have also obtained fair results by means of a wood chisel and a special clamp.

2 *A Knife Properly Sharpened.* A knife that has been properly sharpened, honed and stropped is indispensable for the success of this method. A dull or serrated edge will yield surfaces covered with scratches and cold worked metal. A razorlike edge is also unsatisfactory because it chips and turns over easily. Best results are obtained when the knife is sharpened to a fine chisel edge and is free from all but the finest imperfections. If used judiciously, a good edge will cut 50 or more lead specimens between stroppings. Sharpening the knife is a laborious operation that requires considerable skill. Detailed instructions are usually supplied by the manufacturers.

3 *An Instrument That Cuts Very Thin Slices.* Lucas has found that unless the instrument cuts sections as thin as 2 microns, the cut surface is not suitable for etching. The shavings themselves are not used for metallographic study, but if they are thicker than 2 microns, the cut surface of the specimen will contain cold worked metal and scratches. This is an indication that the knife has not been honed or stropped properly. It should be noted that even specimens that have been well cut and then etched, present to the unaided eye the appearance of slight furrows or undulations on the prepared surface. These are not troublesome under the microscope.

Wood Chisel Method. This method gives satisfactory results when used properly. The specimen is mounted in a hardened tool steel clamp and excessive material is removed with a coarse hacksaw. A rough chisel cut is made, and then a fine one, using the surface of the clamp as a guide.

Polishing With Standard Equipment. This method is rapid and can be carried out successfully with ordinary polishing equipment or by hand. When properly performed, such polishing leads to the formation of ideal surfaces for examination at low and high magnifications.

Procedure. 1 To minimize distortion of the surface metal, the sample should be cut with a sharp hacksaw. Care is necessary to avoid dragging and pushing. It is well to rub a few drops of oil on the saw blade.

2 The specimen should then be ground, with gentle pressure, on a coarse abrasive paper that has been spread previously with a concentrated solution of paraffin in kerosene. This treatment prevents the particles of lead from adhering to the paper and forming a glaze that would drag and distort the surface metal. At least $\frac{1}{64}$ in. of metal should be ground away during this step. The speed of the revolving disks should not exceed 500 rpm at any stage during the entire operation.

3 The specimen is then ground successively on 2, 1, 0, 00 and 000 abrasive papers, all previously spread with the solution of paraffin in kerosene. Grinding on successive papers should be continued for at least one minute after all the scratches left by the preceding paper have disappeared. Care should be taken to exert the minimum pressure needed to secure good cutting action. The scratches left by 000 paper are frequently too deep to be removed easily during the next step (wet polishing). For this reason the specimen should be ground, when necessary, on an old 000 paper that has been well worn by previous use. This last paper, as a rule, yields very fine, even scratches that disappear easily during wet polishing. The specimen should now be freed from paraffin and grit.

4 Wet polishing requires clean broadcloth spread abundantly with soap. The abrasive is a water suspension of the finest levigated alumina obtainable. If, at this stage of the operation, a black smudge appears on the surface of the specimen, polishing should proceed very gently, and care should be taken to keep the cloth thoroughly wet with alumina and soap until all traces of smudge have disappeared and the surface appears bright.

5 The scratches left after polishing on broadcloth are often rather deep and remain visible after etching. For

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* With the Jung microtome, specimens of lead, tin, platinum, gold and silver have been sectioned successfully. Harder metals, such as aluminum, aluminum alloys, copper, zinc, and the brasses and bronzes, may be prepared roughly by sectioning, and may then be given a final polish on magnesium oxide, thus expediting considerably the usual procedure of preparation.

Table I. Etching Reagents for Lead and Lead Alloys

No.	Authority	Composition	Remarks
1	Rutherford[4]	3 parts glacial acetic acid 1 part 9% hydrogen peroxide	Etch for 10 to 30 min, depending on depth of flowed metal on the surface. Dry with alcohol and clean with concentrated nitric acid. The nitric acid is removed by sudden immersion in a large volume of water.
1a	Lucas[1,3]	3 parts glacial acetic acid 1 part 30% hydrogen peroxide	Etching time varies from 6 to 15 min. Used for lead, lead-tin, lead-antimony, and lead-calcium alloys.
2	Vilella[2]	1 part glacial acetic acid 1 part nitric acid 4 parts glycerol	Etching from 10 to 15 sec. Affords best results when used in conjunction with method of alternate polishing and etching. For lead, lead-antimony, lead-calcium, and low-tin alloys. Use freshly prepared solution and discard after using.
2a	Bassett and Snyder[5]	3 parts glacial acetic acid 4 parts nitric acid 16 parts water	Use at a temperature of 40 to 42 C. Recommended for pure lead and lead-tin alloys up to 3% tin. Etching time depends on depth of distorted metal on prepared surface.
3	Johnston[6]	Concentrated nitric acid	Plunge specimen in concentrated acid. Wash in a rapid stream of water. Repeat operation as often as necessary. If acid becomes diluted by water carried by specimen it must be rejected and fresh acid used.
4	Bassett and Snyder[5]	60% solution of perchloric acid	For electrolytic etching. No. 6 dry cell used to supply energy. Also recommended by Dean, Zickrick and Nix.[7]

removing these scratches, the specimen may be polished by hand on a clean pad of silk velvet, well soaked with soap and alumina. The sample should then be washed carefully to remove all traces of soap.

Etching. According to those who advocate the sectioning methods of preparing lead specimens, the sample may be etched as it comes from the microtome. One etching is sufficient to disclose the true structure of the metal. Occasionally a cotton swab, well soaked in the etching reagent, is used for eliminating the heavier knife marks usually present in specimens prepared by the microtome or the chisel method.

The etching of specimens prepared by conventional polishing methods is not considered a process completely independent of polishing. Even well-prepared surfaces are seldom entirely free from a film of cold worked metal that must be eliminated in order to show the true structure of the specimen. This film cannot always be removed satisfactorily by the etching reagent alone, no matter how long the specimen is exposed to the action of the reagent. A prolonged etching attack usually results in pitting and roughening the surface and obliterating the fine details of the structure. It is advantageous to employ a method of alternate polishing and etching, during which the reagent gradually removes the film of distorted metal while frequent light polishings prevent the evils of a long continued chemical attack. The procedure is as follows:

The polished specimen is etched in a suitable reagent and its structure is noted under the microscope. The specimen is then repolished gently on the velvet pad until bright, when the surface is etched again and examined. A considerable improvement in the appearance of the structure will be noted. The surface of the metal should be polished and etched repeatedly, as long as the appearance of the structure improves. Ordinarily three repolishings suffice, but occasionally more may be required.

The etching reagents for lead and lead alloys are listed in Table I.

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Factors That Determine the Applications of Lead

By R. L. Ziegfeld*

LEAD probably has more varied fields of application than any other metal. Many of these applications depend on the chemical properties of such lead compounds as white lead, red lead, litharge, lead arsenate, lead chromate, tetraethyl lead, lead azide and lead silicate, to mention only some of the most important. Since these are chemical rather than metallurgical products, they will not be discussed further here.

However, a still larger tonnage of lead is used in metallic form, either alone or as lead alloys. In most of these applications, the physical properties of the metal determine whether it should be used, or the manner in which it should be employed.

The outstanding characteristics of lead include heavy weight, high density, softness, malleability, flexibility, low melting point, low strength, low elastic limit, ability to alloy with certain other metals, lubricating properties, low electrical conductivity, high coefficient of expansion, and high resistance to corrosion under a wide variety of conditions. Lead is ordinarily selected for use because of one or more of these properties. However, the product or installation should be designed with consideration for the other properties.

Weight and Density. Because of the high specific gravity, lead must usually be excluded where light weight is required, unless some other desired characteristic can be obtained from lead only. As an example, lead is not generally desired in aircraft on account of weight, yet lead storage batteries are used in aircraft because they alone have the desired electrochemical characteristics.

Several instances can be cited where some other characteristic of lead makes it possible actually to reduce the weight of the equipment in which lead is used, despite the high specific gravity of lead. On certain aircraft equipment, lead coatings have sometimes reduced total weight, since they can be thinner than coatings of some lighter materials and still give equal protection. Lead counterbalances on aircraft often reduce weight, because the weight can be concentrated at the point where it has the greatest effect.

Although lead is often out of the question where light weight is important, lead is always considered for weights and counterbalances. In such uses, the higher cost of lead is balanced against its greater ability to save space, as compared with materials of lower specific gravity. Other desirable features are the low melting point and easy casting of lead, making it possible to fit lead weights into irregular and out-of-the-way spaces. When lead is selected for such work, softness and low strength must sometimes be considered if the weight is subjected to mechanical abuse. In such instances, the lead weight is often enclosed in a cast-iron or steel shell.

High density makes lead suitable for a number of purposes. Notable among these is X-ray protection, since the ability of a substance to stop beta rays and gamma rays is proportional to density. Thus for X-ray machines, radium and other radioactive materials and isotopes, lead is usually employed as the protective medium. However, with high-powered machines, the thicknesses of lead required are expensive, so that if space and weight are not too important, concrete is generally employed, often in combination with lead. X-ray experts now recommend using lead in combination with concrete whenever concrete is employed, because lead reduces scattered radiation.

Softness and Malleability. The softness of lead accounts for its use in some instances or makes it necessary to take precautions in others. For example, the softness of lead is largely responsible for its value as a calking material, making it possible to fill the calked joint completely. Softness accounts, at least in part, for the use of lead in bearing metals, gaskets, washers, and lead-headed nails.

On the other hand, softness often makes it necessary to take certain precautions in the use of lead. In pipe lines, for example, high velocities may result in erosion. This disadvantage is sometimes eliminated by increasing the size of lines to reduce velocity, or by increasing the wall thickness to compensate for losses caused by erosion.

The malleability of lead finds its widest commercial application in the manufacture of lead foil, where it is rolled as thin as 0.0005 in. or even less.

Flexibility. Although this is not strictly a property, it is the best word to describe an important characteristic of lead, resulting from its properties. Flexibility is at least a contributing factor in many commercial applications of lead. One of the best examples is cable sheathing; others include piping, molds for rubber hose, and collapsible tubes.

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Low Melting Point. This property of lead, and particularly of lead alloys, results in the use of lead for many purposes, such as solder and fusible alloys. The low melting point makes lead castings and type metal easy to manufacture, but is often a disadvantage—in chemical equipment, for instance, where lead must be confined to use at relatively low temperatures. However, this disadvantage may be lessened to some extent by supporting lead properly with other materials or by actually bonding it to steel for support.

Strength. The fact that lead has both low tensile strength and low creep strength must almost always be considered in applying lead commercially. Strength is important more often than not. Even when strength is essential, however, the low strength of lead does not necessarily preclude its use. Lead products can be designed so that lead will reinforce itself, or inserts or supports of other materials can be provided. Alloying with certain other metals, notably antimony, is a common method of strengthening lead. But in most uses for lead, adequate support should always be provided. Thus horizontal lead pipes are usually supported continuously and vertical pipes are supported at frequent intervals. Sheet-lead linings in deep tanks are supported by lead-covered steel straps.

Lubricating Properties. The fact that lead has good self-lubricating properties results in a number of commercial applications. As a coating on wire and on sheet metal, lead acts as a drawing lubricant. Used in powder or wire form, lead imparts proper lubricating properties to friction materials like brake linings. As a powder, lead is employed in heavy-duty lubricating greases and in pipe-joint compounds.

Expansion. The relatively high coefficient of thermal expansion of lead is another property that must be considered in many uses of lead. For instance, in pipe lines subject to wide variations of temperature, provision must be made for free expansion. In lead roofing and flashing, where expansion is always a factor, it is provided for by using small sheets to minimize expansion in any one sheet, and by loose-locking each sheet to the next, in order to prevent cumulative expansion.

Alloying. Lead alloyed with other metals is used commercially in large tonnages. Antimony and tin are the alloying metals most commonly employed. Antimony is generally used to give greater hardness and strength, as in storage-battery plates, sheet, pipe and castings. Tin also increases hardness and strength, but the lead-tin alloys are most commonly used for their melting characteristics, as in solder. In solder, terne metal and other lead alloy coatings, tin imparts the ability to bond with metals like steel and copper. High-purity lead has very slight bonding ability. Both tin and antimony improve the casting qualities of lead. Bismuth and tin are often alloyed with lead to obtain the extremely low-melting alloys. Although lead does not alloy readily with copper, it is combined in rather high percentages with copper in certain bearing alloys, and is frequently used in smaller percentages in bronzes and free-machining brasses. Likewise, though lead is difficult to alloy with steel, fractional percentages of lead are used in the production of free-machining steel. Calcium, magnesium, and sodium in fractional percentages are sometimes alloyed with lead in special bearing alloys and cable sheathing. Cadmium additions prove helpful in coating copper wires with lead.

Resistance to Corrosion. This property of lead determines its use more often than any other. Lead is highly resistant to corrosion by the atmosphere, water and a long list of corrosive chemicals in everyday use, most common of which is sulfuric acid. The selection and use of lead under corrosive conditions is discussed in detail in the article on page 951. Where long life and resistance to corrosion are factors, applications of lead are subject to the limitations of its other properties, such as low strength and high expansivity. As pointed out elsewhere, there are usually ways to surmount these limitations, but they should be kept in mind while designing to get best results with lead.

No attempt has been made here to discuss in detail all the properties of lead determining its fields of application, or all the fields of application of lead. Rather, some salient points and examples have been mentioned as a guide in judging the suitability of lead for a particular purpose.

Type Metals

By Bruce W. Gonser* and J. Homer Winkler*

TYPE METALS, a class of metals used in the printing industry, are generally alloys of lead, antimony and tin, with small amounts of copper in the hardest alloys. Various other alloying elements, such as cadmium and tellurium, have been added to type metals, but any advantage from these elements has been insufficient to warrant such additions, except for special purposes. Tin-base alloys might be suitable for type metals, but are considered too expensive. Zinc-base alloys—for example, a 94% Zn, 6% Al alloy—offer too much difficulty in handling. A modified 95% Al, 5% Si alloy has been used to a very limited extent in making aluminotype printing plates, but the advantages in lightness and resistance to corrosion by colored inks have usually been more than offset by the need for casting in plaster of Paris molds. For present commercial usage, therefore, the term "type metals" refers to lead-base alloys of compositions listed in Table I.

The lead base provides low cost, low melting point and ease in casting—properties desired in all type metals. Additions of antimony not only harden the alloy and make it more resistant to compressive impact and wear, but also lower the casting temperature and minimize contraction during freezing. Tin adds fluidity and greater ease in casting, reduces brittleness, and imparts a finer structure—a property helpful in reproducing fine detail.

Constitution.[2, 4, 6] The constitution of the Pb-Sn-Sb alloys is described elsewhere.* A ternary eutectic exists at 462 F (239 C) with the composition of the linotype metal, 84% Pb, 4% Sn and 12% Sb. At 476 F (246.5 C), with the composition 80% Pb, 10% Sn and 10% Sb, there is the eutectic of a pseudobinary system of the compound SbSn and lead.

Compositions for Specific Uses.[1, 3] Electrotype metal contains the lowest percentages of tin and antimony, since it is used as a backing metal only, and is not required to resist wear. In making an electrotype, a thin copper (or nickel plus copper) sheet is electroformed over a wax, lead, or thermoplastic impression to give a wear-resistant replica of the surface to be printed. This "shell" is removed, flux and solder-foil are applied to the nonprinting side, and molten electrotype metal is poured into the shell to give an adherent backing of requisite thickness. Since such a printing plate is frequently curved for attachment to rotary presses, it is necessary that the plate of electrotype metal (0.065 to 0.250 in. thick) be ductile. Fluidity of the molten metal is also essential to avoid local cavities or soft spots in the printing surface. Thus, the ratio of tin to antimony is high, as compared with other type metals. Electrotypes are used where long printing runs are required and where the highest quality of printing is needed.

Stereotype metal is also cast in fairly large printing plates of relatively thin cross section. The metal is cast against a fiber composition impression of the surface to be printed, usually in curved vertical steel molds, and frequently with the porous fiber mat held in place by vacuum. Good castability is needed to reproduce the printing surface accurately. Unlike electrotype metal, however, stereotypes are ordinarily used directly for printing; hence

* Battelle Memorial Institute, Columbus, Ohio

* *See* Constitution of Alloys Section, page 1267.

a harder, wear-resistant metal is needed. This necessitates the use of higher contents of tin and antimony. Sometimes, for greater resistance to wear, stereotypes are lightly electroplated with chromium or nickel. Newspapers with a large circulation are usually printed from stereotypes, so that a number of presses can be operated simultaneously on the same work.

Linotype or slug-casting metal is die-cast by such machines as the Linotype, Intertype, and Ludlow casters. These produce an entire line of type characters in each casting. The Linotype and Intertype machines are used in newspaper type composition because of the speed of production that can be obtained. For this purpose, a low melting point and short temperature range during solidification are of greatest importance, and the ternary eutectic alloy or compositions near this are favored.

Table I. Typical Composition and Properties of Type Metals

Kind	Composition, % Pb	Sn	Sb	Brinell Hardness Number[a]	Liquidus, deg Fahr	Solidus, deg Fahr	Ref
Electrotype							
General	■	2.5	2.5	...	578	475	1, 2
General	94	3	3	12.4	568	475	3, 2
Curved plates...	93	4	3	12.5	561	473	2
Stereotype							
Flat plate	80	6	14	23	493	462	4, 2
General	80.5	6.5	13	22	485	462	5, 2
Curved plates...	77	8	15	25	505	462	1, 2, 6
Linotype							
Standard	86	3	11	19	477	462	1, 2
	84	5	11	22	475	462	1, 2
(b)	84	4	12	22	463	462	1, 3, 2
Monotype							
Ordinary	78	7	15	24	503	462	1, 2, 6
Display	75	8	17	27	520	462	1, 2, 6
Case type[c]	72	9	19	28.5	546	462	1, 2, 6
Case type.....	64	12	24	33	626	462	1, 2, 6
Rules	75	10	15	26	518	462	1, 2, 6
Foundry Type							
	70	10	20	30	553	462	1, 2, 6
	62	13	25	34	617	462	1, 2, 6
	54	18	28	...	637	462	1, 6
Hard[d]	60.5	13	25	...	...	...	1
Hard[d]	58.5	20	20	...	...	...	1
Hard[e]	61	12	25	...	...	...	5

(a) 10-mm ball, 250-kg load (reference 1)
(b) Eutectic alloy
(c) Lanston standard
(d) 1.5% Cu
(e) 2.0% Cu

Monotype metal is also die-cast by machine. In this method, since only one type character is cast at a time, a rapid cooling rate is possible, permitting the use of harder alloys of higher melting range. Monotype metal must have excellent casting characteristics, resistance to wear, resistance to the pressures of printing, and of molding for electrotype or stereotype production. The pressure may amount to 2500 psi. Rules, spacing material, metal mounting units, and bearers used in assembling the type composition in chases for printing or molding, are cast on Lanston monotype or Elrod machines.

Foundry type metal is used exclusively to cast type for hand composition. The cast type is used over and over again instead of being melted before reuse, as other type metals are. If not used to print directly, this type is subjected to heavy pressure in forming molds for electrotypes, stereotypes and other duplicate plates. Such service requires the hardest, most wear-resistant alloy that is practical to use. Small additions of copper as a hardener are feasible for foundry type since the metal is remelted infrequently, and then not in printing establishments, but at the plant of a type founder, where dross losses and composition can be carefully controlled.

In making all the machine-cast type, including foundry type, the molten metal is forced into metal dies under only moderate pressure, so there is a tendency for the casting to be porous within, although the printing surface is sound because it is chilled first. There is a tendency for the alloys with high tin and antimony contents—for instance, with more than 12% Sb—to segregate during slow cooling, but these alloys make homogeneous chill castings. To avoid the necessity for handling several alloys of not widely different composition, there has been some tendency to use a compromise composition for monotype, linotype and stereotype metal. The U. S. Government Printing Office has used an 82% Pb, 6% Sn, 12% Sb "universal" alloy for this purpose.

Contraction During Solidification.[7, 8, 9] A common fallacy in accounting for the sharpness of definition of printing characters is to ascribe this excellent reproduction to a slight expansion of the type metal during solidification, rather than to fluidity of the molten metal. In reality, as shown in Table II, all type metals contract slightly.

Table II
Contraction of Type Metals During Solidification[7]

Metal	Composition, percentage Lead	Tin	Antimony	Contraction During Solidification, %
Electrotype	92	4	4	2.6
Stereotype[a]	83.7	4	11.3	2.0
Linotype	79	5	16	2.0
Monotype	76	8	16	2.0
Lead	100	...	...	3.4
Tin	...	100	...	2.8
Antimony	...	...	100	1.4[b]

(a) Specimen contained 0.5% Cu
(b) H. Endo, reference 10

Bismuth additions to type metals will overcome contraction, although the cost of the metal is greatly increased and the mechanical properties are generally inferior.[5] Tests with electrotype metal indicate that an addition of about 25% Bi is necessary in order to obtain an alloy that does not shrink during casting and cooling to room temperature.*

Age Hardening of Type Metals.[11, 12, 13] The solid solubility of antimony in lead decreases with decreasing temperature below the eutectic temperature, making age hardening possible by rapid cooling of the alloy. Type metals, or lead containing both antimony and tin, likewise

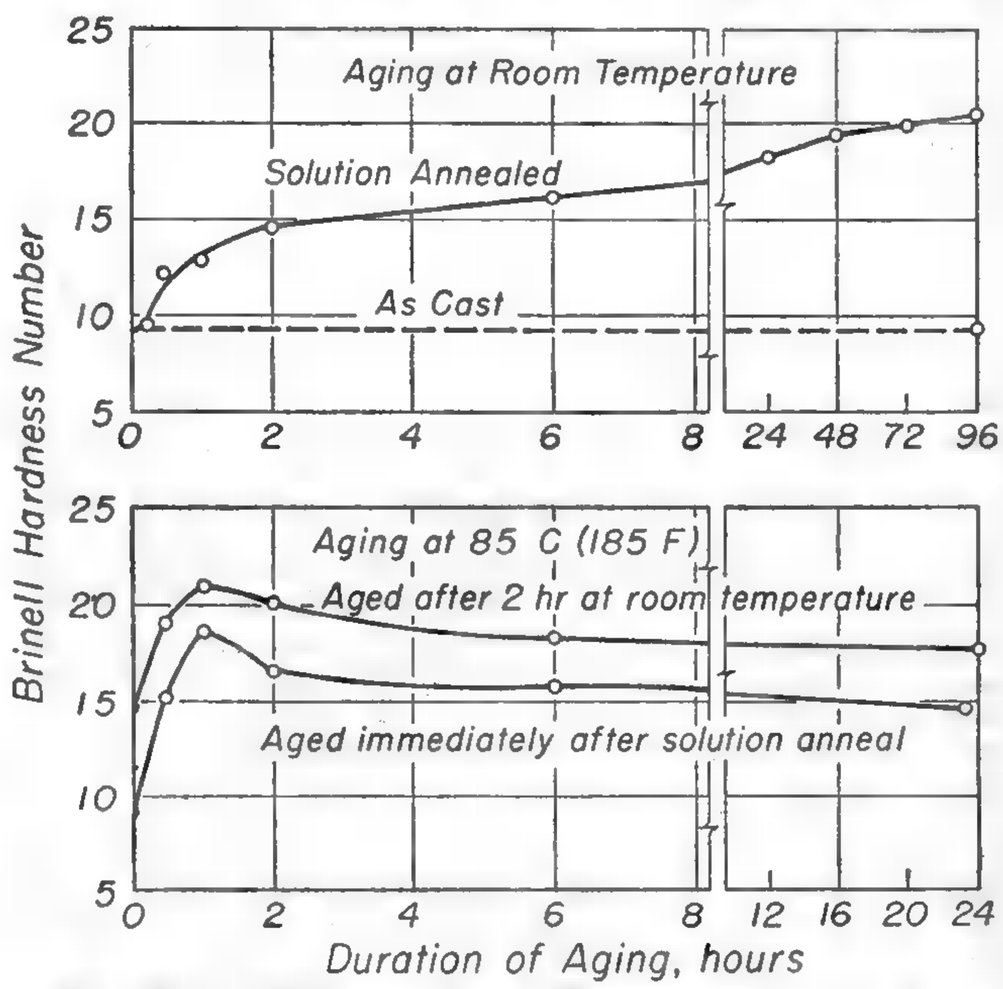

Fig. 1 Age hardening of a type metal containing 97% Pb, 1% Sn, 2% Sb. Alloy solution annealed for 30 min at 455 F (235 C) before being cooled to room temperature.

age harden after proper quenching. In electrotype metals that contain only a small amount of tin and antimony, this effect is much more pronounced than in the harder stereotype and machine-cast type metals.

Frequently, in practice, a slow increase in hardness is noted in electrotype backing metal as cast, and in chill-cast type metal of higher tin and antimony contents. If the metal is quenched from ■ temperature just below the eutectic, age hardening proceeds slowly as shown in Table

* B. W. Gonser and R. M. Schaffert, unpublished data

III. This hardening time can be greatly shortened by aging the metal at slightly elevated temperatures, as for one minute at 212 F (100 C) or for an hour at 185 F (85 C). Increased hardness can be attained also by initiating the aging treatment at room temperature, or by pausing for an hour or two at room temperature before heating to an elevated temperature. Figure 1 illustrates the effect of these factors. When the metal is aged at an elevated temperature after being held for 24 hours at room temperature, a slightly higher hardness is attained, which decreases very little even after six months of storage. Age hardening has been used to a limited extent in practical plant operation, to harden electrotypes.[14]

Table III

Effect of Aging on the Hardness of Type Metals[11]

Composition, %			Brinell Hardness Number[a]					
			As	Duration of Aging at Room Temperature[b]				
Pb	Sn	Sb	Cast	0	6 hr	48 hr	6 days	6 mo
97	1	2	9.2	9.2	17.1	20.2	21.6	18.0
94	3	3	12.4	12.7	14.1	16.9	18.2	16.6
92.5	4	3.5	12.4	12.2	12.7	15.6	16.5	13.9
89	4	7	17.2	17.3	19.0	20.5	...	...
82	6	12	20.3	20.2	20.3	20.1	19.9	17.7

(a) 10-mm ball, 250-kg load impressed in 40 sec, held 1 min
(b) Water-quenched after solution annealing for 30 min at 455 F

Effect of Impurities.[3,16] Since type metals, other than foundry type, are remelted and recast repeatedly, there is always danger of contamination by unwanted metals, as well as by oxide and dross formed during melting and handling of molten metal. Also, since new type metal usually comes from secondary metal refineries, it is seldom as pure as the virgin constituent metals. Copper, zinc, nickel, aluminum, and arsenic are the principal metallic impurities that may cause trouble in type metals.[1,4] Iron is present in very small amounts, principally because of the action of tin on the iron equipment used in melting and casting; but iron is not usually considered a harmful impurity, except that it increases the amount of dross.

Copper forms needles of high-melting intermetallic compound with both tin and antimony. Aside from its general effect in hardening the metal, when present in amounts of 1 or 2%, smaller amounts of copper may cause unwanted hard spots. Moreover, the crystals tend to catch at the nozzle in machines used for casting, and to interfere with the flow of metal. The presence of more than 0.1% Cu is considered definitely harmful. Nickel has much the same effect as copper since, in a similar manner, it forms a high-melting, hard, intermetallic compound with tin. Prolonged heating will remove this compound as a dross, but an increase in the amount of dross is not desirable.

Zinc increases the surface tension of lead alloys and seriously impairs castability, particularly when present in amounts greater than 0.1%. Aluminum has a similar effect. These metallic impurities all contribute to loss of metal by the formation of dross. Since cadmium has properties similar to those of zinc, it might be expected to be harmful also, but actually small amounts of cadmium are helpful. An addition of 0.5% Cd has been suggested in order to lower the melting point slightly and to improve castability.

Some users of type metal consider that arsenic decreases the fluidity of the metal; others have found that normal amounts, up to 0.15%, cause no trouble; and as much as 0.75% As has been added purposely to increase hardness and castability. With increase in hardness there is loss of ductility, however. Addition of 0.1% As to electrotype metal increases the hardness about one Brinell number. Such an addition has no appreciable effect on age hardening characteristics.* Arsenic has been held at least partially responsible for corrosion of the nozzles of type-casting machines.

General Handling Characteristics. The type metals melt and cast easily, without being particularly sensitive to temperature, segregation or oxidation. In machine casting, of course, where speed of solidification is important, the temperature of the molten metal should be controlled carefully to obtain solidification in the time before ejection. With monotype metal for casting into chill molds, the temperature of the molten metal is kept about 150 to 200 F above the liquidus; with stereotype metal, where the casting box is kept comparatively hot, the temperature of the metal needs to be only about 70 F above the liquidus.

Since the alloys that contain more antimony than the eutectic composition are chill-cast, segregation is no problem in the cast alloys. It is likely to occur, though, in pots of molten metal, unless the metal is stirred. Metal is lost by formation of dross chiefly in the remelting pots, rather than in the casting machines. Tin and antimony are oxidized selectively, as in the fire refining of lead; hence the composition gradually becomes lower in these metals. A nearly constant composition is maintained, however, by the addition of an alloy abnormally high in tin and antimony.

Oxide skim and dross form on the surface of molten type metal, particularly when the metal is overheated or is being cleaned by treatment with steam or compressed air. Fortunately this coating is readily removed. It is seldom forced into the mold to cause casting defects, but it may cause considerable mechanical trouble by clogging lines and die openings. The dross contains a high percentage of unoxidized metal that has become entrained in the oxide and high-melting crystals. Part of this metal is recovered by treatment with charcoal-oil mixtures, which are reducing as well as combustible, or with tallow, palm oil, or rosin.

Grain Refinement.* Grain size of type metal depends on the rate of cooling during solidification. A fine grain size is favored and may be obtained by lowering the temperature of the molten metal or by reducing the temperature of the mold, or both. Small amounts of added elements also affect the grain size drastically. Addition of only 0.1% As or about 0.15% Te is sufficient to give electrotype metal a desirable fine grain, without appreciably affecting the hardness or ductility. Small amounts of calcium, lithium, or magnesium increase markedly the grain size of electrotype metal, probably because of deoxidation.

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* B. W. Gonser and R. M. Schaffert, unpublished data

* B. W. Gonser and R. M. Schaffert, unpublished data

PROPERTIES OF LEAD AND LEAD ALLOYS

Lead (99.90+ Pb)

COMPILED BY C. R. INCE* AND G. O. HIERS*

A *1 Common name.* **Chemical Lead**†
3 ASTM number. B 29–43 (pig lead)
B *1 Typical uses.* Principally as a material of construction in the chemical industry; also for most of the things for which other grades of lead are used.
C *1 Density* at 20 to 25 C (68 to 77 F). 11.340 g per cu cm (0.4097 lb per cu in.)
D *1 Melting point.* 325.6 C (618 F)
19 Recrystallization temperature. Below 0 C (32 F) for 99.999% Pb
I *2 Resistance to specific agents.*

Corrosive Agent	Resistance	Remarks
Acetone	Resistant	
Acetylene	Resistant	
Acid acetic	Moderate general attack	Used to handle acetic anhydride and glacial acetic acid
Acid chromic	Resistant	
Acid citric	Moderate general attack	
Acid hydrochloric	Moderate general attack	Use not recommended generally
Acid hydrofluoric	Resistant	
Acids mixed	Resistant	At ordinary temperatures with 30% H_2O
Acid nitric	Severe general attack	Used at normal temperatures above 80% conc
Acid phosphoric	Resistant	Up to 80% conc at 200 C
Acid sulfuric	Resistant	Up to 96% conc at room temperature or 85% conc at 220 C
Acid sulfurous	Resistant	
Acid tartaric	Moderate general attack	
Air	Resistant	
Alcohol ethyl	Resistant	
Alcohol methyl	Resistant	
Aluminum sulfate	Resistant	
Ammonia	Resistant	Unless Na or K is dissolved in it
Ammonium chloride	Resistant	Up to 10% conc at ordinary temperature
Ammonium hydroxide	Resistant	
Ammonium phosphate	Resistant	
Ammonium azide	Resistant	
Benzol	Resistant	
Bromine	Resistant	When cold and free from acid
Carbon dioxide	Resistant	
Carbon tetrachloride	Resistant	At ordinary temperatures
Chlorine	Resistant	Moist to 110 C, or dry
Dyestuffs	Generally resistant	
Formaldehyde	Moderate general attack	
Magnesium chloride	Severe general attack	
Magnesium sulfate	Resistant	
Motor fuel	Resistant	
Nickel sulfate	Resistant	
Oxygen	Resistant	
Phenols	Resistant	
Photographic solutions	Generally resistant	
Sodium carbonate	Resistant	
Sodium chloride	Resistant	Dilute solutions at ordinary temperatures
Sodium hydroxide	Resistant	Up to 25% conc and 80 C
Sodium sulfate	Resistant	Up to 10% conc boiling
Sulfur dioxide	Resistant	Moist up to 200 C, or dry
Water chlorinated	Resistant	
Water sea	Resistant	

K *Mechanical Properties.* See Table I and Fig. 1 and 2.
8 Surface tension (in natural gas atmosphere).

Temperature, deg Cent	350	410	480	525	550
Temperature, deg Fahr	662	770	896	977	1022
Surface Tension, dynes per cm	440	437	431	424	423

* St. Joseph Lead Company, New York
* National Lead Company, Brooklyn
† Only Chemical Lead is discussed here, but there are other commercial grades of lead more than 99.90% pure.

L *4 Preferred tension-test specimen.* Flat, ½ in. by ⅛ in. with 2-in. gage length
Preferred fatigue-test specimen. See Fig. 3.
Preferred hardness tests. Rockwell, using ½-in. ball, 30-kg load, 30-sec duration (special scale); Brinell, using 10-mm ball, 100-kg load, 30-sec duration

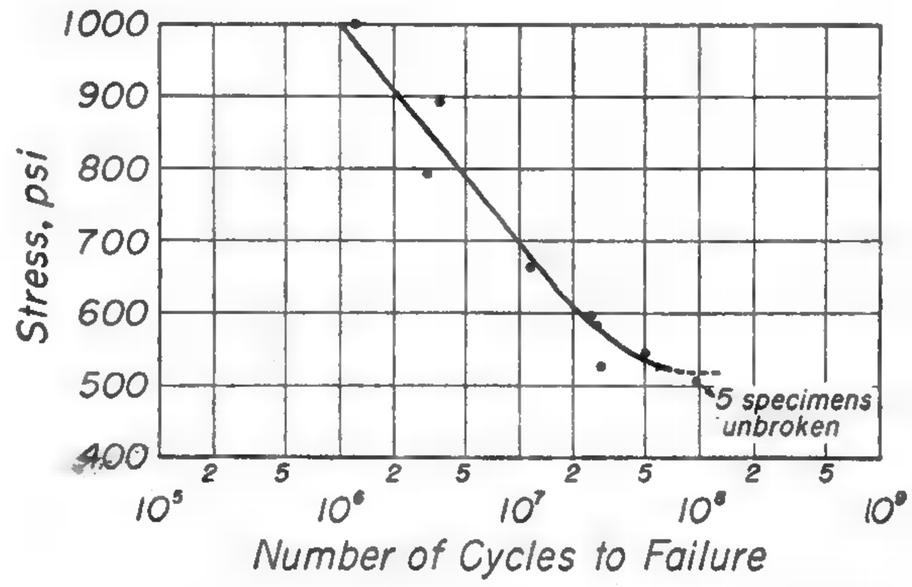

Fig. 1 Fatigue characteristics of chemical lead. Commercial rolled sheet, ⅛ in. thick. Length of specimen parallel to the direction of rolling. Stressed by flexure, 860 cycles per min.

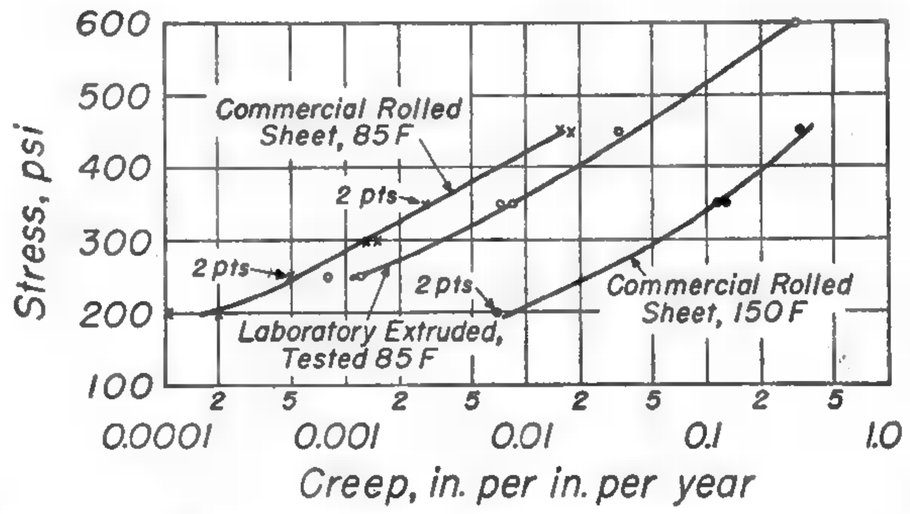

Fig. 2 Creep of chemical lead. Specimens, ¾ in. by ⅛ in. with 10-in. gage length. Length of specimen parallel to the direction of rolling or extrusion.

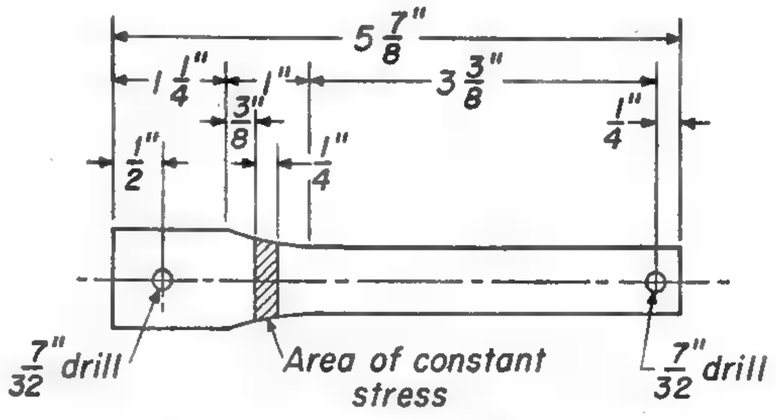

Fig. 3 Fatigue-test specimen for sheet lead

N *1 Melting temperature range.* 400 to 450 C (750 to 850 F)
2 Casting temperature range (ingot). 420 to 445 C (790 to 830 F)
11 Suited to forming by casting, cold rolling and extrusion

See also data sheet for 99.73+ Pb.

Table I. Mechanical Properties of Chemical Lead

Lot	Tensile Strength, psi	Yield Strength (0.5% offset), psi	Percentage Elongation	Rockwell Hardness (special scale)	Micro-character K	Conditions of Material
A	2961	....	42.2	84	....	Laboratory rolled. 2-in. gage length. Less than 30 days after rolling
A	....	....	....	80.9	6.14	Cross section of pig
B	2750	....	35.0	75	....	Laboratory rolled. 2-in. gage length. 3 years after rolling
C	2580	1380	22.0	75	....	Laboratory rolled. 8-in. gage length. 3 years after rolling
C	2800	....	44.0	80	....	Laboratory rolled. 2-in. gage length. 30 days after rolling
C	2150	....	48.0	70	....	Laboratory extruded tape. 2-in. gage length. 30 days after extrusion
D	2630	....	52.0	75	....	Commercial rolled sheet. 2-in. gage length. Cut parallel to direction of rolling. Age unknown
D	2510	1320	27.0	75	....	As above, except 8-in. gage length
E	2575	....	57.0	78	....	Commercial extruded sheet. 2-in. gage length, cut as above. Age unknown
F	2385	1180	29.0	71	5.58	Commercial rolled sheet. 8-in. gage length, cut as above. Age unknown
G	....	....	....	....	5.77	Commercial, steel-backed lead plate

Lead (99.73+ Pb)

COMPILED BY G. O. HIERS*

A *1 Common names.* **Corroding Lead, Common Desilverized Lead, Soft Undesilverized Lead**
3 ASTM number. B 29-43
4 Government number. QQ-L-171

B *1 Typical uses.* Storage batteries, sheath for electric cable, paint, ammunition, anti-knock fluid, sheet, calking, insecticides, type metal, solder, bearing metals, foil, ceramics, liquid medium for heat treating, collapsible tubes, coatings, seals, powder.
2 Precautions in use. Avoid inhalation of lead dust and fumes. Do not use lead to conduct very soft water for drinking, or in contact with food products.

C *1 Density* at 20 C (68 F).
(cast) 11.34 g per cu cm (0.4092 lb per cu in.)
(rolled) 11.36 g per cu cm (0.41 lb per cu in.)
2 Density versus temperature.

Temperature, deg Cent	20	318	(l) 327	400	600	800
Density, g per cu cm	11.34	11.00	10.686	10.597	10.359	10.139

D *1 Melting point.* 327.4 C (621.0 F)
4 Boiling point. 1725 C (3137 F)
6 Thermal expansion (linear)
17 to 100 C (63 to 212 F) 0.0000293 per °C
−190 to 19 C (−310 to 66 F) 0.0000265 per °C
11 Specific heat at 0 C (32 F). 0.0309 cal per g
12 Specific heat versus temperature.

Temperature, deg Cent	−180 to 20	0 to 100	150	200	
Specific heat, cal per g	0.0300	0.03046	0.03176	0.03243	
Temperature, deg Cent	250	300	365	378	459
Specific heat, cal per g	0.03312	0.03380	0.0335	0.0338	0.0335

Heat content (above 25 C) versus temperature

Temperature, deg Cent	100	200	300	400	500	600	800	1000
Heat content, cal per g	2.3	5.5	8.8	18.0	21.3	24.6	31.2	37.7

13 Latent heat of fusion. 6.26 cal per g
15 Latent heat of vaporization. 223 cal per g
16 Thermal conductivity at 0 C (32 F). 0.083 cal/sq cm/cm/°C/sec
17 Thermal conductivity versus temperature.

Temperature, deg Cent	100	200	400	500	600	700
Ther cond, cal/cm/°C/sec	0.081	0.077	0.038	0.037	0.036	0.036

E *1 Volume conductivity* referred to standard copper. 8.3%
2 Electrical resistivity at 20 C (68 F). 20.648 microhm-cm
4 Electrical resistivity (liquid) at 340 C (644 F). 97.867 microhm-cm
5 Temperature coefficient of electrical resistivity 20 to 40 C (68 to 104 F). 0.00336 microhm-cm per °C
Electrical resistivity versus temperature.

Temperature, deg Cent	100	200	300	400
Resistivity, microhm-cm	27.021	36.478	47.938	101.8

10 Electrochemical equivalent.
(valence 2) 1.0736 mg per coulomb
(valence 4) 0.5368 mg per coulomb
11 Electrolytic solution potential vs. hydrogen. 0.122 v
16 Supraconductive at 4 deg Kelvin

F *1 Reflectivity.* 62% for $\lambda = 5890$ A
2 Refractive index.
Solid, 2.01 in yellow light
Molten, 0.415 for $\lambda = 6020$ A
3 Absorptive index.
Solid, 3.48 in yellow light

G *2 Magnetic susceptibility.* minus 0.12×10^{-6} cgs

H *1 Velocity of sound* at 18 C (64 F). 4026 ft per sec

I *1 General resistance to corrosion.* Similar to that of chemical lead (99.90+ Pb)

J *1 Crystal structure.* Face-centered cubic; $a_0 = 4.9389$ kX
5 Minimum interatomic distance. 3.492 kX

K *Mechanical Properties.*

Form	Tensile Strength, psi	Yield Strength, psi	Percentage Elongation	Percentage Reduction of Area	Brinell Hardness Number
Sand cast	1700 to 1900	800	30	100	3.2 to 4.5
Chill cast	2000	...	47	100	4.2

Form	Modulus of Elasticity, psi	Impact Value (Charpy), ft-lb	Shear Strength, psi	Endurance Limit for 10^6 cycles, psi	Poisson's Ratio
Sand cast	2,000,000	....	1825	470	....
Chill cast	.....	10.4	1825	...	0.40 to 0.45

7 Viscosity at 376 C (709 F). 0.0167 cgs units
8 Surface tension at 400 C (752 F). 438 dynes per cm

N *17 Joining.*
Soft solder with 50-50 or 40-60; rosin or stearic acid flux.
Oxyhydrogen welding. No flux; slightly reducing flame. Thin lead requires small torches; thick lead, larger torches.

* Research Laboratories, National Lead Company, Brooklyn

Pb – 0.028 Ca

COMPILED BY E. E. SCHUMACHER*

B *1 Typical uses.* Cable sheath and creep-resistant pipe or sheet
2 Precautions in use. Same as for lead
C *1 Density* at 20 C (68 F). 11.34 g per cu cm (0.409 lb per cu in.)
D *1 Liquidus temperature.* 327.5 C (621.5 F)
2 Solidus temperature. 327.4 C (621.3 F)
E *1 Volume conductivity* referred to standard copper. 8.2%
2 Electrical resistivity at 20 C (68 F). 21.1 microhm-cm
I *1 General resistance to corrosion.* Similar to lead.
K *Mechanical Properties.* See Table I.
6 Minimum creep rate at 26.7 C (80 F). 360 psi, 0.1% per year
M *Composition Limits.* Extrusions, *components:* 0.023 to 0.033% Ca; 0.02 to 0.1% Cu; 0.002 to 0.02% Ag; *impurities:* 0.005% max Bi; 0.005% max Sn.
N *3 Alloying.* Add calcium as 1 to 2% Ca-Pb at 380 to 400 C (715 to 750 F).
Precautions in melting. Do not break the surface of the melt more than necessary.
16 Joining. Solder with most soft solders; stearin flux.

* Bell Telephone Laboratories, Inc., New York City

Table I. Mechanical Properties of Pb – 0.028 Ca

Condition	Tensile Strength, psi	Percentage Elongation	Endurance Limit, 700 cycles per min, psi
Extruded	3000	40	....
Extruded and aged 1 yr at room temperature	4500	25	1700

References

E. E. Schumacher and G. M. Bouton, Age Hardening Lead-Calcium Alloys, Metals & Alloys, 1, 405 (1930)
R. S. Dean and J. E. Ryjord, Alloys for Cable Sheathing, Metals & Alloys, 1, 410 (1930)
N. Baar, Z anorg Chem, 70, 352 (1911)

99 Pb – 1 Sb

COMPILED BY H. E. HOWE*

A *1 Common name.* **1% Antimonial Lead**
B *1 Typical uses.* Cable sheathing
C *1 Density* at 18 C (64 F). 11.27 g per cu cm (0.406 lb per cu in.)
5 Solidification shrinkage. 3.72%
D *1 Liquidus temperature.* 320 C (608 F)
2 Solidus temperature. 312 C (595 F)
6 Thermal expansion 20 to 100 C (68 to 212 F). 0.0000288 per °C
11 Specific heat 20 to 100 C (68 to 212 F). 0.0312 cal per g
16 Thermal conductivity at 0 C (32 F). 0.080 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 7.88% (heat treated at 235 C, quenched, and aged 150 days)
2 Electrical resistivity at 20 C (68 F). 22.0 microhm-cm
K *Mechanical Properties.* Sample extruded and aged 1 month: tensile strength 3000 psi; elongation 50%; Brinell hardness 7; modulus of elasticity 2,000,000 psi; endurance limit (20,000,000 cycles) 1150 psi
6 Minimum creep rate. (extruded cable sheath)
at 0 C (32 F). 650 psi, 1% in 10,000 hr
at 30 C (86 F). 350 psi, 1% in 10,000 hr
at 66 C (150 F). 150 psi, 1% in 10,000 hr
N *2 Casting temperature range* (ingot). 400 to 500 C (752 to 932 F)

References

R. S. Dean, L. Zickrick and F. C. Nix, Lead-Antimony System and Hardening of Lead Alloys, Trans AIME, Inst Metals Div, 73, 505 (1926)
W. E. Goodrich, Volume Changes during the Solidification of Metals and Alloys of Low Melting Point, Trans Faraday Soc, 25, 558 (1929)
G. O. Hiers, Discussion of paper on Some Peculiar Results in Hardness of Antimony-Lead Alloys, Proc AIME, Inst Metals Div, 373 (1928)
G. W. Vinal, "Storage Batteries", 3d Ed, John Wiley & Sons, 1940
B. Blumenthal, The Constitution of the Lead-Antimony and Lead-Antimony-Silver Systems, Trans AIME, 156, 240 (1944)
H. F. Moore, B. B. Betty, and C. W. Dollins, The Creep and Fracture of Lead and Lead Alloys, Univ Ill Bull 27 (1935)
A. A. Smith, Jr., and H. E. Howe, Creep Properties of Some Rolled Lead-Antimony Alloys, Trans AIME, 161, 472 (1945)

96 Pb – 4 Sb

COMPILED BY H. E. HOWE*

A *1 Common name.* **Hard Lead**
C *1 Density* at 18 C (64 F). 11.04 g per cu cm (0.398 lb per cu in.)
5 Solidification shrinkage. 3.36%
D *1 Liquidus temperature.* 299 C (570 F)
2 Solidus temperature. 252 C (486 F)
6 Thermal expansion 20 to 100 C (68 to 212 F). 0.0000278 per °C
11 Specific heat 20 to 100 C (68 to 212 F). 0.0318 cal per g
16 Thermal conductivity 20 to 100 C (68 to 212 F). 0.073 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 7.7% (heat treated at 235 C, quenched, aged 150 days)
2 Electrical resistivity at 20 C (68 F). 24.0 microhm-cm
K *Mechanical Properties.*

Condition	Tensile Strength, psi	Elongation, percentage	Brinell Hardness Number (⅛-in. ball, 9.85-kg load, 30 sec)	Endurance Limit (20,000,000 cycles), psi
Commercially cold rolled, 95% reduction	4,020	48.3	8.1	1500
Heated 235 C, quenched and aged 1 day	11,670	6.3	24	....

6 Minimum creep rate at 30 C (86 F). Cold rolled in the laboratory, 210 psi, 1% in 10,000 hr
N *2 Casting temperature range* (ingot). 400 to 500 C (752 to 932 F)

References. *See* **99 Pb – 1 Sb.**

* American Smelting and Refining Company, Barber, N. J.

94 Pb – 6 Sb

COMPILED BY H. E. HOWE*

A *1 Common name.* **Hard Lead**
B *1 Typical uses.* Rolled sheet, extruded pipe for industrial purposes where similar corrosion resistance but higher strength is necessary than in soft lead
C *1 Density* at 18 C (64 F). 10.88 g per cu cm (0.393 lb per cu in.)
5 Solidification shrinkage. 3.11%
D *1 Liquidus temperature.* 285 C (545 F)
2 Solidus temperature. 252 C (486 F)
6 Thermal expansion 20 to 100 C (68 to 212 F). 0.0000272 per °C
11 Specific heat 20 to 100 C (68 to 212 F). 0.0322 cal per ■
16 Thermal conductivity 20 to 100 C (68 to 212 F). 0.069 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 7.6% (held at 225 C, quenched, and aged 150 days)
2 Electrical resistivity at 20 C (68 F). 25.3 microhm-cm
I *2 Resistance to specific agents.* See Table I.
K *Mechanical Properties.*

Table I. Resistance of 94 Pb – 6 Sb to Corrosion

Corrosive Agent	Resistance	Corrosive Agent	Resistance
Acetone	Good	Ammonia	Resistant
Acid acetic	General attack	Ammonium sulfate	Resistant
Acid carbonic	Severe general attack	Bromine	General attack
Acid citric	Severe general attack	Calcium chloride	General attack
Acids fatty	Satisfactory in absence of O_2	Carbon dioxide	Moderate attack in H_2O solution
Acid formic	Severe general attack	Carbon tetrachloride	Resistant in anhydrous
Acid hydrochloric	General attack	Copper sulfate	Resistant
Acid hydrofluoric	General attack	Ferric chloride	Severe attack
Acid nitric	Severe general attack	Hydrogen sulfide	General attack
Acid oxalic	Severe general attack	Iodine	General attack
Acid phosphoric	Resistant	Magnesium sulfate	Resistant
Acid sulfuric	Resistant	Potassium nitrate	General attack
Acid tartaric	Moderate attack	Refrigerants	Resistant in anhydrous
Air	Resistant	Sodium sulfate	Resistant
Alcohol ethyl	Resistant	Water distilled	Considerable attack
Alcohol methyl	Resistant	Water sea	Resistant
Alcohols higher	Resistant		
Aluminum sulfate	Resistant		

Condition	Tensile Strength, psi	Elongation in 2 in., percentage	Brinell Hardness Number	Endurance Limit (20,000,000 cycles), psi
Chill cast	6840	24	13.0	2500
Commercially cold rolled 95%	4100	47	...	1500
Extruded	3300	65	10.7	1200

Strength and Hardness at Elevated Temperatures.

Condition	Tensile Strength, psi 100 C	Tensile Strength, psi 200 C	Brinell Hardness Number 100 C	Brinell Hardness Number 200 C
Chill cast	3500	850	6.8	2.0
Cold rolled	1850	600	3.9	1.6

6 Minimum creep rate at 30 C (86 F). Colled rolled in the laboratory, 400 psi, 1% in 10,000 hr
100 C (212 F). 50 psi, 1% in 10,000 hr
N *2 Casting temperature* (ingot). 400 to 500 C (752 to 842 F)

References. *See* 99 Pb – 1 Sb.

92 Pb – 8 Sb

COMPILED BY H. E. HOWE*

A *1 Common name.* **8% Antimonial Lead**
C *1 Density* at 18 C (64 F). 10.74 g per cu cm (0.388 lb per cu in.)
5 Solidification shrinkage. 2.88%
D *1 Liquidus temperature.* 271 C (520 F)
2 Solidus temperature. 252 C (486 F)
6 Thermal expansion 20 to 100 C. 0.0000267 per °C
11 Specific heat 20 to 100 C. 0.0326 cal per g
16 Thermal conductivity. 20 to 100 C (68 to 212 F). 0.065 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 7.5% (held at 235 C, quenched and aged 150 days)
2 Electrical resistivity at 20 C (68 F). 26.5 microhm-cm

K *Mechanical Properties.*

Condition	Tensile Strength, psi	Percentage Elongation	Brinell Hardness Number (⅛-in. ball, 9.85-kg load, 30 sec)	Endurance Limit (20,000,000 cycles), psi
Commercially rolled, 95% reduction	4,650	31.3	9.5	1750
Heat treated at 235 C, quenched, aged 1 day	12,350	4.7	26.3	....

6 Minimum creep rate at 30 C (86 F). Cold rolled in the laboratory, 425 psi, 1% in 10,000 hr
N *2 Casting temperature* (ingot). 400 to 500 C (752 to 932 F)

References. *See* 99 Pb – 1 Sb.

91 Pb – 9 Sb

COMPILED BY H. E. HOWE*

A *1 Common name.* **Grid Metal**
B *1 Typical use.* Battery grids
C *1 Density* at ■ C (64 F). 10.66 g per cu cm (0.385 lb per cu in.)
5 Solidification shrinkage. 2.76%
D *1 Liquidus temperature.* 265 C (509 F)
2 Solidus temperature. 252 C (486 F)
6 Thermal expansion. 0.0000264 per °C
11 Specific heat 20 to 100 C (68 to 212 F). 0.0328 cal per g
16 Thermal conductivity 20 to 100 C (68 to 212 F). 0.064 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 7.4% (held at 235 C, quenched, and aged 150 days)
2 Electrical resistivity at 20 C (68 F). 27.1 microhm-cm
K *Mechanical Properties* (chill cast). Tensile strength 7500 psi; elongation 17%; Brinell hardness number 15.4; endurance limit (20,000,000 cycles) 2700 psi.
N *2 Casting temperature* (ingot). 400 to 500 C (752 to 932 F)

References. *See* 99 Pb – 1 Sb.

* American Smelting and Refining Company, Barber, N. J.

97.5 Pb – 1.5 Ag – 1 Sn

COMPILED BY G. O. HIERS*

A *1 Common name.* **Silver Lead Solder**
3 ASTM number. B 32-46T, Alloy grade 02
B *1 Typical uses.* For coating and joining
2 Precautions in use. Generally applied by hot dipping or with a torch.
D *1 Melting point.* 310 C (589 F)
I *2 Resistance to specific agents.* The tin is required in order to make this alloy resistant to humid air.
K *Brinell hardness number.* 13.0
M *Composition Limits* (ASTM B 32-46T, Alloy grade 02). *Components:* 97.5% Pb nominal; 0.75 to 1.25% Sn; 1.3 to 1.7% Ag; *impurities:* 0.40% max Sb; 0.25% max Bi; 0.08% max Cu; 0.02% max Fe; 0.005% max Al; 0.005% max Zn; others (total) 0.08% max.

95 Pb – 5 Sn

COMPILED BY G. O. HIERS*

A *1 Common name.* **5-95 Soft Solder**
3 ASTM number. B 32-46T, Alloy grade 5B
B *1 Typical uses.* For coating and joining metals
2 Precautions in use. Usually applied by hot dipping or by torch
C *1 Density* at 20 C (68 F). 11 g per cu cm (0.397 lb per cu in.)
5 Solidification shrinkage. 3.6%
D *1 Liquidus temperature.* 312 C (594 F)
2 Solidus temperature. 270 C (518 F)
6 Thermal expansion 15 to 110 C (59 to 230 F). 0.0000287 per °C
16 Thermal conductivity at 54 C (129 F). 0.085 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 8.8%
2 Electrical resistivity. 19.5 microhm-cm
G *2 Magnetic susceptibility.* minus 0.01×10^{-6} cgs
I *2 Resistance to specific agents.* This alloy is resistant to acetone, milk, mineral oils, motor fuel and petroleum products, and sea water. It is resistant to air, but does tarnish. It is subject to moderate general attack by ammonium sulfate, photographic solutions, potassium chloride, sodium chloride, sodium sulfate.
K *Mechanical Properties.* Tensile strength 3400 psi; yield strength 1500 psi; elongation 50%; reduction in area 80%; Brinell hardness number 8.
M *Composition Limits* (ASTM B 32-46T, Alloy grade 5B). *Components:* 95% Pb nominal; 4.5 to 5.5% Sn; *impurities:* 0.50% max Sb; 0.25% max Bi; 0.08% max Cu; 0.02% max Fe; 0.005% max Al; 0.005% max Zn; others (total) 0.08% max.

80 Pb – 20 Sn

COMPILED BY G. O. HIERS*

A *1 Common name.* **20-80 Soft Solder**
3 ASTM number. B 32–46T, Alloy grade 20B
B *1 Typical uses.* For coating and joining metals; for filling dents or seams in automobile bodies (body solder).
C *1 Density* at 20 C (68 F). 10.20 g per cu cm (0.368 lb per cu in.)
5 Solidification shrinkage. 3.0%
D *1 Liquidus temperature.* 277 C (531 F)
2 Solidus temperature. 183 C (361 F)
6 Thermal expansion 15 to 110 C (59 to 230 F). 0.0000265 per °C
16 Thermal conductivity at 54 C (129 F). 0.089 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 9.8%
2 Electrical resistivity. 17.5 microhm-cm
G *2 Magnetic susceptibility.* minus 0.08×10^{-6} cgs
I *2 Resistance to specific agents.* This alloy is resistant to milk, mineral oils, motor fuel and petroleum. It is fairly resistant to air, but does tarnish on exposure.
K *Mechanical Properties.* Tensile strength 5800 psi; yield strength 3650 psi; elongation 16%; reduction in area 50%; Brinell hardness number 11.3; impact value, Charpy 12.2 ft-lb; shear strength 4740 psi.
M *Composition Limits* (ASTM B 32-46T, Alloy grade 20 B). *Components:* 80% Pb (nominal); 20% Sn; *impurities:* 0.50% max Sb; 0.25% max Bi; 0.08% max Cu; 0.02% max Fe; 0.005% max Zn; 0.005% max Al; others (total) 0.08% max.

50 Pb – 50 Sn

COMPILED BY G. O. HIERS*

A *1 Common name.* **50-50, Half and Half, Soft Solder**
3 ASTM number. B 32-46T, Alloy grade 50A, 50B
B *1 Typical uses.* For general purposes, the most popular of all lead-tin solders
C *1 Density* at 20 C (68 F). 8.89 g per cu cm (0.321 lb per cu in.)
5 Solidification shrinkage. 2.3%
D *1 Liquidus temperature.* 216 C (421 F)
2 Solidus temperature. 183 C (361 F)
6 Thermal expansion 15 to 110 C (59 to 230 F). 0.0000234 per °C
11 Specific heat at 16 C (60 F). 1.41 cal per g (liquid) 1.27 cal per g
16 Thermal conductivity at 54 C (129 F). 0.111 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 11%
2 Electrical resistivity. 15.6 microhm-cm
G *2 Magnetic susceptibility.* minus 0.04×10^{-6} cgs
I *2 Resistance to specific agents.* This alloy is resistant to the following chemicals: carbonic and phosphoric acids; ammonium chloride, nitrate and sulfate; magnesium sulfate, milk, mineral oils, motor fuel, petroleum products, potassium chloride, sodium carbonate, chloride, nitrate and sulfate, and sea water. It is moderately resistant in air but does tarnish. It is subject to severe general attack by nitric acid.
K *Mechanical Properties.* Tensile strength 6100 psi; yield strength 4800 psi; elongation 60%; reduction in

* National Lead Company, Brooklyn

area 70%; Brinell hardness number 14.5; impact value, Charpy 15.9 ft-lb; shear strength 5870 psi.
7 Viscosity at 350 C (662 F). 0.0127 poise
8 Surface tension at 350 C (662 F). 472 dynes per cm
M *Composition Limits* (ASTM B 32-46T, Alloy grades 50A and 50B).

Designation	Components — Pb nominal	Sn desired	Impurities — Sb max	Bi max	Cu max	Fe max	Al max	Zn max	Others total max
Grade 50A..	50	50	0.12	0.25	0.08	0.02	0.005	0.005	0.08
Grade 50B..	50	50	0.50	0.25	0.08	0.02	0.005	0.005	0.08

85 Pb – 10 Sb – 5 Sn

COMPILED BY A. A. SMITH, JR.*

A *1 Common name.* **Lead-Base Babbitt**
5 Other designations. Similar to AAR (car and tender bearings), SAE 13
B *1 Typical uses.* A babbitt for light loads and speeds, car journal bearings
C *1 Density.* 10.24 g per cu cm (0.38 lb per cu in.)
5 Solidification shrinkage. 2 + %
D *1 Liquidus temperature.* 256 C (493 F)
2 Solidus temperature. 240 C (464 F)
11 Specific heat 20 to 237 C (68 to 459 F). 0.036 cal per g
13 Latent heat of fusion. 21.5 cal per g

Table I. Mechanical Properties of 85 Pb – 10 Sb – 5 Sn

Testing Temperature, deg Cent	Tensile Strength, psi	Percentage Elongation	Brinell Hardness Number	Modulus of Elasticity, psi	Endurance Limit (20,000,000 cycles), psi
25	10,000	5	19	4,200,000	3700
100	4,900	30	8.5	.....	....

E *1 Volume conductivity* referred to standard copper. 6.0%
2 Electrical resistivity. 28.7 microhm-cm
These last two values will vary depending on the thermal treatment of the alloy.
K *Mechanical Properties* (chill cast). *See* Table I.
M *Composition Limits* (specification SAE 13). All forms, *components:* 4.50 to 5.50% Sn; 9.25 to 10.75% Sb; *impurities:* 0.5% max Cu; 0.60% max As.
N *2 Casting temperature range.* 325 to 400 C (617 to 750 F)

References

J. R. Freeman, Jr. and R. W. Woodward, Some Properties of White Metal Bearing Alloys at Elevated Temperatures, Nat Bur Standards Tech Paper 188 (1921)
J. R. Freeman, Jr. and P. F. Brandt, The Effect of Impurities on the Compressive Strength and Hardness of Babbitt, Proc ASTM, 24, Pt 1, 253 (1924)
"Mechanical Properties of Metals and Alloys," Nat Bur Standards Circular C 447 (1943)

80 Pb – 15 Sb – 5 Sn

COMPILED BY A. A. SMITH, JR.*

A *1 Common name.* **Lead-Base Babbitt**
3 ASTM number. B 23–46T, Alloy grade 8 (formerly EA B 23b, No. 8)
4 Government number. QQ-M-161, grade 6; Navy 46M2, grade 6
B *1 Typical uses.* A babbitt for light loads and moderate speeds; mining machinery, transmission machinery, car journals; used with all kinds of shafting.
C *1 Density* at 20 C (68 F). 10.04 g per cu cm (0.36 lb per cu in.)
5 Solidification shrinkage. 2% approx
D *1 Liquidus temperature.* 272 C (522 F)
2 Solidus temperature. 240 C (464 F)
6 Thermal expansion 20 to 100 C (68 to 212 F). 0.000024 per °C
11 Specific heat 20 to 100 C (68 to 212 F). 0.036 cal per g
13 Latent heat of fusion. 26.2 cal per g
16 Thermal conductivity at 20 C (68 F). 0.058 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 6.1%
2 Electrical resistivity at 20 C (68 F). 28.2 microhm-cm
These last two values will vary depending on the thermal treatment of the alloy.
K *Mechanical Properties* (chill cast, 0.125 in.).

Testing Temperature, deg Cent	Tensile Strength, psi	Percentage Elongation	Brinell Hardness Number	Modulus of Elasticity, psi	Endurance Limit (20,000,000 cycles), psi
25	10,000	5	20	4,200,000	3900
100	5,400	27	10	.....	....
150	2,900	55	7.3	.....	....

M *Composition Limits.* All forms, *components:* 4.5 to 5.5% Sn; 14 to 16% Sb; *impurities:* 0.5% max Cu; 0.20% max As.
N *2 Casting temperature range.* 340 to 425 C (645 to 800 F)
References. *See* 85 Pb – 10 Sb – 5 Sn.

75 Pb – 15 Sb – 10 Sn

COMPILED BY A. A. SMITH, JR.*

A *1 Common name.* **Lead-Base Babbitt**
3 ASTM number. B 23–46T, Alloy grade 7 (formerly EA B 23b, No. 7)
4 Government number. Federal QQ-M-161, grade 7; Navy 46M2, grade 7
5 Other designations. SAE 14
B *1 Typical uses.* A babbitt for moderate loads and speeds, blowers, pumps, electric motors, machine tools
C *1 Density* at 20 C (68 F). 9.73 g per cu cm (0.35 lb per cu in.)
5 Solidification shrinkage. 2.3%
D *1 Liquidus temperature.* 268 C (514 F)
2 Solidus temperature. 240 C (464 F)
6 Thermal expansion 20 to 100 C (68 to 212 F). 0.0000196 per °C
11 Specific heat 20 to 100 C (68 to 212 F). 0.038 cal per g
13 Latent heat of fusion. 26.2 cal per g
16 Thermal conductivity at 20 C (68 F). 0.057 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 6.0%
2 Electrical resistivity. 28.6 microhm-cm

* American Smelting and Refining Company, Barber, N. J.

These last two values will vary depending on the thermal treatment of the alloy.

K *Mechanical Properties* (chill cast). *See* Table I.

M *Composition Limits.* All forms, *components:* 9.3 to 10.7% Sn; 14 to 16% Sb; *impurities:* 0.5% max Cu; 0.60% max As; 0.10% max Fe.

N 2 *Casting temperature range.* 325 to 400 C (617 to 750 F)

References. *See* 85 Pb – 10 Sb – 5 Sn.

Table I. Mechanical Properties of 75 Pb – 15 Sb – 10 Sn

Testing Temperature, deg Cent	Tensile Strength, psi	Percentage Elongation	Brinell Hardness Number	Modulus of Elasticity, psi	Endurance Limit (20,000,000 cycles), psi
25	10,500	4	22	4,200,000	4000
100	5,500	25	10.5	.....	.....
150	3,000	[illegible]	8	.....	.....

83 Pb – 15 Sb – 1 Sn – 1 As

COMPILED BY A. A. SMITH, JR.*

A 1 *Common name.* **Arsenical Lead-Base Babbitt**
2 *Trade name.* "S" Babbitt
3 *ASTM number.* B 23-46T, Alloy grade 15
4 *Government number.* QQ-M-161, grade 10
5 *Other designations.* SAE 15

B 1 *Typical uses.* A babbitt for high loads and speeds, diesel engines, automotive engines, steamships, steel mills, and all kinds of machinery.

C 1 *Density* at 20 C (68 F). 10.1 g per cu cm (0.365 lb per cu in.)
5 *Solidification shrinkage.* 2.5% approx

D 1 *Liquidus temperature.* 353 C (667 F)
2 *Solidus temperature.* 247 C (595 F)

K *Mechanical Properties* (chill cast).

Testing Temperature, deg Cent	Tensile Strength, psi	Percentage Elongation	Brinell Hardness Number	Modulus of Elasticity, psi	Endurance Limit (20,000,000 cycles), psi
25	10,350	2	20	4,200,000	4300
100	6,400	9	12.5	.....	.....
150	3,740	26	7.4	.....	.....

M *Composition Limits.* All forms, *components:* 0.75 to 1.25% Sn; 0.8 to 1.4% As; 14.5 to 17.5% Sb; *impurities,* 0.6% max Cu.

N 2 *Casting temperature.* 480 to 540 C (900 to 1000 F)

83.5 Pb – 12.75 Sb – 3 As – 0.75 Sn

COMPILED BY A. A. SMITH, JR.*

A 1 *Common name.* **Arsenical Lead-Base Babbitt**
2 *Trade name.* "G" Babbitt

B 1 *Typical uses.* This babbitt retains its strength and hardness exceptionally well at elevated temperatures, as required in diesel engines, tractors, trucks, and heavy machinery.

C 1 *Density* at 20 C (68 F). 10.1 g per cu cm (0.365 lb per cu in.)
5 *Solidification shrinkage.* 2.8%

D 1 *Liquidus temperature.* 313 C (595 F)
2 *Solidus temperature.* 247 C (477 F)

K *Mechanical Properties* (chill cast).

Testing Temperature, deg Cent	Tensile Strength, psi	Percentage Elongation	Brinell Hardness Number	Modulus of Elasticity, psi	Endurance Limit (20,000,000 cycles), psi
25	9800	1.5	22	4,200,000	4400
100	6700	4	13.5	.....	.....
150	4200	10	10.0	.....	.....

M *Composition Limits.* All forms, *components:* 0.6 to 1.0% Sn; 1.5 to 3.0% As; 12.0 to 13.5% Sb; *impurities,* 0.1% max Cu.

Reference. A. J. Phillips, A. A. Smith, Jr., and P. A. Beck, The Properties of Certain Lead Bearing Alloys, Proc ASTM, 41, 886 (1941)

* American Smelting and Refining Company, Barber, N. J.

Type Metals

Compositions and properties of the following type metals are given in the article on page 957:

Electrotype, Stereotype, Linotype, Monotype, Foundry Type.

MAGNESIUM AND MAGNESIUM ALLOYS

Prepared under the direction of

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The Magnesium Industry

BY W. G. HARVEY*

MAGNESIUM was isolated as a metallic element and some of its properties determined as early as 1830. Commercial production was not attempted, however, until the beginning of the twentieth century. With density approximately 1.74, or about two-thirds that of aluminum, magnesium is the lightest of the structural metals. The gradual increase in its production and use in the years before World War II can be attributed to the lightness of magnesium alloys, which answered the demand for weight saving in aircraft and in portable equipment and moving parts of many types.

Occurrence. The principal ores of magnesium are dolomite, magnesite and carnallite. In addition, magnesium occurs as magnesium chloride in certain natural salt brines. These brines were the chief source of the magnesium produced in this country in the years before World War II. Another important and virtually inexhaustible source of magnesium is sea water, which contains approximately 0.5% magnesium chloride. This fact would indicate that a cubic mile of sea water contains about nine billion pounds of metal. During World War II, sea water furnished the raw material for the greater portion of magnesium production.

Production Methods. Before 1928, magnesium was made in the United States either by the electrolysis of magnesium chloride or by the electrolysis of magnesium oxide dissolved in molten fluorides. The electrolysis of magnesium oxide was discontinued in 1928, and from then until 1939 the electrolysis of magnesium chloride, derived from underground natural brines, was the only source of the magnesium produced in America.

The war years were characterized by a sharp increase in the production of magnesium. A number of new processes were developed and modifications were made in existing ones. The diversification of methods was largely justified by the necessities of war, such as the movement to safer plant locations, the shortage of certain materials and the need for

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Prepared for the Magnesium Committee

economizing in the use of direct-current electricity. At the peak of production in 1943, the following processes were in operation:

Type of Process	Reducing Agent	Source of Magnesium	Derived from
Electrolytic reduction	Electricity (direct current)	Magnesium chloride	Natural brines, potash waste liquors, sea water, dolomite, magnesite
Thermal reduction	Carbon	Magnesium oxide	Sea water
	Ferrosilicon	Magnesium oxide	Dolomite

In the electrolytic process, the cell feed in all instances is molten and substantially anhydrous magnesium chloride. The source of this magnesium chloride varies with the particular installation, and may be underground brines, sea water, waste liquors from the potash industry, dolomite or magnesite. The content of magnesium chloride in brines, waste potash liquors and sea water is low, but its extraction, while not simple, constitutes a well-developed chemical process. Large volumes of raw material must be handled. It is important that the water from the magnesium chloride be eliminated carefully, especially in the final stages, to avoid decomposition. Complete dehydration is not considered essential. Ocean water is treated with lime, which precipitates the magnesium content as hydroxide. This hydroxide is then converted into a concentrated magnesium chloride solution by means of hydrochloric acid made from the chlorine produced by the electrolysis.

One of the electrolytic processes obtains the magnesium chloride by direct action of the byproduct chlorine on dolomite (or magnesite), thus producing an anhydrous cell feed without the need for dehydration. The electrolytic processes, regardless of the source of raw material, are based on the decomposition of substantially anhydrous magnesium chloride into metallic magnesium and chlorine gas. Differences between the density of the molten electrolyte and that of the produced metal cause the metal to rise to the bath surface, where it is ladled out into molds. The chlorine gas is removed through suitable ducts by gentle suction and is used to produce more cell feed by a cyclic process. When the cell feed is not completely anhydrous, some hydrochloric acid gas is produced.

The thermal reduction processes owed their value to the fact that they could be built and put into operation quickly and did not depend on direct-current electricity as a source of power. These processes were of two types, one using carbon and the other using silicon, in the form of ferrosilicon, for the reduction of the oxide. In the carbon reduction, the magnesium oxide (mixed with some suitable form of carbon) is heated to more than 2000 C in a closed electric-arc furnace. Magnesium is liberated as a vapor together with carbon monoxide gas. Since this reaction is reversible at lower temperatures, it requires some form of shock cooling, using natural gas or hydrogen. Oil has also been used for cooling. This rapid reduction in temperature condenses the magnesium vapor to a fine dust which, after being formed into briquettes, is distilled to produce ingot metal. This method is known as the Hansgirg process.

Table I

Production of Primary Magnesium in the United States

Year	1000 Pounds	Year	1000 Pounds	Year	1000 Pounds
1915	88	1926	323	1937	5,782
1916	75	1927	366	1938	6,433
1917	116	1928	521	1939	6,700
1918	284	1929	1330	1940	12,522
1919	127	1930	1174	1941	32,771
1920	124	1931	1161	1942	97,959
1921	48	1932	1946	1943	368,156
1922	60 (a)	1933	1254	1944	336,674
1923	125 (a)	1934	1145	1945	65,584
1924	128 (a)	1935	2889	1946	10,635
1925	245	1936	4805	1947	18,000 (a)

(a) Estimated

Reduction of calcined magnesite or dolomite by the use of ferrosilicon is known as the Pidgeon process. Finely ground ferrosilicon is briquetted with calcined dolomite in the correct proportions and is placed in highly evacuated cylindrical retorts, generally installed in a horizontal position. The temperature of reduction is about 1150 C. The reduced magnesium condenses in the cooler end of the retort in the form of crystalline rings of metal. This is essentially a batch process.

All these processes had their justification in the need for producing enough magnesium to meet the rising demands of military uses. At peak, the total capacity installed in the United States was approximately 586,000,000 lb annually, divided by processes into 72% electrolytic, 4% carbothermic, and 24% ferrosilicon.

The production of primary magnesium for 1915 to 1947 is shown in Table I. Table II gives the percentage produced by the three basic processes in 1942, 1943, 1944 and 1945.

Table II. Production of Magnesium—By Process

Process	Percentage of Total 1942	1943	1944	1945
Electrolytic	94	85	81	91
Carbothermic	2	4	5	0
Ferrosilicon	4	11	14	9

Principal Products. Pure magnesium is produced in the form of ingots, powder, ribbon, wire, and extruded and rolled strip. The alloys of magnesium are available in the following forms: sand castings, permanent mold and die castings; extruded round, square, rectangular and hexagonal bars, shapes and structural sections; tubing and hollow shapes; rolled plate and sheet; and hammer and press forgings.

Alloys. Pure magnesium has only moderate strength (27,000 psi in the annealed condition); consequently, where structural stresses are involved, magnesium-rich alloys are used. With the exception of iron, chromium and, to a lesser extent, manganese, magnesium will alloy with most of the common metals. However, only a few of these form useful alloys. Certain alloys containing aluminum or zinc or combinations of these are used extensively, while an alloy containing tin and aluminum has good hammer-forging properties. In Table III is a list of the most common magnesium alloys with their approximate compositions and principal uses.

Table III. Composition of Magnesium Alloys

ASTM Designation	Percentage Al	Zn	Mn	Sn	Principal Use
A10	10.0	..	0.10	..	Sand and permanent mold castings
AZ92	9.0	2.0	0.10	..	Sand and permanent mold castings
AZ63	6.0	3.0	0.20	..	Sand castings
M1	..	..	1.50	..	Sheet and extrusions
AZ31	3.0	1.0	0.30	..	Sheet and extrusions
AZ51	4.8	0.8	0.25	..	Sheet and plate
AZ61	6.5	1.0	0.20	..	Extrusions and forgings
AZ80	8.5	0.5	0.15	..	Extrusions and forgings
TA54	3.5	..	0.50	5.0	Hammer forgings
AZ91	9.0	0.7	0.20	..	Die castings

Fabricating Methods. Magnesium alloys react with moisture at or near the melting point; consequently, sand castings cannot be made successfully in the ordinary green sand molds used for other metals. A number of inhibitors have been developed for mixing with the green sand to prevent this reaction. Among the most popular are sulfur, boric acid, diethylene glycol, ammonium fluoride, or combinations of these substances. A small amount of the inhibitor is sufficient when mixed thoroughly with the green sand. Some modification of standard casting methods is generally employed to compensate for the lighter weight of the molten magnesium metal. This is accomplished by using more gates and risers and making these higher and of greater cross section.

The mechanical properties of most magnesium alloys used for casting can be improved by heat treatment. Castings are often aged after heat treatment, when the castings are to be used in highly stressed applications.

Certain magnesium alloys, developed particularly for extrusion, can be fabricated by this process into virtually any shape for which die equipment can be constructed. The

alloys plastic from 500 to 650 F are suitable for forging.

Methods for rolling sheet involve an initial breakdown of either large cast ingots or specially made extruded slabs at an elevated temperature. This hot rolling operation reduces the ingots to approximately ¼ in. in thickness. Reduction is continued by hot slabbing until the thickness reaches ⅛ to $\frac{1}{16}$ in. Further reduction, accomplished by cold rolling, produces satisfactory mechanical properties and surface finish. It is necessary to anneal magnesium sheet frequently during cold rolling. Sheet is supplied in hard and annealed tempers and also as hot rolled. Widths as great as 60 in. and lengths as great as 144 in. can be produced with a maximum weight of 220 lb.

Uses. Pure magnesium is employed as a deoxidizer for brass, bronze, nickel, silver and monel metal. It is particularly useful in the nickel industry because of the ability to reduce nickel sulfide and to render the nickel more malleable. Magnesium serves as an important constituent with other metals. A number of high-strength aluminum alloys contain from 0.2 to 10.0% Mg. In the form of powder, magnesium is used as a pyrotechnic for marine and railroad signals and in military applications. Shavings and coarse powder are used for the synthesis of certain organic chemicals.

These applications of pure magnesium have been cited because they are particularly important; however, they constitute only a small proportion of the present uses. The majority of present and future uses are in alloy products, where high strength and lightness are obtainable. The magnesium alloys weigh approximately two-thirds as much as aluminum and one-fourth as much as brass and iron. In aircraft, magnesium castings are used for many engine parts, such as accessory drive housings, blowers and nose pieces, for landing wheels and many parts of the fuselage.

In other industries, magnesium products are used for parts of bread slicers, pneumatic tools, portable sewing machines, typewriters, textile machinery and packaging equipment. In general, in the form of sand castings, permanent mold and die castings, as extrusions and as forgings, magnesium alloy products are used in equipment which must be portable or in which it is desirable to reduce the inertia of moving parts.

Magnesium Sand Foundry Practice

By M. E. Brooks*

THE MAJOR APPLICATION for magnesium alloys is in sand castings, covering a wide variation in complexity of design. Production castings are being made varying in size from a few ounces to as much as 1000 lb. Magnesium sand castings are used in aircraft parts for engines, landing gear and control mechanisms. They are also used in lawn mowers, pneumatic tools, portable saws, X-ray units, and in many other fields where the combination of strength and light weight is advantageous.

Molding Sand. The preferred molding sand for the casting of these alloys is synthetic, made either from washed silica sand or from bank sand, and bonded with 3 to 4% bentonite. The base sand should have an AFA grain fineness of 60 to 90, which is adequate to ensure the desired high permeability.

All green molding sand must be treated with a chemical agent to inhibit the action of the water vapor on the hot metal. At present, American foundries are using various combinations of agents—usually a mixture of two or more of the following materials: sulfur, boric acid, and ammonium fluoride compounds. The concentration of the protective agent decreases slowly as the sand is used, and more agent must be added to maintain proportions.

Gating and Feeding. The proper gating of a casting is one of the most important concerns in operating a magnesium foundry. The metal should enter the mold cavity near the lowest point and flow through a number of small gates rather than a few large ones. For the common type of gating, a runner is placed completely around the casting with a number of gates entering the casting uniformly around its perimeter. To make sound castings, it is necessary to use large risers properly placed to feed heavy sections. Chills should be used to assist in making heavy sections sound. Cast iron makes the best chill material for magnesium alloys.

Cores. Cores should be made from an open sand and must be strong and hard enough to withstand handling. Care should be taken to ensure that cores are well vented, with adequate provision for the core gases to travel back through the cores to the outside of the mold. Magnesium alloys are so light that back pressure, built up in the cores or in the mold, will cause blowholes in the casting. Since magnesium alloys are subject to "hot short" cracking, they must be given freedom to shrink during solidification. If the grain of the metal has been properly refined, these alloys will tolerate harder cores than aluminum casting alloys.

The core binder used should be one that allows easy knock-out, generates a minimum of gas, does not cause the cores to pick up moisture after baking, and allows the core surface to break down under the heat of the poured casting. Although good oil binders have been used satisfactorily, the urea formaldehyde resin binders are more desirable. The use of about 1% each of sulfur and boric acid in a urea formaldehyde core mixture will give enough protection for most castings. Another protective agent that has been used to some extent with satisfactory results is potassium fluoborate. About ½% of this, in addition to the sulfur and boric acid in the core mixture, will give good protection for castings that have heavy sections. In general, cereal binders are used only as an auxiliary to other binders for giving special properties to the cores.

Melting Crucibles. Crucibles fabricated from steel plate are used for melting and casting magnesium alloys and vary in capacity from approximately 60 to 1000 lb. These crucibles are heated with either gas or oil, and under normal conditions of operation, the products of combustion have no effect on the quality of the metal.

Since boiler plate, when unprotected, scales badly under conditions of use, it has been found desirable, both for safety and for economy, to protect the crucibles by treatment with aluminum. This is accomplished by spraying aluminum on the sandblasted or grit-blasted steel surface and then heat treating to alloy the aluminum with the steel. When properly applied, this treatment decreases the scaling to such an extent that crucibles are usually discarded because of distortion resulting from load at high temperatures rather than because of scaling.

Some regular and thorough method of checking the soundness of the crucibles should be carried on at all times. The large premelting crucibles, in particular, should be checked with calipers at regular intervals and should be discarded when spots are found that are too thin for safe use. Also provision should be made in the installation of large premelting furnaces so that if the crucible should leak in service, the molten metal will not flow out onto the working floor, but all of it will be carried into a convenient steel cooling pan.

Both in the large premelting furnaces and in the smaller furnaces for heating the metal for casting, care should be taken to ensure that no appreciable amount of iron scale is allowed to build up. If iron scale is allowed to accumulate in these furnaces and the crucible leaks molten magnesium alloy into this hot iron scale, a thermit reaction may result, causing serious consequences. This can be avoided by keeping the furnaces clean and scale free.

Fluxes. The fluxes used in melting magnesium alloys are mixtures of chlorides with small amounts of other mate-

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rials. Since magnesium chloride is a major constituent, the fluxes are hygroscopic. The two types used in sand foundry melting are known as open-pot flux 230 and crucible flux 310. The open-pot flux fuses to a thin fluid during melting and remains thin in normal operation. The crucible flux fuses to a thin liquid when first heated during the melting operation, but changes to a dry, scaly crust after being held at about 1400 F or higher.

If the metal is melted in a premelt crucible, a melting flux of the open-pot type should be used in the quantities required to prevent burning. Care must be taken to prevent the accumulation of large quantities of this flux, or of sludge, in the bottom of the crucible, since such accumulations will decrease the life of the crucible because of excessive scaling on the outside.

Scrap. All ordinary clean foundry scrap may be melted directly in the premelt furnace and transferred to the casting crucibles for pouring. The normal ratio of ingot to scrap is about one part of ingot to four parts of scrap, although 100% scrap can be melted with no bad effects on the quality or properties of the casting. Scrap that is damp should always be dried thoroughly before being placed in the melting crucible. If the moisture content is large, a blow may result when a damp casting is placed in the crucible, and even a small amount of moisture is undesirable because it may cause gassed metal. Hydrocarbon oils on a magnesium alloy that is being melted may also cause gassed metal.

The only impurity that is likely to be picked up in ordinary foundry operations is silicon. If castings are charged into a melting furnace with cores only partly knocked out, or with sandblast or foundry sand on the casting, the SiO_2 will be reduced by the molten magnesium alloy, with an increase in the silicon content of the metal.

Melting. After the casting crucible has been filled, either from the premelt furnace or by melting directly in the crucible, the metal must be stirred thoroughly to clean it. This can be done by means of an iron stirring rod or by treatment with chlorine gas. If the metal is to be stirred by hand, the surface of the melt should be covered with a thin layer of crucible flux, and the melt should be stirred with an iron rod in such a manner that the flux is mixed with the metal. This flux wets the nonmetallic impurities and the stirring helps to coalesce these particles, causing them to separate from the metal as sludge. Enough flux should be used to maintain a liquid film on the surface of the melt during stirring. The metal should be heated to between 1320 and 1350 F during this operation.

In all melting operations, the amount of flux used should be the minimum that is necessary to control burning and to clean the metal properly. If the premelt method is used, a normal consumption is about 2% each of the open-pot and crucible fluxes. If all metal is melted in the casting crucibles, about 3% of the crucible flux is normal consumption.

The use of chlorine gas in magnesium foundry melting practice has been developed recently and is similar to that used in aluminum melting. It not only removes gas from the metal, thus decreasing trouble from microporosity, but also stirs and cleans the metal, thus replacing the hand stirring. The gas is bubbled through the melt in the casting crucibles at about 1350 F for the length of time found necessary to remove the dissolved gas, usually between 5 and 15 minutes. The gas is bubbled through the metal at the highest rate possible without spattering metal from the crucible.

Grain Refinement. The grain size of the cast metal is refined by superheating and the mechanical properties are improved. Superheating practice varies somewhat in different foundries. In general, 5 to 15 minutes at a temperature of 1650 F, or heating to 1700 F, gives good grain refining. For best results, the crucible should be removed from the furnace at a temperature of about 1650 F and should be cooled in air to the casting temperature. Slow cooling to casting temperature in the furnace causes part of the grain refining effect to be lost.

An alternate method of grain refinement consists of treating the metal at about 1400 F with a material that contains carbon. At present (1947), this method has not been used enough in production to permit a definite recommendation. The two variations of this method that have been tried most extensively involve stirring solid fine graphite into the melt and treating the metal with chlorine gas bubbled through carbon tetrachloride.

Pouring. Just before time to pour the casting, the flux and oxide skin on the top of the metal are either completely removed from the crucible or pushed back from the pouring lip; then a protective agent is dusted on the molten metal. The crucible is tilted and the metal is poured into the pouring basin in such a way that the stream does not go directly down the sprue. The proper use of a pouring basin is absolutely necessary in producing magnesium alloy castings of good quality. Some oxidation always takes place on the stream of metal flowing into the pouring basin, and since the magnesium oxide has very nearly the same specific gravity as the magnesium alloy, it does not separate from the metal unless a properly designed pouring basin is used. The dimensions of the pouring basin will vary with the size of crucible from which the metal is poured. The pouring basin may be made of cast iron, core sand, or green sand rammed up in a box. The basin must be long enough so that the stream of metal from the crucible will not go directly into the sprue. The injection of a small amount of sulfur dioxide gas into the mold cavity, just before pouring, will help prevent oxidation on the surface of metal while castings of heavy section are being made.

The proper pouring temperature for each casting can be determined by trial and should be that at which misruns are avoided and sound castings are produced. In general, the pouring temperature of castings ranges from about 1400 to 1600 F.

Since magnesium alloys are hot short, it is essential that they should be allowed to stand in the mold undisturbed while cooling through this range. The interval of time required will vary with the size of casting. Small bench castings can be shaken out a few minutes after pouring, but large castings (poured weight, 200 to 500 lb) may have to stand for an hour.

Cleaning. The first step after shake-out and knock-out should be a sandblast operation to reveal gross surface defects. The blasting material commonly used is a flint silica sand of 35 AFA fineness.

Gates and risers of magnesium alloy castings are usually removed by means of a band saw. The band saws are coarse toothed, usually 4 or 5 teeth to the inch, and set with a large clearance angle to clean out the chips from the cut. The saws operate at from 4000 to 9000 linear ft per min. In order to provide maximum safety, care must be taken not to permit the accumulation of large quantities of chips; good housekeeping should be practiced and chips should be cleaned up at short intervals. It is also necessary to keep the saws sharp and to change them as soon as they get dull. The saw guides used should be of such a design as to minimize sparking.

The rough cleaning operations are done on a grinding wheel wherever possible, because that is the most rapid way to remove metal. Magnesium grinding dust must be collected in a recommended type of collector that contains a water-spray dust-precipitation unit. Ducts from the grinding wheel to the collector should not be more than 3 to 4 ft long and should not have abrupt turns or changes in section. The sludge must be cleaned from the collectors at a definite time, preferably daily, and the material should be disposed of safely. At no time should the sludge be allowed to dry out; it should be kept wet with an excess of water.

Magnesium sludge is best disposed of by burning. This is accomplished by spreading in a thin layer, 3 to 6 in. deep, on a porous burning area that will allow the water to drain and by covering the sludge with combustible waste. Small quantities of sludge may be disposed of by mixing with 4 to 5 parts of sand and burying or by placing in a dump area.

If the sludge is collected at a central point from the individual collectors, it should be stored in covered metal drums, kept wet, stored away from buildings or other combustibles, and disposed of daily.

The general over-all cleaning of the castings is done with rotary files. The operating conditions in this work

area are such that the possibility of the filings becoming ignited is slight, but they should be cleaned up frequently.

Finished castings also are blasted just before the final surface treatment operation, primarily to give a uniform appearance to the pickled casting. This final blasting may be done with either sand or steel grit. No hazard has been observed that is caused by the dust from sandblasting, but if steel grit is used, the dust formed is usually flammable and should be collected in a wet type of dust collector.

Pickling. All castings are given a chrome pickle treatment before shipment. This is primarily for protection against corrosion during shipment and storage in the customer's plant before machining. After machining, more effective chemical treatments form a paint base.

The chrome pickle treatment consists of dipping for about one minute in an aqueous solution containing 1.5 lb of sodium dichromate, and 1.5 pt of concentrated nitric acid per gallon. The strength of this solution is checked by a simple analytical method and the constituents are added in amounts necessary to maintain the composition.

The most suitable tank materials are type 316 stainless steel, 2 S aluminum, or synthetic rubber materials applied over a mild steel base.

Heat Treatment. The mechanical properties of most magnesium alloy castings are improved by suitable heat treatment. The type of heat treatment given depends on the service in which the casting is to be used. The solution heat treatment gives maximum toughness and shock resistance. The aging or precipitation heat treatment, after the solution treatment, gives maximum hardness and yield strength with some sacrifice of ductility. The stabilization heat treatment is a recent development and is really high-temperature aging. Its full use has not been developed, but stabilization will probably find the major use as a stress-relief treatment on cast parts where service conditions do not require maximum strength.

The commercial use of alloys A8, A10, A12, and AZ101 has been limited and the heat treating recommendation given here may need revision upon further development.

The solution heat treatment for the various alloys is given in Table I.

These alloys are slightly plastic at the solution temperature, and the castings must be placed in the furnace in such a way as to prevent warping during heat treatment. This means that some castings must be placed on supports, and heavy castings must not be piled too high.

The aging heat treatment for alloys A8, A10, A12, and AZ101, requires 16 hr at 350 F; for AZ63, 16 hr at 370 F; for AZ92, 10 hr at 425 F. No special atmosphere is required for this treatment.

The stabilization heat treatment cycle consists of 4 hr at 500 F. No special atmosphere is required.

In the solution heat treating furnaces the temperature must be uniform throughout the load within plus or minus 5 F. Control within plus or minus 10 F is satisfactory for the stabilization or aging treatments.

Table I. Schedule for Solution Heat Treatment

Alloy	Solution Temperature, deg Fahr	Duration of Heat Treatment, hours
A8 and A8X	800	10
A10	800	16
A12	800	20
AZ63 and AZ63X[a]	730	12
AZ92[a]	770	20
AZ101[a]	790	20

(a) This alloy must be heated to temperature in not less than 2 hr.
NOTE. All the above alloys should be heat treated in an atmosphere containing 1% SO_2.

Impregnation. Some castings meant to hold oil or air pressure in service, have sections that cannot be made sound because of design or limitations of foundry practice. These areas may be made pressure-tight by using any one of several impregnants. Sodium silicate solutions as well as mixtures of some synthetic resins are used. Of these resins a mixture of styrene and linseed oil has found wide acceptance as an impregnant.

Castings may be impregnated either individually or as a batch in an autoclave built to withstand vacuum and pressure. The impregnation step must follow any required solution heat treatment since temperatures above 500 F will destroy the impregnant.

Repair of Castings. Certain types of defects in magnesium alloy castings may be repaired by shielded-arc welding. The method uses a tungsten arc shielded by helium or argon gas to prevent oxidation of the metal during the welding operation. The defects that can be successfully welded are sand holes, blowholes, gouges and, in general, defects where the operator can be sure of the exact extent of the affected area.

Castings should be welded in the heat treated condition. After welding, the castings are solution heat treated again for one-half hour at temperature, and then aged if required. Castings from alloy AZ63 can be given the full solution heat treatment after welding, without harm to the weld area, but castings from the other alloys must not be held longer than one-half hour for reheating, to avoid trouble from grain growth.

Castings to be welded may be preheated to a temperature of 725 F and welded in the range from 650 to 725 F. They must then be returned to the preheating furnace long enough to equalize the temperature of the casting before cooling in air. The quality of welds is checked by both visual inspection and radiography.

The Permanent Mold Casting of Magnesium Alloys

BY EDWIN C. SANDHAM*

MAGNESIUM permanent mold castings combine the advantages of uniformity, accuracy, high ratio of strength to weight, high production rates and low cost.

Application. Castings are made ranging from a few ounces to more than 70 lb in weight, as long as 6 ft, and more than 400 sq in. in projected area. Because both light and heavy sections may be cast sound, and massive equipment is not required to close the molds, larger castings are quite practical.

Walls as thin as ⅛ in. are cast, although $\frac{5}{32}$ in. is preferable in areas more than 2 in. wide, and $\frac{3}{16}$ in. in areas more than 4 in. wide or 30 sq in. in area. Sections from ⅛ to more than ▮ in. thick may be cast pressure-tight and of full strength.

Ordinarily, a minimum of 1000 to 2000 pieces or about 2000 lb is required to justify the purchase of permanent mold equipment. Typical casting costs are appreciably less than those of sand castings when made in large quantities.

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Prepared for the Magnesium Committee

Alloys and Properties. Most magnesium permanent mold castings may be made of the 9% Al, 2% Zn alloy AZ92. In the as-cast condition, the average mechanical properties of this alloy exceed those of sand castings by about 15%, but in the heat treated or heat treated and aged conditions the mechanical properties are equivalent to those of sand castings.

This applies also to the 6% Al, 3% Zn alloy AZ63. This alloy has greater toughness than alloy AZ92 but is more difficult to cast in permanent molds.

With proper design and treatment, alloys that contain 8 to 10% Al and 0.25 to 0.75% Zn have the best permanent-molding characteristics, satisfactory strength, and resistance to corrosion. The fact that permanent mold castings are uniform in properties permits high design stresses and actual loading.

Alloys containing cerium have better mechanical properties than the present alloys above 400 F.

Molding Practice. The general method of casting magnesium alloys in permanent molds is similar to that used for aluminum; that is, molten metal is hand ladled from a melting pot into a hot iron or steel die, filling the cavity by gravity. Devices operated by hand or by power are used to close the die and eject the casting, since high pressures are not applied as in pressure die casting.

Cast or wrought steel melting pots that hold 300 to 800 lb of metal are charged with flux, and ingot, scrap or melted metal, usually continuously. The welded steel ladles have bottom-pour spouts shaped to prevent flux and drosses from entering the mold. A single heating to the pouring temperature (1200 to 1350 F) produces an inherently finer grain in permanent mold castings than in sand castings. Superheating or inoculation may be employed to obtain a further grain refinement, which is quickly lost by holding at temperatures near 1300 F.

The mold comprises two or more sections into which have been cut the cavities and suitable gates and risers. In making sand castings, the sand mold is destroyed when the casting is removed, and undercuts, openings and intricate detail are possible. The permanent mold, however, is formed of rigid sections, and must be shaped to permit easy removal of the hot casting. Undercuts on the outside of the part are produced only by loose pieces or by retractable slides or metal cores, which add to the mold and casting cost, and slow the operation. Round holes or those of other shapes may be made by pulling out metal cores before opening the mold. Such methods are limited to holes larger than about ¼ in. in diam and with a depth of two to five times the diameter.

Undercuts or holes that cannot be formed with metal cores are made by using a new baked sand core for each casting. Cores made of silica sand and a dry type of mineral or cereal binder have the necessary strength, permeability and rapid rate of baking. Such cores require less than ½% each of sulfur and boric acid for protection against burning and other defects associated with casting against sand surfaces. Such "semipermanent" mold castings are more expensive than "full permanent mold" castings, but offer most of the advantages of the method.

Draft angles necessary to permit removal of the casting from the mold are: 2 deg minimum, 3 to 4 deg preferred on the outside of the casting, and 3 deg minimum, 4 to 7 deg preferred on inside dimensions and cored holes.

A considerable amount of skill and experience is required in the designing of all parts of the die in order to meet the operating requirements described below.

Proper filling of the cavity is ensured by making suitable gates through which the metal is poured. The size must be adequate, the position correct and provision must be made for the escape of air that would otherwise be trapped. Good surfaces, free from seams, pits or other defects, are secured primarily by gates shaped to avoid turbulence of the metal. Rapid and efficient operation of the equipment depends on temperatures, the devices used to move the die parts and castings, and other factors. Most important, and most dependent on proficiency in the foundry, is the production of adequate soundness of the metal in the casting. The tendency for magnesium alloys to shrink or develop porosity and reduced strength is controlled by providing gates and risers or shrink heads, which supply the necessary additional molten metal to feed each part of the casting. Changes in the shape of the gate can be made only by taking the die out of service, and then only within the limits prescribed by the shape of the part and the die.

Permanent molds for magnesium are commonly made of cast iron, and usually produce from 20,000 to more than 100,000 pieces. Because of the light weight and low heat content of magnesium, die wear is slower than the wear of dies used with aluminum, iron or copper alloys, or for pressure die castings. All surfaces of the cavity are covered with a refractory coating, applied to the hot die by spray or brush. Various coatings are used; an effective one is a suspension of one volume of kaolin and one volume of sodium silicate in ten to thirty volumes of water. By this means, thin sections are made to fill, and proper rates of cooling are employed to produce sound castings and to maintain a fast operating cycle. Gates and risers are small compared with those needed on light metal sand castings; typical ratios of metal poured to trimmed casting weight are 2 to 1 for aircraft, and 1½ to 1 for commercial castings.

Because the design and economical operation of the die depend so much on the shape and details of the part itself, the foundry should recommend the best design modifications regarding cores, undercuts, wall thickness, draft angles and fillets. The rules for magnesium casting design given on page 1005 in this Handbook are particularly applicable to permanent mold castings, because the results of their application are sharply defined and predictable. Parts otherwise difficult to make may be cast economically if the proper conditions are present.

Trimming and Other Operations. The part is separated from the gate by means of a band saw, circular saw, or a fast simple operation on a lathe or drill press. Because the part is already smooth and can be accurately fixtured for the trimming operation, subsequent grinding, filing and sandblasting are eliminated or sharply reduced.

Heat treating, when required, is done in the same manner as for sand castings.

For most parts, with good foundry practice, impregnation is not necessary to ensure leakproof permanent mold castings. When impregnation is necessary, one pressure treatment with the customary natural or synthetic oils should be sufficient.

Castings are usually finished with a chrome pickle treatment. For further information, see the article "Surface Protection and Finishing of Magnesium Alloys", page 991.

The Die Casting of Magnesium Alloys

By J. C. Fox*

THE salient properties of magnesium alloys—ultra lightness, high ratio of strength to weight, excellent machinability, dimensional accuracy, excellent surface finish, and low cost—account for the wide use of magnesium die castings.

In common with the die casting of other alloys, the chief requirements for the successful production of magnesium alloy die castings are: the use of a suitable casting machine to hold and operate a die under pressure, a properly designed die, and a suitable alloy.

In addition to these common requirements, magnesium, because of its particular physical behavior in the molten state, needs special methods of handling when molten.

The Die-Casting Machine. The die-casting machine found most suitable for the production of magnesium die castings is the so-called "high-pressure cold chamber" type. (For an illustration of such a machine, see the article on page 1078.) The molten magnesium alloy is held in a separate furnace beside the machine. The alloy is ladled into an opening of a piston-cylinder arrangement on the casting machine, and directly after pouring, the alloy is forced into the die by means of a hydraulically operated ram.

Injection plunger speeds may vary from 5 to 500 in. per sec. The slower speeds are used particularly with relatively heavy-sectioned gates, giving rise to a flowing effect of the metal as opposed to a spraying effect, usually obtained with the higher plunger speeds. The slow shot, when coordinated with properly controlled gating, venting, pressure, die and metal temperatures, produces sound castings, while the higher speeds are necessitated chiefly for thin-walled

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Prepared for the Magnesium Committee

castings having thin gate runners. With such conditions the higher speeds are required to fill out a casting properly and to produce good surface finish. The higher speeds of plunger operation, generally used with thin-sectioned gate runners, produce a "spray" effect of alloy into the die cavity.

Die-locking pressures ranging from 1,000,000 to 3,000,000 lb are necessary because of the high injection pressures regularly used. The casting machine must have a supporting frame that is rigid and massive enough to prevent deflection when the die is mounted on it, and to keep the two halves of the die closed when the pressure is exerted in making a casting.

Alloys. The die-casting alloy in most general use today is the 9% Al, 1% Zn alloy AZ91. This alloy is balanced with regard to castability, resistance to corrosion and other properties. The 10% Al, 0.5% Si alloy AS100 has been used to some extent. It has better castability but inferior properties and resistance to corrosion.

Recently a new alloy AM11 (1.25 Al, 1% Mn) has been used commercially to some extent. This alloy has greater ductility but a lower yield strength than AZ91; it can be aged to produce strengths approaching those of AZ91 and still retain good ductility. Lower injection speeds and larger gates are generally employed.

The mechanical properties and the compositions of the die-casting alloys are given in the data sheets, page 1019.

To minimize burning and to retard oxidation at elevated temperatures above the liquidus, a very small amount of beryllium, in the form of a beryllium-aluminum alloy, is added to the molten alloy. The amount of beryllium added is generally less than 0.001%.

Casting Technique. Unlike other die-casting alloys, magnesium alloys must be protected against burning and oxidation while in the molten state. This is done by means of an atmosphere containing sulfur dioxide (SO_2) gas, generated in a specially constructed, double-walled dome, mounted over the alloy melting pot. When elementary sulfur is placed between the walls of the dome, the heat from the pot causes the sulfur to melt and the sulfur vapor to issue through holes surrounding the ladle-opening in the sides of the cover. The sulfur vapor burns on contact with air, forming SO_2, which inhibits the oxidation of the alloy effectively up to operational temperatures of 1250 F.

The cast carbon steel pots for holding the magnesium alloy usually have a capacity of about 400 lb. It is essential that the temperature of the alloy be controlled automatically for the best results.

Fluxes. The die-casting flux is quite different in action from other melting fluxes. The main function of the flux is to refine the molten metal during stirring of the melt. The flux then settles to the bottom of the pot. No protection is offered the surface metal except the protection provided by the sulfur dome.

When ingot and scrap are melted in another pot and liquid metal is transferred to the die-casting pot, the melting practice is the same as given in the section on sand foundry procedure, page 969, for the open pot and crucible.

Dies.* Since magnesium-base and aluminum-base alloys have approximately the same melting points and casting temperatures, the dies for both these alloys can be used interchangeably. The nominal composition of the steel most commonly used is 0.40% C, 5% Cr, 1% Mo and 0.5% V.

This steel will give long die life when heat treated (1800 to 1825 F, air quench, temper at 1050 to 1075 F) to a Brinell hardness of 418 to 460.

Die-casting dies for magnesium are quite similar in design to those used for aluminum alloys, but particular attention must be paid to the factors of gating, venting, size of fillets, and regulation of change of section, in dies for magnesium production.

The magnesium alloy must enter the die with as little turbulence as possible. Therefore the proper gating must be provided, especially where there are cores, lugs, and other protuberances interfering with the smooth flow of the alloy into the die cavity. As in the die casting of other alloys, the maximum efficiency of castings can be achieved only by careful co-ordination of such factors as gating, venting, pressure, temperature of dies, metal temperature and controlled plunger or injection speeds.

Die Temperatures. The control of the die temperature is extremely important in the production of sound castings with good surface finish. Temperatures of the dies may range from 300 to 600 F. The best operating temperature for each die is determined only after actual experience in production. The amount of metal entering the die and the rate of production usually determine the temperature of the dies. Water cooling of the die is resorted to, especially for some heavy-sectioned parts that tend to increase the temperature of certain die sections. Relatively cold dies are likely to produce run-marks, swirls and surface porosity; extremely hot dies promote the formation of excessive oxide films on the die, resulting in rough-surfaced castings.

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C. E. Nelson and R. C. Cornell, Principles of Die Casting Magnesium Alloys, American Foundrymen's Association, July 1945

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* *See also* the article "Composition and Heat Treatment of Die-Casting Dies", page 673.

The Casting of Magnesium Ingots for Working

By Kurt R. Gustafson*

FURNACES for melting, alloying, refining, settling and casting magnesium alloys are generally of the pot type, heated by gas or oil, and have capacities of 100 to 4000 lb. The burners may be set tangentially to the crucible or fired into a combustion chamber immediately below it. Burners of the radiant type, using premixed air and gas, may permit longer service for the pot and faster melting rates. Pots are usually of cast or welded steel, protected with a sprayed metal coating for longer service. Though all operations may be performed in the same furnace, it is generally considered that a product of higher quality can be obtained when separate pots are used for settling and casting.

The metal may be transferred from one pot to another by pumping or pouring; however, pumping is the more popular method. Pumps are of the centrifugal type, driven by an air motor. Ample clearance is provided between the housing, impeller and impeller shaft to prevent binding when the pump becomes heated.

All equipment and tools must be of low-nickel steel (0.2% max Ni). Other tools used in the melting, alloying and preparation operations are a sludging tool, alloying tool, mechanical stirrer, skimming tool, tool for adding calcium, and flux pot.

Durville-type molds, air-cooled cast-iron molds and the direct chill method are used in producing ingots. Because the greatest quantity is produced by the direct chill method, this procedure will be discussed. A sketch of the basic parts of the casting unit is shown in Fig. 1. Since the hydraulic piston that governs the length of the ingots is usually 144 to 168 in. long, the casting operation is semicontinuous. More than one mold is generally used, and as many as six have been operated successfully.

Melting. During the melting, a cover of flux is used to prevent oxidation or burning. When a crucible is being started, the walls are wetted with flux and a small quan-

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Prepared for the Magnesium Committee

tity of flux is placed in the bottom. Pig or heavy scrap is charged first, followed by light scrap. Charging is continued until enough material has been added to ensure a full crucible when melting has been completed. Additions are made while the melting proceeds from the bottom; thus the newly charged metal is supported by solid metal and does not enter the molten bath until it is thoroughly preheated. When it is necessary to introduce solid metals into a molten bath—for example, into the heel of the previous melt—the material to be charged is thoroughly preheated on the sides of the crucible. During charging, precautions are taken to prevent bridging, which may result in a sudden dropping of the solid metal above into the molten heel beneath. It is advisable to work the charge with a poker in order to maintain a constant settling of the solid metal into the molten heel; also, melting efficiency is improved in this way.

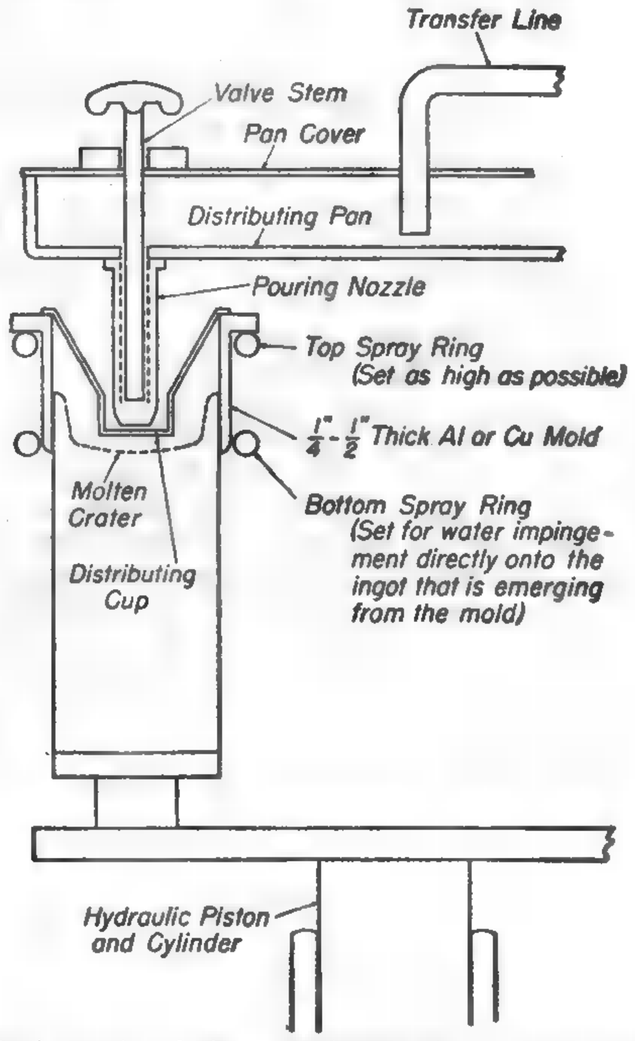

Fig. 1 Basic parts of the unit for casting magnesium ingots

Alloying. Pre-alloyed pig may be used for preparation of all wrought magnesium; however, in large-scale operations it may be advantageous to use magnesium pig and perform the alloying operation. Aluminum, zinc and manganese comprise the chief alloying components of magnesium alloys; aluminum is added to increase strength and hardness in alloys AZ31X, AZ51X, AZ61X and AZ80X,* while zinc and manganese are added to improve the resistance to corrosion. In alloy M1, manganese is added to increase both mechanical properties and corrosion resistance. Calcium in quantities of 0.1 to 0.3% is added to alloys M1 and AZ31X. Exactly how calcium functions in these two alloys is not definitely established at present; however, improvement is observed in the surface of M1 and AZ31X extrusions and M1 rolled sheet when calcium is present. Further, some fabricators maintain that additions of calcium to AZ31X and M1 improve rolling characteristics and reduce susceptibility to splitting in direct chill casting. Beryllium may be added to the aluminum-bearing alloys to reduce their reactivity with water.

High-purity aluminum and zinc are added immediately after the melting, by placing small pieces in the alloying tool and immersing it just below the surface of the melt. Beryllium is added in the same manner and at the highest possible temperature. About 50% of the beryllium is recovered when proper amounts of a 5% Be aluminum master alloy are added in order to obtain a 0.0005% Be content in the melt. Calcium is introduced into the melt 15 to 30 min before casting is started, in order to avoid excessive losses. It may be introduced as a master alloy of 20% Ca in magnesium or in the pure form. Good uniformity of calcium throughout an entire cast is difficult to obtain; however, with close control, maximum variations of 0.015% and recoveries of 75% are obtainable. Recovery will be decreased by increase in temperature, holding time, and the amount of flux present.

* For nominal compositions of these alloys, see page 968.

Refining, Settling and Sludging. Refining is performed by the introduction of a manganese flux to condition the melt for the removal of iron in settling, and to agglomerate oxides and other impurities. When the temperature of the melt is between 1360 and 1400 F, a manganese flux is sprinkled on the bath and stirred simultaneously. The addition is made in order to produce in the melt, before settling, the percentage of manganese given in Table I, and is based on an 80% recovery of the manganese contained in the flux (*see also* Table II).

Table I. Refining and Settling

Alloy	M1	AZ31X	AZ51X	AZ61X	AZ80X
Required percentage manganese	1.50	0.75	0.60	0.60	0.50
Settling temperature, °F max	None	1275	1250	1250	1240

After refining, settling is performed to precipitate iron, the agglomerated oxides and other impurities. For a minimum of 30 min the temperature is reduced below the limits specified in Table I. In order to decrease the temperature as rapidly as possible, heavy preheated low-iron scrap is sometimes added to the melt; this practice is known as "seeding".

During the melting, refining and settling processes, oxides and impurities settle to the bottom of the pot, intermingle with excess flux and form sludge. In the transferring or casting, care is taken not to transfer or disturb this heel of sludge; after the transferring operation the heel is removed. Prior to sludging, the walls of the pot are scraped clean to prevent a build-up of magnesium oxide, which would reduce melting efficiency.

Fluxes. All processes for the production of magnesium ingots require the use of fluxes, and a proper selection is of prime importance if a product of high quality is to be obtained. Table II gives the approximate composition of various fluxes employed.

Table II. Composition of Fluxes for Melting and Refining Magnesium[1]

Dow Chemical Co. Number	Percentage					
	KCl	$MgCl_2$	MgO	CaF_2	BaCl	$MnCl_2$[a]
230	55.0	34.0	...	2.0	9.0	...
232	37.5	42.0	7.5	8.5	4.5	...
250	23.0	...	...	2.5	2.5	72.0
310	20.0	50.0	15.0	15.0	...	...
320	...	...	11.0	13.0	...	76.0

(a) $MnCl_2$ contains 44.0% Mn

The fluxes Dow 230 and 232 are generally used in melting operations where two or more pots are employed in the operating cycle and where transferring is performed by pumping. Both fluxes offer good protection during melting, have good refining characteristics, and are self-healing when tools are inserted. The consistency of the sludge ordinarily determines the choice of flux. If the sludge is too fluid, Dow 232 or perhaps even 310 may be employed to increase the viscosity. Formation of a heavy crust on the walls of the pot and difficulty in loosening the sludge indicate that a more fluid flux is needed.

When all operations are performed in one pot and casting is done by pouring, it is essential to use Dow 310, which remains fluid for melting and then dries while standing, forming a crust that may be skimmed off or held back during casting. However, tools cannot be inserted after the crust has formed, because then the crust would be broken, the protection lost, and the flux carried into the cleansed metal.

Casting. The freezing rate, perhaps the most important factor in direct chill casting, is governed by casting temperature, rate of withdrawal, and application of cooling water. Casting temperatures and rates that have proved satisfactory are shown in Table III; proper spray locations

are indicated in Fig. 1. Application of water should be uniform around the mold and ingot, and impingement should not be so strong that water will rebound from either the mold or the ingot.

Table III. Casting Temperatures and Lowering Rates

Alloys	Temperature, deg Fahr		Rate of Lowering, inches per minute	
	min	max	First 6 in.	Remainder
M1	1260	1275	2.50	3.00
AZ31X	1250	1260	2.25	2.75
AZ51X	1250	1260	2.00	2.50
AZ61X	1240	1250	1.75	2.25
AZ80X	1240	1250	1.25	2.00

Underpouring is always performed so that the sulfide skin in the mold or distributing pan is not broken; otherwise the protection would be lost, and both sulfides and oxides would be incorporated into the ingot.

Common Defects. Some of the most common defects found in magnesium ingots are outlined below, together with some possible causes.

Flux Inclusions. These often result from (1) improper balance of flux causing too fluid a sludge; (2) transfer or disturbance of the flux heel during casting; or (3) too large a heel of sludge in the casting pot because of transfer from other pots, improper sludging, or excessive use of flux.

Oxide Inclusions. These inclusions are generally caused by (1) dirty casting equipment, including transfer pipes; (2) turbulence and insufficient sulfur dioxide for covering the metal at the casting unit; or (3) inadequate refining.

Segregation. Manganese segregation is ordinarily caused by an excessive amount of manganese in the melt, after the settling. A settling temperature that is too high may fail to precipitate the excess manganese, or reheating in the same pot after settling will redissolve manganese and produce an excess. Segregation of magnesium-aluminum compound is less prevalent in direct chill ingots and may be somewhat relieved by homogenizing. This segregation is often caused by improper freezing as a result of high temperatures during casting or insufficient chilling.

Folds. These defects are prevalent in direct chill casting and are often caused by (1) peripheral skin formation in the mold or (2) deep-seated freezing at the crater top.

Splitting. This defect generally results from an excessively rapid rate of lowering.

Reference

1 C. E. Nelson, Melting and Refining of Magnesium, Trans AIME 159, 392 (1944)

The Extrusion of Magnesium

By G. Ansel*

MAGNESIUM rods, bars, shapes and tubing can be produced in many sizes and shapes by the extrusion process. Square and round rods and bars are obtainable in sizes as large as 8 in.; rectangles, angles, channels, I-beams and special shapes are available in sizes as large as 14.75 in. Tubing is made in diameters ranging from 0.25 to 12 in., and in many wall thicknesses.

The properties and compositions of magnesium alloy extrusions are presented in the data sheets, page 1013. Various alloys are available for different purposes. M1 (1.5% Mn) is used where a low-cost, weldable alloy of moderate strength is desired. The largest single application of magnesium extrusions to date has been in making rocket-launcher tubes of M1 alloy. The alloys that contain aluminum as the chief alloying ingredient, plus a small amount of manganese and zinc, increase in strength as the aluminum content increases. The strongest commercial magnesium alloy AZ80X HTA (8.5% Al, 0.5% Zn), has found considerable use as structural material for aircraft.

Both direct and indirect extrusion presses are used for the hot extrusion of magnesium alloys. Such presses vary in size from 250 to 5500 tons. The majority are of the horizontal type, though some vertical presses are employed. Either direct pumps or accumulators are used to produce the required pressures.

Billets for the extrusion process are cast either by the direct chill process or in permanent molds. General practice is to extrude M1 alloy in the unscalped condition, whereas the alloys that contain aluminum are usually scalped prior to extrusion to prevent feed-in of the aluminum-enriched cast skin. The largest billet in commercial use is 16 in. in diam by 40 in. long, weighing 500 lb. Billets of small diameter are often cut from extruded bar stock.

The billets are preheated in electric or gas-heated furnaces. No special atmospheres are employed, although extra long heating, which may cause excessive oxidation, is to be avoided because die loading will be increased. Suitable temperatures for heating billets range from 650 to 850 F, depending on the alloy and the section to be extruded.

A brief summary of the extrusion conditions for the various alloys is presented in Table I. It is necessary to include a range of temperatures and speeds to cover individual die characteristics.

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Prepared for the Magnesium Committee

It will be noted that containers are generally maintained at somewhat lower temperatures than the initial metal temperature. This combination of temperature is used to ensure easy starting and yet achieve a low effective working temperature, so that the "hot shorting" tendency will be greatly reduced and desirable properties maintained.

Table I. Extrusion Data for Magnesium Shapes

Alloy	Metal Temperature, deg Fahr	Container Temperature, deg Fahr	Speed of Extrusion, fpm
M1	780 to 820	680 to 730	20 to 100
AZ31X	700 to 750	450 to 600	15 to 40
AZ61X	700 to 750	450 to 550	7 to 20
AZ80X	680 to 750	450 to 550	4 to 7

Containers are heated either electrically or by gas. Uniform circumferential heating helps to produce straight extrusions. Die and head are usually heated during operation.

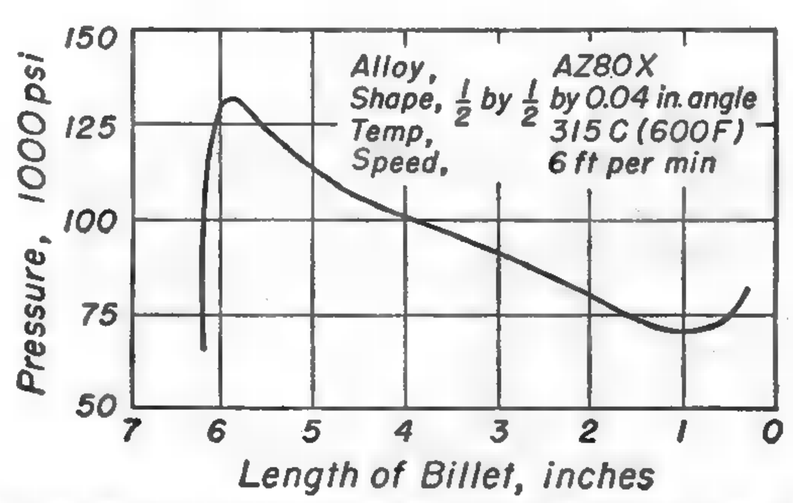

Fig. 1 Extrusion pressure-stroke diagram (Reduction, 184 to 1)

Pressure. Metal pressures used for extruding magnesium alloys vary from 50,000 to 100,000 psi; some jobs require as much as 135,000 psi at the start of a push. Figure 1 is the pressure-stroke curve for an angle ½ by ½ by 0.040 in., extruded from a 3-in. container—a reduction of 184 to 1. Extrusion pressures depend on composition, temperature, speed, length of billet, diameter of container, and the amount and complexity of reduction. Composition,

temperature and speed affect the resistance to deformation. The length of the billet and the diameter of the container affect the friction in direct extrusion.

The factors mentioned above cannot be varied at will, since the properties of magnesium alloy extrusions are determined by the conditions of fabrication. Speed, reduction and temperature affect grain size and orientation and

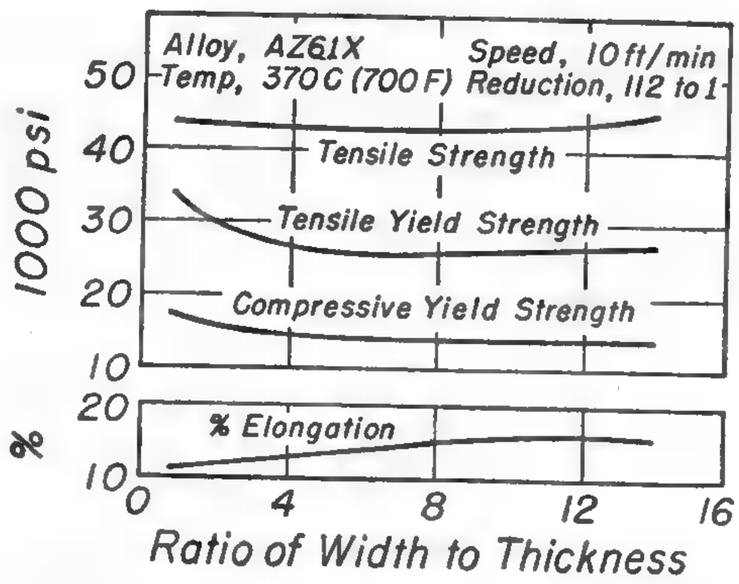

Fig. 2 Effect of the ratio of width to thickness (at constant reduction) on mechanical properties

thereby the mechanical properties. The orientation of magnesium extrusions can be described approximately as one with the basal plane nearly parallel to the direction of extrusion. More will be said later about the way orientation influences properties. The effect of the ratio of width to thickness on the properties of bars extruded at a constant reduction is presented in Fig. 2. The effects here are those of orientation and of temperature developed at the die. The amount of reduction has a considerable influence on properties, and to ensure good grain refinement, the ratio of reduction (ratio of areas) should be at least 10 to 1 and preferably 20 to 1. A great many shapes are made in the region of area reductions ranging from 50 to 1 to 150 to 1, although some bar stock is made with reductions as low as 4 to 1. This latter type of material will show a variation in properties from surface to center.

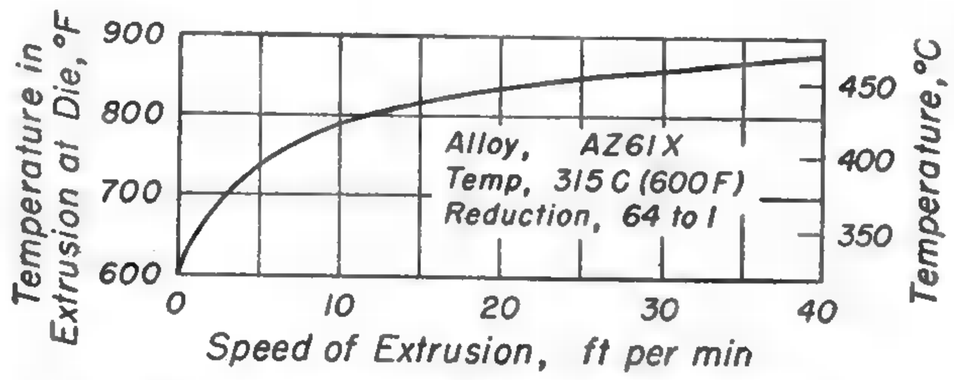

Fig. 3 Effect of speed on the temperature developed during extrusion

Speed of Extrusion. The influence of speed of extrusion on properties is determined largely by the temperature developed in an extrusion at the die. The effect of speed on the developed temperature is shown in Fig. 3. At slow speeds, great changes in temperature take place with relatively small increases in extrusion speed. At low billet temperatures, when the metal is work hardened and the grain size small (as demonstrated in Fig. 4), the rapid increase in temperature produces a change in properties with relatively small increases in speed of extrusion. This is because of relief of work hardening and increase in grain size.

At the higher extrusion temperatures (as illustrated in Fig. 5), changes in properties with variation in extrusion speed are not so pronounced, because the change in temperature with speed is less, and because the effects are mainly those of a moderate enlargement of the hot worked grain size. The speed of extrusion in production varies from 4 to 100 fpm, depending on composition and shape.

Temperature. The effects of billet temperature can be associated with changes in grain size and orientation. The influence of temperature of extrusion on M1 alloy is illustrated in Fig. 4. This figure exaggerates the effect because it was carried out at low speeds. Commercial extrusions, however, exhibit the trends shown. The combination of high strength and ductility at low temperatures is associated with fine grain size, cold work and a more random orientation. As the temperature of extrusion is increased, the influence of cold work decreases, the orientation becomes sharper, and grain size increases. Finally, at very high temperatures, the orientation becomes so sharp that both tensile strength and yield strength rise in spite of increased grain size. Compressive yield strength and elongation continue to decrease as the temperature rises.

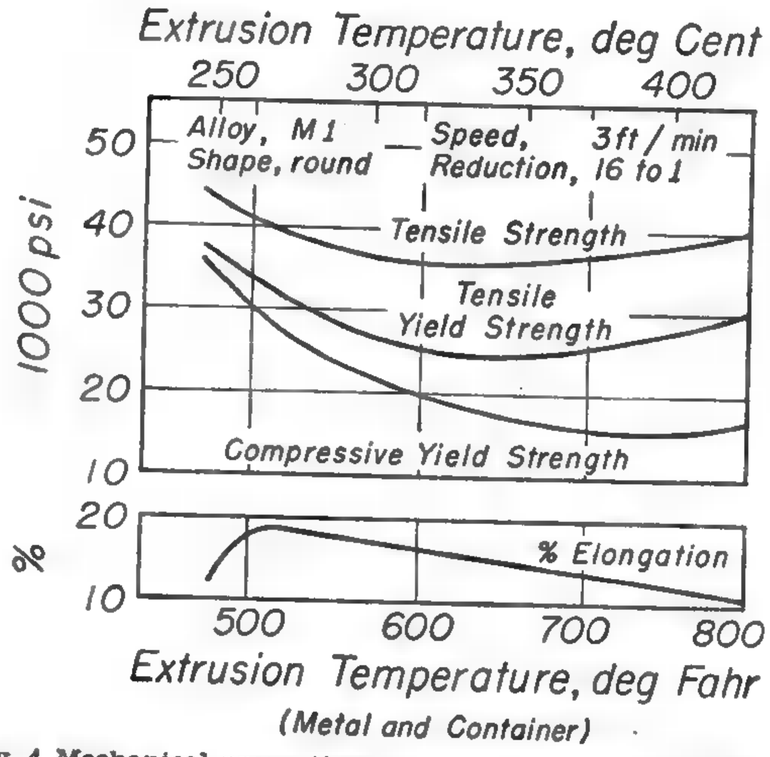

Fig. 4 Mechanical properties versus temperature of extrusion

Compressive Yield Strength. The compressive yield strength of extruded magnesium is important when the material is to be used for structural purposes. The ratio of compressive yield strength to tensile yield strength is often considerably less than 1; in fact, this ratio is about 0.7 for most alloys, but decreases to 0.5 occasionally. The cause of this phenomenon is related to the orientation in the extrusion and the mechanisms of deformation in magnesium. As previously indicated, the basal planes of the magnesium lattice are approximately parallel to the direction of extrusion. In flat shapes, the basal plane is parallel to the extrusion surface also.

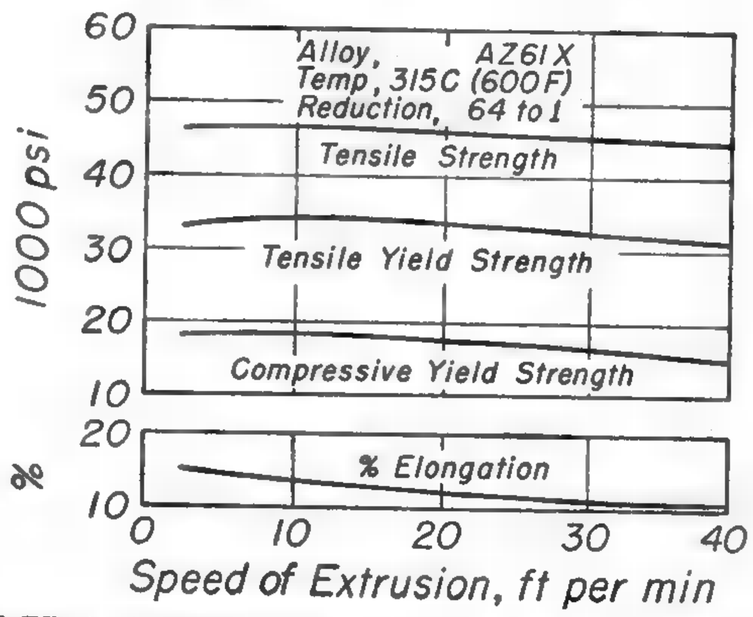

Fig. 5 Effect of speed of extrusion on the mechanical properties

Mechanism of Deformation. At room temperature the mechanisms of deformation in magnesium are mostly slip on the basal plane and twinning on the second-order pyramidal planes. In an extrusion, because of the orientation, the stress to cause yielding in tension is relatively high as a result of the unfavorable orientation of the basal slip planes. Twinning is not likely to occur in tension. In the compression of an extrusion, the crystallographic arrangements are favorable for twinning at relatively low shear stresses, while the stresses required for slip are too high for slip to take place.[1,2]

The stress to cause twinning can be increased by decreasing the grain size. In AZ80X HTA fine grain size and aging combine to make a high-strength extrusion alloy, with a ratio of compressive yield strength to tensile yield strength of about 1.

Methods. Magnesium tubing and hollow shapes are produced by two methods: the rod mandrel, and the porthole or supported-mandrel method. The rod mandrel method uses a bored billet. In the porthole or supported-mandrel method, solid billets are extruded through chambers in the male portion of the die, and the various segments are rewelded under pressure to form a tube.

Sections of magnesium are frequently guided by tension devices during extrusion, in order to maintain straightness. Extrusions can be straightened by stretching or roller straightening. The roller method must be used with caution because excessive bending can produce twinning, which will lead to a decreased tensile yield strength.

Besides the common defects that may occur in extrusions, such as hot shortness, die scores, and piping, other defects may develop, such as incipient fusion, "orange peel", and coarse grain. Incipient fusion, caused by a low-melting phase becoming liquid, most frequently affects elongation. A roughness similar to "orange peel" is found, generally in the softer alloys, and is associated with a difference in metal flow between surface and center of an extrusion.

References

1 P. W. Bakarian and C. W. Mathewson, Trans AIME, 152, 226 (1942)
2 Adolph Beck, "The Technology of Magnesium and Its Alloys", F. A. Hughes & Co., Ltd., London, 1943

The Rolling of Magnesium Sheet

By R. T. Myer*

MAGNESIUM sheet and plate are produced in thicknesses from about 0.016 to 2 in., widths as great as 60 in., and lengths as great as 144 in. Both annealed and hard rolled material are available. The typical properties of rolled products are given on pages 1020 to 1022.

Magnesium alloys for sheet products are melted according to practices much the same as those commonly employed for remelting magnesium for other products, such as castings. The use of manganese chloride or zirconium chloride flux as a means of reducing the maximum iron content to less than 0.005% in certain sheet alloys is an accepted practice in order to improve their resistance to corrosion in salt water. Calcium has been added in amounts up to 0.3% to control the grain size of the ingot, for improved hot and cold rolling characteristics and ductility. The calcium content is controlled preferably within very close limits, because in some alloys excessive amounts of calcium are considered detrimental to welding characteristics. In M1 alloy (1.5% Mn), for example, amounts in excess of 0.15% Ca are reputed to increase the incidence of cracks when restrained welds are being made. In this same alloy, a calcium content of less than 0.08% may lead to difficulties in rolling and to low mechanical properties.

In this country most ingots for magnesium sheet are cast by some type of continuous casting process. Between the melting and casting operation the metal is best transferred by pumping. This method serves the dual purpose of reducing the number and size of inclusions by improving the metal transfer, and refining the grain size, as a result of the agitation involved.

The alloys that contain aluminum may be homogenized in cast form. Temperatures for this operation are in the range from 700 to 800 F. The use of some form of protective atmosphere is necessary, according to some producers, to prevent combustion caused by ignition of the segregated exudation product on the surface of the ingot. Contact between the ingots and iron scale, aluminum, zinc, cadmium, or lead alloys should be prevented during heating, because such contact would initiate a reaction that would cause combustion at the homogenizing temperature.

Most magnesium alloy sheet and plate are produced from extruded slab. A round ingot 14 or 16 in. in diam is used; the ingot may be machined to remove the cast surface, depending on the composition of the alloy involved. Such ingot is then extruded into 3 by 9 in. or 4 by 12 in. in order to work the cast structure as thoroughly as possible under the conditions of compression that exist in the extrusion process before beginning the more critical rolling operations. One producer has used cast ingots successfully for the production of the more readily rolled compositions, and further progress in this direction may be anticipated.

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Prepared for the Magnesium Committee

The two factors that have the greatest effect on magnesium rolling practices are these: (1) A much greater amount of deformation can be taken hot than cold; and (2) the maximum hot rolling temperature is relatively low and the safe working range is narrow.

Amount of Deformation. The permissible amount of cold rolling varies from 16% on heavy gages of AZ51X alloy (5% Al, 1% Zn) to more than 50% on the thinner gages of M1 alloy. The comparatively low reductions in cold rolling are accounted for by the hexagonal crystal structure of magnesium alloys as compared with the cubic structures of the more readily workable alloys of aluminum, iron and copper, and the pronounced tendency for the occurrence of twinning in magnesium alloys.

Mechanism of Deformation. The deformation of the hexagonal structure of magnesium solid solutions at room temperature is believed to occur originally by slip along a single set of slip planes, the (0001) planes. As deformation proceeds, the grain fragments rotate so that the slip planes tend to become parallel to the surface of the sheet. Eventually, as rolling continues, shear stress on the slip planes decreases to the point where twinning becomes the principal means of deformation. Although twinning is not so effective in allowing deformation of magnesium as it is for zinc or cadmium, because twinning produces an extension along the [0001] direction, instead of compression, it does result in reorientation of the (0001) planes in the twinned regions so that further deformation by slip can occur. Cracking—known as "shear failure"—takes place when these planes of slip are exhausted.

The higher reductions during hot rolling are accounted for by the decreased rate of work hardening as a result of the higher temperature, as well as the fact that slip can occur on an additional set of planes, the $\{10\bar{1}1\}$ planes, at temperatures higher than about 450 F. When deformation by slip along the (0001) planes becomes more difficult, slip on the $\{10\bar{1}1\}$ planes, rather than twinning, is initiated. Thus, hot working involves uniform deformation as long as the temperature is kept sufficiently high.

Hot Rolling. Magnesium plate (0.250 in. and heavier) is hot rolled to gage. Practices for the fabrication of magnesium sheet (lighter than 0.250 in.) are based on the greatest possible use of hot rolling to take advantage of the economies of larger reductions. Cold working is introduced as the final gage is neared, in order to control flatness and improve mechanical properties, or as the gage becomes too light to hot work well by existing procedures.

Two different types of practices are used for hot rolling magnesium. One method calls for the use of cold rolls (operating at 250 F or less), with the result that metal temperature drops rapidly during rolling, so frequent reheating of the slab is required. However, because of the cool rolls, little or no lubrication of the slab is required, which is beneficial to the surface quality of the slab. On

the other hand, one producer uses heated rolls operating at 400 to 600 F. This has the advantage of maintaining the temperature of the slab at a higher level, making possible the use of greater reductions between reheatings. The higher temperatures for the rolls necessitates the application of lubricant to the slab. The lubricant must be applied evenly for uniform working; otherwise cracking may result, in a direction perpendicular to the direction of rolling. The use of elevated temperatures for the rolls accentuates the problem of maintaining satisfactorily uniform control of gage, and introduces a cleaning problem because no satisfactory lubricant is known which does not leave a residue on the slab. Temperature of the metal during hot rolling is between 575 and 850 F, depending on the alloy and the gage at which the reheating occurs. Reductions per pass vary greatly, depending on the alloy and hot rolling conditions; but, as an example, a 2.6-in. slab of AZ31X (3% Al, 1% Zn), prepared by hot rolling a cast ingot to 3-in. thickness, followed by a machining operation, would normally be rolled to 0.300-in. slab in ten passes starting with a metal temperature of 750 to 800 F and using heated rolls.

Cold Rolling. Wherever possible, cold rolling operations are performed using 4-high rolling mills because of the importance of uniformity of gage and because of the increased reductions that are possible in each pass. However, it is difficult, particularly in the lighter gages, to obtain satisfactory flatness when using 4-high mills for finish rolling. Therefore some producers may take the last stage of cold reduction on 2-high mills in spite of the higher costs involved. The practices in application of 4-high as compared with 2-high rolling vary greatly among the producers.

Almost all rolled magnesium is fabricated as flat sheet. Coiled sheet made of pure magnesium is available in widths as great as 8 in. Despite early experimental difficulties, it is quite probable that wide coiled sheet can be rolled in production if all the characteristics of the metal are taken into consideration.

Annealing operations are necessary between successive stages of cold rolling, and may also be used after hot rolling, although not always necessary at this point, since the hot rolled slab is usually recrystallized. Annealing temperatures vary from 600 to 800 F, depending on the alloy and the purpose of the annealing operation.

Cleaning. Because of the general high standards for surface quality required of magnesium sheet in most applications, cleaning procedures have been devised to remove mill scale and other surface contamination. These procedures involve dipping the surface in acid or cleaning mechanically by scratch brushing. The cleaning is usually performed after the last stage of hot rolling; however, at times such a procedure must be introduced at more than one point during fabrication. Acid dipping is generally used, although undesirable variations in gage may be introduced as a result of uneven etching. Scratch brushing is also employed after acid dipping, or after annealing, to remove oxide coating.

Flattening. Mechanical means of flattening magnesium sheet and plate, such as roller leveling, must be used with care. The accepted practice adapts thermal treatments for flattening the product. The sheets are loaded in horizontal stacks under pressure of approximately 100 lb per sq ft. They are then either annealed or given a much milder stress-relief treatment, depending on whether the final specification calls for "annealed" or "hard rolled" sheet. Ordinarily the temperature for thermal flattening is 300 F for alloys AZ31X and AZ51X, 400 F for M1 alloy; the alloys are held at temperature for ½ hr. Some slight sacrifice in strength is brought about in thermal flattening the hard rolled sheet, but elongation is improved considerably and there is evidence that the resistance to stress-corrosion cracking is improved in the alloys that contain aluminum.

Finishing.* Before shipment, finished magnesium sheet and plate ordinarily are dipped into a bath of chromic acid or sodium dichromate with nitric acid. Such a dip removes or passivates any small particles of the heavy metals—principally iron that may have become embedded in the surface—thus increasing the resistance to corrosion. The treatment also gives a coating that serves as a protection for the finished article. Magnesium sheet is sometimes coated with oil before shipment. Such a coating gives sufficient protection against corrosion for shipment under mild conditions and is removed more easily than the chrome pickle. This ready removal is of greatest importance when the material is to be spot or seam welded, because then chrome pickling interferes. Oiled sheet is also frequently preferred by users performing severe forming or drawing operations. The preference for oiled sheet over that with the chrome pickle coating is increasing, and oiling is now the standard method of protection employed by at least one producer.

* *See also* "The Surface Protection and Finishing of Magnesium Alloys", page 991.

The Forging of Magnesium Alloys

By A. L. Rustay* and F. B. Rote*

IN GENERAL, it is best to forge the magnesium alloys of higher strength, AZ61X (6% Al, 1% Zn) and AZ80X (8.5% Al, 0.5% Zn), in hydraulic or slow-stroke mechanical presses. A few parts have been made successfully by first preforming or blocking the stock in a press to place most of the metal in the desired position, and then finishing under a hammer to fill difficult sections that otherwise would require presses of large capacity. Some of the newer, rapid-stroke vertical and horizontal presses are not suitable for forging alloy AZ80X. These presses, like hammers, cause shearing and cracking of the metal during forging, if considerable movement is involved, because the metal flows too rapidly.

Alloy TA54 (5% Sn, 3% Al) may be successfully forged on hammers, presses, and other equipment that is satisfactory for aluminum. The mechanical properties are somewhat lower than those of alloy AZ80X. In common with all magnesium alloys, TA54 tends to move laterally instead of longitudinally when forged. "Drawing out", "fullering" or "rolling" operations must be performed under carefully controlled conditions. These require that the dies for such operations have radii adjusted to the stock size, and that the contour of the dies be carefully proportioned in such a manner that the metal is forced to move longitudinally. This results in a rather lumpy preformed blank, which sometimes requires smoothing dies to shape the piece before it is placed in an impression die.

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Prepared for the Magnesium Committee

Temperature for Forging. Forging stock may be heated in electric, gas or oil-fired furnaces without an atmosphere of SO_2. The forging temperature of magnesium alloys is considerably lower than the melting point, so that the danger of fire during heating for forging is slight provided adequate furnace controls are employed. Further, since small, easily ignited sections are seldom produced during forging, the fire hazard is essentially no greater than that encountered in the heating of other metals for forging. Temperatures used for forging magnesium alloys vary from about 650 to 850 F, depending on the type of alloy, the section size of the forging, and the method of forging. Alloys AZ61X and AZ80X are usually forged at about 725 F, and the temperature should be held within plus or minus 25 F for best results. At lower temperatures the dies may be difficult to fill and the metal may crack. When forgings are made in several operations and difficulties with grain growth are encountered, it is considered good practice to lower the temperature with each subsequent operation.

Dies. Up to the present time, the dies customarily used

for magnesium forgings have been made from standard blocks carried in stock by die block manufacturers. It should be possible, however, to make press dies from cheaper materials and by cheaper methods; for instance, by casting the impressions to approximate size. Such a process, or any other process that lowers die costs, is attractive, especially for short production runs.

It is essential that the temperature of the die be relatively high in order to avoid chilling the stock as it flows. Generally the die temperature to be used for a given job will be adjusted for the type of alloy to be forged, the number of operations to be performed in a given heat, and the properties desired in the final forging. If multiple operations are to be performed, the preblocker and blocker dies should be operated at about 550 to 650 F, which permits the production of thin sections without danger of excessive cooling and, hence, cracking and underfilling.

The finish die may be operated as high as 600 F, if the section is thin and its projected area is large in comparison with the size of the equipment available for the production of the forging. However, if adequate power is available, it is desirable to operate the finish die at a low temperature, in order that the forging may benefit from strain hardening during the finishing step. In this operation the finish die may be operated at 400 F for thin sections and as low as 200 F for heavy sections to be "cold worked".

Dies for magnesium alloys should be designed according to the practice employed for dies used in forging aluminum, except for a few minor changes intended to make the dies easier to fill. Corner radii and fillets on magnesium forgings should be made as generous as possible, particularly when forging is done with a press. The use of large radii and fillets allows easier filling of a die.

The blocker dies for magnesium alloys should be held inside the finish die contours as much as possible, in order that the flow of metal during finishing can be simultaneously outward and upward. For example, in filling a high rib, magnesium tends to flow laterally rather than upward.

Dies are heated by encircling manifolds that carry gas burner tips which may be fastened on the dies during operation, if the forging is done in a hydraulic or mechanical press. In hammer forging it is unsafe to attempt to hang a manifold on the top die.

Lubrication. The lubrication of the dies in the production of magnesium forgings presents many problems not encountered in the forging of other materials. The best lubricants available at present contain graphite, either in flake or colloidal form, suspended in a mineral or animal oil, or occasionally in water. When considerable graphite is used to help a magnesium forging fill the dies, the deposits of graphite that adhere to the forging are difficult to remove by any but mechanical means, such as sandblasting. If the adhering graphite is relatively thick, attempts to remove it by chemical action result in severe pitting and surface deterioration and, usually, incomplete removal. Small forgings may require only sparing applications of die lubricant, and in these instances a chromic acid pickle will remove the graphite satisfactorily. The development of an improved lubricant that contains no graphite but that has adequate lubricating qualities is one of the problems now facing the magnesium forging industry. There is a possibility that some of the high-temperature, high-pressure lubricants developed for wartime applications may serve this purpose when their properties become well known and the products become easily available.

Wherever possible, the use of die lubricants that contain no graphite is desirable.

Trimming Forgings. Considerable care must be used in the trimming of magnesium forgings, because of the tendency to crack or tear if the trimming temperature is not within the proper range. The safe limits for most of the alloys are from about 300 to 500 F. For trimming forgings of alloy AZ80X, the temperature should not exceed 375 F and the time at temperature should be short if aging is to be avoided. At higher temperatures the metal is more likely to tear; at lower temperatures it may crack along the flash, into the forging. Dies for trimming must be made to close tolerances, if clean trims are to be obtained. Properly designed punch-out trimmers may be used satisfactorily, although trimmers that have a shearing action are usually more desirable for large forgings that have a relatively heavy flash. For short forging runs it is more economical to saw off the flash with a band saw and smooth the rough sawed edges with a rotary burr or file.

Heat Treatment. Of the standard forging alloys, only AZ80X may be benefited appreciably by aging, or by solution and aging heat treatments. The primary purpose of such treatments is to improve the tensile yield strength, and frequently more important, the compressive yield strength. The other alloys either contain insufficient amounts of hardening compounds for much improvement during aging, or the hardening compounds are insoluble at the forging temperature. Under optimum conditions AZ80X, after trimming, subsequent to finish forging, will have virtually all of the magnesium-aluminum compound in solid solution as a result of adequate homogenization at a sufficiently high temperature during heating for forging, and the maintenance of sufficiently high temperature during the forging operations. After forging or trimming at forging temperature, the alloy may be quenched in water if necessary to prevent grain-boundary precipitation of the magnesium-aluminum compound, which results in the loss of a certain amount of this compound to subsequent age hardening heat treatment. After quenching, a uniform solid solution is retained, recrystallization and grain growth are halted, and the structure is characteristically fine-grained with uniform straight grain boundaries free from high-temperature precipitate.

Alloy AZ80X may be fully aged by heating at a temperature of 350 F for 24 hours. This will result in maximum tensile properties, maximum compressive yield strength, and maximum hardness. Variations in properties can be obtained by aging and underaging.

Where resistance to creep at elevated temperatures is of primary interest, the forgings should be given a solution heat treatment before aging. The solution heat treatment consists of heating the forging at 725 F for ■ hours. This temperature should not be exceeded or excessive grain growth may result. The solution treatment may also be necessary where inadequate solution was achieved in heating for forging, or where some precipitation occurred during cooling after trimming. In general, forgings solution-treated and aged have somewhat lower tensile properties and ductility than those properly handled during heating and forging and then subsequently aged without an intermediate solution heat treatment.

Mechanical Properties. The typical mechanical properties obtained in the standard forging alloys are given in Table I, page 1000 in this Handbook. The minimum specification or design values for the mechanical properties are given in Table II, page 1001. Sections, forged from extruded stock 3 in. in diam, or smaller, usually possess tensile and compressive yield strengths greater than the design values. Forgings made from larger stock that undergoes considerable movement of metal may also exceed the design values, but usually by a lesser amount than do small forgings. However, heavy, chunky forgings made from 6-in. or 8-in. extruded rod or cast billets may have properties considerably less than average because of the difficulty of producing adequate mechanical work during either extrusion or forging. Designers planning to utilize magnesium forgings should consult with the forge shop regarding the properties that may be obtained in a particular forging, since the properties of the magnesium alloys may be changed considerably by variations in the amount of mechanical work or the working procedure.

The Press Drawing, Forming, Spinning and Bending of Magnesium Alloys

By J. V. Winkler*

SINCE magnesium sheet and extrusions are "formed" in much the same manner as other common metals, the same type of fabricating equipment is used. Most operations are performed hot, particularly those requiring bends of small radius and deep draws. Both the tools and the work material are heated; consequently deformation is easy, with little or no spring-back. Methods of applying heat vary with the type of operation used and depend also on the number of parts required.

Press Drawing. *Equipment.* Both hydraulic presses and mechanical presses are used for drawing magnesium sheet. Hydraulic or pneumatic devices for applying pressure to the blank-retaining portion of the die are essential where maximum draws are required. Single-action presses are sometimes used for hot drawing magnesium; springs or C-clamps restrain the sheet in the blank-holder. Control of clamping pressure is inferior, but the equipment is adequate when moderate draws are to be made or when a small number of parts is required. When springs are used, they should be located away from the die, and pressure should be exerted through pressure pins to eliminate the danger that the springs may become hot enough to be deformed plastically.

Materials for dies used in hot forming must obviously be able to withstand the temperatures employed in the drawing operation, without ill effect. Pressure rings and draw rings are usually made of mild steel. It is important to stress relieve the steel before the final machining, in order to remove strains that would warp the die in service. Plate thicknesses recommended for mild steel draw rings and pressure rings are given in Table I. Gray iron is also

Table I

Plate Thickness for Die Rings

Largest Blank Dimension, inches	Minimum Plate Thickness, inches
0 to 14	1.5
14 to 22	2.0
22 to 30	2.5
30 and more	3.0

used, as well as certain alloy cast irons that have the advantage of exhibiting little or no growth when long production runs are made. Steel, cast iron, aluminum alloys and magnesium alloys are used in making punches. Zinc alloy diestock (*see* Zinc Section for compositions of the alloys) may be used where the temperature does not exceed 450 F. The supporting structure for a built-up die is invariably made from mild steel. If welding is required, the structure should be stress relieved before final machining, in order to ensure parallel surfaces.

In designing dies for materials that have a coefficient of thermal expansion different from that of magnesium, allowance must be made to obtain accurate dimensions of parts. Steel and cast-iron die parts should be increased in size 0.0008 in. per in. for each 100 F above room temperature required for the operation of the die. The factor for aluminum die parts is 0.0004 in. per in.

A drawing of a conventional built-up die is shown in Fig. 1. This open type of die is desirable for reducing the transmission of heat to the press. Where solid cast dies are used, asbestos sheet should be placed between them and the press as insulation to conserve heat in the die.

For maximum drawability, the entering radius on the draw ring or female die should be from five to seven times the thickness of the sheet being worked. When only a small number of parts is required, dies can be heated either by playing a hand torch over them or by placing them in ovens, where temperature can be checked by means of a contact pyrometer. For production work, dies are heated by electricity or gas, and the temperature is controlled by automatic instruments.

Either electric-cartridge heaters inserted in holes drilled in the die, or strip heaters clamped to the die surface, are used for small dies. Large dies may also be heated by such means where an open gas flame is undesirable, and the increased cost is therefore warranted. The temperature is controlled by means of a controlling pyrometer that operates a magnetic contactor.

Gas and compressed air, mixed by means of suitable equipment, are conveyed to the die burners through a rubber hose. The die burners are made of ¾-in. or 1-in. steel pipe, bent to shape as required. Burner ports in the pipe are No. 40 drilled holes, spaced about ½ in. apart. The burner is mounted ⅝ in. from the die, so the flame impinges on the surface to be heated. A controlling pyrometer regulates the amount of gas burned, by operating a solenoid valve.

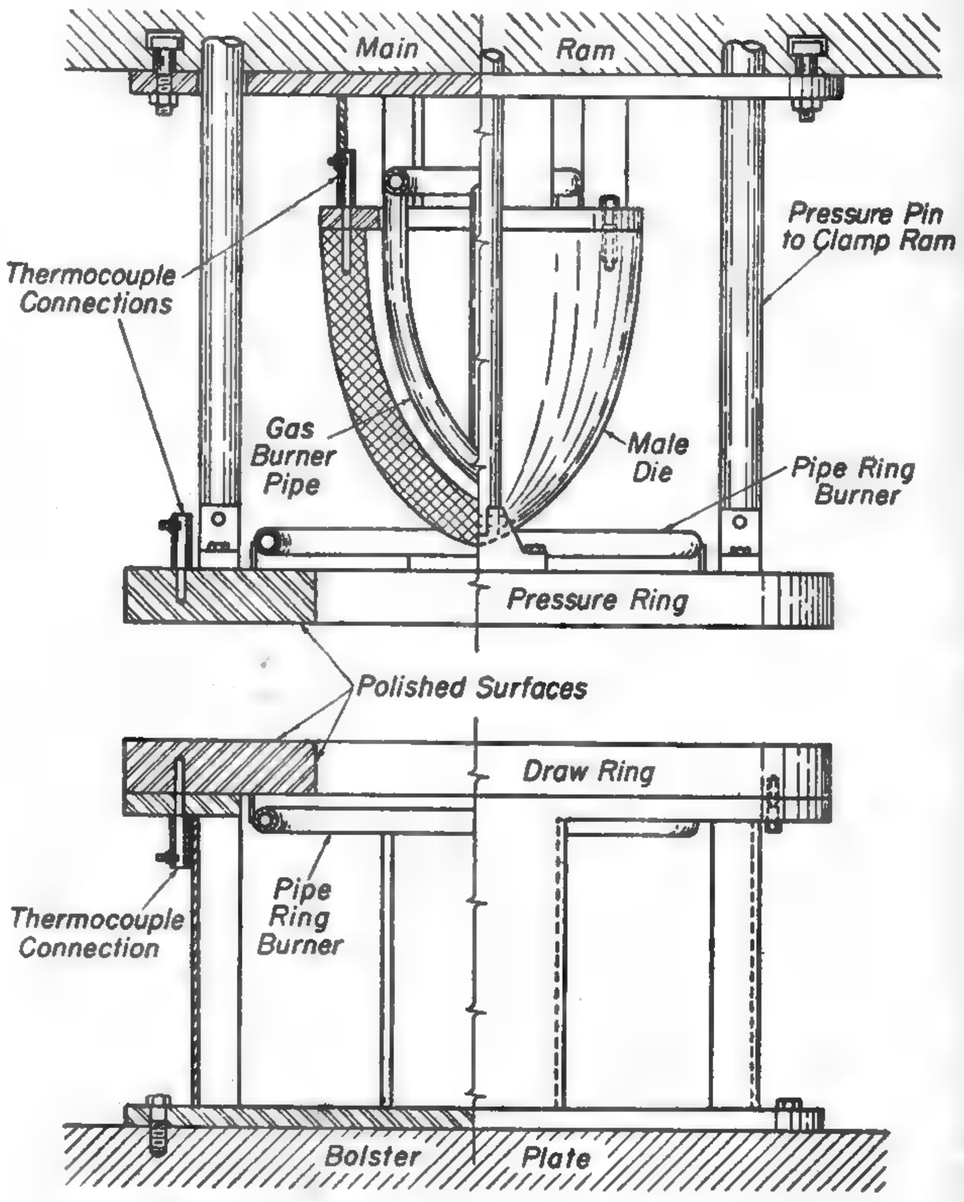

Fig. 1 Typical die for hot drawing magnesium alloy sheet

Burners should be located so that the magnesium sheet will not be subjected to an open gas flame. General arrangement of the burners and thermocouples may be seen in Fig. 1.

Two types of oven are used for heating the sheets. A contact-plate heater is preferred, in which the sheet is pressed between two steel or cast-iron plates heated with electric strip-heaters. Standard air ovens are also used for flat sheet, although the operation is slow because a waiting period is required to bring a new stack of sheet to temperature. The air oven is essential where heating of formed sheet is required for subsequent operations.

Operation. Graphite is used for lubricating sheet to be hot formed at about 260 to 343 C (500 to 650 F). The material most commonly used is a colloidal graphite suspended in a volatile carrier. When this material is sprayed on the sheet, the carrier evaporates, leaving a thin film of graphite that clings tenaciously. This coating prevents scoring while

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Prepared for the Magnesium Committee

the sheet is being formed, and stays on the sheet during the drawing operation, protecting the die from being fouled.

Graphite coatings are removed by a ½ to 2-min immersion in an aqueous solution that contains 15 to 20% chromic acid and 3% sodium nitrate. The bath is usually operated at room temperature.

A number of factors determine the temperature to which a sheet must be heated to provide sufficient ductility for forming. The alloy and temper of the sheet must be considered. Hard rolled sheet is usually limited to parts in which a moderate amount of shaping is required, since the forming temperature must be limited to prevent excessive loss of mechanical properties as a result of annealing. Generally the maximum temperatures used on hard rolled sheet are 163 C (325 F) for AZ31Xh sheet (3% Al, 1% Zn); 204 C (400 F) for AZ51Xh (5% Al, 1% Zn); and 260 C (500 F) for M1h (1% Mn). The temperature required to form annealed sheet for draws of various depths is shown in Fig. 2. Here the drawability factor $(D - d)/D$ is the ratio obtained by dividing the blank diameter minus the draw diameter by the blank diameter. For production

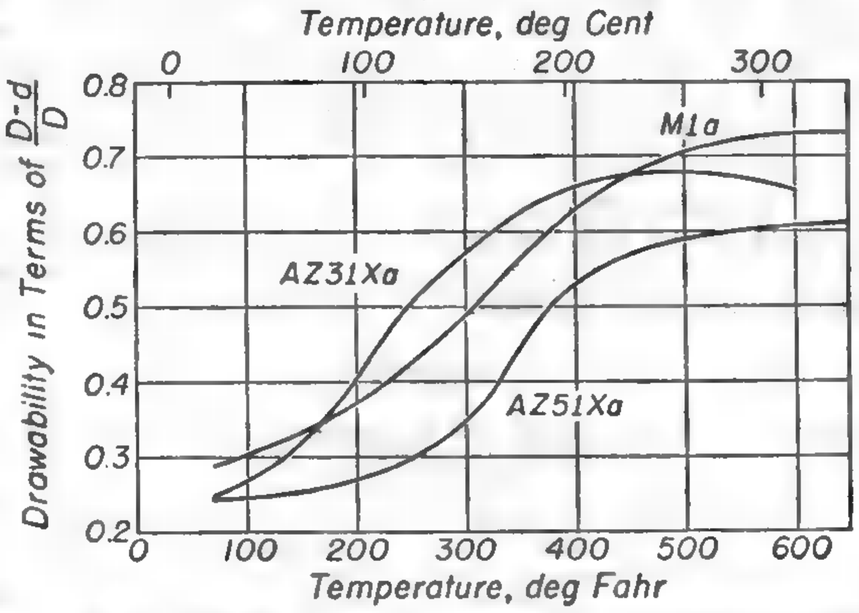

Fig. 2 Drawability limits for hot working annealed magnesium alloys in a single operation

design, maximum single draws should be held somewhat lower than the top limits shown on the curve, since these draws can be obtained only with very accurate control.

The shape of the part often dictates the temperature requirement, especially for the punch. In ordinary draw work, a punch will absorb sufficient heat from gas burners on the draw ring and pressure pad. Where the sheet must be stretched sufficiently to allow it to shape to the punch (for instance, in a hemisphere) the punch must be heated so that the sheet can be kept hot enough during the operation to preclude puckering. When draws of maximum depth are required, the punch is sometimes cooled by water to a temperature of 150 to 200 F. This permits the sheet between the holding plates to be heated high enough for compression without forming wrinkles, while the sheet drawn over the die radius is cooled by contact with the punch so that the strength is raised to permit drawing from between the plates. A working rule is to provide the amount of heat required for making a straight bend in the sheet, as shown in Fig. 3 in the section on bending sheet. A temperature of 316 C (600 F) may be used for drawing all annealed sheet. In the drawing of hard rolled sheet, the temperature should not exceed 149 C (300 F) for AZ31Xh, and 204 C (400 F) for M1h and AZ51Xh sheet, to avoid a loss in mechanical properties as ■ result of annealing.

Speed of draw and sheet thickness must be controlled, as well as any tendency of the sheet to be locked so that the shape is obtained in stretch rather than draw. In general the ram speed of 2 to 4 fpm, obtained with typical hydraulic presses, is the most satisfactory range for drawing magnesium. Faster speeds obtained on mechanical presses permit greater production, when requirements for deep draws, small bends, or excessive stretching do not prohibit their use. Where water-cooled punches are used for very deep draws, ram speed must be slow enough (usually 1 fpm or less) for the punch to cool the sheet.

Forming. *Forming in Rubber.* Flanged parts, lightly contoured parts, and other shapes that do not require drawing action are often formed by means of the Guerin process, as developed by Douglas Aircraft Company, for producing shapes such as ribs, fuselage frames, beaded panelings and fairings. Cost of labor is higher, but where a small number of parts is required, the advantage of low cost for dies and speed of producing or revising dies, will offset this disadvantage. In this process, sheet to be shaped is placed on forming blocks and a rubber pad about 6 to 8 in. thick is forced down on the sheet. The sides of the pad are confined in a steel box and the forming blocks are

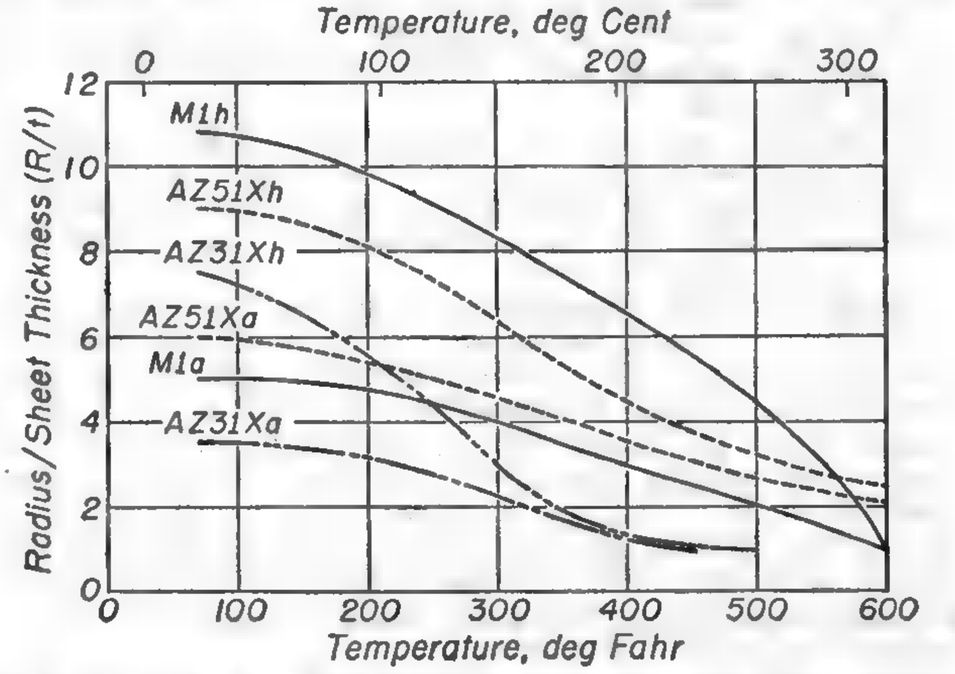

Fig. 3 Die radii for 90-deg bends. Heated punch and rubber bottom die. (Rubber retained in conventional U-shaped press-brake die.)

placed on a steel plate, which enters the rubber box. Pressure developed in the confined rubber is therefore applied to press the sheet to the shape of the form block.

This type of forming is normally limited to hydraulic presses, since form blocks of different sizes result in varying ram travel. On mechanical presses, this method would require excessively careful adjustment of ram travel in order to develop sufficient pressure for forming, without danger of overtravel, which might harm the press or even cause failure in the rubber box, with possible injury to workmen in the vicinity. The size of the rubber box for forming magnesium should be limited so that a minimum pressure of 1000 psi will be developed on the entire pad.

Form blocks are made from aluminum or magnesium, either machined from plate or produced as castings. Better forming characteristics are obtained by use of external rather than internal beads, lightening holes and stiffeners. ("External" means that the portion of the die to form these elements projects from the surface of the block, as opposed to "internal", where the sheet is pressed into cavities cut into the block).

Rubber forming for magnesium is usually conducted at temperatures between 149 and 232 C (300 to 450 F). Compounded heat-resistant natural rubber or synthetic rubber is employed either as a facing on a natural rubber pad or as the entire pad. This material withstands temperatures developed when dies are used at 232 C (450 F).

Ordinarily an oven provides the necessary heat. The blank is placed on a forming block, is brought up to the forming temperature in the oven, and is then transferred to the press for forming.

Forming Under a Drop Hammer. Under a drop hammer, magnesium sheet can be formed into shapes as complicated as those produced in other metals. Comparatively recent experience has established this process as an economical means of forming magnesium sheet.

Zinc-base alloys with melting points from 371 to 380 C (700 to 725 F), normally used in making drop-hammer dies, have proved satisfactory for forming at temperatures as high as 232 C (450 F). Antimonial lead (which usually serves as a punch, since it may be cast into the die, thus eliminating the necessity for a pattern) has been used at temperatures as high as 204 C (400 F).

The dies must be heated so that hot sheet will not be

chilled too rapidly to permit forming. Heating is accomplished by means of a hand torch or by means of pipe burners mounted on the sides of the die. When a torch is used, the flame should be moved continuously to prevent local rise in temperature. Flames from pipe burners produce heat less intense than the heat of a torch, and may be mounted on zinc alloy dies, since the conductivity of such dies is high enough to prevent local melting.

Sheet may be preheated in an oven or it may be heated by contact with the heated dies. When the dies serve as heating mediums, restraining rubber placed at the edge of the die, supports the punch so that its weight will not deform the sheet, while it is still relatively cold, sufficiently to cause a fracture. A one-minute pause is required for allowing the sheet to heat, before the punch is raised and a blow delivered.

When lead punches are used, provisions must be made to prevent lead from contaminating the magnesium sheet, or corrosion may be encountered. A thin sheet of steel or aluminum placed on the punch affords adequate protection.

Hand Forming. Because of the heating requirement, the hand forming of magnesium is more difficult than the hand forming of other metals, which is possible at room temperature. When the material is clamped to a block, simple bends are made with a soft hammer. Metal form blocks are usually employed, although a heat-resistant wood, such as birch, may be used for a small number of pieces. For making contoured shapes, simple dies are used with magnesium more extensively than with other metals, because such dies permit more rapid forming and thereby reduce the heating problem.

Heating is usually accomplished with a hand torch and temperatures are checked with a hand pyrometer. Metal dies and form blocks may be heated by placing them in an oven, or by attaching electric heaters to them.

Although heating does present a problem in the hand forming of magnesium, when the material is hot it forms so readily that much less force is required to produce a desired shape than is required for other materials. This factor is so important in many instances that it alone warrants the use of heat.

Stretch Forming. The excellent elongation of hot magnesium sheet permits the production of very complex shapes by stretch-forming operations. Forming is possible at room temperature, but severe working must be done hot. A hand torch playing over the surface will heat magnesium sheet or, if production parts are being run, the heated punch will convey enough heat to the sheet to facilitate forming.

Punches for hot stretch forming can be made from a zinc-base alloy if the temperature is limited to 204 C (400 F). Aluminum or magnesium castings are used at higher temperatures. The punch is heated by means of gas and the sheet is heated by contact with the punch. Graphite-tallow mixtures are most satisfactory for punch lubrication, because they provide adequate body to eliminate slip chatter.

Bending. *Bending Sheet.* Figure 3 shows the bends that may be obtained in magnesium sheet alloys as a function of temperature. These curves represent values obtained from bend tests on sheet that has typical forming properties, but they are not recommended as minimum bends.

Press-brake dies are heated by electric strip-heaters. A holder for the upper brake blade, as shown in Fig. 4, incorporates heaters, so it is unnecessary to attach heaters to each blade. This holder includes insulation. With lower dies the insulation is placed between the press bed and bed rail. Temperature is usually controlled manually and checked by a contact pyrometer, or it may be controlled automatically.

Bending Extrusions. An extrusion may be formed by clamping one end and bending it to a form block by hand or with a soft hammer. If heat is required, a hand torch is played on the extrusion while the bending is in progress. In addition to permitting smaller bends, use of heat reduces the work required to complete the bend and reduces the spring-back—a definite advantage where the extrusion must conform to a form block, or where a bend through 360 deg is required.

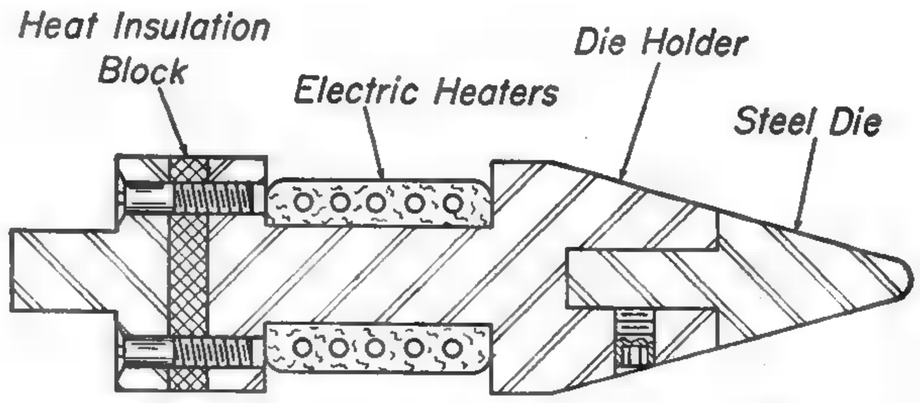

Fig. 4 Electrically heated press-brake blade holder

Angle rolls, mating dies, stretch-forming presses, and specialized bending machines are employed where production quantities are required. Heating, when necessary, is accomplished by placing the stock in an oven. Dies are heated by placing electric elements in them or by attaching gas burners in such a manner that the flame may be directed against the die.

Table II shows the radius to which a rectangular section can be bent at room temperature and at the highest temperature that may be used.

Table II

Minimum Bend Radii for Extruded Strip in Terms of Strip Thickness, t

Alloy	Room Temperature Bend	Elevated Temperature Temperature[a]	Elevated Temperature Bend
AZ80X HTA	7 to 9 t	193 C (380 F)	1.5 to 2.5 t
AZ80X	2 to 3 t	316 C (600 F)	1 t
AZ61X	1.5 to 2.5 t	316 C (600 F)	1 t
M1	4.0 to 5.5 t	371 C (700 F)	1.5 to 2.5 t
AZ31X	2 to 3 t	316 C (600 F)	1 to 2 t

(a) The maximum permissible forming temperature for each alloy is listed. Exceeding this temperature will result in excessive loss of strength, and also reduced ductility in AZ80X, AZ61X, and AZ31X.

Spinning. The spinning process for magnesium has proved very successful. Small quantities are produced at an appreciable saving because of the lower cost of tooling. Where the shape of a part is such that press-tooling would be very complex, spinning may be employed to advantage for making even a large number of parts.

Spinning at room temperature is limited to shallow parts that do not require bends of small radius. Heating the sheet permits it to be spun as readily as any other material.

Heat is normally applied by playing a torch on the rotating part. The spinner can regulate the heat applied, according to the "feel" of the material. Chucks for spinning may be made of maple or of metal, but aluminum or magnesium is preferred. Maple chucks are satisfactory for a small number of parts; metal chucks may be heated by playing a gas flame on the base of the chuck, thus reducing or eliminating the necessity for playing a torch on the sheet while it is being spun.

The spindle speed should be selected so that the peripheral speed of the outside of the blank will be about 2000 fpm.

Standard spinning tools are satisfactory. Brown laundry soap or a paraffin-tallow mixture is the usual lubricant, except in the spinning of certain shapes where high temperatures are required. In such instances a graphite-tallow mixture is applied.

Joining Magnesium Alloys

By Thomas E. Piper*

MAGNESIUM alloys may be joined by welding, riveting, bonding and soldering.

Welding

The principal methods employed are gas welding, arc welding and electric-resistance seam and spot welding. Magnesium alloys cannot be satisfactorily welded to other metals.

Gas Welding. Most of the wrought and some of the cast magnesium alloys can be joined by gas welding. Oxyacetylene, oxyhydrogen and oxycarbohydrogen gases may be used; however, oxycarbohydrogen gas is recommended, because the flame is cooler and is more easily seen. The filler rod should either be of the same composition or have a lower melting point than the parent metal. Table I gives information about the selection and regulation of equipment for the acetylene welding of magnesium alloys. For oxycarbohydrogen welding, a somewhat larger orifice is used, and the carbohydrogen gas pressure is somewhat increased for the thinner metal sections.

Table I. Data for Oxyacetylene Welding Magnesium

Metal Thickness, inch	Welding Rod Diameter, inch	Orifice Diameter, inch	Drill Number	Oxygen Pressure, psi	Acetylene Pressure, psi
0.020	1/16 to 3/32	0.035	65	1 to 4	1 to 3
0.032	1/16 to 3/32	0.035	65	3 to 5	1 to 3
0.040	3/32 to 1/8	0.035	65	3 to 5	1 to 3
0.051	3/32 to 1/8	0.035	65	3 to 5	1 to 3
0.064	3/32 to 1/8	0.040	60	3 to 5	3 to 5
0.072	3/32 to 1/8	0.040	60	3 to 5	3 to 5
0.081	3/32 to 1/8	0.046	56	3 to 5	3 to 5
0.091	1/8 to 5/32	0.046	56	3 to 5	3 to 5
0.128	1/8 to 5/32	0.059	53	3 to 5	3 to 5

Commercial fluxes are available for torch welding magnesium alloys.

The composition of a typical flux is as follows:

Compound	Percentage (by weight)
Potassium chloride	45%
Sodium chloride	25%
Lithium chloride	25%
Sodium fluoride	5%

Total impurities — carbon, oxygen, sulfur, iron or silicon — should not exceed 0.15%. The fluorine content should not be less than 2%.

Welding fluxes are generally supplied as a dry powder which is hygroscopic and should be stored in tightly sealed containers. Preparatory to welding, the powder is mixed with water to form a thin paste, in a glass or porcelain container. Containers made of iron, brass, or other materials that might react with the flux should not be used.

The material to be welded should be cleaned with gasoline, naphtha, carbon tetrachloride or hot alkaline cleaners. The joint area should be cleaned with a fine steel brush made of wire 0.003 to 0.006 in. in diam; with steel wool; or by chemical means.

A flanged joint 1/16 to 1/8 in. high is desirable for sheets thinner than 0.040 in. Sheets 0.040 to 0.125 in. thick can be welded with a butt type of joint. Sheets thicker than 0.125 in. should be beveled to an included angle of 90 to 120 deg, with a root face of approximately 1/16 in. The maximum thickness for a single-pass weld is usually 1/4 in. Gas welding is restricted to butt-joint and single-pass welds to avoid corrosion by entrapped flux.

The flux should be brushed on both sides of the joint and the rod. A neutral flame is recommended for all types of gas.

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Prepared for the Magnesium Committee

The material should be preheated slowly until the flux fuses. Then the torch is moved forward in a straight line with no rotary motion. As the puddle forms, the rod should be dipped into it intermittently and the torch should be moved forward, inclined toward the work material at an angle of about 45 deg.

As soon as the welded parts are cool, the flux should be removed by a thorough cleaning with hot running water and a bristle brush. The part should then be given a chrome-pickle treatment for one minute at 70 F in the following solution:

Sodium dichromate ($Na_2Cr_2O_7.2H_2O$)	1.5 lb
Concentrated nitric acid (sp gr 1.42)	1.5 pt
Water	to make 1.0 gal

After treatment, the parts should be washed in cold running water, then boiled for two hours in the following solution:

Sodium dichromate ($Na_2Cr_2O_7.2H_2O$	0.5 lb
Water	to make 1.0 gal

The assembly should then be rinsed in cold running water and dipped in boiling water.

If an assembly is too large for immersion, it should be cleaned and heated to about 150 F; then a chrome-pickle solution should be brushed over the seam and allowed to remain for one minute, after which the assembly should be thoroughly rinsed in hot water. This treatment does not afford the same protection against corrosion as the preceding method.

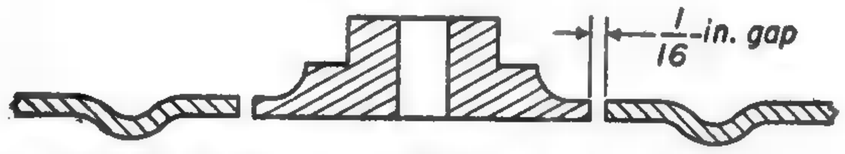


Fig. 1 Heavy section tapered to thickness of sheet before welding

Extrusions and castings can be welded to sheet stock. The edges of both should be beveled so as to be near the thickness of the sheet material, as shown in Fig. 1. More heat should be directed on the area having the greatest mass in the vicinity of the weld.

Shielded Arc Welding. Magnesium sheet, extrusions, forgings, sand castings and permanent mold castings can be welded by the gas-shielded arc method. The torch employs a tungsten electrode shielded by an inert gas, such as argon or helium. This method requires no flux; therefore, all types of joints commonly employed on steel can be welded with magnesium.

To weld magnesium by an automatic machine is practicable when production methods warrant the expense of the machine. Welding speeds of 12 to 40 in. per min are possible with such equipment. Higher mechanical properties and more uniform welds are thus obtained.

A standard d–c arc–welding generator or rectifier equipped with a variable current control is satisfactory for welding magnesium. An a–c transformer type of machine with high-frequency unit is also satisfactory. Commercial torches are supplied in various sizes and tip angles. A conventional welder's helmet for the face and suitable protection for hands and arms should be used to prevent exposure to the radiation from the arc.

A pure inert gas is essential for sound welds. Impurities in amounts greater than the following will cause welding difficulties:

Helium		Argon	
Helium	97.8 %	Argon	99.8% min
Carbon dioxide	0.2 %	Nitrogen	
Nitrogen	1.6 %	Neon	
Water	0.029%	Xenon	
Hydrogen	0.2 %	Helium	0.2%
Hydrocarbons	0.0 %	Oxygen	
		Hydrogen	

Water vapor decomposes in the arc and yields hydrogen and oxygen. Hydrogen, very readily absorbed by the molten metal, produces porosity. Oxygen reacts to form magnesium oxide, resulting in poor fusion and inclusions. Nitrogen reduces the welding speed.

Electrodes are manufactured in sizes from 3/32 to 1/2 in. in diam. The filler rod should have the same composition as the parent metal or should have a lower melting point than the parent metal. Selection and regulation of arc-welding equipment is shown in Table II. Alloy M1 (Mg – 1.5% Mn) requires somewhat more current than is indicated in Table II.

Table II. Data for Arc Welding Magnesium

Metal Thickness, inch	Current, amperes	Filler Rod Diameter, inch	Helium Flow, cu ft/min	Helium Pressure, oz/sq in.	Tungsten Diameter, inch
0.030	20	1/16	0.3	6	3/32
0.040	30	1/16	0.3	6	3/32
0.050	35	3/32	0.3	6	1/8
0.060	45	3/32	0.3	6	1/8
0.070	55	1/8	0.3	6	1/16
0.080	60	1/8	0.3	6	3/16
0.090	65	1/8	0.3	6	3/16
0.100	70	1/8	0.3	6	3/16
0.125	75	1/8	0.3	6	3/16
0.150	80	5/32	0.3	6	3/16
0.200	90	5/32	0.5	12	1/4
0.250	100	5/32	0.5	12	1/4
0.500	115	5/32	0.5	12	1/4
1.000	130	5/32	0.5	12	1/4

The first and most important operation in welding is to clean the material thoroughly of all paint, coatings, oxides, grease and other foreign matter. Naphtha or carbon tetrachloride can be used for removing oil and grease. For removing oxides and chemical coatings previously applied, a hand or rotary brush is recommended, made of wire 0.003 to 0.006 in. in diam. Steel wool or abrasive cloth (not emery cloth) may also be used. If the butting edges are rough, they should be smoothed by filing or grinding.

The arc is started by brushing the tungsten electrode lightly on the metal and then raising the electrode to a minimum arc length. As the metal becomes molten the filler rod is advanced into the arc, which rapidly bites off small pieces of the rod. The rod should not be pushed into the molten metal, but rather into the arc. The torch should be held close to the surface to maintain a short arc and at an angle of not more than 60 deg to the work. The filler rod should be held at an angle of not more than 30 deg to the work, and in such a way that the torch and filler rod make an angle of 90 deg to each other. For good sound welds, it is recommended that the entire weld be made with as few stops as possible. When stops are necessary, the weld should be wire-brushed before continuing.

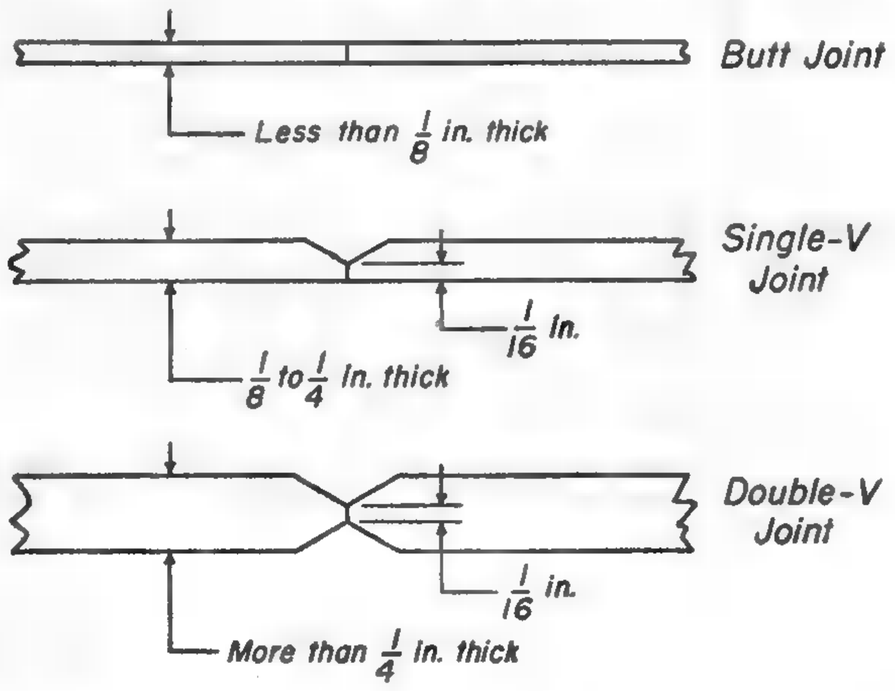


Fig. 2 Preparation of joints for arc welding

The recommended preparation for joints of various thicknesses is shown in Fig. 2.

When no backing plate is used with metal 0.125 in. thick or less, the metal drops through on the under side, permitting 100% penetration; however, a good fit is necessary when this method is followed.

Sometimes it is necessary and advantageous to use a backing plate that has a small groove directly below the seam. The groove allows a smooth cast through on the under side. Dimensions for the groove vary with sheet thickness. For sheet 0.064 in. thick, a depth of 1/16 in. and width of 3/16 in. are suitable. For sheet 0.125 in. thick, a depth of ⅛ in. and width of ¼ in. are required. More uniform penetration and greater ease of welding are two advantages of this method.

Steel, copper and magnesium can be used for backing plates on thin material. A magnesium jig is advantageous in reducing warpage and residual stresses, since the jig is heated during welding and the weld is permitted to cool slowly.

Warpage, residual stresses and cracking are reduced by preheating between 200 and 400 F. Preheating increases the speed of welding and permits the use of lower current.

Since no flux is necessary for arc welding magnesium the welds need only be wire-brushed to remove the gray powder deposited on the material. Parts can then be given the chrome-pickle or dichromate treatment, and if desired, painted for greater resistance to corrosion.

Stress Relieving After Welding. Residual stresses set up by arc welding range from 1,000 to 15,000 psi adjacent to the weld in a longitudinal direction, and therefore require a thermal treatment to reduce these stresses to a minimum. The parts should be placed in a jig and clamped to prevent any warpage during the thermal treatment. If possible, the entire jig should be placed in a furnace at the temperature and for the time indicated in Table III, which gives the recommended stress-relieving treatments for the weldable magnesium alloys. After thermal treatment, the parts should be left in the jig in still air until they are cool.

Table III. Recommended Stress-Relieving Treatments for Magnesium Alloys

Alloy	Temperature ±10 deg Fahr	Temperature ±6 deg Cent	Time at Temperature, minutes
AZ31X Annealed	500	260	15
AZ31X Hard Rolled.....	300	150	60
M1 Annealed	500	260	15
M1 Hard Rolled.....	400	204	60
AZ51X Annealed	500	260	15
AZ51X Hard Rolled.....	375	190	60

Resistance Welding. Most magnesium sheet, extrusion and casting alloys can be spot welded. The best spot welds are secured when alloys of the same composition are welded together, but reasonably good joints can be made between different alloys. When sheets of unequal thickness are to be spot welded, the ratio of sheet thickness should not be greater than 3 to 1. The recommended distance between the spots is at least 8 times, and preferably 16 times, the thickness of the sheet (minimum ¼ and preferably ½ in.). The recommended distance from the edge is at least 4 times, and preferably 6 times, the sheet thickness (minimum 3/16 and preferably 5/16 in.). The minimum shear strength required per weld for spot-welded specimens is given in Table IV.

Table IV. Minimum Required Shear Strength Per Weld for Spot Welds of Magnesium

Nominal Thickness of Thinner Sheet, inch	Shear Strength, pounds
0.020	75
0.040	202
0.064	357
0.081	472
0.125	800

Magnesium alloys are supplied with two different protective coatings, chrome pickle or oil. The oil-protected material is preferred for spot welding, because the neces-

sary removal of the chrome-pickle coating is difficult. Oiled sheet should be degreased in solvents or alkaline cleaners before either mechanical or chemical cleaning. Mechanical cleaning may be done with a wire brush, steel wool or abrasive cloth.

Welding tips and machines similar to those used on aluminum are satisfactory for spot welding magnesium.

To prevent corrosion, the spot-welded joint should be wire-brushed and chemically treated.

Seam welds, of either the continuous or the intermittent type made in magnesium alloys, develop strength comparable to that of spot welds.

Flash Welding. Hydraulic flash-welding machines with rapid burn-off and fast push-up are best suited for magnesium. Good welds can be made with 90% strength efficiency.

Riveting

Most conventional methods of riveting can be employed with magnesium. For best results, however, it is necessary that special consideration be given to selection of rivets, design of joints, driving techniques and protection of the assembly.

Rivet Alloys. Magnesium is not suitable for use as a rivet alloy because of its characteristically rapid work hardening at room temperature. Aluminum alloy rivets that contain 5.2% Mg (Alloy 56 S) cause almost no galvanic action on magnesium. Steel, brass or 17 S aluminum rivets are not recommended unless service conditions include no appreciable danger of corrosion.

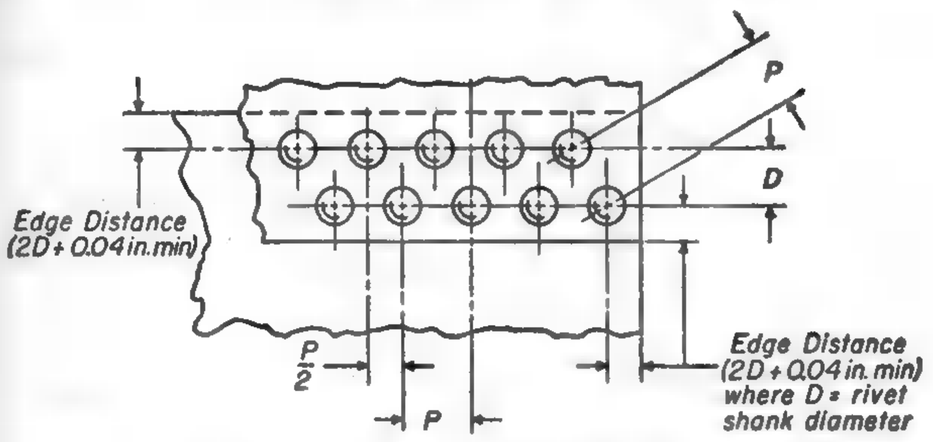


Fig. 3 Rivet spacing and edge distance

Design of the Riveted Joint. The selection of rivet size depends mainly on the rivet alloy, sheet alloy and thickness of sheet used.

The minimum normal rivet spacing or pitch, shown as *P* in Fig. 3, is four times the diameter of the rivet shank for all types of rivet. The absolute minimum spacing is three times the diameter of the shank for all types of rivets except those with flush heads. Flush-head rivets, when installed in dimpled countersinks, should not be spaced more closely than four times the diameter of the rivet shank. This minimum normal rivet spacing should be maintained whenever possible, since it permits drilling out an unsatisfactory rivet and replacing it with a larger size in order to salvage a part. Where the rivet spacing is too great, the sheet may warp or bow between rivets.

The distance between rows of rivets in a pattern should be approximately the same as the rivet spacing or pitch. If the rows are staggered, as shown in Fig. 3, the distance between rows can be less than the rivet spacing, but the diagonal distance in this instance should equal the rivet spacing *P*.

The minimum distance from a rivet to the edge, as shown in Fig. 3, should be limited to a minimum of twice the diameter of the rivet shank plus 0.04 in. Excessive distance at the edge should not be allowed where it would add weight unnecessarily or would form a moisture trap in horizontal parts (Fig. 4).

Types of Rivets. Most of the common types of heads supplied on aluminum rivets can be used for riveting magnesium alloy structures. Cone-shaped driven heads are less likely to cause damage to the magnesium sheet; first, because cone-shaped heads require less driving pressure and, second, because when a rivet is unintentionally driven at an angle, the rivet set is less likely to cut into the sheet.

Riveting Methods and Equipment. Driving methods for riveting magnesium are similar to those for other metals.

Squeeze-riveters are generally preferable to other machines for driving rivets in magnesium assemblies. Pneumatic hammers are suitable for riveting, provided they are large enough to upset the rivets properly.

Rivet Holes. Rivet holes in magnesium structures should be drilled or subpunched and reamed to obtain a smooth surface. Reaming reduces edge stresses and fatigue failures. Parts that are drilled together should be taken apart and all the chips should be removed from the joints before final assembly.

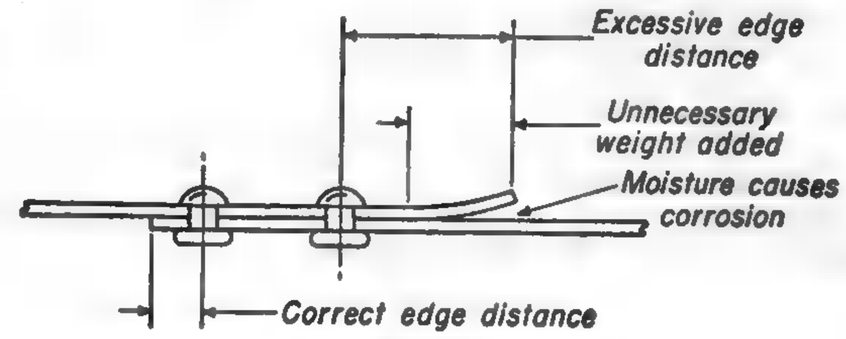


Fig. 4 Excessive edge distance with riveted joint

Flush Riveting (Dimpling). Several methods have been devised for dimpling magnesium sheet. Of the different processes, two seem the most practicable for production: first, resistance-heated dimpling, because of speed; and second, spin dimpling, because expensive equipment is not necessary. Another method is the use of heated dimpling dies.

Resistance-Heated Dimpling. In preparing the material for dimpling, any protective treatment must be removed around the area contacted by the dimpling sets, to prevent arcing or burning.

Before dimpling, it is essential that the holes be drilled several thousandths of an inch undersize so that they can be reamed to size after dimpling. Burring the holes is not necessary before dimpling, and in most instances is detrimental unless the holes are left smooth. The cutting edge of the burring tool leaves a sharp notch, which develops a crack when dimpled.

Spin Dimpling. The material to be dimpled is placed between two dies. The spinning male die is brought down on the metal, while the pilot indexes the material. Enough pressure is applied at first to create frictional heat; then pressure is increased until the dimple is formed.

Magnesium 0.050 in. thick or less can be dimpled satisfactorily. Heavier gages are countersunk by machine.

Prevention of Corrosion. The extent of the protection required for riveted magnesium joints depends on service conditions and on the composition of the aluminum alloy rivets that are used.

All parts to be riveted should be chemically treated in detail and given two coats of primer (Army-Navy Specification AN-TT-P-656b recommended) before assembly.

All rivets should be anodized or chemically treated to obtain good adhesion of paint. When the rivets have been driven, all the heads should be primed. Before a riveted structure is painted, all areas from which the surface-treatment chemical has been removed should be given the "brush-on" chrome-pickle treatment.

Exterior magnesium alloy surfaces that are assembled in contact with dissimilar metals should be insulated with high-pressure zinc chromate compound on the faying surfaces. Interior surfaces need only two coats of zinc chromate primer on each faying surface.

In assemblies requiring watertight joints, gasket material or heavy calking compounds offer the best means of sealing and preventing corrosion.

Adhesive Bonding

The numerous plastic and rubber compounds available for bonding magnesium surfaces, are generally classified as thermoplastic or noncuring, and thermosetting or curing types. The thermoplastic adhesives soften, become tacky

and dissolve when in contact with solvent or when heated; the thermosetting adhesives actually become a new and different compound when fully cured. The selection of the proper adhesive for a specific application depends on the conditions of service and stress to which the bonded magnesium will be subjected.

Magnesium surfaces to which adhesives are to be applied should be chrome-pickled, clean and free from grease. Cleaning may be done first with a fine wire brush, then with a strong alkaline cleaning solution. The sheet should not be "solvent cleaned" before cementing.

Thermoplastic adhesives may be applied as hot solutions or as solvent solutions and may be roller coated, brushed or sprayed. Sheet and strip film are applied by heat activation. Thermosetting adhesives are usually supplied in solvent solutions and may be applied by brush, roller or spray gun.

Most modern adhesives, when used for bonding magnesium, may be expected to be effective for about 10 years, under normal weather conditions and 50% stress. Sunlight and oxygen are probably the most detrimental conditions to the life of adhesive bonds.

Soldering

Soldering is ordinarily used only for filling imperfections in castings or sheet metal where a smooth surface is necessary. Soldering is not recommended where stresses are involved.

Two types of commercial solders have been developed especially for magnesium alloys. One type melts at 315 F and contains 60% Cd, 30% Zn and 10% Sn; the other type melts at 500 F and contains 90% Cd and 10% Zn. The area to be soldered should be preheated to approximately 350 F when the first type of solder is used, and to approximately 500 F when the second type is used.

The area to be soldered should be cleaned to a bright metallic luster so that a good alloying action can take place. Filing, wire-brushing and sanding with an aluminum oxide abrasive cloth are suitable methods.

A small amount of solder should be applied and the interface between the solder and the magnesium should be rubbed vigorously with a sharp pointed tool or brushed with a stiff wire brush continuously until the solder is alloyed. No flux is necessary or recommended for soldering.

Machining Magnesium and Magnesium Alloys

By H. Menking*

MACHINING TOOLS of standard design as used for other metals may, in most instances, be employed for magnesium. However, for maximum economy, tools for machining magnesium should be of slightly different design. The main factors governing the design of tools for cutting magnesium are: (1) the extremely low resistance of magnesium to cutting, (2) the comparatively low heat capacity of the metal, and (3) the large volume of the chips obtained because of the easy cutting. The low resistance to cutting leads to high speeds and heavy feeds; therefore the problem is to dispose of the chips quickly and smoothly, without jamming and subsequent development of frictional heat. The power required to remove a given amount of magnesium by machining is much lower than that required to remove an equal amount of any other metal used commercially. The power per cubic inch per minute normally required for machining magnesium varies from 0.15 to 0.3 hp. These basic factors have led to the development of tools with the following principal characteristics: smooth tool faces; large peripheral relief angles; large chip spaces and (in milling cutters) small number of blades; as well as comparatively small rake angles.

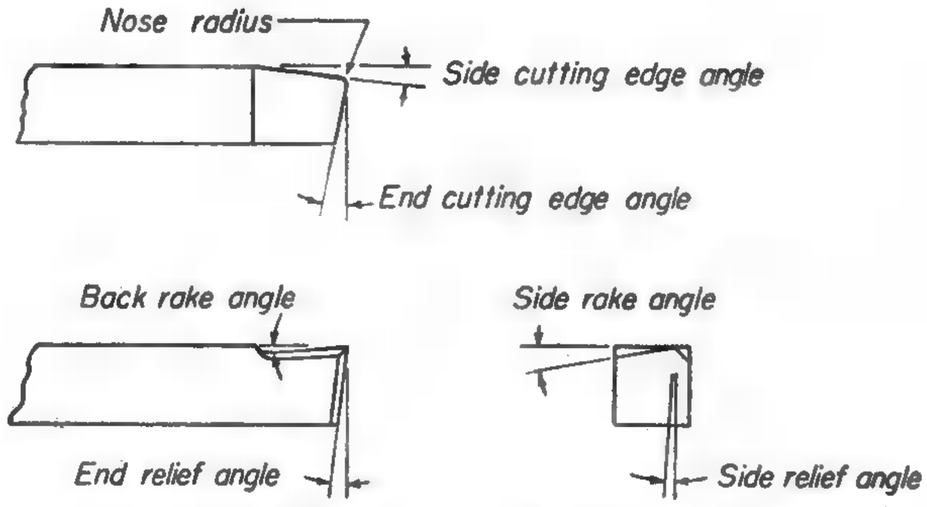


Fig. 1 Terminology of single-point tools according to the American Standards Association

In grinding the tools, it is most essential to keep the cutting edge as keen and smooth as possible and free from grinding wheel scratches, burrs or wire edges. In addition, the tools should be kept as smooth as possible wherever they come in contact with the chips, in order to facilitate chip flow. Keen tool edges and smooth tool surfaces are obtained best by finish grinding on a fine or very fine abrasive wheel, followed by a careful hand-stoning with a fine or extra fine oilstone when necessary. Tools previously used for other metals should always be resharpened before cutting magnesium, regardless of whether the cutting angles are changed or not.

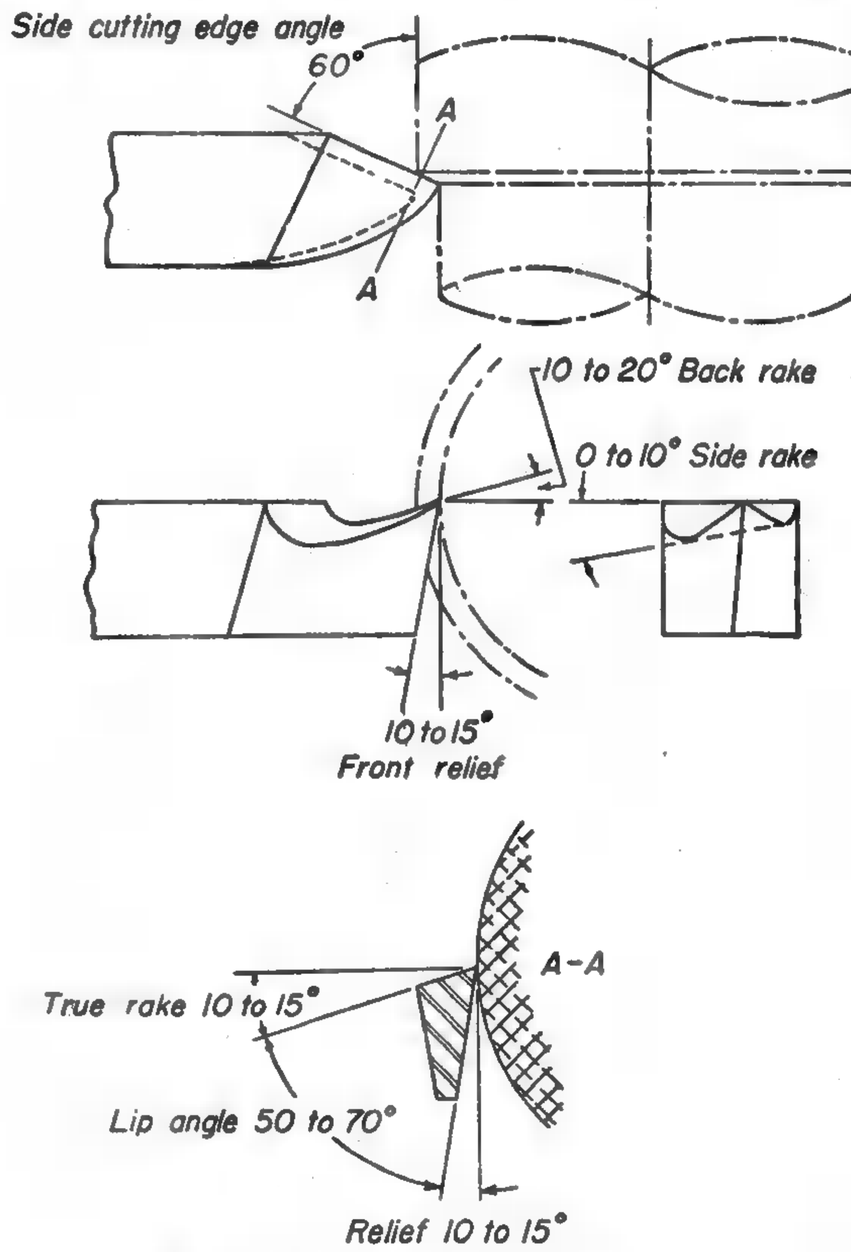


Fig. 2 Lathe tool for turning magnesium

Tools tipped with sintered carbide give considerably better results than tools made of high-carbon steel or

* Revised for this edition by the Magnesium Committee

high speed steel. Carbide tools are recommended for maximum efficiency, especially when extremely high cutting speeds are employed. The higher price of these tools is more than offset by their longer life, greater accuracy and greater operating economy, because of less frequent resharpening.

The terminology used in this article is in accordance with that advocated by the ASA. (*See* Fig. 1.)

Turning. Figure 2 shows a recommended lathe tool for rough cutting. The large relief (10 to 15 deg) and the small back rake (10 to 20 deg) are important. A larger back rake often causes feeding of the tool into the work. In some machine shops no back rake is used, an advantage in breaking up chips and preventing curling. Such a tool, however, is not generally recommended, since it reduces the smoothness of the machined surface slightly and increases the power consumption. The side rake may vary from 0 to about 10 deg.

The recommended finishing tool differs from the roughing tool by having a round nose on the tool tip, producing a smoother finish on the surface. General experience indicates that tool noses narrower than those used for aluminum are sufficient to obtain the same degree of smoothness for articles made of magnesium.

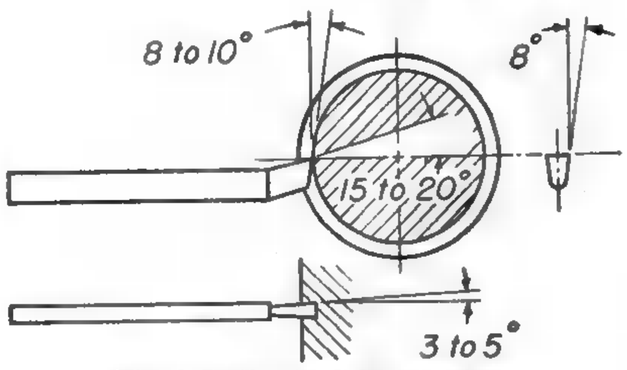


Fig. 3 Lathe tool for parting

Form tools (broad-nose tools) for taking wider cuts or turning specially shaped contours, should be designed along the same lines, except that the back rake should be reduced to about 3 to 8 deg to avoid chattering. Figure 3 illustrates a parting tool. The large relief angles are important to reduce friction and to avoid breaking the tool.

Recommended speeds, feeds and depths of cut for turning are shown in Table I.

Planing and Shaping. In principle, the same cutting angles are used as for lathe tools.

Table I. Recommended Speeds, Feeds, and Depths of Cut for Turning and Boring Magnesium

Operation	Speed, ft per min	Feed, in. per min	Maximum Depth of Cut, inch
Roughing	300 to 600	0.030 to 0.100	0.500
	600 to 1000	0.020 to 0.080	0.400
	1000 to 1500	0.010 to 0.060	0.300
	1500 to 2000	0.010 to 0.040	0.200
	2000 to 5000	0.010 to 0.030	0.150
Finishing	300 to 600	0.005 to 0.025	0.100
	600 to 1000	0.005 to 0.020	0.080
	1000 to 1500	0.003 to 0.015	0.050
	1500 to 2000	0.003 to 0.015	0.050
	2000 to 5000	0.003 to 0.015	0.050

Milling. Milling cutters for magnesium should be of the coarse smooth type. They should have considerably fewer teeth, preferably only one-half or one-third as many as are standard with conventional cutters used for steel and other metals. The larger chip space and the heavier cut resulting from the smaller number of teeth,

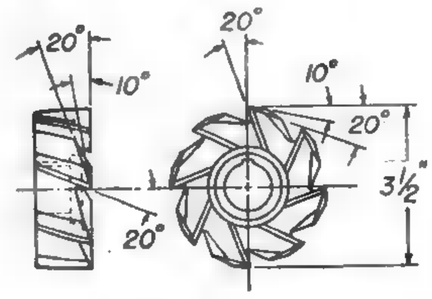


Fig. 4

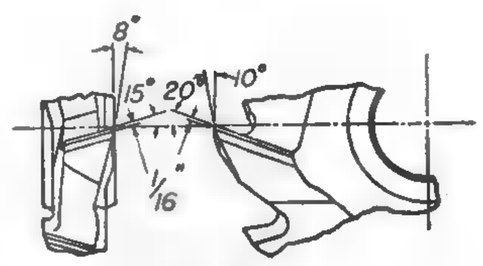


Fig. 5

Fig. 4 Face mill
Fig. 5 Staggered-tooth cutter. Recommended design of tooth

lead to a reduction of frictional heat, greater chip clearance, and consequently higher speeds, decreased distortion, lower power consumption and smoother finish. Unless otherwise stated, a relief angle of 10 deg, 1/16 in. wide, followed by a secondary clearance of 20 deg is common to all cutters illustrated.

Solid Cutters. Figure 4 shows a recommended type of face cutter. Figure 5 illustrates a staggered-tooth (slotting) cutter 6 in. in diam with 12 teeth. A helix angle of 15 deg, a rake of 20 deg, and relief of 8 deg on the side of the tooth are suggested for the latter type of cutter. Plain mills (Fig. 6) are recommended with 25-deg rake and 45-deg helix angle. On form cutters (Fig. 7) the rake is reduced to 5 to 8 deg, because of the heavier cutting pressure. A larger rake may result in chattering.

Inserted-Blade Cutters. These are less expensive than solid cutters of large diameter and offer a better chance to obtain large chip space. They are, therefore, used for high peripheral speeds. Figure 8 shows the design of an inserted-blade face mill 8 in. in diam with 6 to 8 blades. The blade design of a cutter 18 in. in diam, as used for extremely high cutting speeds (7000 to 8000 fpm), is shown in Fig. 9 and 10. Particular attention is called to the unusually small number of blades, the free unobstructed chip space between cutter body and work piece, the curved-out and polished face of the blade and the large relief (16 deg). All these features aid chip flow and reduce friction, thus making higher cutting speeds possible and increasing the life of the teeth.

A suitable type of shell-end cutter (Fig. 11) is designed similarly to the milling cutters described before.

With the type of machining equipment now used as standard, magnesium alloys, under ordinary conditions, can be machined at maximum spindle speeds and with feeds and cuts as great as the capacity of the machines. Recommended speeds, feeds and depths of cut for milling magnesium are shown in Table II.

Reaming. Reamers for magnesium should have a small relief (4 to 7 deg), a clearance of 15 to 20 deg and a small rake (5 to 8 deg) in order to secure a steady cut without vibration. A recommended reamer is shown in Fig. 12. The special steel and diamond boring tools often

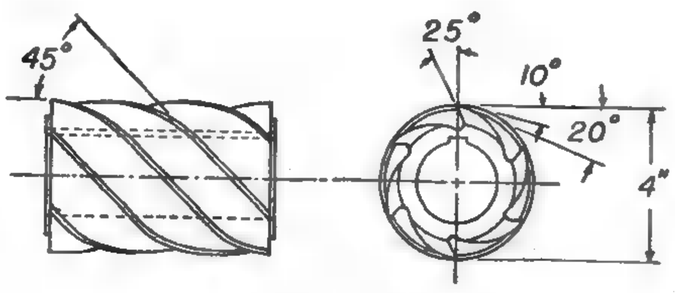


Fig. 6

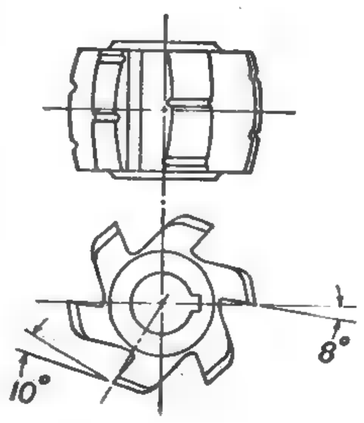


Fig. 7

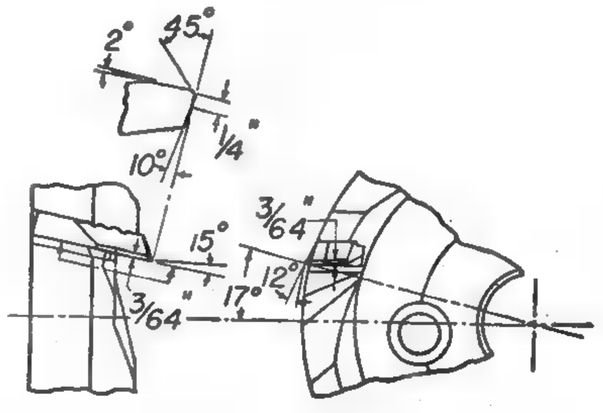


Fig. 8

Fig. 6 Plain mill. Fig. 7 Form cutter. Fig. 8 Inserted-blade face mill. Recommended design of blade

Table II. Recommended Speeds, Feeds, and Depths of Cut for Milling Magnesium

Operation	Speed, ft per min	Feed, in. per min	Feed, in. per tooth	Depth of Cut, inch
Roughing	Up to 900	10 to 50	0.005 to 0.025	Up to 0.500
	900 to 1500	10 to 60	0.005 to 0.020	Up to 0.375
	1500 to 3000	15 to 75	0.005 to 0.010	Up to 0.200
Finishing	Up to 900	10 to 50	0.005 to 0.015	Up to 0.075
	1000 to 3000	10 to 70	0.004 to 0.008	0.005 to 0.050
	3000 to 5000	10 to 90	0.003 to 0.006	0.003 to 0.030
	5000 to 9000	10 to 120	0.002 to 0.005	0.003 to 0.030

used for reaming are well suited for magnesium. A definite cut (minimum of 0.025 in. on the diam) should be taken with the reamer; otherwise the metal will compress, resulting in an undersize hole with poor finish.

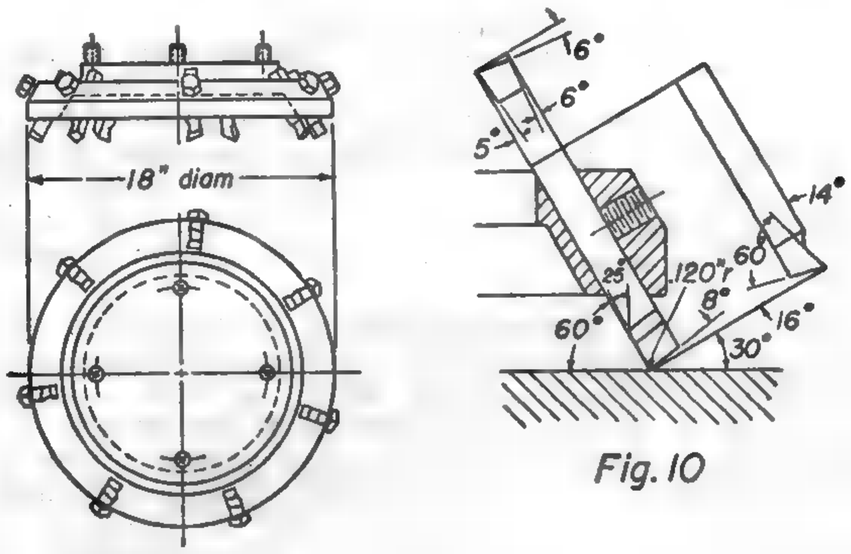


Fig. 9

Fig. 10

Fig. 9 Inserted-blade face mill for extremely high speeds
Fig. 10 Design of blade for inserted-blade face mill shown in Fig. 8

Drilling. The type of twist drill recommended for magnesium depends on the depth of the hole to be drilled. The speeds and feeds recommended when drilling magnesium are shown in Table III.

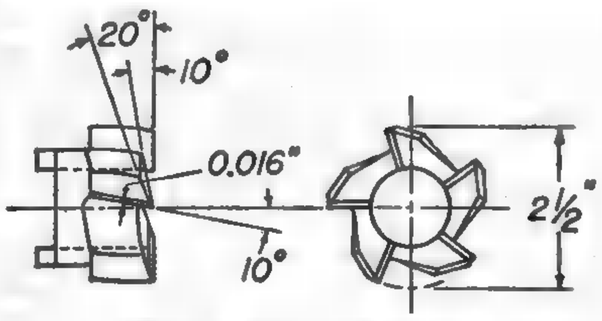


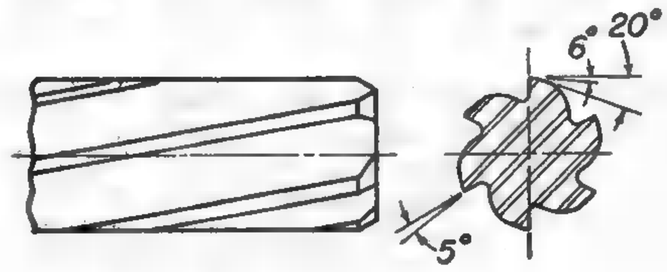
Fig. 11 Shell-end cutter

Deep Holes. A drill for deep holes (more than about four times the diameter) should have a helix angle of about 40 deg and smoothly polished flutes in order to ensure rapid flowing of chips. A web of uniform thickness is preferred. The clearance (relief behind land) should be twice as deep as with standard drills. The margin should be narrower than customary (one-half the standard width). A point angle of 110 to 120 deg and a lip relief of 15 deg is recommended. A drill of this design will cut freely and will readily clear out the chips. Raising the drill to remove the chips will be unnecessary unless the hole is deeper than about 20 times the diameter. A drill of suitable design is illustrated in Fig. 13. To prevent drill marks and to keep the drill straight, a spur or pilot may be ground on the point.

Table III. Speeds and Feeds for Drilling Magnesium

Diameter of Drill, inch	Speed, ft per min	Feed, inches per revolution — Sheet	Shallow Holes	Deep Holes
¼	300 to 2000	0.005 to 0.030	0.004 to 0.030	0.004 to 0.008
½	300 to 2000	0.010 to 0.030	0.015 to 0.040	0.012 to 0.020
1	300 to 2000	0.010 to 0.030	0.020 to 0.050	0.015 to 0.030

Insufficient distance between the drill jig bushing and the surface of the drilled part will prevent the chips from flowing out readily and will cause them to jam in the flutes. An approximate minimum distance of 1½ times the hole diameter is recommended.



Helix angle	0° (Straight) or 10°
Rake angle	5 to 8°
Relief angle	4 to 7°
Clearance angle	15 to 20°
Margin	0.010 to 0.025"
Flutes	4 to 6°

Fig. 12 Reamer recommended for use on magnesium

Shallow Holes. Drilling holes in magnesium to a depth less than about five times the diameter presents few difficulties and standard drills may be used. Polished flutes are recommended to aid in clearing chips and it is extremely important that the cutting edges be kept sharp. Dull drills result in poor surface finish, undersize holes, burrs and overheated work.

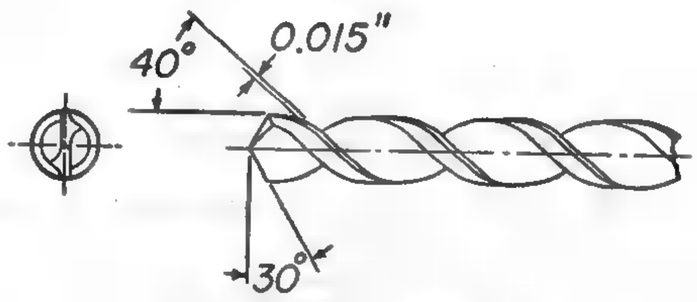
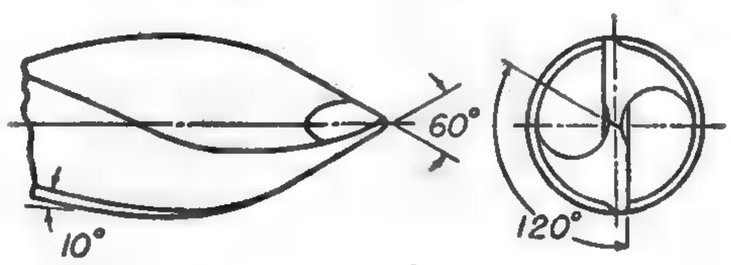


Fig. 13 Drill for deep holes

Drilling Sheet. Magnesium sheet can be drilled with a sharp, standard drill (118-deg point angle); but for high production of accurate holes with a good finish and minimum burn, a slightly modified drill may be used. The point angle should be reduced to approximately 60 deg to prevent "walking" of the drill, to reduce thrust and to prevent abrupt change of thrust when breaking through. The chisel-edge angle should be within the range of 120 to 135 deg. The web should be thinned and the ends of the cutting edges rounded. A thin web at the point helps to center the drill and reduce thrust; the rounded corners provide a smooth finish and reduce burrs. A helix angle of approximately 10 deg will prevent the work from climbing the drill on the break-through. Figure 14 illustrates a drill recommended for magnesium sheet.



Point angle	60°
Helix angle	10°
Chisel edge angle	120 to 135°
Web	Thinned at point
Corners	Rounded

Fig. 14 Data concerning drills for magnesium sheet

Counterboring. A recommended tool for counterboring is shown in Fig. 15. An important feature is the narrow cylindrical land, which is only about 0.015 in.

Tapping. A suitable tap design is illustrated in Fig. 16. The acute back angle of the land (3 to 4 deg) results in cutting rather than squeezing the metal when backing out of the tapped hole. The slightly greater spring-back of magnesium, as compared with other metals, makes this

precaution advisable. The lands should be shorter than usual and cylindrical; that is, there should be no clearance on the land. This will reduce the possibility of chips getting jammed in the clearance space and building up on the land. Taps for magnesium are usually not made oversize. A thread length of two to three times the diameter is recommended.

No trouble is encountered with the "seizing" of threaded magnesium parts, when in contact with magnesium, aluminum or any other metal. Steel or brass inserts should be used in assemblies where the screw bolt or stud is removed frequently.

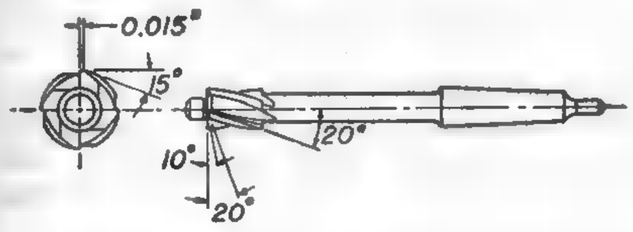


Fig. 15

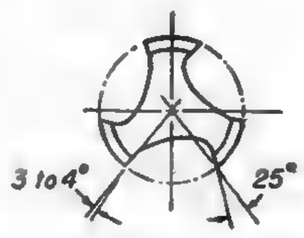


Fig. 16

Fig. 15 Counterboring tool
Fig. 16 Angles recommended for taps

Grinding. Finish grinding of magnesium is usually unnecessary because of the fine finish obtained by normal machining operations. Rough grinding or snagging is widely used, however, in foundries and for cleaning die castings and forgings. Grinding wheels should have a relatively coarse grain and an open structure in order to prevent loading. A grain size of 20 to 40 is satisfactory for rough grinding and a grain size of 40 to 80 should be used for finishing operations. The structures should be open with a rating of four to eight. Silicon carbide or aluminum oxide wheels with a vitrified or resinous bond are satisfactory for magnesium. Various types of abrasive cloths using fused alumina or silicon carbide abrasives are widely used on portable grinding units.

Magnesium dust creates a fire hazard and every precaution should be taken to ensure the proper collection and disposal of such dust.

Wet Grinding. If magnesium is to be ground wet on a belt sander or disk grinder, sufficient cutting fluid should be used to collect all the dust adequately and convey it to a central collecting point. At all times the dust should be wet with a copious supply of fluid and there should be no opportunity for dry or damp dust to collect on the machine. Water, soluble oil or mineral oil can be used as the cutting fluid. The magnesium sludge should be disposed of as discussed under Dry Grinding.

Dry Grinding. If magnesium is ground dry with a portable sanding unit or a grinding wheel, the magnesium dust created must be collected in an approved type of dust collection unit, in which a water or oil spray as near the dust-producing unit as possible, washes the dust from the air stream. Any ducts used should be short and as straight as possible. Multiple units, in which a number of dust-producing units are connected to a single exhaust system, are not recommended. The controls of such collecting systems should be interconnected so that they cannot be operated unless the water spray and the exhaust system are working. The dust collectors should be kept clean and ventilated to the atmosphere. The magnesium-water sludge should be collected at least daily, and more frequently if required, to prevent excessive accumulation. Such sludge should be stored under water and should be disposed of by burning or by mixing with sand and burying. The following additional precautions are suggested in order to ensure safe operation:

1 Wheels should be used for magnesium alloys only. Before wheels are dressed, the collector should be cleaned thoroughly.
2 Grinding operators should wear hard-finished clothing to prevent accumulation of dust thereon. Clothing should be brushed frequently.
3 The areas around grinding units should be kept free from magnesium dust. Rafters and ledges should be cleaned regularly.
4 An adequate supply of recommended extinguishing compound should be available.
5 Warning signs should be displayed in order to prevent unnecessary exposure to miscellaneous fire hazards.

Polishing. Sandpaper, fused alumina or silicon carbide cloths of a suitable grade should be used in polishing. Emery paper will tend to cause sparking and is therefore not recommended. In order to maintain a bright shine, the polished surface should be slightly greased with vaseline or an equivalent grease, or painted with a suitable clear lacquer. Polished surfaces will tarnish if not protected. For larger polishing operations, the same precautions as for grinding are recommended.

Sawing. Magnesium is readily cut by circular saws or band saws. Sharp blades are essential for satisfactory results. A tallow stick lubricant facilitates the work.

The following is recommended for band saws:

	Thickness of Blade, inch	Width of Blade, inches	Teeth per inch
For lighter work.....	0.030 to 0.040	$\frac{13}{16}$ to 1	6
For heavier work.....	0.045 to 0.050	1½ to 2½	4

The set of the teeth should be greater than standard to reduce friction. For circular saws, blades about 10 in. in diam and 0.040 in. thick with 3 to 7 teeth to the inch and a set of about 0.055 in. are satisfactory for cutting sections as large as approximately 2 in. in diam. Hack saws should have 14 to 18 teeth to the inch, every third tooth a clearance tooth without set. A satisfactory size is 0.025 to 0.030 in. thick and ½ in. wide. Power hack saws should have 2 to 10 teeth per inch, depending on the size of the work being cut.

Filing. For hand work, single-cut or double-cut files may be used, although single-cut files work better. Files with rasp cut produce too rough a surface. Depending on the smoothness desired, bastard, second-cut or smooth files are used. For rotary files, medium-coarse single-cut files are found best. Too coarse a cut causes chatter.

Cutting Fluids. Experimental tests and experience in many plants have shown that the purpose of cutting fluids when machining magnesium is primarily to cool the work and reduce the fire hazard. Any improvement in surface finish and increase in tool life obtained are minor.

Although less heat is generated in cutting magnesium than in cutting other metals, the high cutting speeds, the high thermal expansion, and the low heat capacity of magnesium make it necessary, in some machining operations, to dissipate the heat developed in cutting. Machining heat may be reduced by correct tooling and machining technique, but this heat is often of such intensity that application of cutting fluids is necessary.

Efficient machining practice demands that high cutting speeds be used wherever possible. When such speeds are used in machining magnesium, a fire hazard sometimes exists, particularly when fine chips are being produced. Although sharp tools greatly reduce this hazard and cutting feeds must be in the range of 0.001 in. or less to start fires, uncertainties in operations make it necessary to take precautions against fire. Iron or steel inserts and sand-cast surfaces, which are likely to spark when hit with a cutting tool, also add to the fire hazard. A stream of cutting fluid, of 4 to 5 gal per min per tool, will virtually eliminate the fire hazard. If a particular job or machine tool prohibits the use of a cutting fluid, cutting speeds should be reduced to less than 500 ft per min, and the recommendations regarding sharp tools and feeds should be followed rigorously.

A wide variety of mineral-oil cutting fluids will function satisfactorily on magnesium. Almost any oil will reduce the fire hazard materially if applied in sufficient quantities; but to secure adequate cooling, the cutting oil should have low viscosity. The chemical nature of magnesium makes it necessary that the free acid content of cutting fluids be less than 0.2% and that the use of vegetable or animal oils be restricted, since these may oxidize and increase the acid content.

Water-soluble oils, oil-water emulsions, or water solutions of any kind, although good coolants, should not be used on magnesium. Water will greatly intensify any chip fires that might accidentally be started and will also make the reclaiming of machine scrap very inefficient. The presence of moisture on turnings causes the generation of small amounts of hydrogen, a circumstance that presents

a definite hazard during shipment or storage. Experience has shown that the use of water-base cutting fluids on magnesium is inadvisable.

Prevention of Distortion. Occasionally, a slight distortion of magnesium parts is observed during or after machining. This is infrequent and can generally be attributed to one of the following causes.

Frictional Heat. This will often result in distortion. Magnesium has a high coefficient of expansion and is, therefore, likely to warp when heated locally by friction. Avoidable factors causing frictional heat include dull tools, improperly designed tools, very fine feeds and cuts, and slow speed. This last is likely to cause jamming of chips, especially in combination with small feeds. Fast speeds increase the centrifugal force and throw out the chips, thus reducing the tendency of chips to jam.

Improper Clamping or Chucking. Magnesium alloys have lower modulus of elasticity than most other alloys commonly machined. This may, at times, lead to somewhat greater deformation, when clamping pressure or spacing is excessive. Light sections may also deform under the pressure of the cutting tool if the work is not rigidly mounted.

Casting or Heat Treating Stresses. These stresses have seldom been found to cause distortion of magnesium castings during machining. Castings with a tendency to such stresses can be stress relieved thermally when necessary, before machining. In exceptional circumstances, however, this treatment may be ineffective and the casting stresses will be released only by the roughing cut. Complete relief of stress may require considerable time if it is allowed to proceed at room temperature. In such instances, the castings may be stress relieved between the rough and the finish cuts by heating from 1 to 2 hr at 500 F and then cooling slowly in still air.

Automatic Screw-Machine Work. *Speeds and Feeds.* Magnesium alloy screw-machine stock may be machined at higher speeds and feeds than are used for other metals. Because of speed limitations of the machine, however, the maximum economies offered in machining magnesium may not be obtainable in all instances. The possibility of using a feed heavier than that used for other metals will depend on the conditions; but a feed approximately 40% greater than is used on free-cutting brass may be considered an average figure. In general, better results are obtained with heavy feeds than with light ones.

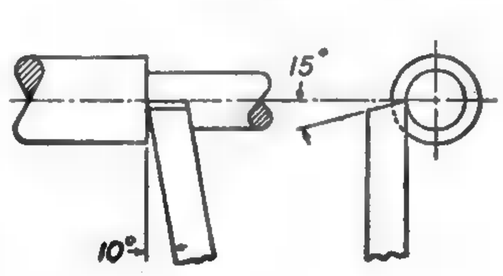


Fig. 17

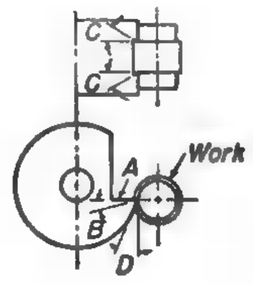


Fig. 18

Fig. 17 Box tool for screw-machine work
Fig. 18 Circular forming tool for screw-machine work

Box Tool. Tool angles recommended for box tools are shown in Fig. 17. A tool ground in this way will produce a satisfactory finish. The angle shown as 10 deg is to be considered an average and may vary within a relatively wide range (about 8 to 15 deg) depending on conditions.

Circular Forming Tool. The circular form tool shown in Fig. 18 is one of the types most commonly used for automatic screw-machine work. At *A* the tool is shown without back rake, which is satisfactory for magnesium. Frequently, it is necessary to grind the tool with a few degrees back rake, as shown at *B*, to correct a slight error in the steps of the tool. Back rake will produce satisfactory results, but no rake is preferable, giving better breakage of chips. The side relief indicated at *C* should not exceed one quarter degree. In most instances best results are obtained when the tool is without side relief or with a slight negative rake.

The front relief angle *D* is controlled by the design of machine and of toolholder. A standard relief angle has been determined for each type of machine and is considered satisfactory for all metals. This angle may vary slightly from one machine to another.

When a side forming tool is used without support, the ratio of the width of tool to the smallest diameter on the work should not exceed 2:1 for magnesium.

Chips. With light feeds in machining magnesium, the chips form in coils or ribbons. When the feeds are increased, the chips break up, and with relatively heavy feeds they are well broken. The chips produced in machining magnesium do not increase in thickness as they pass across the tool. Their thickness is about equivalent to the advance of the tool, indicating no adherence of metal.

Machine-Shop Scrap. Care should be taken to keep the magnesium scrap free from contamination with other metals, floor sweepings and the like, and as far as possible free from moisture. During accumulation, scrap should be stored in tightly covered metal containers, and grindings should be kept under several inches of water until disposed of. The disposal of grindings should occur daily in the manner recommended under Grinding.

Fire Precautions. Ordinarily, the fire hazard in machining magnesium is slight and, with sound knowledge of the correct machining practice, ignition of the shavings may be easily avoided. In order to ignite magnesium, it is first necessary for the metal to reach the melting point. Partial melting begins, depending on the alloy, at temperatures between 800 and 1200 F. In roughing operations, it is very difficult to attain such temperatures, for the high heat conductivity of magnesium rapidly dissipates any frictional heat generated.

In finishing operations, however, where light shavings are necessarily produced, temperatures sufficiently high for ignition may be reached under certain circumstances. Factors that will tend to produce such temperatures in the chips or shavings include very fine feeds or cuts, dull or chipped tools, tools with small relief angles and small chip space, and high cutting speeds in the absence of coolants.

A combination of two or three of the above factors may lead to the ignition of the shavings. Sharp tools with ample clearance will greatly reduce the fire risk. Coarser feeds, deeper cuts and lower speeds will act in the same direction; but where fine feeds and cuts and highest speeds are essential to quality and economy, a liquid coolant should be used.

In turning, ignition may occur if the cutting is interrupted and if the feed is stopped while the work still revolves. In these instances, the tool should be backed away from the work. In machining magnesium parts with an insert of ferrous metal, sparking sometimes occurs when the tool strikes the insert. In such instances, the use of a cutting oil has often been found advisable.

Under no circumstances should water or any other type of standard fire extinguisher (such as the pressure or liquid type) be used for extinguishing a magnesium fire, because such extinguishers will make the fire more violent instead of smothering it. An effective way to extinguish a magnesium fire is to cover the burning chips with dry graphite powder, dry cast-iron turnings or graphite-base proprietary compounds. It is suggested that a container full of one of the recommended extinguishers be placed at each machine and that the operator be trained in the application of the extinguisher. The smothering material should be applied gently to avoid scattering the fire.

In its initial stage, the fire should be localized by scraping away adjacent turnings. The accumulation of magnesium chips or turnings, on, under or around the machine, should be avoided. The danger of the spread of fire will be minimized if the quantity of chips near the machine is small. Avoiding the possibility of any accumulation of magnesium dust on the body or clothing of the operator is of particular importance. The chips should be removed from the machine at regular and frequent intervals and should be stored in tightly covered metal cans until reclaimed. Special fire precautions are discussed under Grinding.

Precautions During Machining. (1) Do not allow chips or dust to accumulate on the machine or clothing. (2) Store chips in covered metal cans. (3) Place a container of extinguisher at each machine. (4) Keep cutting tools sharp; use tools with proper relief angles. (5) Take heavy cuts. Back tool away from revolving work when not cutting. (6) Use a coolant when machining magnesium cast-

ings that have ferrous inserts, or when taking light cuts at high speeds. (7) Avoid generation of sparks; avoid smoking. (8) Grind with oil coolant or water or with dust-exhausting equipment that precipitates the grindings in water. (9) When grinding, wear a smooth and easily removable apron. (10) Do not grind steel or other metal on wheels used for grinding magnesium. (11) Store grindings under several inches of water and dispose of them as recommended.

Directions for Extinguishing Fires. Localize fire and scrape away adjacent turnings. Cover the ignited turnings with one of the following materials: cast-iron turnings, graphite, graphite-base proprietary compounds. DO NOT use water or any standard fire extinguisher.

The Surface Protection and Finishing of Magnesium Alloys

By W. S. Loose*

THIS ARTICLE describes the cleaning and finishing of magnesium alloys. Both mechanical and chemical methods for cleaning are discussed. Finishing processes include the chemical and electrochemical treatments that are in current use for providing surface protection for magnesium alloys. A brief discussion of painting is included also.

Cleaning

Mechanical Cleaning and Surface Conditioning. *Sandblasting.* Sandblasting is normally used as a cleanup method on sand castings and permanent mold castings. Shot or grit blasting is employed to a limited extent. For sandblasting, silica sand that has a No. 35 AFA rating is often employed with 70 to 90-lb air pressure. AFA No. 70 steel shot (approximately 0.07 in. in diam) has been used with 90-lb air pressure for shot blasting. For grit blasting, SAE No. 35 steel grit has been used with approximately 90-lb air pressure. Other blasting mediums —corncob grit, rice hulls and the like—have been used to a limited extent, mainly for surface appearance or for removing oxides and surface contaminants without affecting the surface dimensions appreciably.

Scratch Brushing. Scratch brushing has been used widely for removing mill scale from sheet or for improving the appearance of the surface. For removal of mill scale, steel wires approximately 0.010 in. in diam are preferred, but for surface appearance a finer wire, 0.003 to 0.005 in. in diam, is normally employed. Wheels 6 to 10 in. in diam with bristles 2 to 4 in. long are operated at approximately 1700 rpm. Long bristles are normally employed, because short bristles may pit the surface.

Grinding. Grinding is employed widely as a method of cleaning castings or wrought products and as a final finish. Built-up cloth wheels prepared with 100 to 200-grit abrasive and operated at peripheral speeds of 4000 to 6000 surface ft per min, are usually employed, but tend to become loaded with metallic particles. The most satisfactory grinding is accomplished with abrasive cloths containing 50 to 320-mesh abrasive, operated as either belt or rotating-disk sanders. The drum type of sanders that have sponge rubber backing for the abrasive cloth, may be used, but belt sanders are more satisfactory if they have sufficient length and cooling area to keep the abrasive cold so that loading of the abrasive is virtually prevented. These belt sanders operate at approximately 4000 to 6000 surface ft per min.

The grinding and polishing of magnesium produce highly flammable dust which, in the proper proportions with air, may ignite with explosive violence. It is essential, therefore, that this dust be removed immediately from the working area to prevent the formation of explosive mixtures. This can be accomplished effectively with a dust-collection system of the proper design. A system considered safe for the collection of magnesium dust from grinding and polishing, is one in which the dust is precipitated by a heavy spray of water or mineral oil of low viscosity, to form a sludge with a great excess of fluid. The equipment should be designed to prevent the accumulation of dust or sludge in any location where it could dry out to flammable composition. The collecting systems should be inspected periodically to ensure against such conditions. The best collectors for grinding stands are small units that serve one or two stands where the power supply for the grinder, water circulation, and air blower is interconnected so that the grinders cannot operate without having the collector in operation. The grinders are connected to the collector by short, straight ducts.

A central system that serves a large number of grinding hoods or stands can be operated safely if the dust is precipitated by heavy sprays at each booth or stand. The dust should be conveyed, by a flowing stream of water or oil, to a central settling tank from which it is removed. Such a system is safe if dust or sludge does not accumulate in the ducts. The power for the grinders, air blowers, and circulation of liquid, should be interconnected, as in the smaller unit systems.

Sludge pits should be ventilated adequately to prevent the accumulation of hydrogen gas. The sludge, which collects under the liquid in the pit, should be removed frequently. For disposal this sludge should be mixed with five parts of sand and buried or spread in thin layers on noncombustible surfaces. After draining, the mixture should be burned. The same principle of dust collection can be applied to grinding and polishing booths where the work is done on a grating. In the hood the air flows past the work material, through the grating and through a liquid spray that removes the dust. The hoods or booths should be designed to catch as much of the dust as possible, keeping it off the floor and workmen's clothes.

Central collecting systems in which the dust is passed through long, dry or partly dry ducts, and the conventional dry type of filter collectors are dangerous and emphatically not recommended for the collection of magnesium dust. Records of accidents in systems of these two types have proved them to be very hazardous.

Polishing. A finer surface finish may be obtained by the use of greases on the abrasive cloth or wheels. The greases act as lubricants and aid in preventing the wheel from becoming loaded with metallic particles. Before buffing, final polishing is normally accomplished with a greaseless polishing compound applied to sewed or string buffing wheels operated at peripheral speeds of 4000 to 6500 ft per min. Loose muslin buffs or loosely sewed muslin buffs are normally employed. For many products, greaseless polishing compounds are sufficiently abrasive to be used alone before the buffing operation.

Buffing. For the buffing of parts that require a high luster, tripoli composition is used on loosely sewed buffs. Hard sewed buffs may cause dragging. Best results are obtained by the use of approximately 74 to 82-count cloth wheels operating at a peripheral speed of 6000 to 8000 ft per min. Usually 10 to 14-in. buffs are employed. The tripoli should be free-cutting to avoid the need for high pressures, which may cause waviness and dragging. Coloring operations are performed through the use of dry lime compositions on 12 to 16-in. Canton flannel buffs operated at peripheral speeds of 8000 to 12,000 ft per min. Light pressures are sufficient.

Chemical Cleaning. *Alkaline Cleaning.* A satisfactory method of degreasing magnesium is alkaline cleaning, which removes not only oily matter but also previously applied chemical treatments. Proprietary cleaners of the strongly alkaline type, such as those commonly used on

* The Dow Chemical Company, Midland, Mich.
Prepared for the Magnesium Committee

steel, are the most desirable for magnesium. The milder type of aluminum cleaners are satisfactory in some instances but should be tested before using. An alkaline cleaning solution should have a pH value greater than 11 for best results. Alkaline cleaners containing pyrophosphate may be employed with a bath of high pH.

A satisfactory bath that can be used as a soak cleaner or as an electrolytic cleaner, can be prepared according to the following formula:

Trisodium phosphate ($Na_3PO_4.12H_2O$)	4 oz
Sodium carbonate ($Na_2CO_3.10H_2O$)	4 oz
Soap	0.1 oz
Water	to make 1 gal

After alkaline cleaning, rinsing must be very thorough to avoid contamination of subsequent chemical baths.

Acid Pickling. Cleaning by pickling is an important step in the fabrication and surface finishing of magnesium alloys either as an intermediate treatment or as a final operation before application of protective coatings. Oxide layers, drawing compounds, mill scale and foreign metallic impurities that cannot be removed by common solvent and alkaline cleaning, may be removed readily in various acid solutions; no single acid pickle can remove every type of surface contamination satisfactorily. Pickling is sometimes used for producing decorative effects but applications are limited.

Sulfuric Acid Pickle. After blasting operations in foundry casting cleanup, general oxide coatings and surface impurities such as iron and silica, may be removed from castings by treatment in a solution of 3 to 5% sulfuric acid. The solution is operated at room temperature and the duration of pickling varies from 10 to 30 sec. The parts are rinsed in cold running water and are then dipped in not water to facilitate drying. Satisfactory containers for this solution are earthenware crocks, rubber-lined tanks or lead-lined tanks.

Chromic Acid Pickle. An aqueous solution containing 15 to 20% chromium trioxide is used extensively in the surface cleaning of magnesium. The solution may be operated at room temperature, but is most effective when used at or near the boiling point. Chromic acid does not attack magnesium seriously, but readily removes oxide and hydroxide coatings. Consequently, chromic acid is employed to remove oxides as well as various chemical coatings before retreatment. Chromic acid is also satisfactory for removing the standard graphite-base lubricants from drawings and forgings. The usual duration of treatment is 2 to 15 min, depending on the temperature and freshness of the bath, and the type of material to be removed. After the chromic acid treatment, the work material is rinsed in cold running water and then dipped in hot water if drying is required.

Hydrofluoric Acid. Magnesium is not attacked appreciably by this acid. A solution containing 10 to 15% hydrofluoric acid removes surface impurities—silica, iron and the like—without causing a dimensional change. In the past this pickling treatment has been used primarily for processing finished machined parts as a pretreatment before chemical treatment and painting, in certain standard procedures for chemical treatment. The hydrofluoric acid bath is operated at room temperature and the duration of treatment is usually 5 min. Subsequently the work material is thoroughly rinsed in cold water and, if further processing is not immediately anticipated, the material is given a final dip in hot water. Steel tanks, lead-lined or rubber-lined, and also magnesium tanks are satisfactory for holding this solution.

Nitric-Sulfuric Acid Pickle. In certain instances a solution that contains 8% nitric acid plus 2% sulfuric acid, is used instead of the 3 to 5% sulfuric acid solution, for pickling alloys of higher aluminum content. This solution of mixed acids reduces the tendency for smut to form on the surface during pickling and usually produces a clean surface from matte to bright. The pickling procedure is similar to that for sulfuric acid pickling. Satisfactory containers for the nitric-sulfuric acid pickle are made of crockery, glass, ceramic, or steel lined with synthetic rubber.

Acetic Acid Pickle. Acetic acid is used primarily for the removal of mill scale from sheet after hot rolling. The scale is removed very effectively and the loss of metal is lower than when inorganic acids are employed. An aqueous solution that contains 15 to 20% glacial acetic acid, is used at room temperature. The pickling time is 30 sec to 1 min or longer. Dilute acetic acid (0.1 to 0.25%) is sometimes used for producing a decorative light gray to white hydroxide coating on magnesium. Since this coating has very little protective value, wax or clear lacquer is ordinarily applied subsequently. Pickling in acetic acid is followed by rinsing in cold running water and then dipping in hot water to facilitate drying. Containers for these solutions may be of crockery, glass, pure aluminum, or steel lined with synthetic rubber.

Vapor Degreasing. Vapor degreasing may be accomplished in either trichlorethylene or perchlorethylene solvents. These materials do not attack magnesium while they are dry, but contamination with water may cause corrosion. Commercially inhibited solvents of this type will prevent attack on magnesium.

Emulsion cleaners have been widely used, consisting of a low-cost mineral distillate and an emulsifying agent. Ordinarily the bath may be operated at room temperature, but penetration is more rapid if the solution is between 140 and 160 F. Three to five minutes is usually sufficient to permit penetration of the solvent; then the work material is rinsed in hot water or sprayed with it.

Finishing

Although magnesium and magnesium alloys show good resistance to corrosion in most atmospheres, the protective film that is formed does not remain metallic in appearance, but changes gradually to dark gray. The resistance of magnesium to tarnish can be improved greatly by building up supplementary coatings on the surface with either chemical or electrochemical treatment and in either acid or alkaline solutions.

The acid baths used in chemical treatment are normally solutions that contain a dichromate with or without additions of sulfates, phosphates, fluorides or nitrates. The films that are formed are usually amorphous mixtures composed largely of hydrated chromium and magnesium oxides. When alloying elements, such as aluminum, zinc or manganese, are present in the alloy that is being treated, they are also found in the film that is formed; when sulfates, phosphates, fluorides or nitrates are added to the chromate solution, they too are found in the coating. In strongly alkaline solutions, the film that is formed is normally $Mg(OH)_2$, although it may contain traces of other agents that were added to the bath.

Chemical Treatments. *Bright Pickle.* Although magnesium is bright after pickling in an aqueous solution of any one of many acids or a mixture of acids (such as 10% HNO_3 or a mixture of 8% HNO_3 plus 2% H_2SO_4) the film that is formed does not resist tarnish. An acid bath that produces good resistance to tarnish in all commercial magnesium alloys is composed of 18% chromic acid, 4% calcium nitrate and 0.25% magnesium fluoride. After normal degreasing operations, the work metal is immersed for ½ to 5 min in this solution maintained at 20 to 30 C. The duration of the treatment depends on the surface condition of the metal. The bath should be agitated for cooling and stirring. When the parts have been removed from this solution, they should be rinsed quickly in ■ bath containing 5% sodium metasilicate or sodium carbonate. Iridescent coatings may form if parts are not quickly rinsed in this alkaline solution or if they are rinsed in water, if the temperature of the solution is allowed to rise, or if thorough agitation is neglected. When die castings of AZ91 or similar alloys are to be processed, they should first be pickled in a strong phosphoric acid solution (about 75%) for 30 to 60 sec to remove the nonhomogeneous layer normally found on the surface.

This bright-pickle treatment provides a thin, clear film that is quite resistant to atmospheric change. The resistance to interior atmospheres varies with alloy content; pure magnesium or M1 alloy will maintain a bright surface for at least a year after receiving this treatment; without the treatment a gray coating will form in a few weeks.

This bright-pickle coating is also resistant when applied to commercial alloys that contain aluminum and zinc, but the coating will tarnish more rapidly than when applied to the M1 alloy. During exterior exposure exactly opposite effects are produced; the alloys that contain aluminum are more resistant than M1 alloy. Parts given this treatment may be handled extensively without tarnishing. Clear or pigmented organic coatings may be applied.

Chrome Pickle (Type I). Of all chemical treatments for magnesium, the chrome-pickle treatment is the most widely used. It is applied by dipping the work material for ½ to 2 min in a bath consisting of 180 g per liter $Na_2Cr_2O_7 \cdot 2H_2O$ and 187 ml per liter concentrated HNO_3. This bath is maintained at room temperature. Parts are held in the air for 5 sec after removal from the bath, before being rinsed in cold and hot water. This treatment is described extensively in technical publications.

Sealed Chrome Pickle (Type II). This treatment consists of two steps; that is, the chrome-pickle finish described above is subsequently sealed when the metal is held for 30 min in a boiling solution that contains 100 to 150 ■ per liter $Na_2Cr_2O_7 \cdot 2H_2O$.

Dichromate (Type III). Of all the chemical treatments, this one affords the best resistance to corrosion and the best adhesion of paint. This treatment also is applied in two steps, as follows:

Step 1. Dip parts for 5 min in a cold aqueous solution containing 15 to 20% by wt of hydrofluoric acid. Rinse in cold water.

Step 2. Boil parts 30 min in an aqueous solution containing 100 to 150 ■ per liter $Na_2Cr_2O_7.2H_2O$, saturated with either MgF_2 or CaF_2. Rinse and dry.

All three of these treatments may be applied to any of the commercial alloys, although the dichromate treatment does not produce a dark coating on M1 alloy. Exposures of alloys at Kure Beach, North Carolina, have shown that the coatings produced by these treatments maintain surface appearance somewhat better than bare magnesium. However, after 2 years of exposure at a station located 800 ft from the ocean, no effect of the chemical treatment on the losses in mechanical properties can be determined. In aqueous chloride solutions, the dichromate treatment produces considerably superior resistance to corrosion whether the metal is painted or unpainted. When properly applied, all three coatings are excellent bases for paint. The dichromate treatment is generally superior, since it is less subject to variations. The chrome-pickle treatment, when applied from a freshly made solution, is equal to the dichromate treatment as a base for paint; but in normal operations where the solution must be revivified to maintain its coating ability, the adhesion of paint decreases as the age of the solution increases.

Electrochemical Treatments. *Acid Anodizing.* Protective coatings may be applied to magnesium electrochemically, by making it the anode in certain acid or alkaline solutions. All acid solutions employed in commercial treatments involve the use of dichromates with additions of sulfates, fluorides or phosphates. The baths are similar to those used normally for direct chemical treatment. The main advantages gained by the application of current are that the duration of the treatment is greatly reduced and that lower temperatures are required. The main disadvantages are that the throwing power of these baths is often insufficient to coat complicated parts completely and that such baths are often more expensive because of the labor involved. A typical acid anodic treatment is commonly known as the "galvanic anodize" (Type IV). This again is a two-step treatment, as follows:

Step 1. Dip parts for 5 min in an aqueous solution containing 15 to 20% by wt of hydrofluoric acid maintained at room temperature.

Step 2. Anodize the magnesium at 10 amp per sq ft for 10 min in a bath operated at 50 to 60 C and consisting of 30 g per liter $Na_2Cr_2O_7.2H_2O$, 30 g per liter $(NH_4)_2SO_4$ and 2.5 ml per liter NH_4OH (sp gr = 0.88).

The magnesium is connected electrically to the steel tank that contains the solution to generate the current. The resistance to corrosion and value as a paint base are similar to those developed in the dichromate treatment (Type III).

Caustic Anodizing. Some coatings that are produced by anodic oxidation in strongly alkaline solutions, are more resistant to corrosion in aqueous solutions than are coatings formed either chemically or electrochemically in chromate baths. A typical anodizing solution contains 25% NaOH, 7% diethylene glycol and 0.2% sodium oxalate. Several variations of this type composition have been proposed but all produce coatings that are essentially $Mg(OH)_2$ formed in a hard, compact manner.

The anodic oxidation is performed by applying either direct or alternating current to the magnesium for 15 to 25 min at a current density of 10 to 25 amp per sq ft in a bath operated at 75 to 80 C.

The coating formed is normally of a neutral light gray shade. The method of preparing the surface of the magnesium parts before they are anodized, is important in the production of attractive coatings. Surfaces that are buffed or bright-acid-pickled develop a relatively clear coating. Die castings that contain a nonhomogeneous phase on the surface are more difficult to coat than wrought or cast materials; the pickling of die castings in a strong phosphoric acid solution will produce a bright and more homogeneous surface to which the coating can be applied more evenly. The coating process is applicable to all commercial magnesium alloys.

This anodic coating is more resistant to corrosion in aqueous mediums than are coatings formed in chromates, and it shows good resistance to atmospheric change. Maximum resistance may be obtained by waxing or painting the anodized surface. The coating is relatively porous and can be dyed subsequently in organic baths. The coated article is immersed in the dye bath for 5 to 30 min at 90 to 100 C. Concentration of dye and duration of treatment will affect the shade of color obtained and must be closely controlled. A typical dye bath for obtaining ■ red coating contains 0.4% neolin Bordeaux, 0.7% boric acid and 1% sodium chromate. The pH of the dye bath must be maintained at 6 to 8 by the addition of boric acid.

Because of the alkaline nature of the film formed, the coating produced by this electrochemical treatment is not receptive to paint. Modifying treatments, which are essentially controlled neutralizers, provide a surface to which paint adheres well. After being anodized and rinsed in water, the parts are immersed for 15 min at room temperature in an aqueous solution containing 0.5% sodium fluosilicate and 0.1% sodium dichromate. The coating as applied has fair resistance to abrasion; for maximum resistance to abrasion or wear, the parts should be waxed. The abrasion resistance increases with alloy content of the metal; M1 alloy gives the softest coatings.

Electroplating. No commercially acceptable electroplating process has been developed for magnesium, but results of recent research indicate that satisfactory methods will be available shortly for applying various metallic deposits to magnesium.

Painting. In general, the painting of magnesium follows the rather well-established procedure for other metals. As in all metal finishing, the preparation of the surface is important. This includes proper choice of chemical treatment and adequate cleaning before painting. Where suitable chemical treatments cannot be employed, the surface must be finished freshly by mechanical means and cleaned with solvent just before painting.

The chemical treatments discussed previously ensure a satisfactory surface, which should be painted immediately after treatment when practicable. If this cannot be done, the surface usually becomes contaminated and a final cleanup is necessary before painting. Vapor degreasing has proved satisfactory in commercial practice. An alternative method employs a solvent wipe or wash. The solvent chosen should be similar to that used as a diluent for the finish to be applied. Hot alkaline cleaners are not recommended, since they impair the chemical coating.

The finishing schedule can employ either air-dry or baked materials; the selection of paint coatings for magnesium depends on the intended service.

For interior use, organic finishes are chosen ordinarily, because of their decorative value. These finishes may be high-gloss japan or enamel or may consist of the popular novelty finishes—wrinkle, crackle, crystal and the like. Both air-dry and baked finishes may be used. Systems can be employed that comprise one or two coats, depending

Table I. Finishing Schedules for Magnesium Alloys

Service Conditions	Mechanical Finish	Chemical Treatment	Organic Finish: Primer	Organic Finish: Finish
Interior	Buffed	None	None	1 to 3 coats of special clear coatings
	None	Chrome-pickle	One coat of baked	1 or more coats of air-dry, baked or novelty finish
	None	Chrome-pickle	One coat of air-dry	1 or more coats of air-dry enamel or novelty finish
	None	Chrome-pickle	None	1 or more coats of baked japan or novelty finish
	Aloxiting	None	One coat of special baked	1 or more coats of baked japan or novelty finish
	Aloxiting	None	One coat of special air-dry	1 or more coats of compatible enamel or novelty finish
Ordinary exterior	None	Chrome-pickle	One coat of baked	2 or more coats of air-dry or baked enamel, or lacquer
	None	Chrome-pickle	One coat of air-dry	2 or more coats of air-dry enamel or lacquer
	Aloxiting	None	One coat of special baked	2 or more coats of baked enamel
	Aloxiting	None	One coat of special air-dry	2 or more coats of air-dry enamel or lacquer
Severe	None	Hydrofluoric acid-dichromate	Two coats of baked inhibitive	2 or more coats of baked enamel
	None	Sealed chrome-pickle	Two coats of air-dry inhibitive (P-27)	2 coats of air-dry enamel, aluminized lacquer or spar varnish

on such variables as surface treatment, choice of finishing materials, and conditions of service.

Ordinary exterior use of magnesium usually requires a protective finishing system. Decorative considerations are secondary; in fact, the usual decorative finishes are not intended for exterior exposure. Normally, three-coat systems should be used, and the finishing system should be chosen for ability to withstand the conditions to be encountered in the intended service.

Severe exterior exposure will include aircraft applications, marine exposure and similar applications. For this type of service, two coats of inhibitive primers, such as AN-TT-P-656b, are recommended; these should be followed by two finish coats, which should possess maximum impermeability and be no less than 0.002 in. thick.

Baking schedules that employ either convection or infrared heat are widely used. The heating schedule recommended by the manufacturer should be followed. Baking greatly decreases the drying time and improves the adhesion and the resistance to abrasion.

Air-dry primers are usually applied over a chemically treated surface. However, primers have been developed that give satisfactory performance when applied to bare metal. Finish coats must be compatible with primers to ensure satisfaction.

Clear lacquers may be applied over either freshly polished or bright-pickled magnesium. The protection thus afforded varies widely, depending on the formulation of the clear lacquer, the method of finishing mechanically or chemically, and the mediums to which the magnesium is exposed. Special formulations must be employed to give good adhesion and protection.

Details of baking time, temperature and materials are not included because such information is best furnished by the manufacturer. Table I is a summary of the finishing schedules normally recommended.

Corrosion of Magnesium

By W. S. Loose*

THIS article describes the corrosion of magnesium in various atmospheres, aqueous mediums, nonaqueous mediums, and soils. Galvanic corrosion and corrosion at high temperatures are also discussed. The stress corrosion of magnesium is discussed in the article on page 228 of this Handbook. Protective coatings are described on page 991.

Atmospheric Corrosion. *Exposure.* Magnesium shows inherently different rates of tarnishing, depending on the alloy content, the alloying elements present, indoor or outdoor location, and humidity. During interior exposure M1 alloy (1% Mn) is more resistant than the alloys that contain aluminum, but during exterior exposure the reverse is true. The alloys containing aluminum show a decreased tendency to tarnish during exterior exposure as the aluminum content increases to about 9%. With higher aluminum content, the films formed are much thinner and have a metallic appearance after long periods of exposure to rural atmosphere or to an interior atmosphere. Zinc, especially if more than 5% is present, greatly increases the rate of tarnishing. Small amounts of silver also increase this rate. The increase in resistance to tarnishing with increase in aluminum content correlates with electron diffraction observations that a different type of hydroxide film is formed in which the distance between the molecular magnesium hydroxide sheets has been increased to accommodate amorphous hydrated aluminum oxide.

Humidity plays a major role in the corrosion or tarnishing of magnesium alloys. At 9.5% humidity neither magnesium nor magnesium alloys showed tarnish after 18 months. At 30% humidity a small amount of an amorphous phase and slight tarnish were seen. At 80% humidity, crystalline magnesium with 30% of an amorphous phase was seen, but the surface showed tarnish. Only at 93% relative humidity was crystalline magnesium hydroxide formed.

Atmospheric Pollution. At Midland, Mich., the atmosphere is industrial and contains varying but detectable amounts of chlorine, bromine, caustic soda, hydrochloric acid and magnesium chloride, as well as other inorganic and organic compounds. The slow rate of corrosion on outdoor test racks indicates that these substances do not cause rapid breakdown of the protective film on magnesium. Extensive atmospheric tests on machined test bars were started in 1933 to determine how the cast and wrought alloys of uncontrolled purity that were then commercial, compared with various aluminum-base alloys as well as with certain ferrous materials. With the advent of magnesium alloys of controlled purity, bars of these alloys too were added. The results from sheet alloys are shown in Fig. 1.

The tensile strength of the uncontrolled-purity alloys (commercial, 1933) shows a straight-line loss of approximately 1000 psi per year. The controlled-purity alloys (commercial, 1940) have been under test only four years but they show a somewhat lower rate of corrosion. Longer exposures will be required to show the exact effect of exposure time. The corrosion losses shown are considerably higher than they would have been had panels rather than test bars been exposed, for edge corrosion reduces the strength of the bars abnormally, and especially the elongation.

As shown by Fig. 2, the loss in strength on the machined round test bars of extrusion and casting alloys was only about 500 psi per year. Alloys with controlled purity and those with uncontrolled purity have shown the same rate of loss after four years.

These data, when considered in relation to the results

* The Dow Chemical Company, Midland, Mich.
Prepared for the Magnesium Committee

obtained for aluminum and steel, indicate that magnesium compares favorably with aluminum alloys and is superior to low-carbon steel in this industrial atmosphere.

Marine Exposure. At an extensive marine corrosion station located at Kure Beach, N. C., many thousands of panels of magnesium and other nonferrous as well as ferrous metals are being exposed. Besides immersion racks, stations are being operated 80 ft and 800 ft from the ocean.

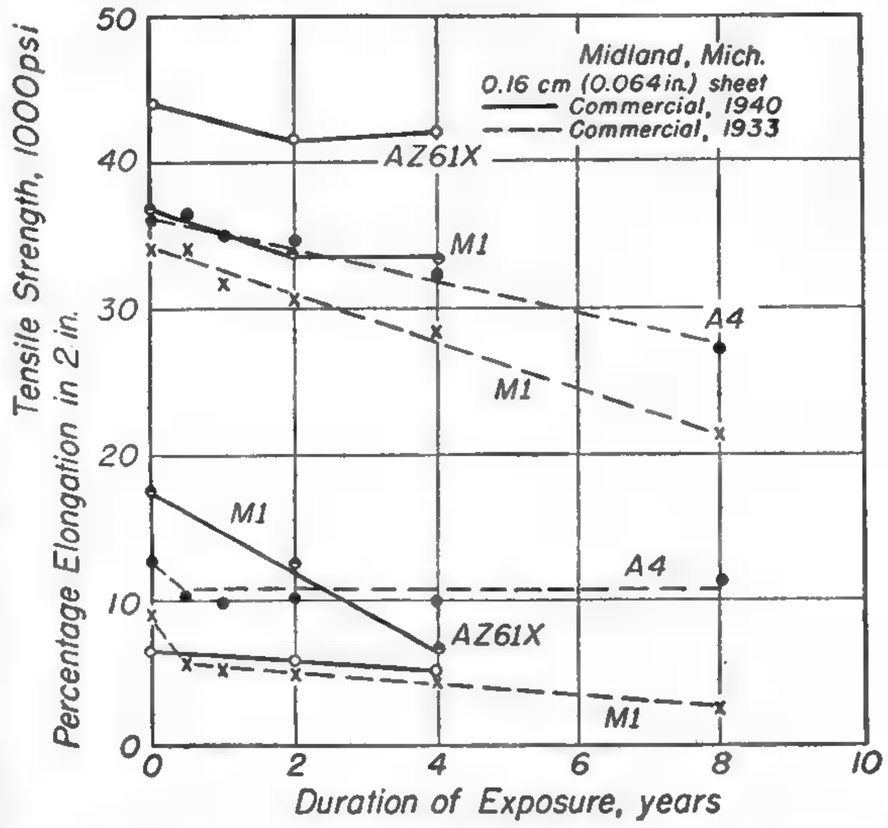


Fig. 1 Decrease of tensile properties during corrosion of sheet-alloy test bars exposed to industrial (Midland) atmosphere

Specimen size. **1933, 1.2 cm (0.5 in.) reduced section test bars, 0.16 cm (0.062 in.) thick. 1940, 0.16 cm (0.062 in.) by 2.5 cm (1 in.) by 17.5 cm (7 in.) sheets.**

Surface preparation. **Commercial 1933, as-rolled. Commercial 1940, chrome-pickled**

Temperature. **Winter, 6 C (21 F); summer, 22 C (71 F)**

The effect of the severe 80-ft marine exposure on the corrosion of sheet alloys that have controlled purity and those that have uncontrolled purity is shown in Fig. 3. The uncontrolled-purity A4 alloy (4% Al) was completely corroded away in one year, but the A6X alloy, similar but with controlled purity, (6% Al, high purity) had suffered little loss in tensile strength after four years. The lesser susceptibility of alloy AZ31X (3% Al, 1% Zn, high purity) to notches, and the fact that this alloy is least sensitive in the annealed state are conditions believed to account for the loss in elongation being significantly lower than that of the other controlled-purity alloys.

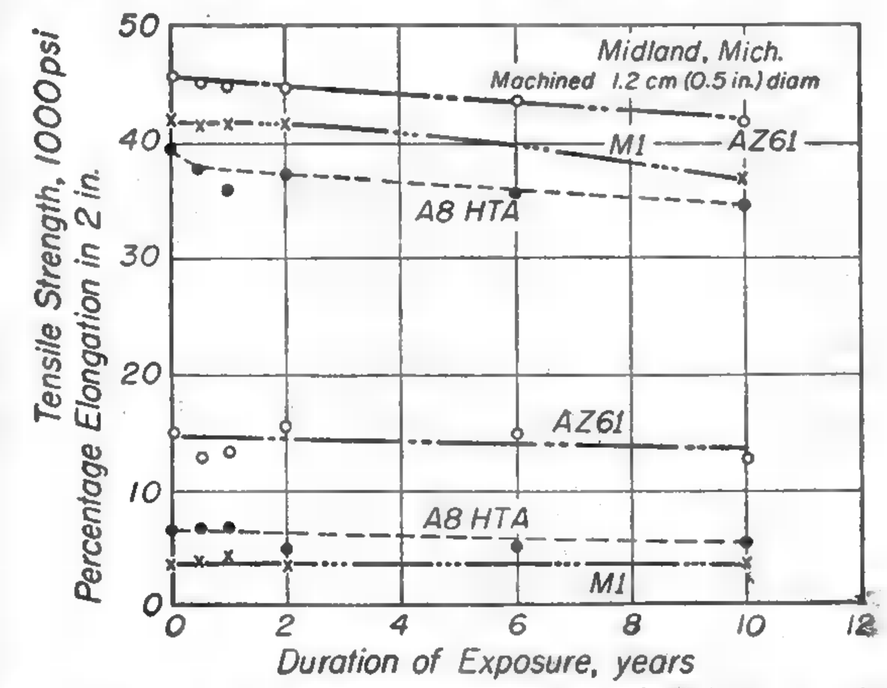


Fig. 2 Decrease of tensile properties during corrosion of extruded and cast magnesium alloy test bars in industrial (Midland) atmosphere.

Temperature. **Winter, 6 C (21 F); summer, 22 C (71 F)**

Similar data have been obtained at this location, for aluminum-base alloy 24 S-T and sheet panels of mild steel, as well as for machined test bars. As at the industrial location, the mechanical-property losses of magnesium and aluminum were similar; however, the steel suffered severe attack in a few months.*

The losses in mechanical properties sustained by round extruded and cast magnesium test bars—some with controlled, others with uncontrolled purity—at this 80-ft station are shown by Fig. 4. Controlled-purity extruded and cast alloys showed no significant loss after four years. Uncontrolled-purity extruded and cast alloys showed considerably higher losses than controlled-purity alloys, but did not exhibit such a severe decrease in mechanical properties as the sheet alloys shown in Fig. 3.

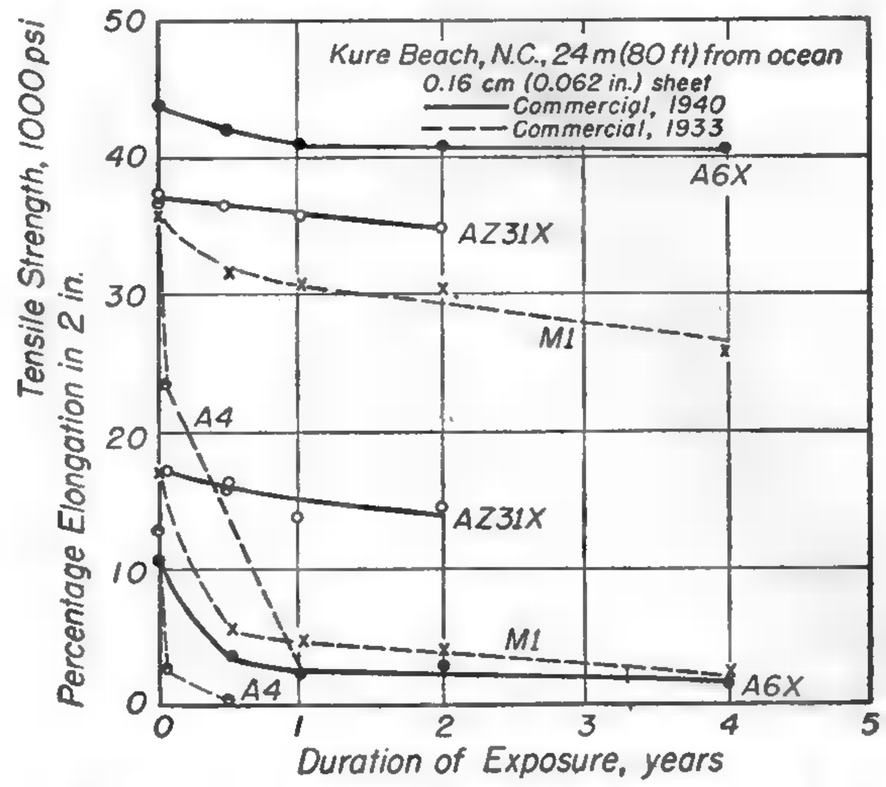


Fig. 3 Effect of controlling purity on the decrease in tensile properties of sheet exposed to corrosion under marine conditions.

Specimen size. **1933, 1.2 cm (0.5 in.) tensile test bars, 0.16 cm (0.062 in.) thick. 1940, 0.16 cm (0.062 in.) by 2.5 cm (1 in.) by 17.5 cm (7 in.) sheets**

Surface preparation. **A4, as-rolled A6X, AZ31X and M1, acetic pickle plus chrome pickle**

Controlled-purity cast alloys show no effect of heat treatment at the marine location. Uncontrolled-purity cast alloys, in the heat treated state, show a somewhat greater loss than as-cast or aged alloys at the coastal site; but after both types of alloy had been exposed ten years at Midland, no effect of heat treatment could be observed.

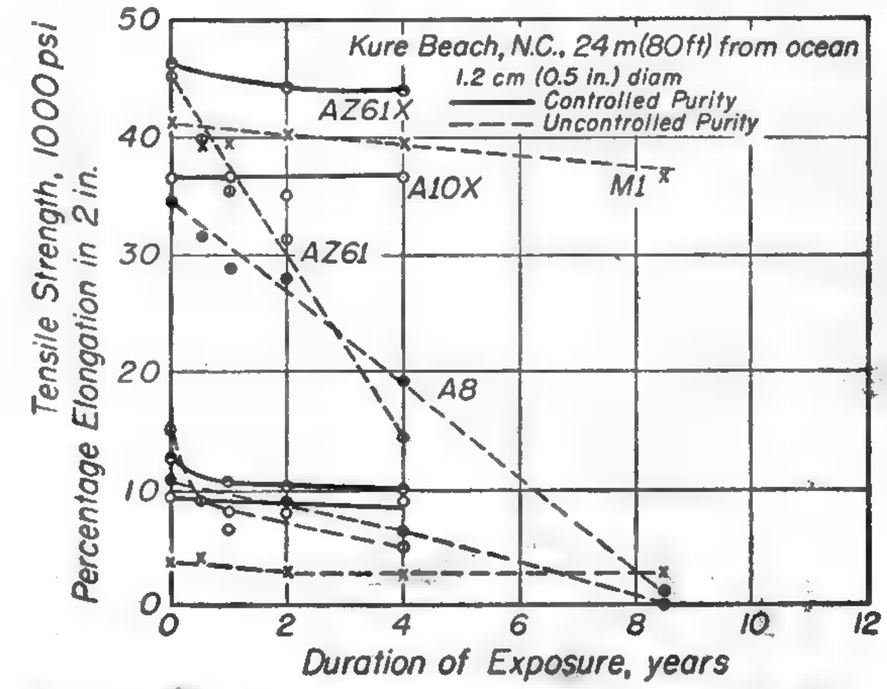


Fig. 4 Effect of controlling purity on the decrease in tensile properties of magnesium alloy test bars exposed to corrosion under marine conditions.

Surface preparation. **A8 pickled in acid. All others machined.**

At the more recently installed 800-ft station, data concerning mechanical properties have been obtained over a two-year period only. With cast alloys A10 (10% Al), AZ92 (9% Al, 2% Zn) or AZ63 (6% Al, 3% Zn) no effect of purity has been noted.

* The copper content of this steel is unknown. It is well known that 0.05% Cu additions will improve considerably the stability of steel in coastal atmospheres.

Aqueous Mediums. Certain fundamental factors control the corrosion of magnesium in aqueous mediums. Tests on controlled-purity magnesium or magnesium alloys indicate that dissolved oxygen does not play a major role in the corrosion process in solutions containing salt. Carbon dioxide, however, probably because of the acidic tendency, increases the rate of corrosion.

The effect of temperature depends largely on the purity of the metal. With increases from room temperature to the boiling point, the corrosion rate of controlled-purity magnesium and magnesium alloys in 3% sodium chloride solution, approximately doubled. However, when cathodic impurities such as iron and nickel are present in amounts greater than the tolerance limit, the rate of corrosion, and especially the tendency to pit severely, increases rapidly with temperature. In tap water containing approximately 70 parts chloride per million, the rate of corrosion is low but tends to increase just lower than the boiling point, as shown in Fig. 5. Because of localized impurities, M1 alloy shows a greater tendency toward severe pitting with increasing temperature than do the alloys of controlled purity.

The corrosion of magnesium is strongly influenced by the hydrogen ion concentration (pH). Magnesium is resistant to alkalies but is ordinarily attacked by acids. With increasing pH above the point at which magnesium hydroxide is formed (pH 10.2), the effect of cathodic impurities in the metal, and salts in the mediums, is overshadowed by the greater tendency for formation of film.

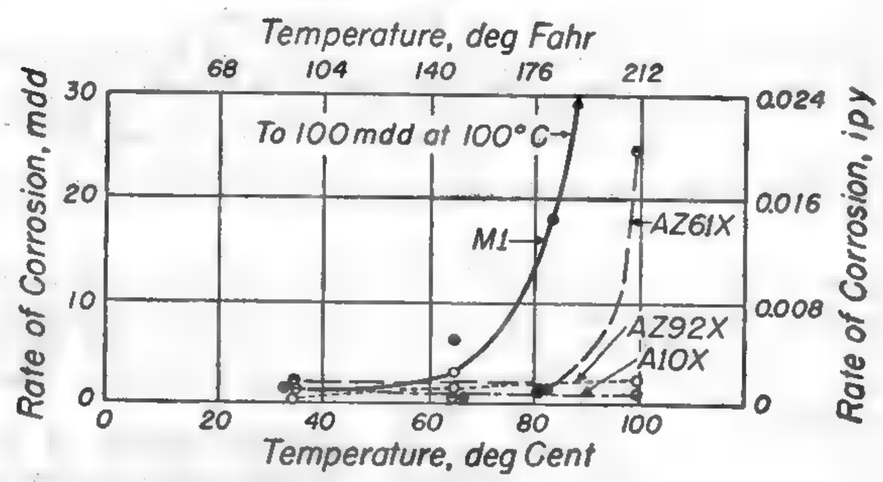


Fig. 5 Corrosion of magnesium alloys in tap water.
Specimen size, 5 cm (2 in.) by 2.3 cm (0.9 in.) by 1 cm (0.4 in.); surface preparation, Aloxite ground; aeration, natural convection; volume of testing solution, 200 ml; velocity, natural convection; duration of test, 14 days; test, continuous immersion.

Salts. Table I shows the effect of representative oxidizing and nonoxidizing salt solutions on the corrosion of a commercial magnesium alloy of controlled purity. Chloride solutions are normally more corrosive, since the only formation of film on the magnesium is of a porous magnesium hydroxide type. Neutral or alkaline fluorides form insoluble magnesium fluoride and are not appreciably corrosive. Ammonium salts usually show more attack than salts of alkali metals. Oxidizing salts, especially some containing chlorine or sulfur atoms, are more corrosive than nonoxidizing salts; but chromates, vanadates, phosphates and many others form a film and tend to retard corrosion, except at elevated temperatures.

Acids. Magnesium is attacked rapidly by all mineral acids except hydrofluoric and chromic acids. Hydrofluoric acid, because of the formation of an insoluble magnesium fluoride film, does not attack magnesium to an appreciable extent; but at low concentrations of acid, pitting develops. With increasing temperature, the rate of attack at the waterline increases, but below the surface the increase in rate of attack is negligible. Magnesium has been used commercially for float-control units, tanks, and piping for closed units handling concentrated hydrofluoric acid.

Chromic acid, when pure, attacks magnesium and magnesium alloys at a very low rate, but traces of chloride or sulfate ions increase this rate. A boiling solution of 20% chromic acid is widely used to remove products of corrosion from magnesium alloys.

Most organic acids attack magnesium and magnesium alloys. The stronger acids, such as acetic and tartaric, are often used at about 10% concentration to pickle cast and wrought products.

Alkalies. Magnesium is resistant to dilute alkalies at temperatures as high as the boiling point, and is resistant to 50% caustic liquors as high as about 60 C; but at higher temperatures the corrosion rate increases rapidly.

Aqueous Solutions of Organic Compounds. In aqueous solutions of organic compounds, magnesium is normally resistant. With the exception of methanol, alcohols attack magnesium at a slow or moderate rate. In acid organics, such as fruit or tomato juices, a slow but definite attack occurs. Milk will cause attack, particularly while souring.

At room temperature, ethylene glycol solutions produce negligible corrosion on magnesium used alone or connected galvanically with steel; but at elevated temperatures, such as 115 C, the normal rate increases to some extent and galvanic corrosion will occur unless inhibitors, like those used for aircraft engines, are added.

The M1 alloy has been used extensively for oil and gasoline tanks on aircraft, since there is no tendency for attack. The addition of tetraethyl lead and ethylene dibromide, in order to raise the antiknock rating of gasoline, may cause pitting at the waterline in gasoline-water mixtures, unless slushing compounds, or special capsules that contain slightly soluble chromates, or other inhibitors are used.

Metallurgical Factors. Impurities such as iron, nickel and copper have definite tolerance limits.[1] The quantity and state of these impurities in magnesium alloys determines the resistance of the metal to corrosion in aqueous salt solutions. Commercially pure magnesium exhibits corrosion rates that vary from 500 to 10,000 mdd* in 3% sodium chloride solution. Figure 6 gives a broad view of the corrosion of magnesium-base binary alloys. Some elements are not harmful in large proportions, but others are detrimental even when present in minute amounts. The present commercial alloy compositions come from a combination of elements that are not harmful. The effect of impurities on these alloys is of maximum importance.

The M1 alloy shows a marked tolerance for both iron and nickel. The limit of tolerance for iron is 0.017%, the same as for pure magnesium; but greater amounts of iron are much less deleterious when manganese is present than with

* mdd = milligrams per square decimeter per day

Table I. Corrosion of Magnesium Alloy AZ61X in Salt Solutions

Specimen size, 7.5 cm (3 in.) by 2.5 cm (1 in.) by 0.15 cm (0.06 in.)
Surface preparation, HNO_3 pickled
Temperature, 35 C (95 F)
Volume of testing solution, 100 ml
Duration of test, 7 days
Test, alternate immersion, 30 sec in solution, 2 min in air
Concentration of solution, 3% by weight

Acid Salt	Corrosion Rate, mdd	Neutral Salt	Corrosion Rate, mdd	Alkaline Salt	Corrosion Rate, mdd
		Nonoxidizing			
Aluminum sulfate	112	Sodium chloride	14	Sodium silicate meta	0.7
Zinc chloride	770	Sodium bromide	6	Sodium sulfite	2
Sodium acid tartrate	155	Sodium iodide	29	Sodium borate meta	5
Sodium dihydrogen phosphate	85	Sodium fluoride	3	Sodium phosphate	3
		Sodium sulfate	8		
		Sodium nitrate	5		
		Oxidizing			
Ammonium persulfate	465			Calcium hypochlorite	155
Sodium dichromate	4	Sodium chromate	2	Sodium hypochlorite	5
Ferric sulfate	297	Sodium chlorate	59	Sodium iodate	40
		Sodium pyrophosphate	51		

magnesium alone. Manganese also greatly increases the tolerance limit for nickel.

With the magnesium-aluminum binary alloys, the tolerance limit for iron is strikingly changed. With even as little as a few hundredths per cent aluminum, the tolerance limit for iron decreases from 0.017% to a few thousandths per cent. With 7.0% Al, the limit is about 0.0005% Fe; while with 10.0% Al, the limit is too low to be determined. An explanation of this may lie in the formation of an iron-aluminum phase, which is even more active than discrete iron particles alone.

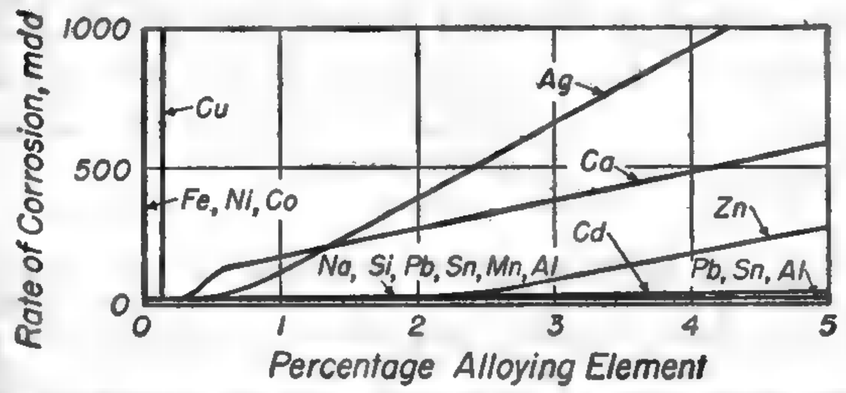


Fig. 6 Corrosion rate of binary alloys in 3% sodium chloride solution.
Corrosive medium, 3% sodium chloride solution; size of specimen, 3.8 cm (1.5 in.) by 2.5 cm (1 in.) by 0.6 cm (0.25 in.); surface preparation, Aloxite ground; temperature, room; aeration, natural convection; volume of testing solution, 100 ml; velocity, quiescent; duration of test, 16 weeks; type of test, alternate immersion, 30 sec in medium, 2 min in air.

The addition of even a few hundredths per cent of manganese to the magnesium-aluminum binary alloys is sufficient to raise the tolerance limit for iron to 0.002%.

Of maximum practical importance is the effect of iron, nickel and copper on the Mg-Al-Mn and Mg-Al-Zn-Mn alloys. Figure 7 shows the results of adding 0.5% and 3% Zn to alloys containing 6% Al, 0.2% Mn. The presence of 0.5% Zn does not shift the position of the tolerance limit at 0.002% Fe, but somewhat reduces the magnitude of the corrosion rates for higher percentages of iron. The addition of 3% Zn raises the tolerance limit to 0.003% Fe and greatly reduces the rate for higher concentrations of iron. Zinc additions show somewhat similar effects in raising the tolerance limit for nickel and copper, and in reducing the corrosion rates at higher concentrations of zinc.

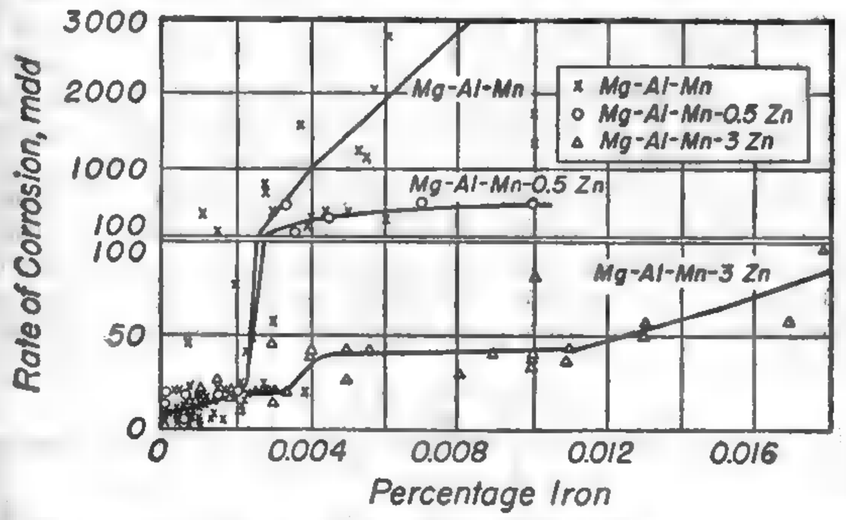


Fig. 7 Effect of iron on the corrosion rate of three magnesium alloys in 3% sodium chloride solution.
Corrosive medium, 3% sodium chloride solution; specimen size, 3.8 cm (1.5 in.) by 2.5 cm (1 in.) by 0.6 cm (0.25 in.); surface preparation, Aloxite ground; temperature, room; aeration, by convection; volume of testing solution, 100 ml; velocity, quiescent; duration of test, 16 weeks; type of test, alternate immersion, 30 sec in solution, 2 min in air.

Heat Treatment and Cold Work. The effect of heat treatment on the corrosion rate of magnesium alloys in aqueous electrolytes, varies with the heat treating temperature, rate of cooling, the alloying elements, and the impurity content of the alloys. With M1 alloy, heat treatment of sheet in the range of 260 C (500 F) to about 485 C (900 F) usually at least doubles the corrosion rate and greatly increases the tendency to pit. Heat treatment at 540 C (1000 F) to 620 C (1165 F), followed by rapid cooling, completely eliminates pitting and provides increased resistance to corrosion. These effects of heat treatment on M1 account for the pitting tendency adjacent to welds corroding in a salt solution.

With controlled-purity Mg-Al-Mn alloys, containing 0 to 1% Zn, slight if any difference in corrosion rate is noted between the as-fabricated, solution heat treated, or solution heat treated and aged states, if cooled in air from the solution heat treating temperature. With similar cooling, controlled-purity alloys containing ▪ to 3% Zn show a slight increase in the corrosion rate in the solution heat treated state or solution heat treated and aged state when compared with the rate in the as-cast state. In alloys that contain iron in amounts greater than the tolerance limit, solution heat treatment will increase the corrosion rate by a factor of two to five, and solution heat treating and aging will usually increase the rate to a somewhat slighter extent.

The heat treatment, and especially the cooling rate from the solution heat treating temperature, appear to affect the tendency toward pitting. However, with increasing zinc content as high as 3%, the pitting caused by quenching appears to decrease. This effect of heat treatment and quenching on the corrosion rate is particularly noticeable adjacent to welds in alloys containing aluminum and zinc, corroded in a 3% sodium chloride solution. Severe attack may take place in the rapidly cooled heat-affected zone.

Comparison of Atmospheric and Salt-Water Tests. It is extremely difficult to evaluate the way a material will withstand varying atmospheric conditions, by the use of an accelerated test in salt water. Extensive data have been compiled attempting to correlate results from the 3% sodium chloride, alternate-immersion test with the results obtained in atmospheric tests. The distinct lack of correlation is

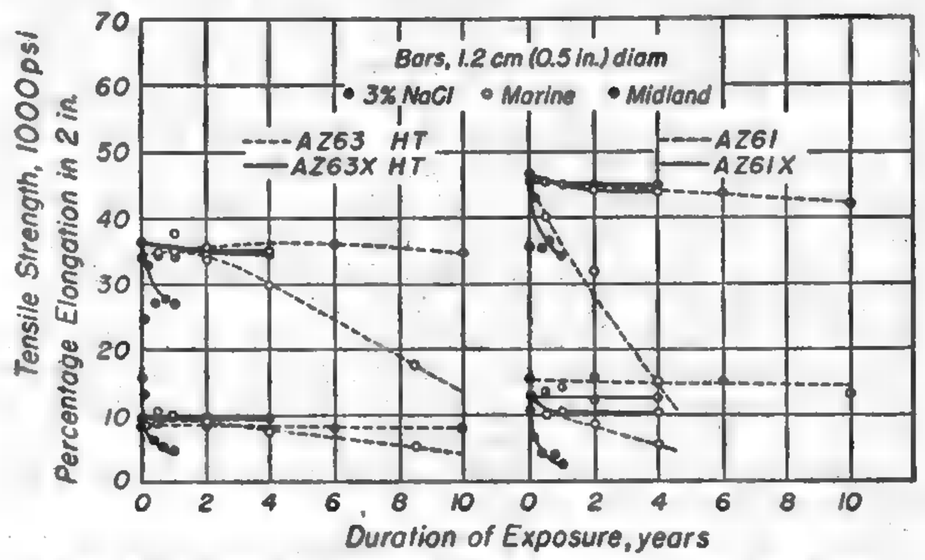


Fig. 8 Comparative behavior of magnesium alloy test bars, in accelerated and atmospheric mediums.

shown in Fig. 8 where the mechanical properties are given that were obtained on AZ61, AZ61X, AZ63, and AZ63X alloys after exposure to various mediums. The amount and distribution of impurities present in magnesium alloys strongly affect the results obtained in 3% salt solutions. In an industrial atmosphere, however, the influence of these impurities is apparently negligible. Although the effect of impurities in the alloys is more evident both in 3% salt solutions and in the marine atmosphere, the difference in results in these two mediums is so great that it would be extremely difficult to predict the life of a magnesium structure, basing the estimate on the tests in 3% salt solution.

Soil Corrosion. Extensive data in a wide variety of soils are not available, but the information which has been obtained indicates that magnesium is quite resistant to soil corrosion. Bare M1 and AZ31X extrusions and an AZ63 casting were buried in a vertical position in loam soil on the bank of a river for a year. The bottom of each section was immersed approximately 6 in. below the lowest river level. During examination after this exposure, a heavy calcareous-like deposit was found on the sections. No corrosion was evident. Parts coated with a bitumastic type of paint and buried at the same time showed no evidence of failure.

Similar results were obtained on extruded telephone poles used in the Panama Canal Zone. After several months of use, their condition was reported as very satisfactory.

Nonaqueous Corrosion. *Liquids.* Magnesium exhibits good resistance to corrosion in a wide variety of organic compounds. Aliphatics and their halide derivatives, as well as aromatics, cause little or no corrosion. A welded drum has been used for intraplant shipment of phenol for five

years. Methyl bromide storage containers are similarly unattacked. A storage tank for phenyl-ethyl alcohol has been in use for ten years. Alcohols, with the exception of methanol, cause little or no corrosion. Anhydrous methanol attacks magnesium vigorously with the formation of magnesium methylate. The attack may be partially inhibited by the addition of a little water; however 1% ammonium sulfide and beet-pulp distillate will inhibit the solution completely. Aliphatic acids and many of the compounds containing nitrogen cause appreciable corrosion.

Gases. Dry chlorine, iodine, bromine, and fluorine cause little or no attack on magnesium at room temperature. Dry bromine, containing 0.02% water, causes no more attack at the boiling point (58 C) than at room temperature. The presence of a small amount of water causes pronounced attack by chlorine, some attack by iodine and negligible attack by bromine or fluorine. Sulfur dioxide, ammonia and Freon cause no attack in either the liquid or vapor phase. Water vapor may cause some corrosion.

Galvanic Corrosion. Although the strongly electronegative potential has prevented the use of magnesium in some instances where otherwise the chemical and physical properties would make it an ideal material, in actual practice the widest usage of magnesium is under conditions of atmospheric exposure where, because of the poor conductivity of the mediums encountered, very small galvanic corroding currents are usually obtained.

Aqueous Systems. In completely aqueous systems, inhibitors may decrease galvanic corrosion radically. Alkaline chromates, fluorides and sulfides have proved effective in many instances. The addition of magnesium or calcium nitrate to solutions containing chloride, provides inhibition, apparently because of the precipitation of a magnesium or calcium hydroxide on the cathode. In aircraft systems that use ethylene glycol and water as a coolant, corrosion at 240 F, resulting from contact with iron, was inhibited by the addition of small amounts of phosphoric acid and triethanolamine. The type of inhibitor that is most effective is normally specific for a given medium.

Since magnesium is not ordinarily used in highly conducting mediums, the galvanic effects that may be produced under various atmospheric conditions are of more practical significance. Because of the strong effect on the conductivity, the type of atmosphere largely controls the galvanic corrosion that may be produced.

Inland Atmospheres. For an inland atmosphere, even under severe industrial conditions, the possibility of galvanic corrosion is relatively remote, and the extent is usually slight if such corrosion does occur. Under severe inland conditions, painting is normally sufficient to protect magnesium during long periods of exposure. Canoes were constructed using 2S aluminum rivets with steel bolts to fasten air chambers. After 10 years service they showed no galvanic attack. Die-cast generator parts, having steel inserts and bolted connections, showed little galvanic attack after 5½ years exposure on the roof of the Midland laboratory. During the same exposure, the steel parts had become badly corroded. Automobile wheels in use for more than a year have shown no galvanic corrosion at contacts with cadmium-plated steel bolts or between wheel and hub.

Where exposure is severe (as, for example, where contact with weak electrolytes may be expected) proper choice of alloy combinations or other protective measures may be required. The Germans have used plastic washers under steel bolts to protect both magnesium and aluminum from corrosion on artillery wheel applications. Aluminum alloy 52 S washers will give equal protection to magnesium and are superior where bearing loads are high.

Coastal Exposure. In coastal exposure, galvanic corrosion may occur, but the extent may be reduced or entirely eliminated by proper choice of the dissimilar metals, by application of protective treatments and paints, or by use of insulating plastics.

At the 80 and 800-ft coastal stations, the effect of a wide variety of metals on the promotion of galvanic corrosion was determined by fastening sheets of dissimilar metals directly to AZ61X alloy sheet by means of cadmium-plated steel bolts. The relative galvanic corrosion effects of the different metals are shown in Table II. Aluminum alloy 52 S and zinc caused less galvanic attack than lead and the other aluminum alloys. Copper, brass, monel, 18-8 stainless steel and mild steel caused appreciable galvanic corrosion. At the 80-ft station the severe exposure caused perforation of the magnesium panels at contacts with the more noble metals after six months to one year. At contacts with zinc or 52S aluminum, the galvanic corrosion was relatively much less severe.

Table II

Qualitative Evaluation of Effect of Equal Areas of Dissimilar Metals on the Galvanic Corrosion of AZ61X Magnesium Sheet at the 800-ft Station, Kure Beach, N. C.

Most galvanic attack	Copper, brass, monel, 18-8, mild steel, 17 S-T
Intermediate	3 S, 24 S-T, and clad 24 S-T, lead, galvanized iron, zinc
Least galvanic attack	52 S

Rivets. In ordinary inland atmospheres the choice of rivet alloy would have little or no effect on the corrosion resistance of an assembly, but in coastal atmospheres galvanic corrosion both of the magnesium rivet alloy and of an aluminum rivet alloy may occur unless proper selection is made. The alkaline nature of the corrosion product of magnesium causes pronounced attack on the rivet when aluminum rivets that contain copper are used, but none when the more alkali-resistant type, such as 56 S, is used. Painting riveted structures will normally delay somewhat the galvanic attack adjacent to A17 S-T (aluminum alloy) rivets; but because of the porosity usually found at section changes, painting may be insufficient for prolonged exposure to a coastal atmosphere.

Bolted Connections. When galvanic corrosion may be expected adjacent to bolts, proper choice of washer alloy may eliminate it. The effect of washer-alloy composition under cadmium-plated steel bolts was determined at the 800-ft station. Plain steel, cadmium-plated steel, zinc-plated steel, and 52 S aluminum alloy washers were used. After exposure during 19 months, severe corrosion had taken place adjacent to the plain steel, and some at the juncture with the cadmium-plated washer; but the zinc-plated steel washer had caused almost no galvanic corrosion, and no attack adjacent to the 52 S washers.

Paint will greatly reduce the galvanic corrosion that may occur at dissimilar metal connections, particularly when the faying surfaces are painted. If only one metal may be painted, it should preferably be the cathode, because this greatly reduces the cathodic area involved and consequently reduces the generated currents. At contacts between magnesium surfaces, negligible corrosion has been found after two years exposure at the 800-ft location. Zinc chromate primers on the faying surfaces are usually sufficient for dissimilar metal connections; however, very severe service may require more impervious paint system or plastic insulators.

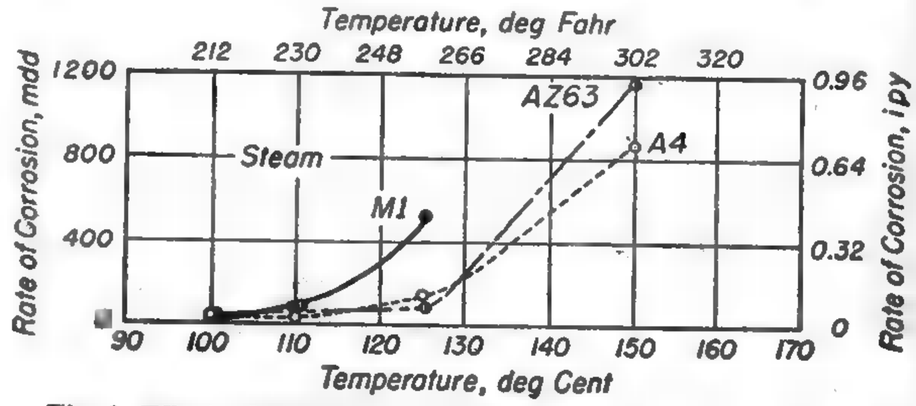


Fig. 9 Effect of steam temperature on the rate of corrosion of magnesium alloys.

Corrosion at High Temperatures. At elevated temperatures the rate of oxidation of magnesium in oxygen is a linear function of time; with increasing temperatures the rate also increases markedly. In general, the rate of oxidation is higher in air than in oxygen. Most alloying elements, such as aluminum and zinc, increase the rate of oxidation at a given temperature. Cerium, lanthanum and beryllium have been shown to reduce the rate of oxidation lower than that of pure magnesium. Beryllium additions have the most striking effect, giving protection to some alloys up to the

melting point, over extended periods of time. It has been observed that in the molten state, 0.010% Be will protect aluminum-containing magnesium alloys from burning at a temperature of 870 C (1600 F); however, the presence of dust and acid fumes in the atmosphere will reduce the protection afforded.

Water vapor in air or in oxygen increases markedly the rate of oxidation at temperatures greater than 100 C (212 F), but carbon dioxide and sulfur dioxide are effective in reducing it. Fluorides are also effective at temperatures lower than about 375 C (707 F) but at higher temperatures the film breaks down to form magnesium oxide.

The corrosion of typical magnesium alloys in steam is shown in Fig. 9. At 100 C (212 F) the rate of corrosion in the steam phase is distinctly greater than in the liquid phase. At temperatures higher than this, M1 exhibits a more rapid rate of corrosion than alloys that contain aluminum or aluminum and zinc. None of the magnesium alloys appear to be resistant to steam at temperatures higher than approximately 120 C (248 F), since magnesium hydroxide is formed rapidly.

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Designing for Magnesium

By A. M. Lennie*

ALTHOUGH principles of good design apply to all structural metals, every material possesses distinct characteristics, each warranting separate consideration. The rules of design established for magnesium are based on principles of good design modified according to the inherent properties of the metal. The basic qualities responsible for the widespread acceptance of magnesium may be summarized as follows: (1) extreme lightness in conjunction with good mechanical properties, resulting in a material with a high ratio of strength to weight; (2) adaptability to modern processes of fabrication, such as casting, extrusion, rolling, forging, welding, riveting, and forming; (3) excellent machinability.

In addition to these basic characteristics, magnesium possesses other properties useful in specific applications. It is nonmagnetic and nonsparking. Further, it has electrical resistivity useful in certain applications, good corrosion stability under normal atmospheric conditions, high capacity for absorbing elastic energy, excellent hot drawability, and etching qualities that make it desirable as a photoengraving material.

The combination of properties of magnesium offers to the engineer possibilities for saving weight, reducing cost, and improving quality and performance of products.

Weight can be reduced by substituting magnesium directly in some designs, but reduction can be obtained best by designing efficiently for magnesium. Many structural sections are heavier than necessary because of manufacturing limitations; for example, in castings where, for successful pouring, wall thicknesses must not be less than a given minimum. When such sections are made of magnesium rather than other structural metals, they can be used more efficiently with greater saving in weight than a comparison of the mechanical properties would seem to indicate. The lightness of magnesium is an advantage also in forgings and extrusions, which must sometimes be made heavier than is required.

Since the strength and stiffness in bending of many structural members increase approximately as the square and cube of the depth respectively, it is possible to obtain large increases in strength with some enlargement of section that involves little increase in weight. When such changes in section are permissible it is usually possible to redesign a part more efficiently for magnesium than for other metals. The greater bulk of magnesium also eliminates the problem of local instability. Even where redesign, using increased sections, does not result in maximum saving of weight, the design can usually be simplified and manufacturing costs can be lowered.

Incorporating magnesium into the design of a product may achieve one or more of the following effects: reduced operating costs, because of the higher operating speeds of machines, particularly those with intermittent or reciprocating motions; reduced wear and consumption of power; greater payloads; easier handling; improved efficiency of workers through reduction of fatigue; decreased shipping costs.

Fabricating costs may be reduced by taking advantage of the machining characteristics, the methods of fabrication and the design possibilities of magnesium. Magnesium may be machined so as to produce excellent surface finish at higher feeds and speeds than are suitable for other structural metals, and with consequent possible reduction in machining costs. Magnesium die castings offer the possibility of low-cost units that require much less machining than cast-iron parts. The extrusion process makes available an almost unlimited variety of special cross sections that can usually be produced more cheaply than shapes fabricated from other metals, which may require welding or riveting. The light weight of magnesium makes it possible to utilize heavy-gage monocoque sheet structures which, because of their simple design, are usually cheaper to fabricate than structures requiring ribs and stiffeners.

The combination of lightness and strength may improve machine operation by removing vibration and increasing speed; thus, imperfections in quality of the product can be minimized and production can be increased. Portable consumer goods may be made lightweight and easy to handle. In some applications such as aircraft engines, improvements in performance have been made to an extent impossible with other metals.

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Prepared for the Magnesium Committee

Mechanical Properties

Values for all mechanical and physical properties of magnesium are given in the data sheets for each alloy, pages 1013 to 1024. The mechanical properties given are typical values. The properties of castings are determined from separately cast test specimens; the properties of wrought products are determined from specimens machined from extrusions, sheet or forgings. A summary of the typical mechanical properties of several magnesium alloys in various forms is given in Table I.

The following designations, suffixed to the alloy number, are used to indicate the condition of heat treatment or temper.

- a, Annealed sheet
- h, Hard rolled sheet
- AC, As cast
- ACS, As cast plus a stabilizing heat treatment
- HT, Heat treated
- HTA, Heat treated and aged
- HTS, Heat treated and stabilized
- A, Aged

Typical stress-strain curves in tension and in compression have been reported but are not included in this discussion. The mechanical properties of wrought magnesium alloys may vary somewhat, depending on the amount of working and the direction of metal flow. The lowest properties will usually be found in the heaviest

or least worked sections and in a direction perpendicular to the direction of metal flow. In sheet, however, the properties in the transverse direction may be somewhat higher than those in the longitudinal direction—that is, the direction of rolling.

Tensile Properties. On the basis of equal weight, most of the magnesium alloys have properties comparable with those of other structural metals.

The yield strength of magnesium alloys is defined as the stress required to produce a deviation or offset of 0.2% from the modulus line. Minimum tensile properties normally used for purposes of specifications and as a ready means for determining the acceptance or rejection of material are given in Table II.

Compressive Strength. The compressive yield strength is defined as the stress required to produce a deviation or offset of 0.2% from the modulus line. Castings have a compressive yield strength approximately equal to the tensile yield strength. In wrought alloys, however, the yield strength in compression may be considerably less than the yield strength in tension. The ratio of the yield strength in compression to the yield strength in tension varies from about 0.4 for M1 alloy to about 1.0 for AZ80X HTA with an average value of about 0.7 for the other alloys.

Columns. The strength of magnesium columns loaded axially and sufficiently stable to prevent local failure may be represented by the following general equation:

$$\frac{P}{A} = \frac{M}{1 + \frac{M(KL/r)^2}{64{,}600{,}000}}$$

where

P = ultimate column load, lb
A = cross-sectional area, sq in.
M = a constant that depends on the compressive yield strength (F_{cy})
K = a constant depending on end conditions, 0.5 for fixed end and 1.0 for pin ends
L/r = slenderness ratio

The values of M corresponding to various values of F_{cy} are as follows:

Table I. Typical Mechanical Properties of Magnesium Alloys

Alloy and Treatment	Tension: Ultimate Strength, 1000 psi	Tension: Yield Strength, 1000 psi	Tension: Percentage Elongation	Compressive Yield Strength, 1000 psi	Bearing Ultimate Strength, 1000 psi	Bearing Yield Strength, 1000 psi	Hardness: Brinell (500 kg, 10 mm)	Hardness: Rockwell E	Ultimate Strength in Shear, 1000 psi	Endurance Limit for 5×10^8 cycles, 1000 psi	Izod Impact, ft-lb	Charpy Impact, ft-lb
Sand Castings and Permanent Mold Castings[a]												
AZ92 AC	25	14	2	14	...	...	65	76	18	12	1	0.5
AZ92 ACS	25	17	1	17	59	52	69	80	19	11	...	...
AZ92 HT	40	14	10	14	...	...	63	75	20	13	4	2.0
AZ92 HTA	40	22	3	22	...	...	81	88	22	12	1	0.8
AZ92 HTS	40	21	3	21	78	63	78	86	21	13	...	...
A1C AC	22	12	2	12	...	...	53	64	18	10	2	0.6
A10 ACS	22	16	2	16	...	...	58	70	...	...	...	...
A10 HT	40	13	10	13	69	45	52	62	20	11	4	2.0
A10 HTA	40	19	1	19	81	68	69	80	■	10	2	0.7
A10 HTS	38	18	1	18	...	...	67	78	...	...	...	...
AZ63 AC	29	14	6	14	...	...	50	■	18	11	3	1.0
AZ63 ACS	29	14	5	14	66	45	...	...	19	11	...	...
AZ63 HT	40	14	12	14	...	...	55	66	19	14	5	2.5
AZ63 HTA	40	19	5	19	...	...	73	83	20	13	2	1.1
AZ63 HTS	40	17	7	17	70	47	59	71	20	13	...	...
A8 AC	29	14	6	14	...	...	46	51	...	6	...	0.9
A8 HT	39	12	14	12	...	...	48	55	■	8	...	2.2
A8 HTA	39	15	9	15	...	...	...	...	...	...	...	...
M1 AC	14	4.5	5	4.5	...	...	33	3	11	...	9	3.0
Die Castings												
AZ91	33	22	3	22	...	...	60	72	20	14	2	2.0
Forgings												
AZ61X	43	26	12	18	...	...	55	66	21	16	...	2.2
M1	36	23	7	...	...	...	47	54	16	...	...	2.1
AZ80X	46	31	8	25	...	...	69	80	22	18	...	1.8
AZ80X A	50	34	6	28	...	...	72	82	23	■	...	...
TA54	40	28	12	21	...	...	52	62	16	11	...	2
Bars & Rods					**Extrusions**							
AZ31X	40	30	17	17	...	...	50	59	19	15	...	3.2
AZ61X	45	32	15	21	...	...	56	67	21	17	...	3.0
M1	38	28	10	■	...	...	42	41	16	9	...	2.1
AZ80X	49	35	12	26	...	...	63	75	21	19	...	2.2
AZ80X A	50	36	7	34	...	...	80	87	22	19	...	...
AZ80X HTA	53	40	7	36	...	...	80	87	22	...	...	...
Shapes												
AZ31X	39	26	15	15	...	...	50	59	19	...	...	3.2
AZ61X	44	29	16	18	76	45	60	72	20	...	...	3.0
M1	36	25	11	12	56	35	46	50	16	...	...	2.1
AZ80X	48	32	12	21	80	51	67	78	21	...	...	2.2
AZ80X A	50	34	10	33	...	...	80	87	22	...	...	...
AZ80X HTA	52	37	9	35	92	62	85	90	22	...	...	...
Tubing												
AZ31X	35	22	18	15	...	...	50	59	...	...	...	...
AZ61X	40	22	15	15	...	...	55	66	...	...	...	...
M1	35	23	8	10	...	...	42	41	...	...	...	...
Rolled Sheet												
AZ31X a	37	22	21	■	76	37	55	66	21	11	...	...
AZ31X h	42	33	11	29	79	54	72	82	23	13	...	...
M1 a	33	18	17	12	51	29	48	55	17	9	...	...
M1 h	35	26	7	20	57	39	54	65	17	10	...	...
AZ51X a	40	21	19	16	...	...	57	68	20	13	...	...
AZ51X h	45	34	10	26	79	54	71	81	22	14	...	...

a, Annealed sheet; h, Hard rolled sheet; AC, As cast; ACS, As cast plus a stabilizing heat treatment; HT, Heat treated; HTA, Heat treated and aged; HTS, Heat treated and stabilized; A, Aged.
(a) Properties determined on separately cast test bars.

F_{cy}	M	F_{cy}	M	F_{cy}	M
6,000	13,100	14,000	21,100	22,000	47,000
8,000	14,100	16,000	25,500	26,000	68,800
10,000	15,700	18,000	31,200	30,000	97,000
12,000	17,900	20,000	38,500	34,000	129,000

Typical values for F_{cy} of various magnesium alloys, to be used in the above formula are:

Alloy	F_{cy} Shapes	F_{cy} Tubing
M1	9,000	7,000
AZ31	15,000	12,000
AZ51	18,000	14,000
AZ80	20,000	.....
AZ80 HTA	30,000	.....

The values for the column loads, as determined in the foregoing equation, are ultimate. As with steel it is recommended that ½ the value obtained be used for the working stress. Column curves are given in Fig. 1.

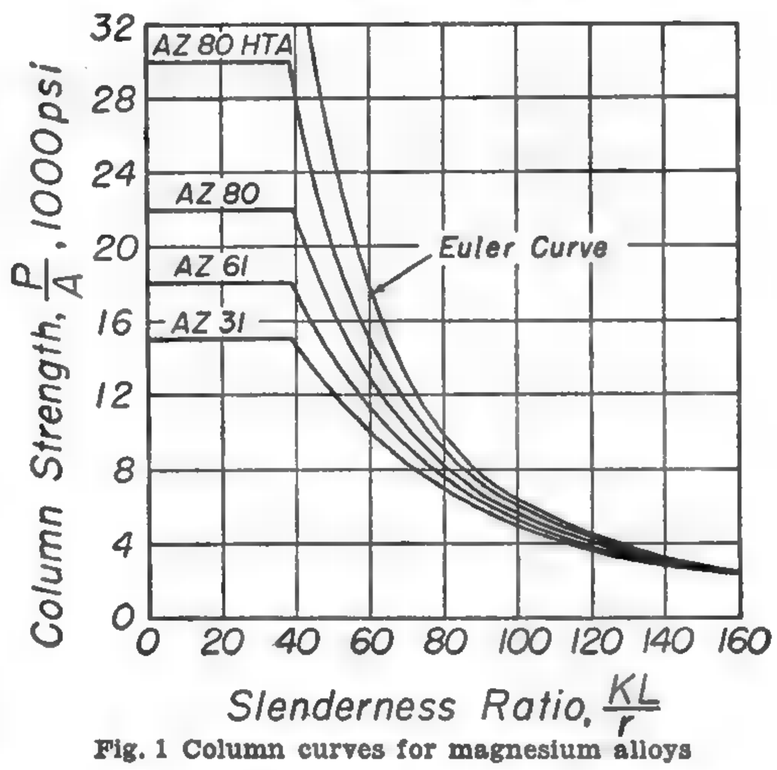


Fig. 1 Column curves for magnesium alloys

Bearing Strength. Bearing strength is particularly important in the design of bolted and riveted joints. The bearing yield strength is defined as the stress required to produce an offset of 2% from the initial curve of bearing stress versus hole elongation. Bearing-strength values listed in Table I were determined on specimens having an edge distance of 2½ times the pin diameter and a width of 8 times the pin diameter. It has been shown that increasing the edge distance to more than approximately 2 times the pin diameter has little effect on the bearing values.[1] Sheet thicknesses within a wide range have been tested and no effect of the ratio of pin diameter to sheet thickness was observed.

Moduli. The modulus of elasticity is approximately 6,500,000 psi in both tension and compression[2] and the modulus of rigidity is approximately 2,400,000 psi. These values give a Poisson's ratio of 0.35. The modulus of elasticity must be considered in any design involving stiffness or rigidity. When stiffness is a factor, the modulus can be compensated by increasing the section size, preferably the depth or thickness, since stiffness increases with the cube of the depth, and relatively small increases in depth will result in large increases in stiffness.

Bending Strength. Since magnesium alloys are ductile, no values for the modulus of rupture can be given. In the design of beams, the bending strength may be defined as the moment developed when the outer fibers are stressed to the yield strength of the material. Since the tensile and compressive yield strengths of most wrought magnesium alloys are not equal, the maximum stress to use in the standard formula $f = \frac{Mc}{I}$ has been determined as the average of the tensile and compressive yield strengths.[4] This applies to solid sections, such as rounds, squares, and rectangles, as well as to tubes that have a D/t ratio of less than 20. In standard I-beams, channels and such, the yield strength in bending will be slightly less than the average yield strengths in tension and in compression.

Shear Strength. This property is important in the design of connections in magnesium such as threaded joints and spot welds. The values for castings and extrusions were obtained by the conventional double shear method using solid rods. The values for sheet and AZ80X HTA structural shapes were obtained by the punch method, using a flat specimen.

Hardness and Wear Resistance. Magnesium alloys have sufficient hardness for all structural uses, except where subjected to severe abrasion. Rockwell and Brinell hardness numbers are given in the data sheets and summarized in Table I. Although rather wide variations in hardness are observed, the resistance of the alloys to abrasion varies by only about 15 to 20%. When subjected to wear by rubbing, by frequent removal of studs, or by heavy bearing loads, magnesium may be protected by inserts of steel, bronze, or nonmetallic materials, attached as sleeves, liners, plates or bushings. Such inserts may be attached mechanically by pressing, shrinking, riveting, bolting or bonding; in castings, inserts may be cast in place. Recommended types of inserts are discussed under General Considerations of Design, page 1004.

Magnesium alloys perform very satisfactorily as a bearing material where the following conditions are met: loads not to exceed 2000 psi; hardened shafts (350 to 600 Bhn); ample lubrication; low speeds, 1000 fpm max; and operating temperatures not to exceed 220 F.

Table II

Specified Minimum Tensile Properties of Magnesium Alloys

Alloy	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Percentage Elongation in 2 in.
Sand and Permanent Mold Castings			
AZ63 AC	24	10	4
ACS	24	10	2
HT	34	10	7
HTS	34	13	4
HTA	34	16	3
AZ92 AC	20	10	...
ACS	20	11	...
HT	34	10	6
HTS	34	16	1
HTA	34	18	1
A10 AC	20	10	1
HT	32	10	3
HTA	34	17	...
M1	12	4	3
Forgings			
AZ61X	38	22	6
M1	30	18	5
AZ80X	42	26	5
AZ80X A	42	28	2
AZ80X HTA	42	28	2
TA54	36	22	7
Bars and Rods			
AZ31X	35	22	10
AZ61X	40	26	11
M1	30	20	3
AZ80X	43	28	9
AZ80X HTA	48	33	4
Shapes			
AZ31X	33	20	8
AZ61X	40	22	9
M1	29	17	3
AZ80X	41	25	6
AZ80X HTA	47	30	5
Tubing			
AZ31X	32	18	8
AZ61X	36	16	7
M1	28	13	3
AZ80X	38	17	5
Sheet and Plate			
AZ31X a	32	15	[illegible]
AZ31X h	38	26	4
AZ51X a	37	19	8
AZ51X h	42	32	3
AZ51X r	40	26	8
M1 a	28	12	12
M1 h	32	22	4

Table III. Effects of Surface Condition on the Bending-Fatigue Properties of Sand-Cast Magnesium Alloy Plate

Alloy	Surface Condition	Fatigue strength in psi for given number of cycles[c] 10^5	10^6	10^7
All commercial[a] Sand-casting Alloys	As-cast	16,000 to 10,000	15,500 to 8,500	9,500 to 6,000
	Machined	19,500 to 14,000	16,000 to 10,000	14,500 to 8,500
	Ground[b]	15,500 to 11,000	13,000 to 9,000	11,500 to 9,000
AZ92 HT	Machined & polished	15,000	12,500	10,000
AZ63 HT	Machined & polished	15,500	12,500	10,000

(a) Applies to all commercial sand-casting alloys whether heat treated or not.
(b) Ground surfaces are typical of foundry cleanup.
(c) The limits define the upper and lower boundary of the scatter band.

Fatigue Strength. Magnesium alloys have good resistance to fatigue. Like other metals, magnesium alloys are sensitive in fatigue to the effects of stress raisers, such as notches or abrupt changes in section; therefore consideration should be given to stress raisers when a part is subject to fluctuating stresses.

The values for the endurance limit given in Table I were determined by the R. R. Moore rotating-beam method and are based on 500,000,000 complete reversals of stress. Although the endurance limits of polished bars are of little quantitative use in design, they do have value in a comparative way.

Since the surface condition, type of load application, and design are important in determining the fatigue properties of actual parts, these factors must be considered. In evaluating these variables for magnesium castings, the data given in Table III can be used quantitatively. The limits given in the data are the upper and lower boundary of the scatter band. Any effect shown by alloy composition or heat treatment is inconsequential, since the results were all dispersed at random in one scatter band. There is a significant difference, however, in the endurance limit for the several types of surface finish.

Table IV
Tensile Properties of Magnesium Alloys at Low Temperature

Alloy	Temp, deg Fahr	Yield Strength,[a] 1000 psi	Tensile Strength, 1000 psi	Elong, % in 2 in.	Charpy Impact,[b] ft-lb	Hardness,[c] Rockwell E
		Extrusions				
M1	77	28.0	39.0	3.5	3.9	30
	−110	30.9	52.0	3.0	2.6	66
AZ61	77	33.9	46.8	12.7	6.9	73
	−110	41.0	50.4	12.2	2.9	81
		Castings				
A10	77	15.8	22.3	1.7	0.9	69
	−110	17.9	22.0	1.0	0.7	75
A10 HT	77	15.5	34.7	8.5	3.2	65
	−110	18.4	38.4	7.2	2.6	73
A10 HTA	77	24.6	38.5	3.0	0.8	83
	−110	25.9	38.9	2.0	0.8	91
AZ63	77	13.8	27.1	4.5	1.8	58
	−110	15.4	24.9	2.7	1.6	68
AZ63 HT	77	14.2	34.5	8.7	4.1	59
	−110	17.1	37.2	8.2	3.4	69
AZ63 HTA	77	21.5	38.9	4.5	1.6	75
	−110	24.4	35.4	2.5	1.5	85

(a) Tensile properties are average of 2 tests.
(b) Impact properties are average of 4 tests.
(c) Hardness is average of 5 tests.

Resilience. This property is the ability to absorb energy without permanent deformation. Resilience or elastic potential energy is inversely proportional to the modulus of elasticity and directly proportional to the square of the stress applied. Since resilience concerns only the elastic range, the yield strength of the metal must be considered in evaluating this property. Since magnesium alloys have a relatively low modulus of elasticity, they have a high unit resilience.

Toughness. This property is a function of the strength and ductility of a material. Toughness is measured by the area under the stress-strain curve but can be approximated by multiplying the tensile strength by the elongation in the tensile test. Calculations made according to the latter method show that, on the basis of equal weight, magnesium alloys have toughness equivalent to that of other structural metals.

The single-blow impact test was devised as a method of determining toughness, but since this test normally employs a notched bar, it is in reality a test of the effect of a notch. Values for both Izod and Charpy impact strength are given in Table I. Because the impact test is really a test of notch effect, the test values should be used with caution.

Effect of Temperature. *Low Temperature.* The mechanical properties of magnesium alloys at minus 110 F are given in Table IV.[4] The tensile strength, yield strength and hardness increase slightly with decreased temperature, while the elongation and notch-impact strength show a slight decrease.

Table V
Short-Time Tensile Properties of Magnesium Alloys

Alloy	Temperature, deg Fahr	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Percentage Elongation in 2 in.
		Sand Castings		
AZ63 HTA	95	38.7	17.7	5.5
	200	36.0	17.3	11.0
	250	32.4	16.5	11.0
	300	24.5	15.0	15.0
	400	17.5	12.0	17.0
	500	12.0	8.8	15.0
	600	8.2	5.6	20.0
AZ92 HTA	95	43.4	26.0	2.0
	200	41.3	22.0	25.0
	250	35.6	20.0	29.7
	300	38.0	18.0	35.0
	400	16.9	10.9	36.0
	500	11.3	7.4	33.0
	600	7.8	5.1	49.0
		Extrusions		
M1	95	39.6	30.9	7.6
	200	27.0	21.3	15.0
	250	24.4	18.8	20.2
	300	21.3	15.7	18.7
	400	18.8	11.7	25.0
	500	13.0	7.5	60.0
	600	9.0	5.4	93.0
AZ61X	95	45.8	33.1	14.3
	200	42.3	26.4	21.0
	250	39.0	25.8	30.7
	300	30.4	20.2	40.5
	400	21.4	14.7	42.0
	500	12.9	8.2	64.0
	600	7.9	5.1	70.0
AZ80X HTA	95	56.5	40.5	4.5
	200	48.5	32.1	20.0
	250	42.0	26.6	33.0
	300	33.6	21.4	41.2
	400	21.6	14.7	49.0
	500	13.6	7.8	83.0
	600	8.7	4.7	123.0

Properties at Elevated Temperature. The properties of metals at elevated temperature are usually determined by three different methods: short-time tests, stress to rupture tests and creep tests. Each method gives data of value for particular service conditions.

Short-Time Tests. The short-time test data (*see* Table V) are useful in the various hot working operations.

Stress to Rupture. This test gives the length of time at temperature during which a material will withstand a constant stress before rupture. The data in Table VI give the stress necessary to produce rupture of various magnesium alloys in 1000 hr at elevated temperature. More complete stress-rupture information is available.[5]

Creep. When a design calls for a limiting amount of deformation, creep properties become important. Creep, which may be defined as the continuous deformation of a material under stress, takes place in three distinct stages commonly known as the first, second and third stages. In the first stage, extension starts at a rapid rate, which

Table VI. Properties of Magnesium Alloys at Elevated Temperatures

Alloy	Temperature, deg Fahr	Short-Time Tests: Tensile Strength, 1000 psi	Short-Time Tests: Yield Strength, 1000 psi	Short-Time Tests: Percentage Elongation in 2 in.	Stress to Rupture: Stress for Rupture in 1000 hr, 1000 psi	Stress to Rupture: Elongation in 2 in., 1000 hr, 1000 psi	Creep: Stress for 0.1% Creep in 1000 hr, 1000 psi	Creep: Stress for 0.5% Creep in 1000 hr, 1000 psi
				Castings				
AZ92 HTA	95	43.4	26.0	2.0	35.5	29.7	17.9	...
AZ63 HTA	95	38.7	17.7	5.5	37.4	...	18.2	...
				Extrusions				
M1	95	39.6	30.9	7.6	24.3	22.2	14.3	16.6
AZ31X	95	39.9	28.6	16.6	30.7	29.8	...	...
AZ61X	95	45.8	33.1	14.3	42.4	23.4	...	...
AZ80X HTA	95	56.5	40.5	4.5	40.0	25.2	...	...
				Castings				
AZ92 HTA	200	41.3	22.0	25.0	...	...	6.8	11.2
A63 HTA	200	36.0	17.3	11.0	...	...	8.9	...
				Extrusions				
M1	200	27.0	21.3	15.0	...	...	13.8	...
				Castings				
AZ92 HTA	300	28.0	18.0	35.0	8.0	37.8	1.9	3.8
AZ63 HTA	300	24.5	15.0	15.0	8.3	11.1	1.6	4.2
				Extrusions				
M1	300	21.3	15.7	18.7	12.2	48.0	5.7	7.4
AZ31X	300	24.7	14.5	38.2	6.8	52.0	...	...
AZ61X	300	30.4	20.2	40.5	7.0	57.2	...	...
AZ80X HTA	300	33.6	21.4	41.2	8.3	42.8	...	...

is decreased until a constant value is reached during the second stage. Finally, in the third stage, the rate increases until eventually rupture may take place. The extent of deformation in any material depends on the stress level, temperature and time. The results given in Table VI are stresses required for producing rates of extension of 0.1 and 0.5% in 1000 hr. These rates are determined in the constant-rate or second stage of the creep curves between the 750th and 1000th hr. It is not recommended that creep rates be extrapolated over a wide period of time unless substantiated by tests.

Creep results may also be reported as the total extension by creep at a specified stress and temperature.[5] This total extension does not include the initial extension produced in loading the specimen. The service conditions determine the type of high-temperature data to be used.

Properties at Room Temperature After Heating Magnesium to an Elevated Temperature. In operations such as forming and drawing, it is sometimes necessary to work magnesium at elevated temperatures. Since temperature has a deleterious effect on the properties of hard rolled sheet, maximum working temperatures have been established. The maximum temperatures used in forming, in order to retain the hard rolled properties, are 300 F (135 C) for AZ31Xh, 400 F (204 C) for AZ51Xh, and 500 F (260 C) for M1. Table VII gives the properties of hard rolled sheet at room temperature after the sheet has been heated to various temperatures. Annealed sheet will show no change in properties, since the annealing temperature is higher than the processing temperatures.

Physical Properties

All available information on the physical properties of magnesium alloys is given in the data sheets (pages 1013 to 1024). For convenience, tables summarizing a few properties are given in this section.

Specific Gravity. Specific gravities and weights per cubic inch are given in Table VIII.

Table VIII. Physical Properties of Magnesium Alloys

Alloy	Form	Specific Gravity, 75 F	Weight per cu in.	Thermal Conductivity between 100 and 300 C, cgs units
AZ92	As Cast	1.82	0.066	0.16
A10	As Cast	1.81	0.066	0.17
AZ63	As Cast	1.84	0.066	0.18
AZ91	Die Cast	1.81	0.066	0.17
AZ31X	Extruded	1.78	0.064	0.23
AZ61X	Extruded	1.80	0.065	0.19
M1	Extruded	1.76	0.064	0.30
AZ80X	Extruded	1.80	0.066	0.18

Thermal Conductivity. The thermal conductivity of magnesium is important where rapid dissipation of heat is required. Pure magnesium has a conductivity of 0.376 units, while the alloys have conductivities ranging down to 0.17. Table VIII gives the values of thermal conductivity for the various alloys.

Specific Heat. All the magnesium alloys have virtually the same specific heat, which is 0.25 cal per g per °C.

Coefficient of Thermal Expansion. The mean coefficient of thermal expansion for magnesium alloys is 0.0000143 in the temperature range from 68 to 212 F. The coefficient of expansion increases slowly with temperature; the value for the temperature range from 68 to 752 F is about 0.000016 per degree. Allowance must be made for this expansion of magnesium in structures subjected to variations in temperature, especially where the structures are rigidly connected to dissimilar metals and restrained from expanding and contracting freely. In pressed or shrunk-in inserts, the differential in expansion must be considered so that sufficient grip will be retained on the insert when the assembly is heated.

Table VII. Properties of Hard Rolled Magnesium Sheet at Room Temperature After Heating for 15 Minutes at Various Temperatures

Temperature, deg Fahr	AZ51Xh: Tensile Strength, 1000 psi	AZ51Xh: Yield Strength, 1000 psi	AZ51Xh: Percentage Elongation	AZ31Xh: Tensile Strength, 1000 psi	AZ31Xh: Yield Strength, 1000 psi	AZ31Xh: Percentage Elongation	M1h: Tensile Strength, 1000 psi	M1h: Yield Strength, 1000 psi	M1h: Percentage Elongation
Room	44.5	34.2	12.8	44.8	34.0	10.0	37.3	30.0	10.2
200	44.5	34.2	12.8	44.8	34.0	10.0	37.3	30.0	10.2
250	44.5	34.2	12.8	44.7	33.8	10.1	37.3	30.0	10.2
300	44.5	34.2	12.8	44.0	31.5	12.0	37.2	30.0	10.2
350	44.0	33.5	12.8	42.2	27.0	15.0	37.1	30.0	10.4
400	43.5	32.1	13.8	40.6	25.5	17.8	37.0	29.8	11.0
450	42.6	32.0	16.2	39.2	24.5	20.6	36.8	29.2	12.0
500	41.6	27.9	17.8	38.3	23.8	21.2	36.2	28.0	13.4
550	41.6	25.9	18.5	37.6	23.3	21.3	35.3	26.5	15.1
600	...	...	...	37.0	23.0	21.3	34.1	22.0	16.7

Dimensional Stability. Magnesium alloys generally exhibit good dimensional stability in service, with permanent dimensional changes seldom observed in properly designed parts. Such changes may occur as a result of one or more of the following causes: (1) growth produced by long exposure at elevated temperatures and by the resulting metallurgical change—for example, precipitation of magnesium compounds from solid solution; (2) distortion caused by the relief of residual stresses; (3) creep caused by the gradual yielding of the metal under the influence of stress, temperature and time.

Table IX. Maximum Permanent Growth of Magnesium Alloys at Elevated Temperatures

Alloy	Form	As Cast, in./in.	As Cast and Stabilized, in./in.	Heat Treated, in./in.	Heat Treated and Stabilized, in./in.	Heat Treated and Aged, in./in.
			Castings			
AZ92	Sand Cast	0.00034	0.00017	0.00076	0.00021	0.00029
AZ63	Sand Cast	0.00026	0.00012	0.00054	0.00027	0.00022
A10	Sand Cast	.....	.....	0.00210	.....	0.00100
AZ91	Die Cast	0.00033	0.00016	.....	.....	.....

Alloy	Form	Forged, in./in.	Forged and Aged, in./in.	Extruded, in./in.	Extruded and Aged, in./in.
			Wrought Alloys		
AZ80X	Extruded	.....	.....	0.00144	0.00075
AZ80X	Forged	0.00092	0.00084	.....	.....

Permanent Growth. Some magnesium alloys are subject to small amounts of permanent growth if used at temperatures exceeding 200 F for extended periods of time. For all practical purposes, magnesium alloys are free from growth, but where close tolerances must be maintained, the designer should refer to Table IX, which gives the maximum permanent growth that can be expected from typical magnesium alloys. Under normal operating conditions, however, the growth taking place is only a fraction of the maximum values listed. Growth results from a metallurgical transformation, possible to any appreciable extent only in alloys that can be heat treated; therefore most wrought magnesium forms will exhibit no growth in service.

Table X. Electrical Properties of Magnesium Alloys

Alloy	Volume Conductivity, % IACS[a]	Resistivity at 20 C, microhm-cm
Castings		
AZ92 AC	12.3	14.0
HT	10.5	16.5
HTA	12.3	14.0
AZ63 AC	15.0	11.5
HT	12.3	14.0
HTA	13.8	12.5
Wrought Alloys		
M1	34.5	5.0
AZ31	17.2	10.0
AZ51	12.8	13.5
AZ61	12.3	14.0
AZ80	14.6	11.8
AZ80 HTA	10.8	16.2
TA54	12.5	13.8

(a) International Annealed Copper Standard, percentage of the conductivity of standard copper

Residual Stresses. Residual stresses set up during fabrication or straightening operations may result in warpage or permanent distortion of magnesium parts. The low modulus of elasticity of magnesium, absence of skin effect in castings, wide range of solidification, and use of heat in forming operations mean that stresses will be induced less frequently in magnesium than in other metals. Heating castings to approximately 500 F for 2 hr and cooling slowly will remove residual stresses effectively. Relief of welding stresses is discussed in the article entitled "Joining Magnesium Alloys", page 983.

Creep. See Effect of Temperature, page 1002.

Electrical Properties. The electrical conductivity of magnesium is relatively high. Table X gives the values of conductivity as well as of resistivity in various magnesium alloys. Pure magnesium, on a basis of equal weight, has a conductivity of 198% IACS, that is, 98% greater than standard copper.

The conductivity of the various alloys is influenced by the alloying elements present and by the metallurgical condition. Heat treatment reduces the conductivity; aging increases it.

Magnesium is weakly paramagnetic, but for all practical purposes it may be considered nonmagnetic.

General Considerations of Design

Safety. Magnesium alloys must be heated to and held at their lower melting point (800 to 1200 F) for an appreciable time before ignition occurs. The degree of fineness of the magnesium will also determine to some extent the ease of ignition. Fine particles will ignite more readily; therefore, in grinding and polishing operations, adequate precautions must be taken to prevent accidental ignition of magnesium dust. Ordinary machining scrap presents no unusual hazards if precautions advised by the industry are followed. The great majority of structural parts are thick enough for the burning characteristics to be of no importance to the design engineer. The high thermal conductivity of magnesium dissipates heat rapidly, making it difficult to raise the temperature to the ignition point. If magnesium sections, including thin sheet, are not preheated, local ignition will be restricted and any burning that occurs will cease.

Since the designer is limited to service temperatures below 400 F by the mechanical properties of magnesium, the problem of combustibility need not be considered in normal applications. Even where magnesium might be exposed to accidental fires, tests have shown that structural failures will occur in other metals as well as in magnesium before magnesium ignites. As an additional precaution, however, special paints that greatly inhibit burning may be used on magnesium.

The safety of magnesium was demonstrated strikingly by an experiment in which an aircraft gasoline tank made of magnesium was exposed to a blowtorch. A hole was burned in the tank and the gasoline was burned with no damage to the tank except the hole burned by the torch. Examples of the safety of magnesium are the many applications in aircraft engines, cooking utensils, cigarette lighters and industrial equipment, all of which have been serving successfully for years.

Machining. Although the technique of machining magnesium is not of direct interest to the designer, the good machinability of magnesium creates several factors that influence design. The high speeds and heavy feeds that can be used, as well as the general ease of machining, mean that magnesium can be machined more cheaply than most other metals. The machining cost for magnesium may be 50 or 60% lower than that for iron and steel. Such economies in the cost of processing must be kept in mind by the designer, since it may be cheaper to machine a casting rather than to use some other method for producing the part, or it may be cheaper to specify magnesium rather than some other metal.

When spot faces are specified, or other similar machined surfaces, generous radii should be used in order to eliminate stress concentration. For like reasons, part numbers should not be stamped on stressed sections but should be placed on raised pads.

Inserts. As discussed under Hardness, it is necessary to protect magnesium surfaces where they are subjected to heavy bearing loads or severe wear. Inserts to provide this protection can be of a wide variety and attached in numerous ways.

Cast-In Inserts. Inserts in magnesium may be cast in place in the same manner as in other metals. Cast-in inserts may be made of steel, brass, bronze or other metals. Nonferrous inserts should be plated with cadmium or chromium to prevent alloying with magnesium, and ferrous inserts should be plated with cadmium to decrease the possibility of galvanic effects.

Inserts are made secure when the cast metal shrinks

around them and provides a bond. This anchorage may be obtained more easily by knurling, grooving or shaping the insert suitably. For severe service, some type of nose or hook should be used, but care should be taken to ensure that sharp corners or insufficient metal around the insert do not set up concentrations of stress. In highly stressed castings it may be desirable to cast in a pilot to which the insert may be attached, thus avoiding high shrink stresses around the insert. Cast-in inserts may also be used for providing details not otherwise feasible, such as lubrication lines of steel or copper, or appendages that could not be attached conveniently otherwise. Generally, cast-in inserts complicate the manufacture of castings; hence such inserts should be specified only when other methods of attaching are not feasible.

Press-Fit and Shrink-Fit Inserts. The low modulus of elasticity of magnesium requires that greater interference be used for pressed or shrunk inserts in magnesium than is used for inserts in other metals, in order to obtain sufficient gripping force. An interference of 0.0005 to 0.001 in. per in. is usually satisfactory, but may be increased appreciably where high torque loads are likely to be encountered. Table XI presents recommended interferences for normal service at various temperatures when steel and bronze inserts are to be used. The values given in the table serve only as a guide, since service temperature, type of insert material, severity of service and thickness of insert, all influence the necessary amount of interference. Differences in thermal expansion, yield strength and modulus of elasticity must also be considered for service at elevated temperatures. Inserts are more easily assembled by shrinking, since it is relatively easy to heat the magnesium part and expand the hole sufficiently to receive the insert. Where necessary, the insert may be cooled to facilitate insertion. Assembly by pressing requires careful machining of both insert and hole, and proper lubrication. When large interferences are required, it is generally best to specify shrunk-in inserts, since press-fits may score the magnesium.

Screw Inserts. Various types of screwed-in and mechanically attached inserts may also be used successfully in magnesium parts. When inserts of this type are used, care must be taken to avoid stress concentrations in locating threaded holes and to provide sufficient engagement for the thread.

Assembly Protection. Good design for an assembly of any metal demands that suitable surface protection be provided, especially in enclosed structures and where metal surfaces are in contact. Although magnesium alloys have good general stability at the surface, requiring only normal protection, the possibility of galvanic corrosion, discussed fully in the article entitled "Corrosion of Magnesium", requires that added precautions be taken where magnesium comes in contact with dissimilar surfaces under corrosive conditions.

Enclosed surfaces, when neither tightly sealed from external exposure nor concealed in a structure so as to be inaccessible, should be protected with zinc chromate primer or painted, if service conditions are likely to be severe. Wherever possible, parts that have enclosed surfaces of this sort should be designed to provide drainage and ventilation, thus avoiding entrapped moisture and condensation that provide the corroding mediums.

Faying surfaces on magnesium parts should be primed with zinc chromate primer before assembly, and the entire structure should be painted after assembly.

When magnesium is assembled in contact with dissimilar metals or wood, sealing compounds or gaskets should be used at faying surfaces in addition to priming, in order to provide extra protection. Also the entire structure should be protected with an adequate paint.

Anodized rivets of 56 S aluminum are preferred for use on magnesium structures, since they minimize the possibility of galvanic corrosion; however, other types may be used if the exposure conditions are not severe. Steel bolts, screws, studs or rivets should be plated with zinc or cadmium.

The extent to which these protective precautions should be used depends entirely on the corrosive conditions.

Product Design

Castings. Magnesium alloys may be cast in sand molds, permanent molds or dies. The choice of casting process depends on (1) the number of parts to be produced, (2) the size and intricacy of the part, (3) service requirements, and (4) limitations imposed on the process, such as allowable section size and tolerances. Differences in strength, as well as in cost, exist among the various types of magnesium castings; hence in the following sections the design requirements will be discussed from the standpoint of producing castings that have adequate strength and can be manufactured economically.

Sand and Permanent Mold Castings. Data for the design of sand castings and permanent mold castings are very similar and may usually be applied equally well to both types. Permanent mold castings, made in metal molds, are restricted to smaller and less intricate designs than those made in sand. Properties of both types of casting are very similar, though permanent molds have better finish and closer tolerances. When parts can be made by either method, the choice depends mainly on the number of castings to be produced. If only a few are required, the lower cost of pattern equipment and molding makes sand casting cheaper, but if a relatively large number of castings is required, the cost per piece in a metal mold is minimized and the simpler casting procedure results in cheaper castings by the permanent mold process.

The mechanical properties of cast magnesium alloys are determined from tests made on separately cast specimens poured from the same melt as the castings and in accordance with ASTM specifications. Specimens cut from actual castings will have somewhat lower mechanical properties than separately cast specimens poured from the same melt. Magnesium castings and separately cast specimens are more similar in properties than are castings and specimens of other metals. Average values for coupons from castings will be from 75 to 85% of the value for typical test specimens. However, good design and good foundry practice can minimize factors such as microshrinkage, grain size and foreign inclusions, which cause the variations in properties.

Alloys AZ63 and AZ92 are the most widely used sand-casting alloys; A8 and M1 are used to a limited extent. AZ63 combines good yield strength with maximum toughness and resistance to corrosion, but AZ92 has better castability and combines maximum yield strength and hardness with good soundness and toughness. Since AZ92 is less subject to microporosity, it is preferred to AZ63 for applications where pressure tightness is a factor. Alloy A8 should be used for applications that require maximum toughness, soundness and weldability; however,

Table XI. Approximate Interferences Suggested for Press-Fit and Shrink-Fit Inserts in Magnesium

Inserts		Interference, inch							
		Steel Inserts				Bronze Inserts			
		Operating Temperatures				Operating Temperatures			
Outside Diameter	Approximate Wall Thickness, in.	70 F	100 F	200 F	300 F	70 F	100 F	200 F	300 F
½	1/16	0.0004	0.0005	0.0009	0.0013	0.0004	0.0005	0.0007	0.0009
1	3/32	0.0006	0.0010	0.0017	0.0025	0.0006	0.0008	0.0012	0.0016
2	1/8	0.0010	0.0015	0.0031	0.0048	0.0010	0.0013	0.0019	0.0028
3	5/32	0.0015	0.0024	0.0047	0.0072	0.0015	0.0019	0.0028	0.0044
4	3/16	0.0021	0.0034	0.0062	0.0096	0.0021	0.0026	0.0039	0.0060
5	7/32	0.0028	0.0044	0.0080	0.0121	0.0028	0.0034	0.0053	0.0079
6	1/4	0.0036	0.0053	0.0098	0.0147	0.0036	0.0043	0.0070	0.0098

if resistance to corrosion is a determining factor, the purity of A8 must be controlled. Alloy M1 has relatively low strength but is used to a limited extent for castings such as tank fittings to be welded to sheet assemblies.

Magnesium alloys A8, A10, and AZ92 are used for permanent mold castings; AZ92 has been more widely adopted because of its superior mechanical properties and resistance to corrosion. As in sand castings, A8 is used where maximum toughness, soundness and weldability are desired. Alloy A10 is preferred for more complicated castings because of its superior foundry characteristics, but it has slightly lower mechanical properties and resistance to corrosion than AZ92.

With the exception of M1, all the alloys used for casting in sand and permanent molds, can be heat treated to improve their mechanical properties. Reference to Table I shows the improvement that can be effected in mechanical properties by the various heat treatments.

Co-operation between the designer and foundryman is desirable in all metal casting, and since magnesium requires larger risers and different techniques in chilling and gating, such co-operation means that castings of higher quality will be obtained. The foundryman with an appreciation of the design problem can place risers and chills more efficiently to produce the soundest metal

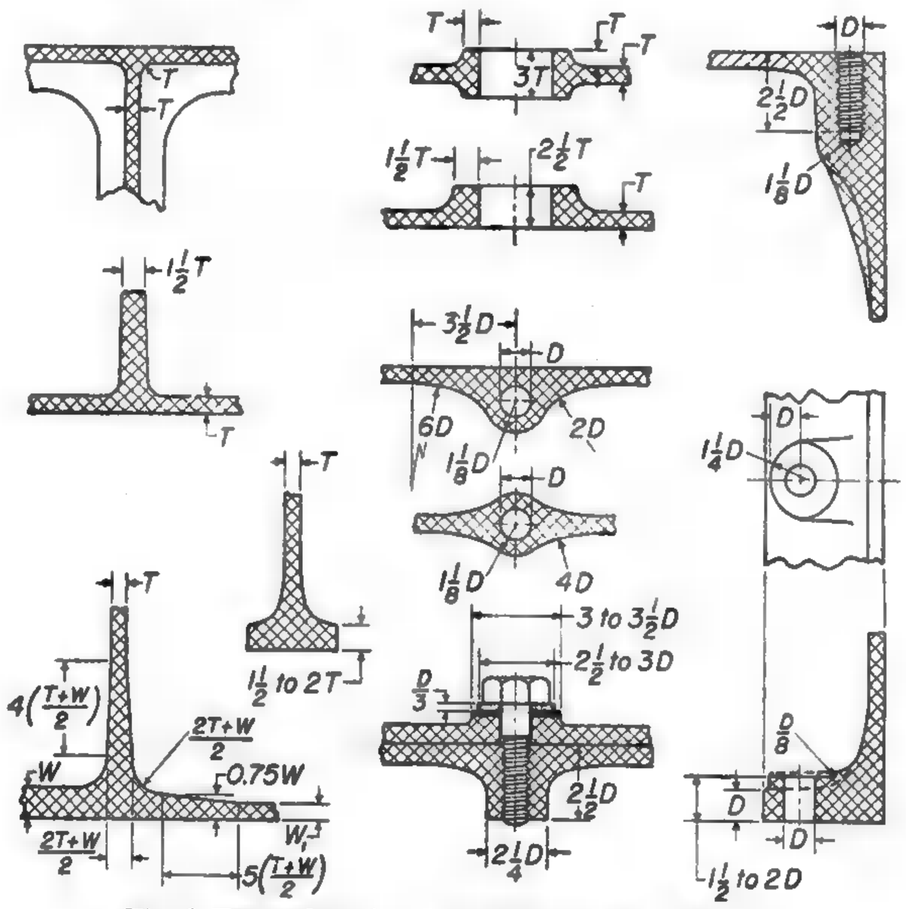


Fig. 2 Examples of recommended casting design

at the most highly stressed locations, and can sometimes recommend changes in design that will result in simplified production and lower cost.

As in all cast metals, magnesium parts designed for strength may fail prematurely as a result of stress concentrations caused by abrupt changes in section, small radii and fillets, and similar factors. In magnesium design, larger radii and more gradual changes in section should be used than are common in designing for other metals. Examples of good magnesium casting design are illustrated in Fig. 2. Particular attention should be given to section changes in order to ensure that thin walls are gradually blended into heavy sections. Fillets should be ample but not excessive, since excess metal in such places might cause shrinkage cracks. Ribs should have broad flat tops rather than pointed or round ones, in order to reduce the intensity of the stress at these points, and should be blended into the supporting members. The low specific gravity of magnesium permits the use of additional metal for providing these features, with very little added weight. Pattern numbers, symbols recording heat treatment and such marks of identification should be placed on raised pads and located in relatively nonstressed areas.

Typical changes in the redesign of a crankcase bearing wall from cast iron to magnesium are shown in Fig. 3.

Limitations of section thickness for magnesium are approximately the same as for other nonferrous metals. The normal minimum wall thickness of a magnesium sand casting is 5/32 in., but thinner walls can be cast, provided they are relatively small in area and favorably located with respect to gates and risers. Low ribs may be cast as thin as 1/10 in. at the top but a 1/8-in. minimum is preferred. Wide variations in thickness of section are permissible in sand castings and permanent mold castings made of magnesium, but the thin sections must

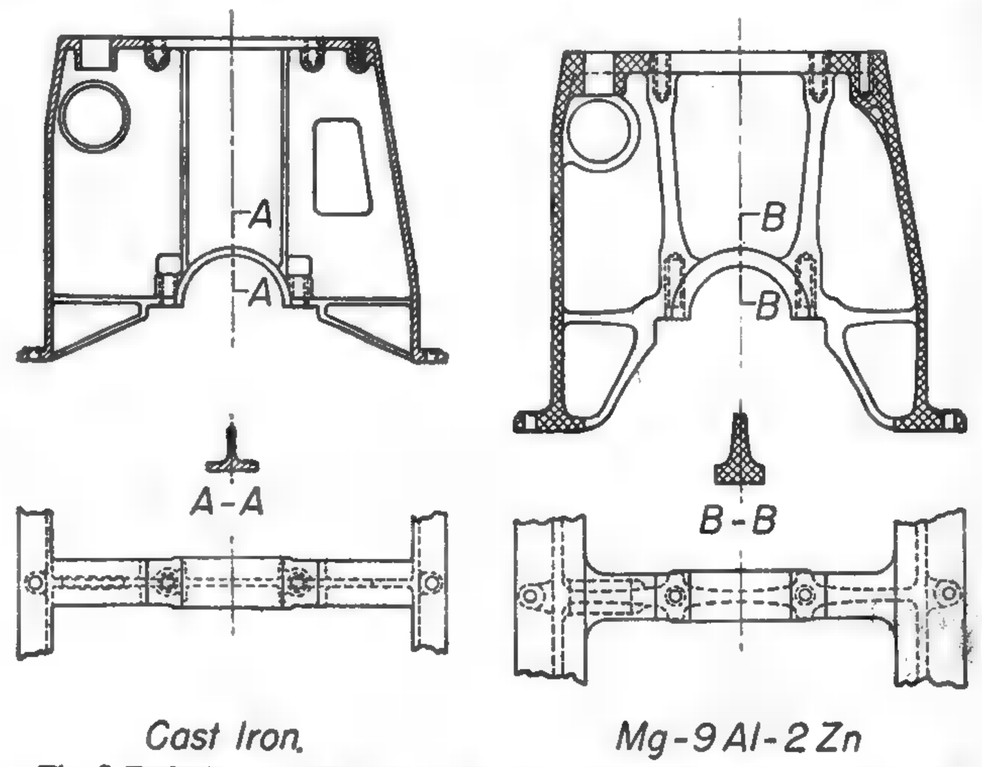


Fig. 3 Redesign of crankcase bearing wall from cast iron to a heat treated magnesium alloy of the AZ92 type. Rigidity and resistance to fatigue of the magnesium crankcase wall at least equal to that of the cast-iron wall.

be blended gradually into heavy walls. Heavy sections (more than 2 in.) may be cast in magnesium with good mechanical properties.

A nominal tolerance of plus or minus 1/32 in. is maintained on dimensions for sand castings—wall thickness, core shift and the like. Tolerances will vary with the casting; occasionally it is possible to hold tolerances to less than 1/32 in.

Magnesium castings made in permanent molds can be held to closer dimensional limits; walls and such can be held within plus or minus 1/64 in. Dimensions greater than 12 in. will have slightly larger tolerances.

The shrinkage of sand castings made of magnesium depends on the size and complexity of the part, number and location of cores and the presence of inserts. The normal unrestrained shrinkage of small magnesium castings is approximately 11/64 in. per ft. In large or complicated castings where shrinkage is restricted by cores, this value may decrease to between 1/10 and 1/8 in. per ft. Inserts will tend to reduce shrinkage further, to the extent that around large inserts no allowance for shrinkage is required.

In permanent mold castings the allowance must be determined on the basis of foundry experience, since shrinkage is greatly restricted by the metal molds.

In both sand mold and permanent mold castings, cores, holes and undercuts should be designed to facilitate production in the foundry. Sand cores should be large enough for easy handling, and projecting parts should be minimized, since they are easily broken. Cores for permanent mold casting should be relatively simple to facilitate removal, and undercuts should be avoided because they necessitate the use of collapsible cores, thus increasing the cost of casting. Sand cores may be used in metal molds (the semipermanent mold process) and they eliminate the necessity for collapsible or complex metal cores.

Inserts may be cast in place in magnesium castings, to provide bearing or wearing surfaces, to attach accessory parts, or to obtain details not otherwise possible, such as oil lines. The section on Inserts provides more detailed information.

Die Castings. Magnesium die castings offer many ad-

vantages, including strength and soundness, low cost in quantity production, reduction in machining, excellent surface finish, dimensional accuracy, and additional saving of weight because thinner sections can be cast. Size is limited by available equipment to approximately 10 lb in weight and to a maximum projected area of 250 sq in.

Magnesium alloy AZ91 is the most widely used die-casting alloy because it combines good mechanical properties, casting characteristics and resistance to corrosion. Magnesium die castings are supplied only in the as-cast condition. Just as with sand castings, the mechanical properties listed in the data sheets for die castings are obtained on separately cast specimens. The mechanical properties of test bars may deviate from actual section properties more than for sand castings. With good conditions of production and casting technique, die castings can be made for use in stressed parts where sand castings would normally be employed.

Generally, good sand-casting design is good die-casting design, using ample fillets, rounded corners, blended sections and similar factors. The use of heavy sections should be avoided in die castings, because such sections tend to be porous and to give areas of low strength. Strength may be secured in thin sections by the use of I-sections and ribbed construction. Section thicknesses within the range from 1/16 to 3/16 in. are preferred, since maximum mechanical properties are secured in that range. Walls as thin as 0.035 to 0.050 in. can be cast, provided the projected area of such thickness does not exceed 30 to 50 sq in. Dimensional tolerances for magnesium die castings are summarized in Table XII.

Table XII. Dimensional Tolerances and Design Limits for Magnesium Die Castings

Dimension	Tolerance[a]
Dimensional Tolerances	
Dimension within solid die block	± 0.0015 in. per linear in.
Minimum tolerance	± 0.0025 in.
Dimensions across and perpendicular to parting line	± 0.010 in. additional [b]
Dimension across and parallel to parting line	± 0.015 in. additional [b]
Dimensions affected by moving cores	± 0.015 in.
Flatness	Bow not to exceed 0.005 in. in any 1 in. or 0.015 in. in 8 in.
Trimming tolerance	To within 0.010 in. of edge
Finishing tolerance	1/32 in.
Design Limits	
Maximum depth of cored holes	3 times the diameter
Draft in cored holes	0.010 in. per in. depth per side
Draft on side walls	0.010 in. per in. depth
External screw threads	Can be cast if coarser than 24 threads per in.[c]
Engraved lettering	
Minimum size of letters	1/16 in.
Minimum face of letters	0.010 in.
Maximum depth of letters engraved in die	0.010 in.

(a) In special instances the tolerances can be reduced. When lower tolerances are required, the die caster should be consulted.
(b) This tolerance is to be added to the total tolerance allowed within solid dies.
(c) If located so as to make the casting of threads practical.

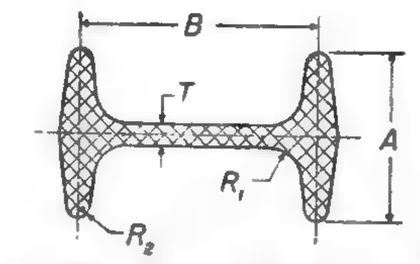
Proper allowance for draft must be made in the design of magnesium die castings so that high production can be maintained. Outside surfaces should have a minimum draft of 0.010 in. per in. of length to prevent galling, but this may be increased for improved surface finish. Allowances for draft of cored holes, side walls, and the like are given in Table XII. Undercuts should be used sparingly since they require loose pieces in the die and reduce rates of production.

External threads can be cast in magnesium die castings, provided they are 24 per in. or coarser and the axis is in the parting plane. If a free fit is permissible, cast threads can be used; otherwise 0.005 to 0.010 in. oversize on the diameter should be allowed for chasing.

Inserts can be used for wear on bearing loads in die castings the same as in sand castings.

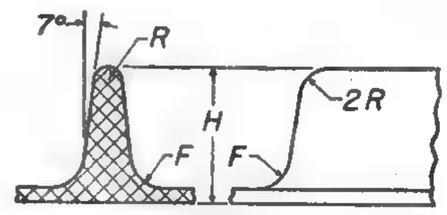
As in other types of casting, close co-operation should be maintained between design engineer and die caster, especially if thick sections or close tolerances are required; in addition, routine factors, such as location of ejector pins, should be discussed in order to produce the best possible casting at the lowest possible cost.

Forgings. Magnesium alloys can be forged readily to give high-strength forgings that have uniform properties, pressure tightness and good fatigue strength. Limitations concerning complexity of shape are the same as for other metals, and design should be as simple as possible to facilitate production.



A	B	R_1	T	R_2
1	1 to 1 1/2	1/4	1/8	1/16
1	1 1/2 to 2 1/2	3/8	5/32	1/16
2	1 1/2 to 2 1/2	7/16	3/16	3/32
2 1/2	2 1/2 to 4	5/8	7/32	1/8

Fig. 4



H	R	F
Up to 5/16	1/16	H
More than 5/16 to 1/2	1/16	3/4 H
More than 1/2 to 3/4	1/16	1/4 to 1/2 H (a)
More than 3/4 to 1 1/2	1/8	1/4 to 1/2 H (a)
More than 1 1/2 to 2	3/16	1/4 to 1/2 H (a)
More than 2 to 2 1/2	1/4	1/4 to 1/2 H (a)
More than 2 1/2 to 3	3/16	1/4 to 1/2 H (a)

(a) 1/4 H when metal is not confined; otherwise 1/2 H

Fig. 5

Fig. 4 Proportions of I-beam sections in magnesium forgings
Fig. 5 Proportions of ribs in magnesium forgings

The principal alloys used for magnesium forgings are AZ61X, AZ80X and TA54. AZ80X has the highest strength of the forging alloys, can be heat treated and aged for improved yield strength and endurance limit, and therefore is used for heavy-duty applications. The creep strength of AZ80X is greatly improved by heat treating and aging. AZ61X has somewhat lower strength but greater forgeability. These alloys can be forged on either hydraulic or mechanical presses. TA54 combines good mechanical properties and forging characteristics and can be forged on upsetters, hammers and rolls, as well as on hydraulic or mechanical presses. Directional properties exist in magnesium forgings, as in other forged metals, with highest properties obtained in the most thoroughly worked sections and in the direction of maximum metal flow.

Since magnesium forgings are generally used for highly stressed applications, good principles of design must be adhered to in order to eliminate stress concentrations. Sharp corners and notches should be avoided by the use

Table XIII
Dimensional Tolerances of Magnesium Forgings[a]

Dimension	Forging Size	Tolerance
Length and width (parallel to parting line)	2 in. or less	± 0.010 in.
	Each inch over 2 in.	± 0.003 in. additional
Thickness (across parting line)	1 lb or less	± 1/32 in.
	More than 1 lb to 5 lb	± 3/64 to 1/16 in.
	More than 5 lb	± 1/16 in.
Straightness	18 in. or less	
	More than 18 in. to 30 in.	± 3/64 in.
	More than 30 in. to 45 in.	± 1/16 in.
	More than 45 in. to 60 in.	± 3/32 in.
	More than 60 in. to 80 in.	± 1/8 in.
Shrinkage[b]	.....	± 0 to 0.002 in. per in.
Mismatch[b][c]	1.5 lb or less	0.015 in.
	More than 1.5 lb to 10 lb	0.024 in.
	More than 10 lb	0.032 in.
Punched holes	.....	± 1/16 in.
Fillet radii	Radii 1/4 in. or less	± 1/64 in.
	Radii more than 1/4 in.	± 1/32 in.
Draft	.....	± 1/2 degree
Trimming tolerance (flash)	.....	flush to 1/8 in. extending

(a) In special instances the tolerances can be reduced. When lower tolerances are required, the forger should be consulted.
(b) Shrinkage and mismatch tolerance should be used in conjunction with each other; not as the sum of two, but as the critical of the two.
(c) Mismatch is caused by a shift of the dies in relation to each other. When mismatch is applied to a dimension, it must be used as a plus or minus. When mismatch is applied as a variation in wall thickness of a circular or boxlike flange, the variation in thickness becomes double the mismatch allowance.

Table XIV. Characteristics of Magnesium Alloy Sheet

Alloy	Temper	Relative Properties[a] Tensile Strength	Tensile Yield Strength	Elongation	Compressive Yield Strength	Hardness	Ultimate Shear Strength	Fatigue Strength	Formability	Weldability	Resistance to Salt Water	Cost
AZ31X	Annealed	C	F	A	E	C	B	C	A	C	B	B
	Hard rolled	B	B	E	B	A	A	A	C	C	B	B
AZ51X	Annealed	B	E	C	E	B	C	B	B	B	A	D
	Hard rolled	A	A	F	A	A	B	A	D	B	A	D
M1	Annealed	D	G	B	F	D	D	E	A	A	C	A
	Hard rolled	C	C	G	C	C	D	D	C	A	C	A

Alloy	Temper	Remarks	Working Temperature Range, deg Fahr
AZ31X	Annealed	Best cold formability with limited gas and arc weldability.	400 to 500
	Hard rolled	Best combination of good fatigue and shear strength and toughness with low notch-sensitivity. Gas and arc weldability are limited.	275 to 300
AZ51X	Annealed	Used for parts requiring medium strength and limited formability, but which are to be arc welded.	550 to 650
	Hard rolled	Best combination of strength, hot formability and arc weldability.	400 max
M1	Annealed	Lowest cost, maximum gas weldability and hot formability, moderate strength.	550 to 650
	Hard rolled	Lowest cost, moderate-strength alloy with heat resistance to creep at elevated temperatures. AZ31X hard rolled is preferred from the standpoint of toughness and general serviceability.	400 max

(a) "A" Rating. Highest property value, best formability, weldability and resistance to salt water. Also lowest cost.

of generous radii and fillets. Fillets must be larger than normal to aid in filling the die and to avoid excessive die wear. Some details of forging design are shown in Fig. 4 and 5.

Dies designed for use on aluminum can often be used for magnesium with only a few changes. Large or complex forgings, however, require dies designed for magnesium. The dimensional tolerances for magnesium forgings are summarized in Table XIII.

Structural Assemblies. Magnesium alloys are well adapted for use in structures that can be fabricated from extrusions, sheet, castings and forgings. The light weight of magnesium alloys often permits the design of magnesium structures that are as stiff and strong as structures made of other metals—and with less weight. Other parts may be designed to have minimum weight-saving but greatly simplified construction and consequent lower cost. The low modulus of elasticity of magnesium alloys can usually be compensated for by increasing depths of section with minimum increase in weight.

Magnesium sheet is available in alloys AZ51X, AZ31X and M1, as hard rolled or annealed material. Sheet is available in a wide variety of sizes and gages. Table XIV summarizes the characteristics of magnesium sheet in regard to workability and weldability.

Magnesium sheet and plate can be readily formed and drawn; arc, gas and spot welded; riveted; and spun. Details concerning these operations are available in the preceding articles in this Handbook (pages 980 to 986).

Extrusions are available in magnesium alloys AZ61X, M1, AZ31X, and AZ80X, in the form of bars, rods, tubing and structural and special shapes. These alloys are furnished as extruded, except AZ80X, which can be heat treated and aged for improved mechanical properties. The characteristics of the extrusions are summarized in Table XV.

The extrusion process not only provides a wide variety of bars, rods, tubes and structural shapes as standard items, but also affords an economical way of producing special sections to meet specific requirements. Many intricate shapes that cannot be produced by other methods can be extruded, thereby simplifying problems of design. The extrusion of such shapes frequently eliminates the necessity of fabricating from standard shapes, thereby making possible more efficient structures at lower cost. Table XVI lists some of the dimensional limitations that apply to the extrusion of magnesium alloys.

Forming. The methods employed for forming magnesium alloys are similar to those used for other metals, except that magnesium alloys are usually formed at elevated temperatures, because of their tendency to work harden when formed at room temperature. Forming at

Table XV. Characteristics of Magnesium Alloy Extrusions[a]

Alloy	Tensile Strength	Tensile Yield Strength	Elongation	Compressive Yield Strength	Hardness	Fatigue Strength	Formability	Weldability	Resistance to Salt Water	Cost
AZ31X	D	D	A	D	D	C	A	B	A	B
AZ61X	C	C	B	C	C	B	B	C	A	C
M1	E	E	D	E	E	D	A	A	B	A
AZ80X	B	B	C	B	B	A	C	D	A	D
AZ80X HTA	A	A	E	A	A	A	D	D	A	E

Alloy	Remarks
AZ31X	Best elongation and cold formability
AZ61X	General-purpose extrusion alloy. Moderate cost and improved strength
M1	Moderate strength alloy with best weldability, hot formability, and lowest cost
AZ80X	Alloy with the highest strength in the extruded condition. Heat treatable
AZ80X HTA	Aged after extrusion to improve strength

(a) "A" Rating. Highest property value, best formability, weldability and resistance to salt water. Also lowest cost.

Table XVI. Dimensional Limitations for Extruded Magnesium Shapes

Over-all dimension, maximum	Approx 7 in.; up to 14.75 in., subject to approval of manufacturer Hollow shapes; approx 5 in.; tubing to 12 in.
Length, maximum	Depends on section; limit of 425 lb max total weight
Thickness, minimum	
Shapes M1, AZ31X	4% of width, min 0.040 in.
AZ61X, AZ80X	6% of width, min 0.060 in.
Hollow shapes, M1, AZ31X	Minimum of 0.060 in.
AZ61X, AZ80X	Minimum of 0.125 in., trial basis
Radii, minimum outside corner	$\frac{1}{16}$ in. recommended
minimum fillet	$\frac{1}{8}$ in. recommended
Blending light to heavy sections	Thin legs attached to thick body should not have length greater than 10 times their thickness

elevated temperatures eliminates the necessity for annealing and redrawing, and for having multiple-stage die equipment for deep-drawn parts. Forming may be done on mechanical and hydraulic presses, press brakes, drop hammers or by hand working.

Sheets of magnesium alloys AZ31X, AZ51X, and M1 are used for formed parts. In the annealed condition these alloys can be hot formed up to the following temperatures: AZ31X, 550 F; AZ51X, 600 F; and M1, 650 F. Heating to the temperature recommended for hot forming has almost no effect on the properties of annealed magnesium alloy sheet at room temperature.

Table XVII shows the approximate bend radii that can be formed in magnesium alloys at various temperatures. The values in the table are based on specimens 6 in. wide, formed in a press brake with a female die made of rubber. Wider sheets will require slightly larger radii than those given; slightly smaller radii can be used if bends are made with the grain instead of across it.

Table XVII
Radii for 90-Deg Bends in Magnesium Alloy Sheet[a]

Alloy	Condition	Minimum[b] Radii at 70 F	Typical Radii at Various Temperatures, deg Fahr 70	300	400	600
AZ31	Annealed	5t	4½t	....	1 to 2t	....
	Hard rolled ..	10t	8t	3 to 4½t	....	....
AZ51	Annealed	9t	7t	....	4 to 6t	2 to 3t
	Hard rolled ..	17t	13½t	....	4½ to 6½t	....
M1	Annealed	7t	5½t	....	3 to 4t	1 to 2t
	Hard rolled ..	12t	9t	....	6 to 7t	....

t = Thickness of sheet

(a) Radii formed in specimens 6 in. wide in square rubber retaining dies

(b) Minimum radius is that which can be formed safely in all sheet with almost no scrap.

Annealed magnesium sheet can be formed readily in the temperature range from 400 to 650 F. The drawability varies with the temper, working temperature and type of equipment used. Maximum drawability is obtained at higher working temperatures and slow working speeds. Reductions as great as 50% can be made in annealed sheet by production methods. Percentage reduction is calculated by the formula

$$R = \frac{D - d}{D} \times 100,$$

where D is the diameter of the blank and d the diameter of the punch. Single cold draws as great as 20% can be made in M1 and AZ31X sheet alloys in the annealed condition, but AZ51X can be reduced only 15% under similar conditions.

Hard rolled sheet can be formed moderately at temperatures from 300 to 400 F, depending on the alloy, but cannot be heated to temperatures for maximum drawability without losing the hard rolled properties. The section on Effect of Temperature discusses more completely the working temperatures for hard rolled sheet. The characteristics of the various sheet alloys and the recommended working temperatures for maximum drawability are indicated in Table XIV.

The tools used in forming magnesium are generally of the same type as those used for other metals. These tools are described in the article on forming magnesium, page 980 in this Handbook.

Joining. Most methods commonly used for joining metals can be used, with minor modifications, for magnesium. Magnesium alloys can be joined by riveting, by arc, gas and spot welding, or by screws and bolts.

Riveting. Riveting is the most widely used method of joining magnesium sheet and extrusions. In general the design of riveted joints follows standard practice.

Aluminum alloy rivets are used and although several rivet compositions are allowable, 56 S is preferred because the possibility of contact corrosion is minimized. Other aluminum rivets can be used where conditions of exposure are not severe. All rivets should be anodized or treated chemically.

Edge distance and minimum spacing, as well as rivet diameters, are governed by the requirements of each design, but certain general rules are established. Figure 6 shows the proportions that give a balanced design when 56 S rivets are used in magnesium sheet. If rough sheared edges are used, the edge distance should be increased by approximately 1/8 in.

Magnesium sheet approximately 0.050 in. thick or less may be readily dimpled for flush riveting, using heated dimpling tools. Sheet thicker than this is countersunk by machine. Countersunk-head rivets with any of the standard included-head angles may be used on machine-countersunk sheet.

Further details of procedure used in riveting magnesium alloys are given in the article entitled "Joining Magnesium Alloys", page 983.

The protection of faying or connecting surfaces of riveted joints is described on page 1005.

Screw Fastenings. Satisfactory joints and connections can be made in magnesium with bolts, screws or studs.

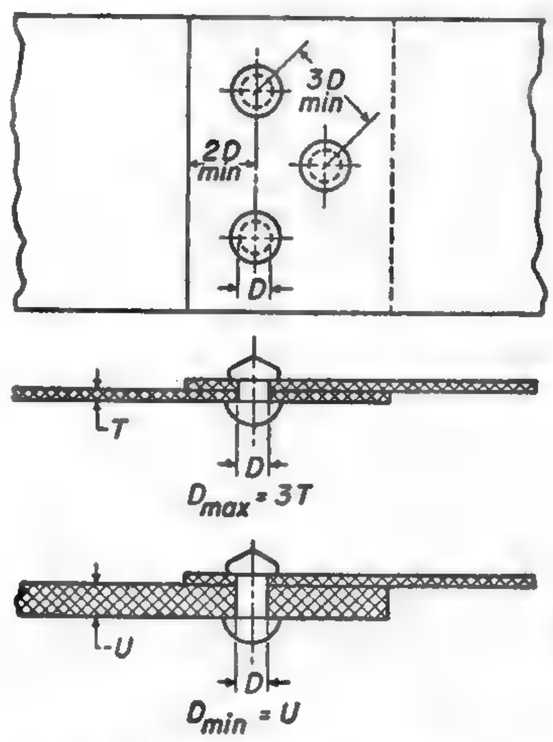


Fig. 6 Proportions of riveted joints in magnesium alloy sheet

In general, a thread length two or three times the diameter of the screw should be provided. When an increase in thread length is not feasible, the diameter of the bolt or stud may be increased or other special features may be utilized to secure adequate shear strength. American Standard coarse threads are preferred and, in addition, they require a smaller engagement. The American Standard fine threads are satisfactory under many conditions, but require the maximum amount of thread engagement. If used as recommended, magnesium threads will sustain a load approximately equal to that which can be held by standard steel bolts. Stress concentrations must be avoided; hence sufficient metal must be left around threaded holes, and a greater number of small screws should be used rather than a few large ones. Examples of properly designed threaded holes are shown in Fig. 2. The use of washers under bolts and nuts is recommended. For heavy service, washers should have an outside diameter two or three times the bolt diameter and a thickness approximately 1/3 the bolt diameter. SAE standard washers will function satisfactorily for moderate service conditions. If parts are to be disassembled frequently, inserts should protect the magnesium threads from wear.

Bolts, studs and washers should be made of anodized aluminum or zinc-plated or cadmium-plated steel. The use of brass or nickel alloys is not recommended because of the possibility of galvanic corrosion.

Arc Welding. Arc welding provides an efficient means of joining wrought magnesium alloys, such as sheet, extrusions and forgings. The molten metal is protected by an inert gas during welding; hence no flux is necessary and there is no danger of flux entrapment. Arc welding can produce welds of high strength at a high rate of production. Table XVIII gives the strengths and joint efficiencies for magnesium arc welds.

Any type of joint commonly used in the arc welding of steel may also be used with magnesium.

Table XVIII. Strength of Arc Welds in Magnesium Alloys

Alloy	Form	Tensile Strength, 1000 psi: Parent Metal	Tensile Strength, 1000 psi: Welded Joint	Average Efficiency of Joint
M1	Annealed sheet	33	20	60
M1	Hard rolled sheet	37	22	60
AZ31X	Annealed sheet	37	32	86
AZ31X	Hard rolled sheet	43	33	77
AZ51X	Annealed sheet	42	41	98
AZ51X	Hard rolled sheet	45	42	93
AZ31X	Extruded	40	34	85
AZ61X	Extruded	45	37	82
AZ80X	Extruded	49	35	71

Heat treatment of arc-welded magnesium structures is recommended in order to relieve the residual stresses set up during welding. The recommended temperatures and times for stress relieving are given in the article entitled "Joining Magnesium Alloys", page 983.

Gas Welding. Magnesium alloys may also be welded by a gas torch. Alloy M1 has superior weldability as compared with AZ31X and AZ51X. The strength of gas welds is somewhat lower than the strength of those made by the arc-welding process.

The molten weld metal must be protected by a suitable flux, which, because of its corrosive nature, must be removed after welding. Cleaning of welds is accomplished by immersing the assembly in hot water and scrubbing, then applying the chrome-pickle treatment, and finally boiling the assembly for 2 hr in a solution of sodium dichromate. Washing followed by immersion in a 1% solution of citric acid will also remove flux effectively. Welded joints must be designed so that they are accessible for the cleaning of the welded seam.

Gas-welded joints are as strong as good cast metal. Efficiencies of welds average 50 to 60% for M1 alloy and 75 to 90% for AZ31X.

Further details concerning welding will be found in the article entitled "Joining Magnesium Alloys", page 983.

Spot Welding. Magnesium alloys can be readily spot welded to produce joints satisfactory for moderately stressed applications.

All wrought magnesium alloys can be joined by this method, but because of limitations of power in welding equipment, 3/16-in. sheet is approximately the maximum thickness that can be spot welded with available equipment. Sections to be welded should be of approximately the same thickness, but if this is impossible, the thicker sheet should be no more than twice the thickness of the thin one. Additional information on the technique of spot welding is given in the article on "Joining Magnesium". Different magnesium alloys may be joined by spot welding, but the differences in electrical conductivity must be taken into consideration and the thicknesses of the sections must be proportioned accordingly. The best welds are secured, however, when alloys of the same composition are welded together.

When spot welds are loaded in direct tension, they should be subjected only to light loads. Shear strengths of spot welds in magnesium alloys are shown in Table XIX. The recommended spacing for spot welds is approximately 16 times the sheet thickness with a minimum of 8 times that thickness. The edge distance should be at least 4 times, preferably 6 times the sheet thickness. Spacing and edge distance should never be less than ¼ in.

After the assembly has been welded, it should be given an appropriate chemical treatment (*see* page 991).

Flash Welding. Wrought magnesium alloys can be flash welded to obtain joints of good strength. Joint efficiencies of approximately 90% have been obtained on alloys AZ31X and AZ61X. Equipment for the flash welding of magnesium is the same as that required for aluminum.

Soldering. Magnesium alloys can be soldered by using special solders developed for the purpose, but soldering is used only for filling surface imperfections.

Adhesive Bonding. Magnesium alloys can be joined by recently developed methods of adhesive bonding. The shear strengths developed depend on the adhesive used, but strengths of approximately 2500 psi can be attained.

Table XIX

Shear Strength of Spot Welds in Magnesium Alloys

Thickness of Single Sheet, inch	Strength, pounds per spot: Alloy M1a	Strength, pounds per spot: Alloy AZ51Xh
0.020	150	200
0.025	175	250
0.032	200	330
0.040	260	415
0.051	350	520
0.064	470	650
0.072	550	730
0.081	650	830
0.091	775	940
0.102	885	1050
0.114	1060	1175

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The Metallography of Magnesium and Magnesium Alloys

By A. M. Montgomery*

SPECIMENS for microscopic examination should be chosen with care so as to be representative. Thus, both longitudinal and transverse samples of sheet should be examined, edge and center sections of large ingots should be considered, the mouth of a casting crack should be studied as the point of origin, and so on. The specimen should be removed from its surroundings with the least possible rough handling, since cold work may alter the microstructure and complicate the subsequent examination. Usually a light band saw or hack saw is satisfactory for this purpose.

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Prepared for the Magnesium Committee

Polishing. Specimens that are too small to be held conveniently during polishing, or that have some edge characteristic to be studied, may be mounted in one of the common plastics—bakelite, lucite, tenite or the like. Wood-filled bakelite, especially if improperly cured, may cause some staining when the mounted sample is immersed in glycol etch. Clear amber bakelite produces mounts with an excellent bond. If plastic mounting equipment is not available, specimens can be mounted in sulfur. A sample is placed on a steel or glass plate inside a shallow metal ring, preferably of magnesium or aluminum, and molten sulfur is poured over the sample to fill the ring. The ring may be removed after the sulfur has solidified. Sheet samples approximately ¾ in. long by ½ in. wide may be bolted to-

gether to form packs, which can be polished satisfactorily.

The rough preparation of mounted or unmounted specimens consists of filing on a single-cut file of second-cut fineness. It is preferable to clamp the file in a vise and draw the sample over it by hand rather than to clamp the sample and file it. Clamping the sample tightly in a vise may induce cold work and lead to an erroneous interpretation. After being filed flat, the specimen is ground on a series of metallographic polishing papers. Good results are obtained by grinding successively on No. 120 abrasive cloth, No. 1 and No. 000 abrasive papers, all moistened with kerosene. The kerosene prevents clogging of the papers and serves as a coolant. It is preferable to grind the specimen by hand with the papers placed on a piece of plate glass, although some time may be saved by mounting the papers on a wheel that can be rotated at about 500 rpm. If the papers are mounted, care should be taken that the specimen does not become overheated during grinding, because this may affect the microstructure and may cause a plastic mount to retract from the metal insert. The specimen should be turned 90 deg in progressing from one paper to the next, and should be cleaned with a cloth saturated with kerosene or gasoline, so as to prevent coarse abrasive particles from being carried to fine papers.

The specimen is rough polished on a wheel that may be equipped with various cloths (Gamal, velvet, Vel-chamee, duvetyn or broadcloth). A tap-water suspension of 600 alundum powder (about 35 g in 500 ml) is employed as an abrasive. The specimen is slowly revolved counter to the direction of rotation of the wheel, which is rotating at a speed of approximately 500 rpm. This polishing should not be prolonged unnecessarily or marked relief of the manganese constituents will result. When the polishing is completed, mild soap is applied to the wet wheel. The specimen is then retouched on the soapy wheel for a few revolutions. This removes clinging alundum particles and leaves the polished surface bright and clean. The sample and the hands of the polisher should be carefully washed to prevent carrying abrasive to the final wheel.

The final polishing is done on a Vel-chamee or a silk velvet cloth with short pile which has been softened by boiling 30 min in distilled water acidulated with a few drops of hydrochloric acid. Merck's USP heavy grade of magnesium oxide is recommended as an abrasive. This can be used after sifting through a 100-mesh sieve. A small quantity is placed on the wheel and moistened with *distilled* water. This paste is then worked into the cloth. Polishing is begun at about 250 rpm by revolving the sample slowly counter to the direction of rotation of the wheel. The wheel speed is gradually decreased, the pressure on the sample is diminished and the paste is diluted with distilled water as the polishing progresses. Final polishing speed may be as low as 50 rpm. The abrasive should not be entirely washed away during polishing or the sample will stain. The sample is then immersed in hot, flowing distilled water for a moment and blown dry. When not in use, the final polishing cloth should be kept moist and covered to prevent the formation of hard magnesium carbonate particles and the collection of abrasive dust particles.

In all the grinding and polishing operations it is recommended that the time of grinding or polishing be twice as long as that necessary to remove the scratches from the preceding operation that are visible to the naked eye. This insures the removal of sufficient distorted material from the surface before the next operation.

Magnesium and magnesium alloys can be polished electrolytically by Jacquet's method to yield excellent surfaces free from flow. A solution consisting of 375 ml of orthophosphoric acid (H_3PO_4), density 1.71, and 625 ml of ethyl alcohol, 95% by volume, is used as an electrolyte. The magnesium specimen serves as the anode while 18-8 stainless steel or nickel sheet is the cathode. The surface of the sample is ground down as described for mechanical polishing, through at least the 000 abrasive paper. Further mechanical polishing decreases the duration of electrolytic polishing and the amount of relief obtained. Manganese particles, magnesium silicide, and massive Mg_4Al_3 eutectic particles are not appreciably dissolved during electrolysis. A closed-circuit voltage between cathode and anode of 1.5 volts is applied with a current density of 0.5 to 1.0 amp per sq dm. The duration of the electrolysis is from 3 min to 1 hr, depending on the extent of previous mechanical preparation. The sample should be removed from the solution while the current is on, washed immediately in running water and dried. It may be examined as polished or etched.

The preparation of large samples for macroscopic examination is best begun by machining a flat surface of the specimen on a lathe or shaper using a high speed, a fine feed and a sharp tool. The machining marks should be removed by rubbing on No. 1 metallographic paper moistened with kerosene. The specimen is then rotated 90 deg and rubbed on ■ 00 or 000 abrasive paper with kerosene to remove the previous scratches. If possible, it is desirable to continue the polishing operations outlined for microscopic test specimens, at least through the alundum wheel. If not, the macro samples can be polished chemically with good results. First, however, the kerosene should be removed from the sample with gasoline or other suitable solvent. The chemical polishing then consists of swabbing the ground surfaces for 30 to 60 sec with a solution of 15% nitric acid in denatured alcohol. This yields a clean, bright surface for macro-etching.

Etching. The chemical characteristics of magnesium preclude the use of strong mineral acids for etching, except in weak solutions. Organic acids in aqueous solutions, inorganic acids in organic solutions, aqueous salt solutions and combinations of these are used for etching. The etching solutions listed in Table I are recommended.

Table I. Etching Solutions for Microscopic Examination

Composition	Use	Procedure
1 ethylene or diethylene glycol 75 ml, distilled water 24 ml, concentrated nitric acid 1 ml	castings—any condition, all aged alloys, best general etch	Pour solution on sample, blow gently to disengage bubbles, wash in hot water and blow dry. Etch as-cast or aged specimens ■ to 10 sec. Etch solution heat treated specimens no longer than 2 min.
2 ethylene or diethylene glycol 60 ml, glacial acetic acid 20 ml, concentrated nitric acid 1 ml distilled water 19 ml	solution heat treated castings and certain wrought alloys	Pour solution on sample, blow gently to disengage bubbles. Etch for 5 to 30 sec, wash in hot water and blow dry.
3 tartaric acid 10 g, distilled water 90 ml	solution heat treated castings and certain wrought alloys	Swab for 5 to 30 sec, wash in hot water and blow dry.
4 concentrated nitric acid 2 ml, denatured alcohol 98 ml	general etch	Immerse 5 to 30 sec, wash in hot water and blow dry.
5 citric acid 10 g, distilled water 90 ml	solution heat treated castings and certain wrought alloys	Swab for 5 to 30 sec, wash in hot water and blow dry.
6 hydrofluoric acid (48%) 1 ml, distilled water 99 ml	used to distinguish between Mg-Al and Mg-Al-Zn constituents. Darkens Mg-Al	Immerse 20 to 30 sec, wash in hot water and blow dry.
7 glacial acetic acid 3 ml, 5% nickel nitrate Ni $(NO_8)_2$. 6 H_2O in water 5 ml, distilled water 92 ml	grain boundary etch for sheet alloys low in aluminum	Immerse 3 to 5 sec, wash in hot water and blow dry.
8 orthophosphoric acid (sp gr 1.70) 0.7 ml picric acid 4.0 g 95% ethanol 100 ml	to determine the amount of massive compound	Immerse face-up with gentle agitation until specimen darkens; wash in ethanol and dry.

Table II. Etching Solutions for Macroscopic Examination

Composition	Use	Procedure
1 glacial acetic acid 10 ml, distilled water 90 ml	grain size of pure magnesium	Swab for 10 sec to 2 min.
2 glacial acetic acid 10 ml, denatured alcohol 90 ml, picric acid 10 g	grain size of as-cast or heat treated castings	Flow etch on polished surface, etch 15 sec to 1 min after red color is obtained, wash off in hot water and blow dry
3 chromic acid (CrO_3) 12 g, concentrated nitric acid 15 ml, distilled water 85 ml	grain size of some solution heat treated and aged cast alloys that do not respond to solution No. 2	Immerse sample in etch, wash immediately in hot water and blow dry
4 same as 3 for high-aluminum alloys increase water to as much as 150 ml	grain flow of forging alloys	Immerse from 10 to 30 sec, wash immediately but carefully in hot water and blow dry. Do not wash etching products off the surface.
5 tartaric acid 10 g, distilled water 90 ml	grain flow of wrought alloys	Immerse 10 to 20 sec, wash in hot water, blow dry. Do not wash etching products off the surface.
6 concentrated nitric acid 15 ml, distilled water 85 ml	wrought Mg-Mn alloys	Etch 10 to 30 sec, wash in hot water and blow dry.
7 ammonium persulfate 10 g, distilled water 90 ml	Mg-Mn wrought alloy ingots	Etch until brown deposit forms; swab off until desired contrast is obtained.

The macro-etches are generally used to reveal the grain size in casting alloys and the grain flow in wrought products. In castings the presence of porosity, cracks, and entrapped oxide films may also be shown. The presence of a segregated constituent that contains aluminum is difficult to reveal unless the material has been aged. Recommended etching solutions for macroscopic examination are listed in Table II.

Interpretation of Microstructures. *Effect of Alloy Additions.* 1 Aluminum combines with magnesium in magnesium-base alloys to form a phase variously described as Mg_3Al_2, Mg_4Al_3, $Mg_{17}Al_{12}$, and β(Mg-Al). This phase forms a eutectic system with magnesium. Magnesium can retain as much as 12.7% Al in solid solution at the eutectic temperature. However, in commercial solid-solution alloys, some eutectic is usually present in the as-cast condition because of the coring effect. The eutectic does not exhibit the familiar lamellar structure, but is of the divorced type consisting of massive white particles of Mg_4Al_3 in a solid solution matrix. The Mg_4Al_3 particles of the eutectic occur chiefly along grain boundaries and to a lesser extent within the grains. Metallographic polishing causes the particles to stand in slight relief above the matrix. The phase Mg_4Al_3, precipitated from the solid solution by slow cooling from solidification or fabrication temperatures or by commercial precipitation treatment, appears in a lamellar arrangement similar to pearlite in steel. This precipitate forms first along grain boundaries and around undissolved intragranular particles. Precipitate formed at temperatures lower than commercial aging temperatures is considerably finer than the pearlitic precipitate, is globular and is more generally distributed throughout the grains. Precipitate formed at high temperatures is coarse and may assume an obvious crystallographic pattern.

Zinc in commercial magnesium alloys does not occur as a binary phase. Zinc is usually dissolved in the magnesium matrix and in the magnesium-aluminum phase in ternary alloys. Occasionally particles of the ternary phase $Mg_3Al_2Zn_3$ may be present and can be distinguished from Mg_4Al_3 by the 0.5% hydrofluoric acid etch.

3 Manganese in binary alloys occurs in solid solution or as hard gray angular particles of elemental manganese (probably containing some magnesium in solid solution). The particles stand out in pronounced relief and, unless properly polished, appear spheroidal. In magnesium-aluminum-manganese alloys, manganese also occurs as a manganese-aluminum phase. Bulian and Fahrenhorst[2] report that this phase appears as needles. However, such needle-like constituents are rare.

4 Tin is slightly soluble in magnesium. Beyond the limit of solubility, tin forms Mg_2Sn, which appears bluish gray as polished. Etching may produce a color, tan to deep blue, depending on the time of the reaction.

5 Calcium, usually present in very small quantities, is chiefly in solid solution. If present in amounts greater than approximately 0.1%, calcium occurs as Mg_2Ca. However, calcium in this amount combines first with the silicon to change the appearance of the Mg_2Si present. In magnesium-aluminum alloys, besides altering the shape of the Mg_2Si, calcium forms an irregular gray constituent closely associated with the Mg_4Al_3 phase.

6 Silicon is the major impurity in magnesium alloys. Silicon is only slightly soluble in solid magnesium and generally occurs as Mg_2Si, which is easily recognized by the distinctive blue color in the as-polished condition. It is angular in form and shows slight relief after polishing. In alloys containing approximately 0.5% Si or more, the particles form imperfectly, yielding a "Chinese script" structure.

General Microscopic Features. Magnesium alloys deform plastically by slip and twinning. As in other metals, slip lines are visible only when a polished surface is deformed or when a deformed specimen has been given a subsequent heat treatment to cause precipitation along the slip planes. Twins, on the other hand, are not destroyed by polishing and may be recognized by their lenticular shape after etching.

Shrinkage and gas porosity, both singly and combined, may form voids in magnesium castings. If the resulting voids are small and dendritic, they are termed "microporosity". Microporosity is chiefly intergranular but may be interdendritic. If the voids are distinctly spherical, it is an indication that the alloy contained excessive gas.

Eutectic melting or incipient fusion occurs if solution heat treatment is performed at a temperature higher than the eutectic temperature. This phenomenon may be detected microscopically by the formation, along the grain boundary, of angular deposits of eutectic material, varying from coarse single particles to extremely fine unresolved deposits, depending on the temperature and the duration of heating.

The absence of a protective atmosphere (usually 0.5% SO_2) during solution heat treatment causes an effect termed "high-temperature oxidation" or "burning". The eutectic deposits are attacked preferentially and the effect proceeds inward from the surface. This high-temperature oxidation is particularly rapid if eutectic melting is present simultaneously. Fusion voids unaccompanied by oxidation of the eutectic can also result from improper heat treatment of castings. High-temperature oxidation and fusion voids are recognizable under the microscope by small voids, chiefly intergranular, which are similar in appearance to microporosity, though microporosity is generally more irregular in outline.

Voids of doubtful origin in magnesium-aluminum alloys can be identified by a partial solution heat treatment, followed by a precipitation treatment to reveal the distribution of Mg_4Al_3 constituent. If no precipitate is formed in the immediate vicinity of the voids, the voids are definitely attributable to microporosity. However, the presence of precipitate in this location does not prove that the voids are caused by high-temperature oxidation.

Oxide films are occasionally found as thin, dark irregular lines in the microstructure of castings. Films formed in the crucible are usually thick and clustered and may contain entrapped manganese particles. Films are thin and extended when produced by the breaking of the oxide "tube" in pouring or by turbulence in filling the mold.

The grain size of magnesium alloys is most easily deter-

mined by the microscopic comparison of suitably etched metallographic specimens with micrographs of samples of known grain size. Grain size can also be determined by Heyn's intercept method or by Jeffries' planimetric method, in the order of increasing accuracy and time required. The results are expressed as the number of grains per unit area or as the average diameter in inches or millimeters. Occasionally samples may not reveal an obvious grain size because of the presence of confusing subgrain boundaries. Such specimens should be given a precipitation heat treatment and should then be examined microscopically under polarized light or with the sensitive tint attachment of some microscopes. The individual grains will have a distinct shade or color, depending on their orientation, and the size and number can be determined readily.

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PROPERTIES OF MAGNESIUM AND MAGNESIUM ALLOYS

Magnesium (99.80 Mg)

COMPILED BY R. A. TOWNSEND*

A *1 Common name.* Pure magnesium
2 Trade name. Mazlo AM2S
3 ASTM number. B 92-45
4 Government number. 46M10 (ingot), 57-21-1 (powder)

B *1 Typical uses.* Alloying agent, deoxidizer, getter in vacuum tube manufacture, dry electric current rectifiers, pyrotechnics
2 Precautions in use. Magnesium powder must be kept dry.

C *1 Density* at 20 C (68 F). 1.74 g per cu cm (0.0628 lb per cu in.)
5 Solidification shrinkage. 3.97 to 4.2%
6 Volume change during cooling from 650 C (solid) to minus 20 C. 2%

D *1 Melting point.* 650 C (1202 F)
4 Boiling point at 760 mm Hg. 1107 C (2025 F)
6 Thermal expansion[3] (polycrystalline) at 40 C (104 F). 0.000026 per °C*

$$L_t = L_0\ [1 + (24.80t + 0.00961t^2) \times 10^{-6}]$$

7 Thermal expansion along *a* axis, 15 to 35 C (59 to 95 F). 0.0000271 per °C
9 Thermal expansion along *c* axis, 15 to 35 C (59 to 95 F). 0.0000243 per °C
11 Specific heat at 25 C (78 F). 0.25 cal per g*
13 Latent heat of fusion. 89 cal per g*
15 Latent heat of vaporization. 1316 cal per g
16 Thermal conductivity at 18 C (64 F). 0.376 cal/sq cm/cm/°C/sec, approx
18 Heat of combustion. 5995 cal per g
19 Recrystallization temperature. 177 C (350 F) for one-hour anneal after 30% cold reduction (99.85% Mg), 93 C (200 F) for one-hour anneal after 30% cold reduction (99.99% Mg).

E *1 Volume conductivity* referred to standard copper. 38.6%
2 Electrical resistivity (polycrystalline) at 20 C (68 F). 4.46 microhm-cm
3 Electrical resistivity along *a* axis, at 18 C (64 F). 4.54 microhm-cm
Electrical resistivity along *c* axis, at 18 C (64 F). 3.77 microhm-cm
5 Temperature coefficient of electrical resistivity at 20 C (68 F). 0.01784 microhm-cm per °C
6 Temperature coefficient of electrical resistivity along a axis at 18 C (64 F). 0.01889 microhm-cm per °C; along *c* axis at 18 C (64 F), 0.01610 microhm-cm per °C

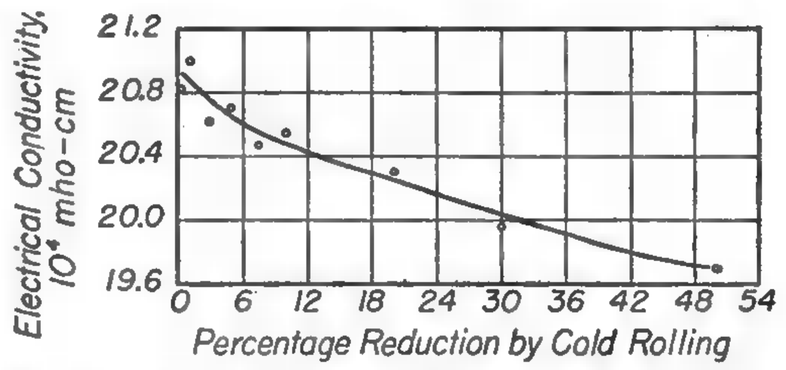

Fig. 1 Effect of cold rolling on the electrical conductivity of cell magnesium

8 Electrical conductivity versus plastic deformation. See Fig. 1.†
10 Electrochemical equivalent. 126 mg per coulomb
11 Electrolytic solution potential versus saturated calomel electrode. 1.63 volts.
Measured in aerated 3% NaCl solution against a saturated calomel electrode at room temperature (20 to 30 C). Surface aloxite ground. Measurements made after 24 hr.
14 Hydrogen overvoltage.[1] 0.30 volts for cast metal

F *1 Reflectivity.*[4] 72%, at $\lambda = 0.500\ \mu$; 74%, at $\lambda = 1.00\ \mu$; 80%, at $\lambda = 3.0\mu$; 93%, at $\lambda = 9.0\mu$

G *2 Magnetic susceptibility* (specific). 0.55×10^{-6} cgs
3 Magnetic permeability 1.000012 cgs

H *1 Velocity of sound.* 15,700 ft per sec

J *1 Crystal structure.* Close-packed hexagonal, $a = 3.2033$ kX; $c = 5.1998$ kX*†
2 Slip plane. Primary (0001) 20 to 225 C (68 to 437 F)*
Secondary $(10\bar{1}1)$ above 225 C (above 437 F)*
3 Twinning plane. $(10\bar{1}2)$*
4 Cleavage plane. (0001)*
5 Minimum interatomic distance. 3.190 kX

K *Mechanical properties.* See Table I.
4 Machinability index[5] (free-cutting brass = 100). 500*
8 Surface tension (liquid).[7]
at 681 C (1258 F). 563 ergs per sq cm
at 894 C (1641 F), 502 ergs per sq cm

* American Magnesium Corporation, Cleveland
* Indicates that values for all magnesium alloys are approximately the same.

† Unpublished data from Dow Chemical Company

Table I. Mechanical Properties of Pure Magnesium

Form	Section	Tensile Strength, psi	Yield Strength, (a) psi	Elongation, percentage	Rockwell Hardness, E scale	Brinell Hardness Number, (b)	Modulus of Elasticity, psi	Modulus of Rigidity, psi	Poisson's Ratio	Shear Strength, psi	Endurance Limit, (c) psi
Sand cast.....	½ in. diam	12,000	3,000	6	minus 16	30	6,500,000	2,400,000	0.35	.....	.....
Annealed	sheet	27,000	14,000	16	36	40	6,500,000	2,400,000	0.35	17,000	9,000
Hard rolled...	sheet	37,000	27,000	9	59	50	6,500,000	2,400,000	0.35	.....	.....

(a) 0.2% offset. (b) 500-kg load, 10-mm ball. (c) Based on 500,000,000 cycles of repeated flexure of a cantilever specimen.

L *2 Radiography.* Type A film with no intensifying screen, 140-kv machine operating at 36-in. focal distance.*

Section, in.	Kilovolts	Milliamperes	Time, min
0.25	50	6.0	1.0
0.50	50	10.0	1.0
0.75	60	10.0	1.0
1.00	70	10.0	1.0
1.25	80	8.7	1.0
1.50	90	7.6	1.0
1.75	100	6.7	1.0
2.00	110	6.0	1.0
2.25	120	5.6	1.0
2.50	130	5.0	1.0
2.75	140	4.65	1.0
3.00	140	5.0	1.1

M *Composition limits* (ASTM B 92-45 for ingot and stick).

Pure magnesium sheet, wire, extrusions, ribbon, and ingot and stick for remelting: 99.80% Mg min; *impurities (max),* 0.02% Cu, 0.001% Ni, 0.20% total of Al, Cu, Fe, Mn, Ni and Si. Powder, Grade C: 96% Mg min; *impurities (max),* metallic Fe 0.05%, insoluble residue 0.25%, Si 0.10%, grease and oil 0.020%, alloyed iron and aluminum as oxides 0.40%.

2 Consequence of exceeding impurity limits. Excessive nickel, copper and iron decrease resistance to corrosion.

N *2 Casting.* (ingot) 650 to 705 C (1200 to 1300 F)

6 Precautions in melting. Molten metal must be kept covered with flux. Crucibles having clay as a bond are attacked by molten magnesium; steel crucibles are not. Low-carbon, welded or cast crucibles are almost always used. Impurities may be picked up from nickel steel crucibles. Moisture should be avoided.

7 Hot working temperature range. 232 to above 482 C (450 to above 900 F)

9 Annealing temperature. 343 C (650 F)

10 Maximum reduction between anneals. 50 to 60%.

17 Joining.

Rivet composition. Aluminum alloy 56 S-H12

Oxyacetylene welding with pure magnesium welding rod, magnesium welding flux and neutral flame.

Resistance welding is satisfactory.

Helium-arc welding is preferred. Use pure magnesium welding rod and no flux.

* Indicates that values for all magnesium alloys are approximately the same.

References

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3 Hidnert and Sweeney, "Thermal Expansion of Magnesium and Some of Its Alloys", J Research Nat Bur Standards, 1, 771 (1928)

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5 Report of Independent Research Committee on Cutting Fluids, ASTE, Automotive Ind, 88, No. 8, 48 (1943)

6 R. S. Busk and R. F. Marande, "Some Properties of Sand Cast Alloys in the Magnesium Rich Corner of the Mg-Al-Zn System", Trans AIME, 166, 346 (1946)

7 V. G. Givov, Trudi Vses, Alumin Mag Inst, 14, 99 (1937)

8 Adolph Beck, "The Technology of Magnesium and Its Alloys", F. A. Hughes and Co., Ltd, London, 1943

9 "Designing with Magnesium", American Magnesium Corporation

10 "Dowmetal Data Book", The Dow Chemical Company

Mg – 4 Al – 0.2 Mn

COMPILED BY R. A. TOWNSEND*

A *2 Trade name.* Mazlo AM244

B *1 Typical uses.* Low-stressed sand castings that must be leakproof

C *1 Density* at 20 C (68 F). 1.76 g per cu cm (0.064 lb per cu in.)

D *1 Liquidus temperature.*[6] 630 C (1165 F)

2 Solidus temperature.[6] 563 C (1045 F)

3 Minimum "burning" (liquation) temperature.[8] 543 C (1010 F)

6 Thermal expansion[3] at 40 C (104 F). 0.000026 per °C*

11 Specific heat at 25 C (78 F). 0.25 cal per g approx*

13 Latent heat of fusion. 89 cal per g approx*

16 Thermal conductivity 100 to 300 C (212 to 572 F). 0.23 cal/sq cm/cm/°C/sec approx

E *1 Volume conductivity* referred to standard copper. 17.2% for cast metal

2 Electrical resistivity at 20 C (68 F). 10.0 microhm-cm for cast metal

11 Electrolytic solution potential versus saturated calomel electrode. 1.54 volts. Same test conditions as for pure magnesium.

14 Hydrogen overvoltage.[1] 0.04 for cast metal

K *Mechanical properties.* (Sand cast, ½-in. diam specimens): tensile strength 24,000 psi; yield strength 0.2% offset) 9000 psi; elongation 6%; Brinell hardness number 44; Rockwell hardness E 46; modulus of elasticity 6,500,000 psi; impact value, Charpy 2.0 ft-lb; shear strength 14,000 psi; Poisson's ratio 0.35; modulus of rigidity 2,400,000 psi; compressive yield strength 9000 psi.

4 Machinability index[5] (free-cutting brass=100). 500*

L *2 Radiography.* Refer to "Magnesium (99.80 Mg)".*

M *Composition limits.* Sand cast (A4): *components,* 3.5 to 5.0 Al; 0.20% min Mn; *impurities,* 0.3% max Zn; 0.3% max Si; 0.05% max Cu; 0.01% max Ni; others (total) 0.3% max.

2 Consequences of exceeding impurity limits. The resistance to corrosion decreases with increasing amounts of copper and nickel. Increased amounts of zinc affect the pressure tightness and the heat treatment. More than 0.50% Si decreases elongation.

N *1 Melting temperature.* 563 to 630 C (1045 to 1165 F)

2 Casting temperature range. (sand) 735 to 843 C (1350 to 1550 F) (ingot) 649 to 705 C (1200 to 1300 F)

3 Alloying. Add aluminum as Al or Al-Mn. Add manganese as 95 Al-5 Mn.

5 Type of flux. Magnesium melting flux.

6 Precautions in melting. Refer to corresponding section for pure magnesium.

17 Joining.

Oxyacetylene welding with AZ61X welding rod, magnesium welding flux, neutral flame.

Resistance welding is satisfactory.

Helium-arc welding is the preferred method. Use same welding rod as for torch welding. Use no flux.

References. *See* "Magnesium (99.80 Mg)".

* American Magnesium Corporation, Cleveland

* Approximately the same as for pure magnesium

Mg – 8 Al – 0.2 Mn

COMPILED BY R. A. TOWNSEND*

A *2 Trade name.* Mazlo AM241, Dowmetal A
3 ASTM number. A8, specification B 80-47T
6 Foreign equivalents. British DTD 59A; DTD 289; Elektron A8; German and Italian, Elektron A8K.
B *1 Typical uses.* Tough, leakproof sand castings
C *1 Density* at 20 C (68 F). 1.80 g per cu cm (0.065 lb per cu in.)
D *1 Liquidus temperature.*[4] 607 C (1125 F)
2 Solidus temperature.[4] 492 C (918 F)
3 Minimum "burning" (liquation) temperature.[4] 432 C (810 F)
6 Thermal expansion[3] at 40 C (104 F). 0.000026 per °C*
11 Specific heat at 25 C (78 F). 0.25 cal per g approx*
13 Latent heat of fusion. 89 cal per g approx*
16 Thermal conductivity 100 to 300 C (212 to 572 F). 0.18 cal/sq cm/cm/°C/sec approx
E *1 Volume conductivity* referred to standard copper. 11.5% approx (solution treated)
2 Electrical resistivity at 20 C (68 F). 15.0 microhm-cm (solution treated)
11 Electrolytic solution potential versus saturated calomel electrode. 1.65 volts. Same test conditions as for pure magnesium.
14 Hydrogen overvoltage.[1] 0.05 for cast metal
K *Mechanical properties.* See Tables I and II.

All forms.

Modulus of elasticity	6,500,000 psi
Modulus of rigidity	2,400,000 psi
Poisson's ratio	0.35

4 Machinability index[5] (free-cutting brass = 100). 500*
L *2 Radiography.* See this item for pure magnesium.*
M *Composition limits* (ASTM A8, B 80-47T for sand castings, B 93-47T for ingot). *See* Table III.
2 Consequences of exceeding impurity limits. The resistance to corrosion decreases with increasing amounts of copper and nickel. Increased amounts of zinc affect the pressure tightness and the heat treatment. More than 0.50% Si decreases elongation.
N *1 Melting temperature.* 492 to 607 C (918 to 1125 F)
2 Casting temperature range. (sand cast) 735 to 843 C (1350 to 1550 F); (ingot) 649 to 705 C (1200 to 1300 F)
3 Alloying. Add aluminum as Al or Al-Mn. Add manganese as 95 Al – 5 Mn.
5 Type of flux. Magnesium melting flux
6 Precautions in melting. See "Magnesium (99.80 Mg)".
15 Heat treatment.

Purpose	Temperature, °C	Temperature, °F	Time, hr	Cooling
Solution treatment	427	800	14	strong air blast
Aging	204	400	16	still air

NOTE. For solution treatment, Alloy A8 requires an atmosphere at least 0.5% SO_2. Aging in air is satisfactory.

17 Joining.
Oxyacetylene welding with AZ101 welding rod, magnesium welding flux, neutral flame.
Resistance welding is satisfactory.
Helium-arc welding is the preferred method. Use same welding rod as for torch welding. Use no flux.
References. *See* "Magnesium (99.80 Mg)".

* American Magnesium Corporation, Cleveland
* Approximately the same as for pure magnesium

Table I. Strength and Elongation of Alloy A8 at Elevated Temperatures[a]

Testing Temperature, deg Cent	Testing Temperature, deg Fahr	Tensile Strength, psi	Yield Strength, psi	Elongation, percentage
	Sand Cast HT			
149	300	21,000	10,000	16
204	400	14,000	8,000	22
260	500	9,500	5,000	40

(a) After prolonged heating at testing temperatures.

Table II. Mechanical Properties of Alloy A8 at Room Temperature

Condition (½-in. diam)	Tensile Strength, psi	Yield Strength,[a] psi	Elongation, percentage	Brinell Hardness Number[b]	Rockwell Hardness	Impact Value, Charpy ft-lb	Shear Strength, psi	Endurance Limit,[c] psi	Compressive Yield Strength,[a] psi
SC	29,000	14,000	6	46	E 51	0.9	.....	6000	14,000
SC HT	39,000	12,000	14	48	E 55	2.2	18,000	8000	12,000
SC HTA	39,000	15,000	9	..	....	...	.....	....	15,000

(a) 0.2% offset. (b) 500-kg load, 10-mm ball. (c) 500,000,000 cycles, R. R. Moore type rotating-beam machine.

Table III. Composition Limits of Alloy A8

Form	Designation	Components: Al min	Components: Al max	Components: Mn min	Components: Mn max	Impurities: Zn max	Impurities: Si max	Impurities: Cu max	Impurities: Ni max	Impurities: Others (total) max
Sand cast	A8	7.8	9.2	0.15	....	0.3	0.3	0.10	0.01	0.3
Ingot	A8	8.0	9.0	0.18	....	0.2	0.2	0.08	0.01	0.3

Mg – 10 Al – 0.1 Mn

COMPILED BY R. A. TOWNSEND*

A *2 Trade name.* Mazlo AM240 (cast), Dowmetal G (cast), Mazlo AM-C59 S (wrought)
3 ASTM number. Alloy A10, specifications B 80-47T (sand cast) and B 199-47T (permanent mold)
4 Government number. 11348 (permanent mold)
5 Other designations. SAE 502 (permanent mold)
6 Foreign equivalents. British DTD 259 (wrought), German and Italian Elektron VI (wrought), French Soc Gen du Magnesium F5 (wrought)
B *1 Typical uses.* Pressure-tight sand and permanent mold castings with good combination of tensile strength, yield strength and elongation; also used in the form of high-strength extruded bars, rods, shapes and structural sections.
C *1 Density* at 20 C (68 F). 1.81 g per cu cm (0.066 lb per cu in.)

* American Magnesium Corporation, Cleveland

D *1 Liquidus temperature.*[6] 594 C (1101 F)
2 Solidus temperature.[6] 464 C (867 F)
3 Minimum "burning" (liquation) temperature.[6] 432 C (810 F)
6 Thermal expansion[3] at 40 C (104 F). 0.000026 per °C approx*
11 Specific heat at 25 C (78 F). 0.25 cal per g approx*
13 Latent heat of fusion. 89 cal per g approx*
16 Thermal conductivity 100 to 300 C (212 to 572 F). 0.17 cal/sq cm/cm/°C/sec, approx
E *1 Volume conductivity* referred to standard copper. (approximate values) as cast 11.5%; solution treated 9.9%; solution treated and aged 12.3%; wrought 9.7%.
2 Electrical resistivity at 20 C (68 F). (approximate values) as cast 15.0 microhm-cm; cast and solution treated 17.5 microhm-cm; cast, solution treated and aged 14.0 microhm-cm; wrought 18.0 microhm-cm.
11 Electrolytic solution potential versus saturated calomel electrode. 1.57 volts for cast metal. Same test conditions as for pure magnesium.
14 Hydrogen overvoltage. 0.27 for extruded metal; 0.06 for cast metal.
K *Mechanical properties.* See Tables I and II.

All forms. Modulus of elasticity 6,500,000 psi
Modulus of rigidity 2,400,000 psi
Poisson's ratio 0.35

Perm mold or SC HT. Bearing ultimate strength (3/16 in. pin diam) 69,000 psi
Bearing yield strength (3/16 in. pin diam) 45,000 psi

Perm mold or SC HTA. Bearing ultimate strength (3/16 in. pin diam) 81,000 psi
Bearing yield strength (3/16 in. pin diam) 68,000 psi

4 Machinability index[5] (free-cutting brass = 100). 500*
L *2 Radiography.* Refer to "Magnesium (99.80 Mg)".*
M *Composition limits.* (ASTM B 80-47T for sand castings, ASTM B 199-47T for permanent mold castings, American Magnesium Corporation AM-C59 S for extrusions, ASTM B 93-47T for ingot). *See* Table III.
2 Consequences of exceeding impurity limits. The resistance to corrosion decreases with increasing amounts of copper, nickel and iron. Increased amounts of zinc affect the pressure tightness and the heat treatment. More than 0.50% Si decreases elongation.
N *1 Melting temperature.* 464 to 594 C (867 to 1101 F)
2 Casting temperature range.
(sand) 735 to 843 C (1350 to 1550 F)
(chill) 649 to 816 C (1200 to 1500 F)
(ingot) 649 to 705 C (1200 to 1300 F)
3 Alloying. Add aluminum as Al or Al-Mn. Add manganese as 95 Al-5 Mn.
6 Precautions in melting. Refer to corresponding section for pure magnesium.
7 Hot working temperature. 232 to 399 C (450 to 750 F)
8 Shortness range. Above 432 C (above 810 F) (wrought)
9 Annealing temperature. 343 C (650 F) (wrought)
15 Heat treatment (castings).

Purpose	Temperature °C	Temperature °F	Time, hr	Cooling
Solution treatment	421	790	20	strong air blast
Artificial aging (partial)	163	325	12	still air
Artificial aging (complete)	177	350	20	still air or oven
Stabilizing[a]	260	500	4	still air

(a) The stabilizing heat treatment is used on castings in the as-cast or solution heat treated conditions to minimize growth when the castings are used at elevated temperatures.

NOTE. For solution treatment. Alloy A10 requires an atmosphere at least 0.5% SO_2. For other heat treatments air is satisfactory.

17 Joining.
Rivet compositions. Aluminum alloy 56 S-H12 for extrusions
Oxyacetylene welding with AZ101 for extrusions, magnesium welding flux, neutral flame.
Helium-arc welding is suitable for extrusions. Use same welding rod as for torch welding. Use no flux.

References. *See* "Magnesium (99.80 Mg)".

* Approximately the same as for pure magnesium

Table I. Mechanical Properties of Alloy A10 at Room Temperature

Condition (½-in. diam)	Tensile Strength, psi	Yield Strength, (a) psi	Elongation, percentage	Compressive Yield Strength,[a] psi	Brinell Hardness Number, (b)	Rockwell Hardness	Impact Value, Charpy ft-lb	Shear Strength, psi	Endurance Limit, (c) psi
Sand cast	22,000	12,000	2	12,000	53	E 64	0.6	18,000	10,000
Perm mold cast	22,000	12,000	2	12,000	53	E 64	0.6	18,000	10,000
Perm mold or SC HT	40,000	13,000	10	13,000	52	E 62	2.0	20,000	11,000
Perm mold or SC HTA	40,000	19,000	1	19,000	69	E 80	0.7	22,000	10,000
Perm mold or SC S	22,000	16,000	2	16,000	58	E 70	...	.....	.....
Perm mold or SC HTS	38,000	18,000	1	18,000	67	E 78	...	.....	.....
Extruded bar	51,000	38,000	9	27,000	70	E 81	1.6	23,000	18,000

(a) 0.2% offset. (b) 500-kg load, 10-mm ball. (c) Based on 500,000,000 cycles, R. R. Moore type rotating-beam machine.

Table II. Mechanical Properties of Alloy A10 at Elevated Temperatures and Subzero Temperatures

Properties of quenched and aged material at elevated temperatures were determined after prolonged heating at testing temperatures.

Condition	Testing Temperature, deg Cent	Testing Temperature, deg Fahr	Tensile Strength, psi	Yield Strength, psi	Elongation, percentage	Brinell Hardness Number	Rockwell Hardness	Impact Value, Charpy ft-lb
SC	−78	−108	22,000	18,000	1	63	E 75	0.8
SC HT	−78	−108	38,000	18,000	7	60	E 73	2.5
SC HT	93	200	34,000	.....	1.5	..	..	..
SC HT	149	300	23,000	.....	9	..	..	..
SC HT	260	500	12,000	.....	22	..	..	..
SC HTA	−78	−108	39,000	26,000	2	85	E 90	0.8
SC HTA	149	300	24,000	9,000	4	..	..	..
SC HTA	204	400	17,000	6,500	25	..	..	..
SC HTA	260	500	12,000	4,000	45	..	..	..
SC HTA	316	600	8,500	2,500	60	..	..	..
SC HTA	371	700	5,500	1,500	100	..	..	..

Table III. Composition Limits of Alloy A10

Form and Designation	Components: Al min	Components: Al max	Components: Mn Min	Components: Mn Max	Impurities: Zn max	Impurities: Si max	Impurities: Cu max	Impurities: Ni max	Impurities: Fe max	Impurities: Others (total) max
Sand cast A10	9.0	11.0	0.10	....	0.3	0.3	0.10	0.01	.....	0.3
Perm mold cast A10	9.3	10.7	0.10	....	0.3	0.3	0.10	0.01	.....	0.3
Extrusions A10X	9.5	10.5	0.10	....	0.3	0.3	0.05	0.005	0.005	0.3
Ingot A10	9.4	10.6	0.13	....	....	0.2	0.08	0.01	.....	0.3

Mg – 6 Al – 3 Zn – 0.2 Mn

COMPILED BY H. W. SCHMIDT*

A *2 Trade name.* Dowmetal H, Mazlo AM265
3 ASTM number. Alloy AZ63, specification B 80-47T
4 Government number. AN-M-36, grade A; Army 57-74-1
5 Other designations. SAE 50, AMS 4420, AMS 4422, AMS 4424
6 Foreign equivalents. Elektron AZG, British DTD 59A (as cast), DTD 289 (HT)

B *1 Typical uses.* General sand-casting alloy having good strength properties with best ductility and toughness.

C *1 Density* at 20 C (68 F). 1.84 g per cu cm (0.066 lb per cu in.)

D *1 Liquidus temperature.*[6] 610 C (1130 F)
2 Solidus temperature.[6] 455 C (850 F)
3 Minimum "burning" (liquation) temperature.[6] 363 C (685 F)
6 Thermal expansion[6] 20 to 100 C (68 to 212 F) 0.000026 per °C*

$$L_t = L_0 [1 + (24.80t + 0.0961t^2) \times 10^{-6}]$$

11 Specific heat at 25 C (78 F). 0.25 cal per g approx*
13 Latent heat of fusion. 89 cal per g approx*
16 Thermal conductivity 100 to 300 C (212 to 572 F). 0.18 cal/sq cm/cm/°C/sec

E *1 Volume conductivity* referred to standard copper. As cast 15.0%; heat treated 12.3%; heat treated and aged 13.8%
2 Electrical resistivity at 20 C (68 F). As cast 11.5 microhm-cm; heat treated 14.0 microhm-cm; heat treated and aged 12.5 microhm-cm.
11 Electrolytic solution potential versus saturated calomel electrode. 1.57 volts. Same test conditions as for pure magnesium.
14 Hydrogen overvoltage.[1] 0.34 for cast metal

* Dow Chemical Company, Midland, Mich.
* Approximately the same as for pure magnesium

K *Mechanical properties.* See Tables I and II.
All forms. Modulus of elasticity 6,500,000 psi
Modulus of rigidity 2,400,000 psi
Poisson's ratio 0.35
4 Machinability index[5] (free-cutting brass = 100). 500*

L *2 Radiography.* Refer to "Magnesium (99.80 Mg)".*

M *Composition limits* (ASTM B 80-47T)
Sand castings and welding wire (both AZ63): *components,* 5.3 to 6.7% Al, 2.5 to 3.5% Zn, 0.15% Mn min; *impurities (max),* 0.3% Si, 0.25% Cu, 0.01% Ni, 0.3% total others. Ingot: *components,* 5.5 to 6.5% Al, 2.7 to 3.3% Zn, 0.18% Mn min; *impurities (max),* 0.2% Si, 0.20% Cu, 0.01% Ni, 0.3% total others.
2 Consequences of exceeding impurity limits. Silicon causes brittleness. Excessive copper affects mechanical properties and resistance to corrosion. Nickel affects resistance to corrosion.

N *1 Melting temperature.* 454 to 613 C (850 to 1135 F)
2 Casting temperature range.
(sand) 734 to 842 C (1350 to 1550 F)
(chill) 648 to 815 C (1200 to 1500 F)
(ingot) 648 to 704 C (1200 to 1300 F)
3 Alloying. Add aluminum as Al or Al-Mn. Add zinc as Zn. Add manganese as 95 Al-5 Mn.
5 Type of flux. Magnesium melting flux
6 Precautions in melting. See "Magnesium (99.80 Mg)".

O *15 Heat treatment.*

Purpose	Temperature, °C	Temperature, °F	Time, hr	Cooling
Solution heat treatment	388	730	10	air
Aging	191	375	18	air or furnace
Stabilizing[a]	260	500	4	air

(a) The stabilizing heat treatment is used on castings in the as-cast or solution heat treated conditions to minimize growth when the castings are used at elevated temperatures.

NOTE. For solution heat treatment, Alloy AZ63 requires an atmosphere at least 0.5% SO_2. For other heat treatments air is satisfactory.

References. *See* "Magnesium (99.80 Mg)".

Table I. Mechanical Properties of Alloy AZ63 at Room Temperature

Condition (½-in. diam)	Tensile Strength, psi	Yield Strength, psi	Elongation, percentage	Brinell Hardness Number [a]	Rockwell Hardness	Impact Value, Izod ft-lb	Shear Strength, psi	Endurance Limit, [b]	Compression Strength, psi	Compression Yield Strength, psi	Bearing Ultimate Strength, psi	Bearing Yield Strength, psi
SC	29,000	14,000	6	50	E 59	3	18,000	11,000	45,000	14,000	.....	.....
SC HT	40,000	14,000	12	55	■ 66	5	19,000	14,000	46,000	14,000	.....	.....
SC HTA	40,000	19,000	5	73	E 83	2	20,000	13,000	50,000	19,000	.....	.....
SC S	29,000	14,000	5	..	E ..	..	19,000	11,000	.....	14,000	66,000	45,000
SC HTS	40,000	17,000	7	59	E 71	..	20,000	13,000	.....	17,000	70,000	47,000

(a) 500 kg-load, 10-mm ball. (b) 500,000,000 cycles.

Table II. Strength and Elongation of Alloy AZ63 at Elevated Temperatures (Short-Time Tests)

Condition	Testing Temperature, deg Cent	Testing Temperature, deg Fahr	Tensile Strength, psi	Yield Strength, psi	Elongation, percentage
As cast	24	75	28,600	13,700	4.5
	66	150	30,500	.....	3.0
	93	200	30,100	.....	4.5
	121	250	27,700	.....	7.5
	149	300	24,100	.....	20.5
	204	400	15,300	.....	50.0
	260	500	10,300	.....	38.0
Heat treated	24	75	36,800	13,600	10.0
	66	150	36,700	.....	9.0
	93	200	34,300	.....	7.0
	121	250	30,000	.....	9.0
	149	300	22,400	.....	33.2
	204	400	14,600	.....	38.0
	260	500	10,900	.....	26.0
Heat treated and aged	35	95	38,700	17,700	5.5
	93	200	36,000	17,300	11.0
	121	250	32,400	16,500	11.0
	149	300	24,500	15,000	15.0
	204	400	17,500	12,000	17.0
	260	500	12,000	8,800	15.0
	316	600	8,200	5,600	20.0

Mg–9 Al–2 Zn–0.1 Mn

COMPILED BY R. A. TOWNSEND*

A *2 Trade name.* Mazlo AM260, Dowmetal C
3 ASTM number. Alloy AZ92, specifications B 80-47T and B 199-47T
4 Government number. AN-M-36, alloy C; 57-74-2; 11349.
5 Other designations. AMS 4430, AMS 4434, AMS 4484, SAE 500, SAE 503

B *1 Typical uses.* Pressure-tight sand and permanent mold castings with high tensile strength and good yield strength

C *1 Density* at 20 C (68 F). 1.82 g per cu cm (0.066 lb per cu in.)

D *1 Liquidus temperature.*[6] 593 C (1100 F)
2 Solidus temperature.[6] 443 C (830 F)
3 Minimum "burning" (liquation) temperature.[6] 410 C (770 F)
6 Thermal expansion[3] at 40 C (104 F). 0.000026 per °C*
11 Specific heat at 25 C (78 F). 0.25 cal per g approx*
13 Latent heat of fusion. 89 cal per g approx*
16 Thermal conductivity 100 to 300 C (212 to 572 F). 0.17 cal/sq cm/cm/°C/sec approx

E *1 Volume conductivity* referred to standard copper. (approximate values) As cast 12.3%; solution treated 10.5%; solution treated and aged 12.3%.
2 Electrical resistivity at 20 C (68 F). As cast 14.0 microhm-cm; solution treated 16.5 microhm-cm; solution treated and aged 14.0 microhm-cm.
11 Electrolytic solution potential versus saturated calomel electrode. 1.56 volts. Same test conditions as for pure magnesium.
14 Hydrogen overvoltage.[1] 0.30 for cast metal

* American Magnesium Corporation, Cleveland
* Approximately the same as for pure magnesium

K *Mechanical properties.* See Tables I and II.
All forms. Modulus of elasticity 6,500,000 psi; Modulus of rigidity 2,400,000 psi; Poisson's ratio 0.35
4 Machinability index[5] (free-cutting brass = 100). 500*

L *2 Radiography.* Refer to "Magnesium (99.80 Mg)".*

M *Composition limits* (ASTM AZ92, B 80-47T for sand castings, B 199-47T for permanent mold castings, B 93-47T for ingot). *See* Table III.
2 Consequences of exceeding impurity limits. The resistance to corrosion decreases with increasing amounts of copper and nickel. More than 0.50% Si decreases the elongation.

N *1 Melting temperature.* 443 to 593 C (830 to 1100 F)
2 Casting temperature range. (sand) 735 to 843 C (1350 to 1550 F) (chill) 649 to 816 C (1200 to 1500 F) (ingot) 649 to 705 C (1200 to 1300 F)
3 Alloying. Add aluminum as Al or Al-Mn. Add zinc as Zn. Add manganese as 95 Al–5 Mn.
5 Type of flux. Magnesium melting flux.
6 Precautions in melting. See "Magnesium (99.80 Mg)".
15 Heat treatment.

Purpose	Temperature, °C	Temperature, °F	Time, hr	Cooling
Solution treatment	405	760	20	strong air blast
Artificial aging	215	420	14	air or oven
Stabilizing[a]	260	500	4	air

(a) The stabilizing heat treatment is used on castings in the as-cast or solution heat treated conditions to minimize growth when the castings are used at elevated temperatures.

NOTE. For solution treatment, Alloy AZ92 requires an atmosphere at least 0.5% SO_2. For other heat treatments air is satisfactory.

17 Joining. Resistance welding is satisfactory.

References. *See* "Magnesium (99.80 Mg)".

Table I. Mechanical Properties of Alloy AZ92 at Room Temperature

Condition (½-in. diam)	Tensile Strength, psi	Yield Strength, (a) psi	Elongation, percentage	Brinell Hardness Number (b)	Rockwell Hardness	Impact Value, Charpy ft-lb	Endurance Limit, (c) psi	Shear Strength, psi	Compressive Yield Strength, (a) psi	Bearing Ultimate Strength, (d) psi	Bearing Yield Strength, (d) psi
Sand cast	25,000	14,000	2	65	E 76	0.5	12,000	18,000	14,000	.....	.....
Perm mold cast	25,000	14,000	2	65	E 76	0.5	12,000	18,000	14,000	.....	.....
Per mold or SC HT	40,000	14,000	10	63	E 75	2.0	13,000	20,000	14,000	.....	.....
Perm mold or SC HTA	40,000	22,000	3	81	E 88	0.8	12,000	22,000	22,000	.....	.....
Perm mold or SC S	25,000	17,000	1	69	E 80	...	11,000	19,000	17,000	57,000	52,000
Perm mold or SC HTS	40,000	21,000	3	78	E 88	...	13,000	21,000	21,000	78,000	63,000

(a) 0.2% offset. (b) 500-kg load, 10-mm ball. (c) 500,000,000 cycles, R. R. Moore type rotating-beam machine. (d) $\frac{3}{16}$-in. pin diam.

Table II. Strength and Elongation of Alloy AZ92 at Elevated Temperatures

After prolonged heating at testing temperatures

Form and Condition	Testing Temperature, deg Cent	Testing Temperature, deg Fahr	Tensile Strength, psi	Elongation, percentage	Days at Temperature Prior to Testing
Sand cast	93	200	25,000	2	80
Sand cast	149	300	22,000	3	160
Sand cast	204	400	16,000	36	160
Sand cast	260	500	12,000	34	40
SC HT	93	200	40,000	8	160
SC HT	149	300	26,000	40	160
SC HT	204	400	17,000	41	160
SC HT	260	500	11,000	52	40
SC HTA	93	200	38,000	7	160
SC HTA	149	300	25,000	40	160
SC HTA	204	400	17,000	43	160
SC HTA	260	500	12,000	47	40

Table III. Composition Limits of Alloy AZ92

Form		Components: Al min	Al max	Mn min	Mn max	Zn min	Zn max	Impurities: Si max	Cu max	Ni max	Others (total) max
Sand cast	AZ 92	8.3	9.7	0.10	...	1.6	2.4	0.3	0.25	0.01	0.3
Perm mold cast	AZ 92	8.3	9.7	0.10	...	1.7	2.3	0.3	0.25	0.01	0.3
Welding wire	AZ 92	8.3	9.7	0.10	...	1.7	2.3	0.3	0.25	0.01	0.3
Ingot	AZ ■	8.5	9.5	0.13	...	1.7	2.3	0.2	0.20	0.01	0.3

Mg – 9 Al – 0.7 Zn – 0.2 Mn

COMPILED BY H. W. SCHMIDT*

A 2 *Trade name.* Dowmetal R, Mazlo AM263
3 *ASTM number.* Alloy AZ91, specification B 94-47T
4 *Government number.* AN-M-16
5 *Other designations.* SAE 501, AMS 4490
6 *Foreign equivalents.* Elektron AZ91, British DTD 136A
B 1 *Typical uses.* Used only for die castings
C 1 *Density* at 20 C (68 F). 1.81 g per cu cm (0.066 lb per cu in.)
D 1 *Liquidus temperature.*[6] 596 C (1105 F)
2 *Solidus temperature.*[6] 468 C (875 F)
3 *Minimum "burning" (liquation) temperature.*[6] 421 C (790 F)
6 *Thermal expansion*[3] 20 to 100 C (68 to 212 F). 0.000026 per °C*

$$L_t = L_0 [1 + (24.80t + 0.00961t^2) \times 10^{-6}]$$

11 *Specific heat* at 25 C (78 F). 0.25 cal per g approx*
13 *Latent heat of fusion.* 89 cal per g approx*
16 *Thermal conductivity* 100 to 300 C (212 to 572 F). 0.17 cal/sq cm/cm/°C/sec
E 1 *Volume conductivity* referred to standard copper. 10.1%
2 *Electrical resistivity* at 20 C (68 F). 17.0 microhm-cm
11 *Electrolytic solution potential* versus saturated calomel electrode. 1.58 volts. Same test conditions as for pure magnesium.
14 *Hydrogen overvoltage.*[1] 0.40 for cast metal
K *Mechanical properties.* (Die casting): tensile strength 33,000 psi; yield strength (0.2% offset) 22,000 psi; elongation 3%; Brinell hardness number (500-kg load, 10-mm ball) 60; Rockwell hardness E 72; modulus of elasticity 6,500,000 psi; impact value, Izod or Charpy 2 ft-lb; shear strength 20,000 psi; endurance limit (500,000,000 cycles) 14,000 psi; ultimate compression strength 58,000 psi; compression yield strength 22,000 psi; Poisson's ratio 0.35.
4 *Machinability index*[5] (free-cutting brass = 100). 500*
L 2 *Radiography.* Refer to "Magnesium (99.80 Mg)".*
M *Composition limits* (ASTM B 94-47T) *See* Table II.
2 *Consequences of exceeding impurity limits.* Excessive amounts of copper and nickel affect the resistance to corrosion in salt water.
N 1 *Melting temperature.* 468 to 596 C (875 to 1105 F)
2 *Casting temperature range.*
(die) 620 to 675 C (1150 to 1250 F)
(ingot) 650 to 700 C (1200 to 1300 F)
3 *Alloying.* Add aluminum as Al or Al-Mn. Add zinc as Zn. Add manganese as 95 Al-5 Mn.
5 *Type of flux.* Magnesium die-casting flux
6 *Precautions in melting.* Protect metal with flux or sulfur dioxide atmosphere. Avoid moisture.
8 *Shortness range.* Above 400 C (above 750 F)

References. *See* "Magnesium (99.80 Mg)".

* Dow Chemical Company, Midland, Mich.
* Approximately the same as for pure magnesium

Table I. Strength and Elongation of Alloy AZ91 at Elevated Temperatures[a]

Testing Temperature, deg Cent	Testing Temperature, deg Fahr	Tensile Strength, psi	Yield Strength, psi	Elongation in 2 in., percentage
35	95	34,200	21,900	4.0
93	200	32,700	21,100	5.0
149	300	27,600	16,200	14.7
232	450	14,600	9,800	17.0
316	600	7,000	3,600	20.7

(a) Short-time tests on die-cast material

Table II. Composition Limits of Alloy AZ91 (ASTM B 94-47T)

Form	Components: Al min	Al max	Zn min	Zn max	Mn min	Mn max	Impurities: Si max	Cu max	Ni max	Others (total) max
Ingot	8.5	9.5	0.5	0.9	0.15	...	0.2	0.08	0.01	0.3
Sand cast	8.3	9.7	0.4	1.0	0.13	...	0.3	0.10	0.01	0.3

Mg – 1.25 Al – 1 Mn

COMPILED BY R. HAUSER AND N. E. WOLDMAN*

A 2 *Trade name.* Eclipsaloy 130
3 *ASTM number.* AM11
B 1 *Typical uses.* All types of die castings. The alloy is particularly adaptable to parts requiring impact strength and ductility.
2 *Precautions in use.* Requires slightly elevated pouring temperatures, large gates, and high pressure.
C 1 *Density* at 20 C (68 F). 1.705 g per cu cm (0.062 lb per cu in.)
D 1 *Liquidus temperature.*[6] 644 C (1190 F)
2 *Solidus temperature.*[6] 629 C (1165 F)
3 *Minimum "burning" (liquation) temperature.*[6] 626 C (1160 F)
6 *Thermal expansion*[3] 18 to 100 C (65 to 212F). 0.000026 per °C*
11 *Specific heat* 20 to 350 C (68 to 662 F). 0.25 cal per g*
13 *Latent heat of fusion.* 89 cal per g*
E 11 *Electrolytic solution potential* versus saturated calomel electrode. 1.55 volts. Same test conditions as for pure magnesium.
K *Mechanical properties.* (Die cast and aged, section 0.061 sq in.): tensile strength 32,000 psi; yield strength 21,000 psi; elongation 9%; Brinell hardness number 60; Rockwell E 65; modulus of elasticity 6,500,000 psi; impact value, Charpy 10 ft-lb; modulus of rigidity 2,400,000 psi.
4 *Machinability index*[5] (free-cutting brass = 100). 500*
L 2 *Radiography.* Same as for pure magnesium*
M *Composition limits.* Die cast: *components,* 1.0 to 1.5% Al; 0.5 to 1.5% Mn; *impurities,* 0.005% max Fe; 0.005% max Ni; 0.05% Cu; 0.30% max Si.
2 *Consequences of exceeding impurity limits.* Lower ductility and resistance to corrosion.
N 1 *Melting temperature.* 629 to 643 C (1165 to 1190 F)
2 *Die-casting temperature range.* 677 to 732 C (1250 to 1350 F)
3 *Alloying.* Add aluminum as Al. Add manganese as 95 Al – 5 Mn, or as $MnCl_2$.
5 *Type of flux.* Magnesium die-casting flux.
6 *Precautions in melting.* Protect metal with flux or sulfur dioxide atmosphere. Avoid moisture.
15 *Heat treatment.* For aging, hold at 246 C (475 F) for 4 hr in air, then cool in air.

References. *See* "Magnesium (99.80 Mg)".

* Crystal Engineering Laboratories, Upper Montclair, N.J.
* Approximately the same as for pure magnesium

Mg – 1.5 Mn

COMPILED BY H. W. SCHMIDT*

A *2 Trade name.* Dowmetal M, Mazlo AM403 (cast), AM3S (wrought)
3 ASTM number. Alloy M1, specifications B 80-47T (cast), B 107-45T (extrusions), B 90-46T (sheet) and B 91-45T (forgings)
4 Government number. AN-M-36 Alloy B (sand castings), AN-M-22 (forgings), AN-M-26 (extrusions), AN-M-30 (sheet), AN-T-73 (tubing)
5 Other designations. SAE 522 (extrusions), SAE 533 (forgings), SAE 51 (sheet), AMS 4370 (sheet)
6 Foreign equivalents. Elektron AM503 (cast and wrought), British DTD 142 (extrusions), DTD 118 (sheet), DTD 140A (castings)

B *1 Typical uses.* As castings to be welded to wrought products of the same composition. As wrought products having low cost with best weldability, hot formability, and moderate mechanical properties.

C *1 Density* at 20 C (68 F). 1.76 g per cu cm (0.064 lb per cu in.)

D *1 Liquidus temperature.* 649 C (1200 F)
2 Solidus temperature. 648 C (1198 F)
6 Thermal expansion[3] 20 to 100 C (68 to 212 F). 0.000026 per °C*

$$L_t = L_0\,[1 + (24.80t + 0.00961t^2) \times 10^{-6}]$$

11 Specific heat at 25 C (78 F). 0.25 cal per g approx*
13 Latent heat of fusion. 89 cal per g approx*
16 Thermal conductivity 100 to 300 C (212 to 572 F). 0.30 cal/sq cm/cm/°C/sec approx
19 Recrystallization temperature. 260 C (500 F) for one-hour anneal after 20% reduction

E *1 Volume conductivity* referred to standard copper. 25.7% cast, 34.5% wrought
2 Electrical resistivity at 20 C (68 F). Cast 6.7 microhm-cm; wrought 5.0 microhm-cm
11 Electrolytic solution potential versus saturated calomel electrode. 1.65 volts for cast, 1.64 volts for hard rolled. Same test conditions as for pure magnesium.
14 Hydrogen overvoltage.[1] 0.51 for cast, 0.42 for hard rolled metal

K *Mechanical properties.* See Tables I, II and III.
All forms. Modulus of elasticity 6,500,000 psi
Modulus of rigidity 2,400,000 psi
Poisson's ratio 0.35

Table I. Directional Properties of Alloy M1 Sheet

Property	Annealed	Hard Rolled
Parallel to rolling direction		
Tensile strength, psi	33,000	25,000
Yield strength, psi	18,000	26,000
Elongation, percentage	17	7
Perpendicular to rolling direction		
Tensile strength, psi	32,000	37,000
Yield strength, psi	17,000	27,000
Elongation, percentage	17	13

4 Machinability index[5] (free-cutting brass = 100). 500*

* Dow Chemical Company, Midland, Mich.
* Approximately the same as for pure magnesium

Table II. Strength and Elongation of Alloy M1 at Elevated Temperatures (Short-Time Tests)

Testing Temperature °C	Testing Temperature °F	Tensile Strength, psi	Yield Strength, psi	Elongation, in 2 in., percentage
		Forgings		
35	95	33,600	18,800	11.6
93	200	23,100	13,800	25.7
121	250	22,400	16,000	25.5
149	300	19,900	12,000	30.7
204	400	17,200	9,100	34.2
260	500	10,100	5,900	87.5
316	600	6,000	3,800	140.0
		Extrusions		
35	95	39,600	30,900	7.6
93	200	27,000	21,300	15.0
121	250	24,400	18,800	20.2
149	300	21,300	15,700	18.7
204	400	18,800	11,700	25.0
260	500	13,000	7,500	60.0
316	600	9,000	5,400	93.0
		Annealed Sheet		
35	95	33,000	20,200	17.7
93	200	24,200	16,200	31.0
121	250	21,600	14,700	40.5
149	300	19,300	12,700	44.0
		Hard Rolled Sheet		
35	95	36,000	27,000	10.0
93	200	29,700	26,700	7.7
121	250	27,300	24,500	11.7
149	300	25,000	21,200	16.0

L *2 Radiography.* Refer to "Magnesium (99.80 Mg)".*

M *Composition limits* (AN-M-26 for wrought, and AN-M-36 for cast alloys). Sand castings: 1.20% Mn min. Ingot: 1.30% Mn min. Sheet, welding wire, extrusions, forgings: 1.20% Mn min, 0.3% Ca max. For all these forms, *impurities (max):* 0.3% Si, 0.05% Cu, 0.01% Ni, 0.3% total others.
2 Consequences of exceeding impurity limits. Silicon tends to precipitate manganese. Copper and nickel affect the resistance to corrosion in salt water.

N *1 Melting temperature.* 649 C (1200 F)
2 Casting temperature range.
(sand) 732 to 843 C (1350 to 1550 F)
(ingot) 677 to 732 C (1250 to 1350 F)
3 Alloying. Add manganese as $MnCl_2$.
5 Type of flux. Magnesium melting flux.
6 Precautions in melting. See "Magnesium (99.80 Mg)".
7 Hot working. 293 to 538 C (560 to 1000 F)
9 Annealing temperature. 371 C (700 F)
10 Maximum reduction between anneals. 20 to 50%
15 Heat treatment. M1 annealed sheet may be stress relieved at 500 F in 15 min, the hard rolled sheet, at 400 F in 60 min, and extrusions, at 500 F in 15 min.
17 Joining.
Rivet compositions. Aluminum alloy 56 S-H12
Oxyacetylene welding with M1 welding rod, magnesium welding flux, and neutral flame.
Resistance welding is in general use.
Helium-arc welding is in general use. Use same filler rod as for torch welding. Use no flux.

References. *See* "Magnesium (99.80 Mg)".

Table III. Mechanical Properties of Alloy M1 at Room Temperature

Form and Condition	Tensile Strength, psi	Yield Strength,[a] psi	Elongation, percentage	Brinell Hardness Number[b]	Rockwell Hardness	Impact Value, Izod ft-lb	Shear Strength, psi	Endurance Limit,[c] psi	Compression Yield Strength, psi	Bearing Ultimate Strength, psi	Bearing Yield Strength, psi
Sheet											
Annealed	33,000	18,000	17	48	E 55	...	17,000	9,000	12,000	51,000	29,000
Hard	35,000	26,000	7	54	E 65	...	17,000	10,000	20,000	57,000	39,000
Forgings	36,000	23,000	7	47	E 54	...	,000	.....	.....	.....	.....
Extrusions											
Bars	38,000	28,000	10	42	E 41	...	16,000	9,000	13,000	.....	.....
Shapes	26,000	25,000	11	46	E 50	...	16,000	.....	12,000	56,000	35,000
Tubing	35,000	23,000	8	42	E 41	...	.....	.....	10,000	.....	.....
Sand cast	14,000	4,500	5	33	E 3	9	11,000	.....	4,500[d]	.....	.....

(a) 0.2% offset. (b) 500-kg load, 10-mm ball. (c) 500,000,000 cycles. (d) Ultimate compression strength for sand-cast sample is 27,000 psi.

Mg – 3 Al – 1 Zn – 0.3 Mn

COMPILED BY R. A. TOWNSEND*

A 2 *Trade Name.* Mazlo AM-C52 S, Dowmetal FS-1
3 *ASTM number.* Alloy AZ31X, specifications B 90-46T (sheet), B 91-45T (forgings), B 107-45T (extrusions) and B 217-46T (tubing)
4 *Government number.* AN-T-72 (tubing); AN-M-27 (extrusions); AN-M-29 (sheet); 57-157, alloy 18 (sheet); 57-193, alloy 18 (tubing); 47-M-2, alloy 18 (sheet); AXS 1328, alloy 18 (extrusions).
5 *Other designations.* SAE 52 (extrusions), SAE 510 (sheet)
6 *Foreign equivalents.* British DTD 120A; German and Italian, Elektron AZ31; French Soc Gen du Magnesium F3 and T28.

B 1 *Typical uses.* Weldable and best forming sheet and plate with good strength and high resistance to corrosion. Low-cost extruded bars, rods, shapes, structural sections and tubing with good mechanical properties and highest elongation. Seldom forged.

C 1 *Density* at 20 C (68 F). 1.78 g per cu cm (0.064 lb per cu in.)

D 1 *Liquidus temperature*[6] 632 C (1170 F)
2 *Solidus temperature.*[6] 565 C (1050 F)
3 *Minimum "burning" (liquation) temperature.*[6] 532 C (990 F)
6 *Thermal expansion*[3] at 40 C (104 F). 0.000026 per °C*
11 *Specific heat* at 25 C (78 F). 0.25 cal per g approx*
13 *Latent heat of fusion.* 89 cal per g approx*
16 *Thermal conductivity* 100 to 300 C (212 to 572 F). 0.23 cal/sq cm/cm/°C/sec approx
19 *Recrystallization temperature.* 204 C (400 F) for one-hour anneal after 15% reduction

E 1 *Volume conductivity* referred to standard copper. 18.5%
2 *Electrical resistivity* at 20 C (68 F). 9.3 microhm-cm
11 *Electrolytic solution potential* versus saturated calomel electrode. 1.59 volts. Same test conditions as for pure magnesium.
14 *Hydrogen overvoltage.*[1] 0.25 for hard rolled metal

K *Mechanical properties.* See Tables I, II and III.
All forms. Modulus of elasticity 6,500,000 psi
Modulus of rigidity 2,400,000 psi
Poisson's ratio 0.35
4 *Machinability index*[5] (free-cutting brass = 100). 500*

L 2 *Radiography.* Refer to "Magnesium (99.80 Mg)".*

M *Composition limits* (AN-T-72 for extruded tubing, AN-M-27 for extruded rod, bar and shapes, and AN-M-29 for sheet). *See* Table IV.
2 *Consequences of exceeding impurity limits.* The resistance to corrosion decreases with increasing amounts of copper, nickel and iron.

* American Magnesium Corporation, Cleveland
* Approximately the same as for pure magnesium

Table I. Strength and Elongation of Alloy AZ31X at Elevated Temperatures and Subzero Temperatures[a]

Testing Temperature, °C	°F	Tensile Strength, psi	Yield Strength, psi	Elongation, percentage
		Hard Rolled Sheet		
–80	–112	48,000	34,000	...
–28	–18	45,000	34,000	...
100	212	30,000	21,000	30
149	300	22,000	13,000	45
204	400	15,000	8,500	55
260	500	11,000	4,500	75
316	600	6,000	3,000	125
371	700	4,000	2,000	140
		Extruded Bar		
93	200	31,000	20,000	33
149	300	26,000	14,000	50
204	400	17,000	9,500	65
260	500	15,000	5,500	55
300	572	.....	3,100	...
316	600	10,000	.....	90

(a) Tests at elevated temperatures for hard sheet determined after prolonged heating at testing temperatures.

Table II. Directional Properties of Alloy AZ31X Sheet

Property	Annealed	Hard Rolled
Parallel to rolling direction		
Tensile strength, psi	37,000	44,000
Yield strength, psi	22,000	34,000
Elongation, percentage	21	11
Perpendicular to rolling direction		
Tensile strength, psi	39,000	46,000
Yield strength, psi	25,000	36,000
Elongation, percentage	19	15

N 1 *Melting temperature.* 565 to 632 C (1050 to 1170 F)
2 *Casting* (ingot). 648 to 704 C (1200 to 1300 F)
3 *Alloying.* Add aluminum as Al or Al-Mn. Add manganese as 95 Al-5 Mn. Add zinc as Zn.
7 *Hot working temperature.* 232 to 427 C (450 to 800 F)
8 *Shortness temperature.* Above 438 C (above 820 F)
9 *Annealing temperature.* 343 C (650 F)
10 *Maximum reduction between anneals.* 20 to 25%
15 *Heat treatment.* The annealed sheet of this alloy may be stress relieved at 500 F in 15 min; the hard rolled sheet, at 300 F in 60 min; and extrusions, at 500 F in 15 min.
17 *Joining. Rivet compositions.* Aluminum alloy 56 S-H12
Oxyacetylene welding with AZ61X or AZ92 welding rod, magnesium welding flux, neutral flame.
Resistance welding is in general use.
Helium-arc welding is in general use. Use same filler rod as for torch welding. Use no flux.

References. *See* "Magnesium (99.80 Mg)".

Table III. Mechanical Properties of Alloy AZ31X at Room Temperature

Form and Condition	Tensile Strength, psi	Yield Strength, (a) psi	Elongation, percentage	Brinell Hardness Number (b)	Rockwell Hardness	Impact Value, Charpy ft-lb	Shear Strength, psi	Endurance Limit, psi	Compressive Yield Strength, (a) psi	Bearing Ultimate Strength, (d) psi	Bearing Yield Strength, (d) psi
Annealed sheet	37,000	22,000	21	55	E 66	...	21,000	11,000	16,000	76,000	37,000
Hard sheet	42,000	33,000	11	72	E 82	...	23,000	13,000	29,000	79,000	54,000
Extruded bar	40,000	30,000	17	50	E 59	3.2	19,000	15,000[c]	17,000	.....	.....
Extruded shape	39,000	26,000	15	50	E 59	...	19,000	.....	15,000	.....	.....
Extruded tubing	35,000	22,000	18	50	E 59	...	.....	.....	15,000	.....	.....
Press forged	38,000	25,000	15	50	E 59	3.2	19,000	.....	.....	.....	.....

(a) 0.2% offset. (b) 500-kg load, 10-mm ball. (c) 500,000,000 cycles, R. R. Moore type rotating-beam machine. (d) $\frac{3}{16}$-in. pin diam.

Table IV. Composition Limits of AZ31X at Room Temperature

Form	Designation	Components: Al min	Al max	Mn min	Mn max	Zn min	Zn max	Impurities: Ca max	Si max	Cu max	Ni max	Fe max	Others (total) max
Sheet	AZ31X	2.5	3.5	0.2	...	0.6	1.4	0.3	0.3	0.05	0.005	0.005	0.3
Welding wire	AZ31X	2.5	3.5	0.2	...	0.6	1.4	...	0.3	0.05	0.005	0.005	0.3
Extrusions	AZ31X	2.5	3.5	0.2	...	0.6	1.4	...	0.3	0.05	0.005	0.005	0.3

Mg – 5 Al – 1 Zn – 0.25 Mn

COMPILED BY H. W. SCHMIDT*

A *2 Trade name.* Dowmetal JS-1
3 ASTM number. Alloy AZ51X, B 90-46T
4 Government number. AN-M-28
5 Other designations. SAE 512

B *1 Typical uses.* Used as sheet only. Best mechanical properties in hard condition. Good weldability and hot formability.

C *1 Density* at 20 C (68 F). 1.79 g per cu cm (0.065 lb per cu in.)

D *1 Liquidus temperature.*[6] 621 C (1150 F)
2 Solidus temperature.[6] 532 C (990 F)
3 Minimum "burning" (liquation) temperature.[6] 482 C (900 F)
6 Thermal expansion[3] 20 to 100 C (68 to 212 F). 0.000026 per °C approx*

$$L_t = L_0\ [1 + (24.80t + 0.00961t^2) \times 10^{-6}]$$

11 Specific heat at 25 C (78 F). 0.25 cal per ■ approx*
13 Latent heat of fusion. 89 cal per g approx*
16 Thermal conductivity 100 to 300 C (212 to 572 F). 0.21 cal/sq cm/cm/°C/sec
19 Recrystallization temperature. 288 C (550 F) for one-hour anneal after 20% reduction

E *1 Volume conductivity* referred to standard copper. 12.8%
2 Electrical resistivity at 20 C (68 F). 13.5 microhm-cm
11 Electrolytic solution potential versus saturated calomel electrode. 1.59 volts. Same test conditions as for pure magnesium.
14 Hydrogen overvoltage.[1] 0.27 for hard rolled metal

K *Mechanical properties. See* Tables I and II.
All forms. Modulus of rigidity 2,400,000 psi
Poisson's ratio 0.35
4 Machinability index[5] (free-cutting brass = 100). 500*

L *2 Radiography.* See corresponding section for pure magnesium.*

* Dow Chemical Company, Midland, Mich.
* Approximately the same as for pure magnesium

Table I. Directional Properties of Alloy AZ51X Sheet

Property	Annealed	Hard Rolled
Parallel to rolling direction		
Tensile strength, psi	40,000	45,000
Yield strength, psi	21,000	34,000
Elongation, percentage	19	10
Perpendicular to rolling direction		
Tensile strength, psi	41,000	49,000
Yield strength, psi	25,000	39,000
Elongation, percentage	18	14

M *Composition limits.* (AN-M-28 sheet): *components,* 4.1 to 5.5% Al; 0.4 to 1.3% Zn; 0.15% min Mn; *impurities,* 0.3% max Si; 0.3% max Ca; 0.05% max Cu; 0.005% max Ni; 0.005% max Fe; others (total) 0.3% max.
2 Consequences of exceeding impurity limits. Silicon, copper, iron and nickel affect resistance to corrosion in salt water.

N *1 Melting temperature.* 532 to 620 C (990 to 1150 F)
2 Casting temperature range. (ingot) 650 to 700 C (1200 to 1300 F)
3 Alloying. Add aluminum as Al; zinc as Zn; and manganese as 95 Al – 5 Mn
7 Hot working temperature. 260 to 418 C (500 to 785 F)
8 Shortness temperature. Above 427 C (above 800 F)
9 Annealing temperature. 343 C (650 F)
10 Maximum reduction between anneals. 15 to 25%
15 Heat treatment. The annealed sheet of this alloy may be stress relieved at 500 F in 15 min; the hard rolled sheet, at 375 F in 60 min.
17 Joining.
Rivet compositions. Aluminum alloy 56 S-H12
Oxyacetylene welding with AZ61X welding rod, magnesium welding flux, and neutral flame.
Resistance welding is satisfactory.
Helium-arc welding is the preferred method. Use same rod as for gas welding, and no flux.

References. *See* "Magnesium (99.80 Mg)".

Table II. Mechanical Properties of Alloy AZ51X at Room Temperature

Form and Condition	Tensile Strength, psi	Yield Strength, psi	Elongation percentage	Brinell Hardness Number (a)	Rockwell Hardness	Modulus of Elasticity, psi	Shear Strength, psi	Endurance Limit, (b) psi	Compressive Yield Strength, psi	Bearing Ultimate Strength, psi	Bearing Yield Strength, psi
Sheet, annealed	40,000	21,000	19	57	E-68	6,500,000	20,000	13,000	16,000	.....	.....
Sheet, hard	45,000	34,000	■	71	E-81	.....	22,000	14,000	26,000	79,000	54,000

(a) 500-kg load, 10-mm ball. (b) 500,000,000 cycles.

Mg – 6 Al – 1 Zn – 0.2 Mn

COMPILED BY R. A. TOWNSEND*

A *2 Trade name.* Mazlo AM–C57S, Dowmetal J–1
3 ASTM number. Alloy AZ61X, specifications B 91–45T (forgings), B 107-45T (extrusions), B 217-46T (tubing)
4 Government number. AN–M–20 (forgings); AN–M–24 (extrusions); AN-T-71 (tubing); AXS-1328, alloy 8 (extrusions); 44T35, alloy 8 (tubing); 46M13, alloy 8 (forgings).
5 Other designations. SAE 520 (extrusions), SAE 531 (forgings), AMS 4350 (extrusions and forgings)
6 Foreign equivalents. British DTD 88B; DTD 120A; DTD 259; British, German and Italian, Elektron AZM; German-Aircraft Material Index 3510.1 and 3510.2; French Soc Gen du Magnesium M1.

B *1 Typical uses.* General-purpose extrusions with good properties, intermediate cost and high resistance to corrosion; press forgings with good mechanical properties and high resistance to corrosion.

C *1 Density* at 20 C (68 F). 1.80 g per cu cm (0.065 lb per cu in.)

D *1 Liquidus temperature.*[6] 615 C (1140 F)
2 Solidus temperature.[6] 510 C (950 F)
3 Minimum "burning" (liquation) temperature.[6] 418 C (785 F)
6 Thermal expansion[3] at 40 C (104 F). 0.000026 per °C*
11 Specific heat at 25 C (78 F). 0.25 cal per g approx*
13 Latent heat of fusion. 89 cal per g approx*
16 Thermal conductivity 100 to 300 C (212 to 572 F). 0.19 cal/sq cm/cm/°C/sec approx

* American Magnesium Corporation, Cleveland
* Approximately the same as for pure magnesium

Table I. Mechanical Properties of AZ61X at Room Temperature

Form	Tensile Strength, psi	Yield Strength,[a] psi	Elongation percentage	Compressive Yield Strength, psi[a]	Brinell Hardness Number[b]	Rockwell Hardness	Impact Value, Charpy ft-lb	Bearing Ultimate Strength, psi[c]	Bearing Yield Strength, psi[c]	Shear Strength, psi	Endurance Limit,[d] psi
Press forged	43,000	26,000	12	18,000	55	E 66	2.2	.....	.....	21,000	16,000
Extruded bar	45,000	32,000	15	21,000	56	E 67	3.0	.....	.....	21,000	17,000
Extruded shape	44,000	29,000	16	18,000	60	E 72	...	76,000	45,000	20,000	.....
Extruded tubing	40,000	22,000	15	15,000	55	E 63	...	.....	.....	.....	.....

(a) 0.2% offset. (b) 500-kg load, 10-mm ball. (c) $\frac{3}{16}$-in. pin diam. (d) 500,000,000 cycles, R. R. Moore type rotating-beam machine.

19 Recrystallization temperature. 288 C (550 F) for one-hour anneal after 20% reduction

E *1 Volume conductivity* referred to standard copper. 11.6%
2 Electrical resistivity at 20 C (68 F). 14.9 microhm-cm
11 Electrolytic solution potential versus saturated calomel electrode. 1.58 volts.
Same test conditions as for pure magnesium.
14 Hydrogen overvoltage.[1] 0.21 for hard rolled metal

K *Mechanical properties.* See Tables I and II.
All forms. Modulus of elasticity 6,500,000 psi
Modulus of rigidity 2,400,000 psi
Poisson's ratio 0.35
4 Machinability index[5] (free-cutting brass = 100). 500*

L *2 Radiography.* Refer to "Magnesium (99.80 Mg)".*

M *Composition limits* (AN-M-20 for forgings, AN-M-24 for extruded rod, bar and shapes, and AN-T-71 for extruded tubing). *See* Table III.
2 Consequences of exceeding impurity limits. The resistance to corrosion decreases with increasing amounts of copper, nickel and iron.

N *1 Melting temperature range.* 510 to 615 C (950 to 1140 F)
2 Casting temperature range.
(ingot) 648 to 704 C (1200 to 1300 F)
3 Alloying. Add aluminum as Al or Al-Mn. Add manganese as 95 Al-5 Mn. Add zinc as Zn.
7 Hot working temperature. 232 to 399 C (450 to 750 F)

Table II. Mechanical Properties of AZ61X at Elevated Temperatures and Subzero Temperatures (Extruded Bar)[a]

Testing Temperature deg Cent	Testing Temperature deg Fahr	Tensile Strength, psi	Yield Strength, psi	Elongation, percentage
–80[b]	–112[b]	47,000	37,000	14
–28	–18	45,000	33,000	14
100	212	35,000	25,000	35
149	300	22,000	17,000	50
204	400	16,000	12,000	60
260	500	12,000	7,000	100
300	572	.....	2,000	...
316	600	9,500	.....	45

(a) Properties at elevated temperatures, determined after prolonged heating at testing temperatures.
(b) 70 Bhn; R_B80; Charpy 2.9 ft-lb; modulus of elasticity 6,800,000 psi

8 Shortness temperature. Above 415 C (above 780 F)
9 Annealing temperature. 343 C (650 F)
15 Heat treatment. Extrusions of this alloy may be stress relieved at 500 F in 15 min.
17 Joining.
Rivet compositions. Aluminum alloy 56 S-H12
Oxyacetylene welding with AZ61X welding rod, magnesium welding flux, and neutral flame.
Resistance welding is in general use.
Helium-arc welding is in general use. Use same filler rod as for torch welding. Use no flux.

References. *See* "Magnesium (99.80 Mg)".

Table III. Composition Limits of Alloy AZ61X

Form	Designation	Components: Al min	Al max	Mn min	Mn max	Zn min	Zn max	Impurities: Si max	Cu max	Ni max	Fe max	Others (total) max
Welding wire	AZ61X	5.8	7.2	0.15	....	0.4	1.5	0.3	0.05	0.005	0.005	0.3
Extrusions	AZ61X	5.8	7.2	0.15	....	0.4	1.5	0.3	0.05	0.005	0.005	0.3
Forgings	AZ61X	5.8	7.2	0.15	....	0.4	1.5	0.3	0.05	0.005	0.005	0.3

Mg – 8.5 Al – 0.5 Zn – 0.15 Mn

COMPILED BY H. W. SCHMIDT*

A *2 Trade name.* Dowmetal O-1, Mazlo AM-C58 S
3 ASTM number. Alloy AZ80X, specifications B 91-45T (forgings) and B 107-45T (extrusions)
4 Government number. AN-M-21 (forgings), AN-M-25 (extrusions)
5 Other designations. SAE 523 (extrusions), SAE 532 (forgings), AMS 4360 (forgings)
6 Foreign equivalents. Elektron AZ855, British DTD 88B (forgings)

B *1 Typical uses.* Highest strength of the wrought alloys. Available as extruded products and press forgings. Can be heat treated.

C *1 Density* at 20 C (68 F). 1.80 g per cu cm (0.066 lb per cu in.)

D *1 Liquidus temperature.*[6] 602 C (1115F)
2 Solidus temperature.[6] 482 C (900 F)
3 Minimum "burning" (liquation) temperature.[6] 427 C (800 F)
6 Thermal expansion[3] 20 to 100 C (68 to 212 F). 0.000026 per °C*

$$L_t = L_o [1 + (24.80t + 0.00961t^2) \times 10^{-6}]$$

11 Specific heat at 25 C (78 F). 0.25 cal per ■ approx*
13 Latent heat of fusion. 89 cal per g approx*
16 Thermal conductivity 100 to 300 C (212 to 572 F). 0.18 cal/sq cm/cm/°C/sec
19 Recrystallization temperature. 343 C (650 F) for one-hour anneal after 10% reduction

E *1 Volume conductivity* referred to standard copper. 10.6% extruded, 14.6% aged
2 Electrical resistivity at 20 C (68 F). Extruded 16.2 microhm-cm. Aged 11.8 microhm-cm
11 Electrolytic solution potential versus saturated calomel electrode. 1.57 volts. Same test conditions as for pure magnesium.
14 Hydrogen overvoltage.[1] 0.27 for extruded metal

* Dow Chemical Company, Midland, Mich.

* Approximately the same as for pure magnesium

Table I. Mechanical Properties of Alloy AZ80X at Room Temperature

Condition	Tensile Strength, psi	Yield Strength, (a) psi	Elongation percentage	Brinell Hardness Number, (b)	Rockwell Hardness	Shear Strength, psi	Endurance Limit, (c) psi	Compression Yield Strength, psi	Bearing Ultimate Strength, psi	Bearing Yield Strength, psi
Forgings										
As forged	46,000	31,000	8	69	E 80	22,000	18,000	25,000	.....	.....
Aged	50,000	34,000	6	72	E 82	23,000	16,000	28,000	.....	.....
Extrusions										
As extruded	49,000	35,000	■	63	E 75	21,000	19,000	26,000	.....	.....
Aged	50,000	36,000	7	80	E 87	22,000	19,000	34,000	.....	.....
Heat treated and aged	53,000	40,000	7	80	E 87	22,000	.....	36,000	.....	.....
Shapes										
As extruded	48,000	32,000	12	67	E 78	21,000	.....	21,000	80,000	51,000
Aged	50,000	34,000	10	80	E 87	22,000	.....	33,000	.....	.....
HTA	52,000	37,000	9	85	E 90	22,000	.....	35,000	92,000	62,000

(a) 0.2% offset. (b) 500-kg load, 10-mm ball. (c) 500,000,000 cycles.

Table II. Strength and Elongation of Alloy AZ80X at Elevated Temperatures (Short-Time Tests)

Testing Temperature °C	Testing Temperature °F	Tensile Strength, psi	Yield Strength, psi	Elongation, percentage
		Forgings HTA		
35	95	52,900	39,500	4.5
149	300	31,000	20,700	30.3
		Extrusions HTA		
35	95	56,500	40,500	4.5
93	200	48,500	32,100	20.0
121	250	42,000	26,600	33.0
149	300	33,600	21,400	41.2
204	400	21,600	14,700	49.0
260	500	13,600	7,800	83.0
316	600	8,700	4,700	123.0

K *Mechanical properties.* See Tables I and II.

All forms. Modulus of elasticity 6,500,000 psi
Modulus of rigidity 2,400,000 psi
Poisson's ratio 0.35

4 Machinability index[5] (free-cutting brass =100). 500*

L *2 Radiography.* Refer to corresponding section for pure magnesium.*

M *Composition limits* (AN-M-25) Extrusions, forgings: *components,* 7.8 to 9.2% Al, 0.2 to 0.8% Zn, 0.10 Mn min; *impurities (max):* 0.3% Si, 0.05% Cu, 0.005% Ni, 0.005% Fe, 0.3% total others.

2 Consequences of exceeding impurity limits. Silicon, copper, nickel and iron affect the resistance to corrosion in salt water.

N *1 Melting temperature range.* 482 to 602 C (900 to 1125 F)

2 Casting temperature range. (ingot) 648 to 704 C (1200 to 1300 F)

3 Alloying. Add aluminum as Al. Add zinc as Zn. Add manganese as 95 Al-5 Mn.

7 Hot working temperature range. 316 to 399 C (600 to 750 F)

8 Shortness temperature. Above 419 C (above 775 F)

9 Annealing temperature. 385 C (725 F)

15 Heat treatment.

Purpose	Temperature °C	Temperature °F	Time, hr	Cooling
Solution heat treatment	399	750	2 to 4	air
Aging	177	350	16 to 24	air
Stress relieving extrusions	204	400	1	....
Extrusions H T A	316	600	0.25	....

17 Joining.

Rivet compositions. Aluminum alloy 56 S-H12

Oxyacetylene welding with AZ61X welding rod, magnesium welding flux, and neutral flame.

Resistance welding. Satisfactory

Helium-arc welding is preferred. Use same rod as for gas welding, and no flux.

References. *See* "Magnesium (99.80 Mg)".

Mg – 5 Sn – 3 Al – 0.5 Mn

COMPILED BY R. A. TOWNSEND*

A *2 Trade name.* Mazlo AM65S, Dowmetal D

3 ASTM number. Alloy TA54, specification B 91-45T
Also known as Alloy AT35

4 Government number. AN-M-23; 46M13, alloy 16

5 Other designation. SAE 53

B *1 Typical uses.* General-purpose hammer-forging alloy of intermediate strength.

C *1 Density* at 20 C (68 F). 1.84 ■ per cu cm (0.067 lb per cu in.)

D *6 Thermal expansion* at 40 C (104 F). 0.000026 per °C*

11 Specific heat at 25 C (78 F). 0.25 cal per g approx*

13 Latent heat of fusion. 89 cal per g approx*

E *1 Volume conductivity* referred to standard copper. 12.5%

2 Electrical resistivity at 20 C (68 F). 13.8 microhm-cm

11 Electrolytic solution potential versus saturated calomel electrode. 1.58 volts. Same test conditions as for pure magnesium.

14 Hydrogen overvoltage.[1] 0.30 for cast metal

K *Mechanical properties.* (*Hammer forged*): tensile strength 40,000 psi; yield strength (0.2% offset) 28,000 psi; elongation 12%; compressive yield strength 21,000 psi; shear strength 16,000 psi; endurance limit (based on 500,000,000 cycles, R. R. Moore type rotating-beam machine) 11,000 psi; Brinell hardness number (500-kg load, 10-mm ball) 52; Rockwell hardness E 62; modulus of elasticity 6,500,000 psi; modulus of rigidity 2,400,000 psi; Poisson's ratio 0.35; impact value, Charpy 2 ft-lb.

4 Machinability index[5] (free-cutting brass = 100). 500*

L *2 Radiography.* Refer to corresponding section for pure magnesium.*

M *Composition limits.* (AN-M-23, forgings): *components,* 3.0 to 4.0% Al; 0.40% min Mn; 4.0 to 6.0% Sn; *impurities* 0.3% max Si; 0.05% max Cu; 0.005% max Ni; others (total) 0.3% max.

2 Consequences of exceeding impurity limits. The resistance to corrosion decreases with increasing amounts of copper and nickel.

N *3 Alloying.* Add aluminum as Al or Al-Mn. Add manganese as 95 Al-5 Mn. Add tin is Sn.

7 Hot working temperature range. 232 to 438 C (450 to 820 F)

8 Shortness temperature. Above 454 C (above 850 F)

9 Annealing temperature. 343 C (650 F)

17 Joining.

Rivet compositions. Aluminum alloy 56 S-H12

References. *See* "Magnesium (99.80 Mg)".

* American Magnesium Corporation, Cleveland

* Approximately the same as for pure magnesium

NICKEL AND NICKEL ALLOYS

Prepared under the chairmanship of

W. A. MUDGE

The International Nickel Company, Inc.

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Properties of Nickel and Nickel Alloys

Nickel (99.95 Ni + Co) (Electrolytic Nickel)	1046	62 Ni–30 Mo–5 Fe (Hastelloy B)	1055
Nickel (99.4 Ni + Co) ("A" Nickel)	1047	58 Ni–17 Mo–15 Cr–5 W–5 Fe (Hastelloy C)	1056
95 Ni–4.5 Mn ("D" Nickel)	1047	85 Ni–10 Si–3 Cu (Hastelloy D)	1057
94 Ni–4.5 Al ("Z" Nickel)	1048	80 Ni–14 Cr–6 Fe (Inconel)	1057
97 Ni–1.5 Si (Cast Nickel)	1049	78 Ni–13.5 Cr–6 Fe–2 Si (Cast Inconel)	1058
67 Ni–30 Cu–1.4 Fe–1 Mn (Monel)	1049	58 Ni–22 Cr–6 Cu–6 Mo–6 Fe (Illium "G")	1058
63 Ni–32 Cu–1.6 Si–1.5 Fe (Cast Monel)	1052	80 Ni–20 Cr	1060
66 Ni–29 Cu–2.75 Al–0.9 Fe–0.75 Mn ("K" Monel)	1052	60 Ni–24 Fe–16 Cr	1060
63 Ni–30 Cu–4 Si–2 Fe ("S" Monel)	1053	35 Ni–50 Fe–15 Cr	1061
57 Ni–20 Mo–20 Fe (Hastelloy A)	1054	45 Ni–55 Cu (Constantan)	1062

The Nickel Industry

BY T. H. WICKENDEN*

NICKEL was used by ancient man in swords and implements fashioned from nickel-bearing meteorites and in coins made from paktong, a nickel-copper alloy first developed in China. It was extracted as an element in 1751 by Axel F. Cronstedt and named nickel from the ore "kupfernickel", so-called by superstitious miners who believed that the ore was bedeviled. The modern nickel industry dates from the opening of the New Caledonia mines in 1875 and those of Sudbury, Ontario, in 1886.

Occurrence. Commercial nickel ores fall into three major classes: (1) Sulfide ores are represented chiefly by the pyrrhotite-pentlandite-chalcopyrite ores of Canada and Norway. Pentlandite, a complex nickel-iron sulfide, is the nickel carrier. Small quantities of ores of this type have been mined in Connecticut, Pennsylvania, California, Missouri, and in Sweden, Finland, Italy, China, Tasmania, South Africa, and Great Britain. (2) Oxidized ores of the garnierite (silicate) type, occur in New Caledonia and, in small quantities, on the border of North Carolina and Tennessee. Similar ores occur in Borneo, Madagascar, Brazil, Spain, Greece, Russia, the West Indies and Oregon. (3) Arsenical ores are found in Ontario, Colorado, New Mexico, Saxony, Bohemia, France and eastern India. Small percentages of nickel are also present in many of the copper ores, in manganese ores of the early class known as "wad", and in nickeliferous ores such as those of Cuba.

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Smelting and Refining. In the Orford process, the ore is ground fine, classified, roasted in Nichols-Herreschoff roasters, and smelted in reverberatory furnaces to remove a large part of the sulfur. The molten matte is charged into converters with siliceous flux to produce a fluid slag that carries off the iron. The resulting nickel-copper Bessemer matte is smelted in a blast furnace with an alkaline sulfide flux and is cast subsequently into large pots. The product solidifies in two layers. The top layer contains copper sulfide; the bottom layer contains nickel sulfide. Resmelting with nitre cake and excess coke purifies the product progressively. The copper is blown to blister in basic-lined converters and refined electrolytically. The nickel sulfide bottoms are crushed, leached and sintered, melted in reverberatory furnaces and cast into anodes. By electrolytic refining in a continuously purified nickel sulfate electrolyte, cathode nickel is obtained that has a purity of 99.95% Ni plus Co. The range of the cobalt content is 0.30 to 0.50%. Impurities may be copper, iron, carbon, sulfur and silicon.

In the Mond process, crushed nickel sulfide bottoms are calcined to drive off sulfur, are reduced to metal and are then treated with carbon monoxide gas, which forms a volatile nickel compound (nickel carbonyl) at 60 C. The nickel-laden gas is passed over pure nickel pellets at a higher temperature (about 180 C). Metallic nickel is deposited on the pellets and the regenerated carbon monoxide is returned for use again as a nickel carrier.

The New Caledonian silicate ore is smelted to matte.

Sulfur is supplied by adding gypsum or any alkaline sulfide to the furnace. The matte is blown to a high grade in Bessemer converters and the iron is eliminated in the slag. After roasting to drive off the sulfur, the oxide is made into a plastic with reducing materials and produced in the shape of cubes or rondelles.

In the Falconbridge process for recovering nickel, the ore containing nickel and copper is smelted to obtain a high-metal matte. The matte is crushed and ground to pass through a 20-mesh screen and is then roasted in Herreschoff roasters to remove most of the sulfur.

The roasted ground matte is charged into a Pachuca tank, is agitated with an acid solution to remove copper, and is then filtered. The filtrate goes to electrolytic tanks with insoluble anodes where copper is plated out. The filter cake containing the nickel is washed, dried, melted with coke, and then cast into crude anodes that are electrolyzed to produce electrolytic nickel cathodes.

The Nicaro nickel recovery process was developed particularly for low-grade nickel ore. It involves crushing and drying, then grinding to a very fine mesh in hammer and ball mills. The dry dust obtained in this way is reduced by producer gas in oil-heated Herreschoff furnaces that have multiple hearths, and the resulting reduced ore is leached in an ammonia solution from which nickel is precipitated

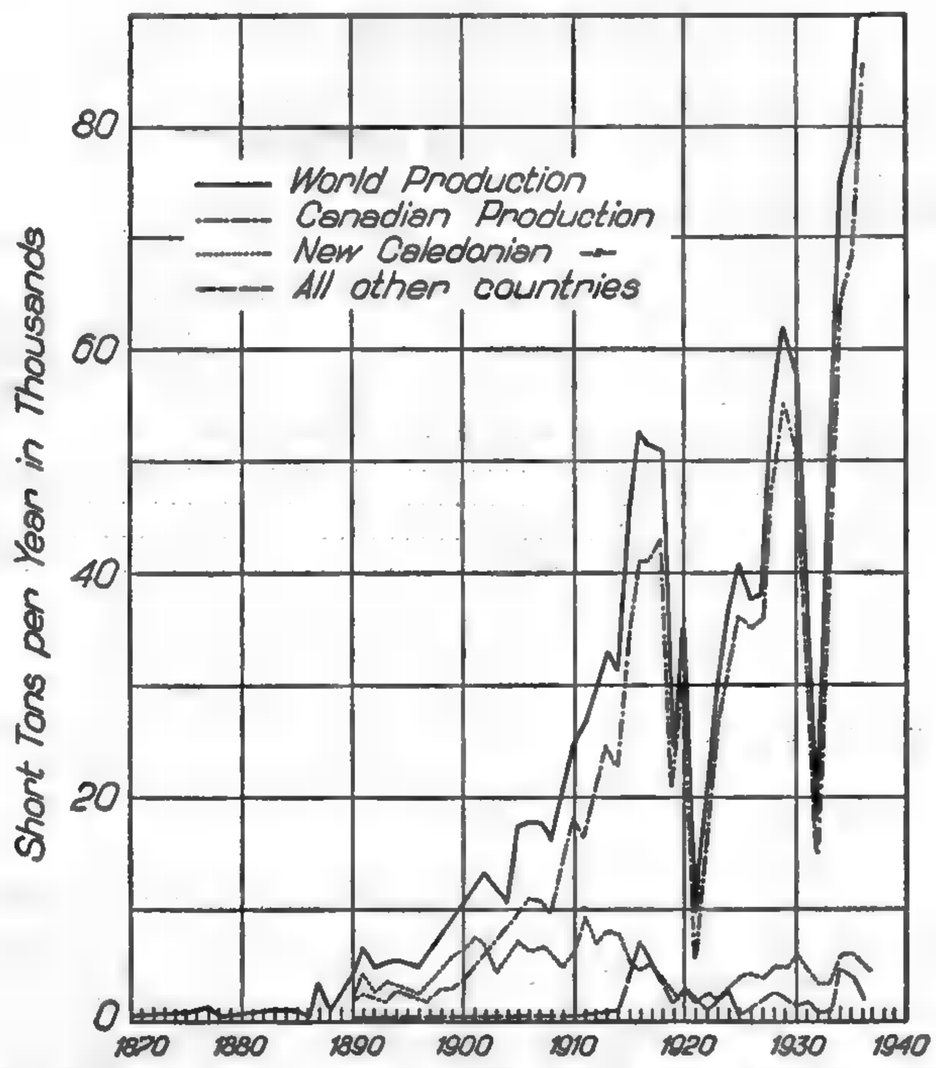

Fig. 1 World production of nickel from 1870 to 1936. Average annual production from 1937 to 1944 was approximately 150,000 tons.

in the form of nickel carbonate. This, in turn, is calcined to nickel oxide, in which form it is marketed.

Products. Nickel is marketed in various forms, as follows: (1) nickel pellets, produced by decomposition of nickel carbonyl gas without fusion; (2) electrolytic cathode sheets cut into various sizes; (3) blocks or shot, obtained by remelting electrolytic nickel, then casting it into pig molds or pouring it into water without deoxidation; (4) malleable nickel, produced by pouring into ingot molds after deoxidation; (5) nickel cubes or rondelles, reduced from the oxide without fusion; (6) nickel salts; (7) nickel oxide; (8) nickel powder; and (9) special alloys for addition to cast irons.

Uses. Nickel is used in the food-processing, radio and chemical industries, in coinage, in the Edison storage battery, and as a catalyst in the hydrogenation of unsaturated organic compounds. Nickel plating is extensively employed and regularly forms a base layer for chromium plating. Heavy nickel plating has been developed for building up the worn parts of machinery, and a hard plate (up to 400 Brinell) is utilized for applications requiring unusual resistance to abrasive wear. Nickel-clad steel has been developed for the construction of heavy tanks and kettles.

Nickel is used most extensively as an alloying element in ferrous and nonferrous alloys. Table I serves to indicate the percentage distribution of nickel in the various metal markets and Fig. 1 shows the world production.

Table I
Approximate World Consumption of Nickel, 1939[a]

Constructional steels, stainless steels and other corrosion-resisting and heat-resisting steels, and steel castings	60%
Nickel cast iron	3%
Nickel-iron alloys	1%
Nickel-copper alloys and nickel silvers	14%
Nickel brass, bronze, and aluminum alloy castings	2%
Heat-resistant and electrical resistance alloys	3%
Malleable nickel, nickel cladding	9%
Electrodeposition	6%
Nickel salts, ceramic materials, storage battery materials and catalysts	1%
Miscellaneous and unclassified	1%

(a) Detailed figures for the war years are not available.

Nickel is one of the chief alloying elements of the alloy steel industry. The most outstanding characteristic of nickel is the ability to impart to steel increased hardness, strength, and toughness without sacrifice of ductility. Nickel steels are applied extensively in the transportation field, in the oil and power industries, and in the production of machine tools and of machinery for agricultural and general purposes. In cast iron, nickel refines the grain, homogeneity and density, and reduces the tendency to chill. Special nickel cast irons have been developed for resistance to abrasion and for applications that require resistance to heat and corrosion.

Nickel-chromium steels, carrying high percentages of the alloying elements, form a series of alloys that resist both corrosion and heat. The most popular of these, 18-8, contains 18% Cr and 8 to 10% Ni. A ferrous alloy containing 60% Ni and 15% Cr is used in electrical resistance heating elements. An 80% Ni, 14% Cr, 6% Fe alloy that has good strength, toughness, and resistance to corrosion and oxidation, is employed in chemical and food-processing equipment.

A variety of nickel-iron alloys have special thermal, magnetic, electrical and elastic properties. Invar, containing 36% Ni and possessing a coefficient of thermal expansion of approximately zero, is one of this series. A 20% Ni alloy, containing aluminum and cobalt, has been developed for permanent magnets.

Monel is a nickel-copper alloy that contains 67% Ni, 30% Cu; the remainder is mostly iron and manganese. Monel is obtained by roasting copper-nickel converter matte and reducing the resulting oxide to metal with charcoal. This is primarily a corrosion-resistant alloy for handling acids, alkalies, brines, water, and food products; it is also resistant to exposure in dry and moist atmospheres.

Nickel-copper alloys containing 20 to 30% Ni are made into condenser tubes for service in contact with sea water. A 25% Ni alloy is used for the five cent coin of the United States. Alloys containing 45 to 55% Ni are marketed for pyrometer and electrical resistance wire, under a variety of trade names.

Table II
Nickel Alloys Used for Nonferrous Melting

	Electrolytic Nickel Cathode	Shot and Ingot from Electrolytic Nickel	Copper-Nickel Shot	High-Nickel-Copper Shot and Blocks
Nickel plus cobalt	99.95%	99.60 %	50.00%	67.00%
Iron	0.01 to 0.04%	0.07 %	0.10%	1.75%
Copper	0.01 to 0.03%	0.026%	49.60%	29.00%
Carbon	trace	0.11 %	0.15%	0.20%
Silicon	trace	0.11 %	0.04%	1.25%
Sulfur	trace	0.01 %	0.02%	0.01%
Manganese	....	....	....	0.75%
Melting point, °F.	2650	2600	2250	2460

The approximate compositions and melting points of the nickel alloys used for melting in the nonferrous industry are listed in Table II.

The effect of nickel as a decolorizer is utilized in the nickel silvers, widely employed for architectural trim and plumbing fixtures, and finds application in the production of white gold. As much as 2% Ni is used in several of the aluminum alloys that are made into sand-cast, permanent mold cast, die-cast, and wrought products.

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The Melting and Casting of Nickel and Nickel Alloys

By L. E. Grubb*

THE melting and casting of nickel and nickel alloys closely parallel the practice in casting steel (*see* page 523). The basic equipment and sand mixtures recommended for steel can be used satisfactorily, and no great difficulties should be experienced if certain precautions are taken.

General Information. Electric-arc, induction, oil-heated, and gas-heated furnaces can be used. Coke-heated pit melting is not recommended because of the danger of contamination by sulfur. Natural and basic furnace linings are preferred to the acid type of lining.

Extreme care should be taken in the selection and preparation of the furnace charge. Only materials of known composition should be used.

Some minor elements, such as sulfur and lead, have well-known harmful effects on the mechanical properties and welding characteristics of the nickel materials, and the importance of holding such elements at minimum levels cannot be overemphasized. This factor should be considered in selecting the alloying and degasifying agents, slag materials and fluxing compounds.

Care should be taken to avoid contamination in the furnace from preceding melts, because nickel and nickel alloys are usually specified for the corrosion resistance that is inherent in their chemical composition.

Furnace linings, ladles and all materials to be charged should be dried thoroughly to avoid gassy heats. This is particularly important in the production of nickel and the nickel-chromium alloys.

Pattern equipment should provide for a linear shrinkage of ¼ in. per ft.

Gates and risers should be proportionately larger than those used for steel, because of the large volumetric shrinkage and small liquidus range characteristic of nickel and nickel alloys.

Recommended Melting Practice. *Nickel.* After charging, the nickel is melted down under a thin protective limestone slag. During or immediately after the melt-down period, the heat is oxidized by additions of nickel oxide. Sufficient carbon should be added next to cause a "boil", and the boil should be maintained long enough to remove any dissolved gases. A practical test to determine the effectiveness of the boil consists of pouring a small sample into a dry sand mold. If the top of the sample shrinks normally, the melt is relatively free from gas. If the metal shrinks and then expands, the boil has not been entirely effective. After a satisfactory sample has been secured, the boil is "killed" by a small addition of silicon, and the heat is finished as quickly as possible. The carbon content is then raised to the desired level by an addition of charcoal. Manganese is added approximately 10 min before tapping. The 10-min period is essential to allow any entrapped oxides that have been fluxed by the addition to rise and clear the bath. When the desired tapping temperature is reached, the melt is poured and deoxidized in the ladle by finishing additions of metallic silicon and approximately 0.10% Mg. The pouring temperature is between 2750 and 2900 F, depending on the size of the casting and the type of mold used.

Nickel-Copper Alloys. When using a charge of Monel block or "revert scrap" of known origin, a straight melt-down is employed under a light protective slag of limestone. A small, adjusting addition of manganese, in the form of a silicon-manganese alloy, is made to the furnace bath approximately 10 min before tapping. After reaching the desired tapping temperature (2700 to 2900 F, depending on the silicon content, which is from 1.6 to 4.0%, and the size and section of the castings to be poured) the metal is deoxidized in the ladle by tapping on top of the silicon addition and with 0.10% Mg. An addition of 0.05% Ti may be added at this time to fix any nitrogen present.

In the production of Monel castings from electrolytic nickel and electrolytic copper, the copper is first charged on the bottom of the furnace along with sufficient charcoal to secure the desired carbon content. The nickel is then placed on top and the charge is melted under a thin protective limestone slag. When the carbon content has reached the desired level, any charcoal remaining on the surface of the bath is removed. The practice for the remainder of the melting cycle is the same as outlined above for charges of Monel block or revert scrap; the silicon and manganese additions are proportionately larger. The pouring temperature is 2650 to 2850 F.

Nickel-Chromium Alloys. Approximately half the nickel is charged on the bottom of the furnace and all the chromium is placed on top of the nickel. If weldability is desired in the finished alloy, a columbium addition is included and the silicon content is maintained at 1% max. The remainder of the nickel is then charged, along with a sufficient amount of iron oxide or nickel oxide to ensure a well-oxidized bath. The melt-down should be accomplished as quickly as possible under a protective limestone slag, and a small amount of cryolite should be added to keep the slag fluid. When the bath temperature reaches 2900 F, a gentle boiling will be observed. If high-carbon ferrochromium is used, sufficient carbon is present in the alloy to cause the boil without the addition of charcoal.

Test samples are taken in the same manner as that described for nickel to verify that the bath is free from gas. When the sample is satisfactory, the boil is "killed" by a small addition of metallic silicon. Small amounts of powdered calcium-silicon are dusted on the surface of the slag to maintain it in a reducing condition. When the tapping temperature has been reached (2850 to 3100 F) the surface of the bath is cleaned and deoxidation is accomplished by a furnace addition of 0.10% Mg. Magnesium additions should not be made in the ladle because of the violent reaction that takes place. The necessary additions of silicon and manganese are made in the ladle while the heat is being tapped. An addition of 0.05% Ti may be added at this time to fix any nitrogen present. The pouring temperature is 2800 to 2950 F.

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The Melting and Hot Rolling of Nickel and Nickel Alloys

By Clarence Bieber*

THIS discussion describes the methods used for melting, refining, teeming and rolling commercially pure nickel, and some nickel alloys containing copper or chromium with small amounts of manganese and iron.

Melting Furnaces. These materials are melted in three types of furnaces, each of which is adapted especially to the particular function to be performed or to the requirements of the alloy to be melted. Nickel is usually melted in acid-lined open hearth furnaces of the reverberatory type, heated with natural gas. Monel (70 Ni, 30 Cu) is melted first in the same type of furnace and then duplexed into basic-lined, electric-arc furnaces for refining. Inconel (80 Ni, 14 Cr, ▮ Fe) is melted either in high-frequency induction furnaces or in basic-lined, electric-arc furnaces.

Raw Materials. Commercially pure nickel is produced from electrolytic nickel cathodes. Monel is produced from a nickel-copper sulfide matte. Inconel is produced from electrolytic nickel and low-carbon ferrochromium, containing approximately 70% Cr.

Melting of Nickel. Since electrolytic nickel has been refined by the method of production, only melting and the addition of small amounts of minor constituents precede casting into ingots. The minor constituents control the mechanical properties as well as the forging and rolling qualities of the material. Charges weighing from about 9000 to 23,000 lb and consisting of electrolytic nickel, clean nickel mill scrap and about 1% low-sulfur charcoal, are melted in gas-heated open hearth furnaces. These furnaces are lined with bricks consisting of about 55% silica and 45% alumina. No slag is added intentionally, but some incidental slag is formed by fusion of the refractories.

The nickel heats are usually melted down with about 0.25% C. When the temperature of the bath has reached 2850 F, the carbon content is reduced to about 0.05 to 0.10% by the addition of nickel oxide. The reaction between this nickel oxide and the carbon dissolved in the molten metal produces ▮ vigorous evolution of carbon monoxide gas, carrying with it most of the hydrogen gas that may be dissolved in the molten metal. After the carbon content has been adjusted to the desired level, approximately 0.3% Mn is added and the metal is tapped into bottom-pour ladles where it is "deoxidized" with small amounts of titanium, boron and magnesium. The metal is then teemed into cast-iron molds provided with cast-copper bases or "stools". The standard molds are 18 in. square and 40 in. long, with a tile "head" about 5 in. high. The weight of these standard ingots is about 4600 lb. Larger ingots, weighing up to about 14,000 lb, are cast for large forgings or heavy plates.

Electric-Arc "Hot Top". The metal in the heads of the nickel ingots is maintained in the molten condition by the use of an electric-arc "hot top".[1] This eliminates the shrinkage cavities or "pipes" normally found in the heads of fully deoxidized or "killed" ingots. It also results in the production of ingots freer from center sponginess than those cast by the conventional methods. The ingots are allowed to solidify and are then processed according to methods that will be described later.

The deoxidizing elements mentioned earlier perform several specific functions in addition to the reduction of oxides.[2, 3] Magnesium is the principal reducing agent for reactions with oxides that have been dissolved by the molten metal. Magnesium also combines with minute traces of sulfur, forming magnesium sulfide. This compound is relatively harmless since it is insoluble in both liquid and solid nickel and therefore occurs as minute particles in random distribution within the grains. Titanium fixes nitrogen gas and also helps to increase the forgeability of nickel. Boron acts as a fluxing agent and improves the fluidity of the molten metal. Boron also combines with the last traces of gases not "fixed" by the other deoxidizers.

The deoxidation practice just described is the standard practice for producing the regular grade of commercially pure nickel. Special grades of nickel are produced for specific applications. For example, the nickel strip supplied to the radio industry is deoxidized only by manganese and magnesium, since the other elements are believed to impair the performance of some types of vacuum tubes.

Melting of Nickel for Rolled Anodes for Electroplating. Two principal types of rolled nickel anodes are produced for use in the electroplating industry: one is an oxidized type containing about 0.15% O as nickel oxide; the other is a carbon-bearing type containing about 0.20% C and 0.25% Si. Both types of anodes contain also traces of sulfur and copper, which are added to improve the smoothness of corrosion in the plating solutions.

The nickel charges for the oxidized anodes are melted in the same acid-lined, gas-heated, open hearth furnaces described above. Electrolytically refined nickel is used as the base material for the charges, which are melted under mildly oxidizing conditions. When the temperature of the molten metal has reached about 2850 F and the oxygen content of the melts has reached the desired level of about 0.15%, small amounts of sulfur and copper are added and the melts are tapped into bottom-pour ladles and teemed into 3300-lb ingots, 14 by 14 by 60 in.

The nickel charges for the carbon-bearing nickel anodes are melted in the same gas-heated furnaces, which are operated under reducing conditions. About 1% of charcoal is added with the charges. When the temperature of the metal has reached about 2800 F, the carbon content of the melts is adjusted to about 0.20% by the addition of nickel oxide if the carbon content has to be lowered, or by charcoal if the carbon content has to be raised. About 0.25% Si and small amounts of copper, sulfur and magnesium are added, and the melts are tapped into bottom-pour ladles and teemed into 3300-lb ingots, 14 by 14 by 60 in.

Melting of Inconel. Inconel is melted usually in a 960-cycle, coreless induction furnace having a maximum capacity of approximately 6200 lb. The furnace is lined with "Normagal" (Lamagal), which consists of 40% alumina and 60% magnesia.

The charges weigh about 4650 lb and consist of electrolytic nickel, low-carbon ferrochromium and clean Inconel mill scrap. The scrap and electrolytic nickel are melted first, followed by the ferrochromium. No slag is added to the material in the furnace. When the temperature of the bath has reached 2925 F, small amounts of aluminum, titanium, boron and magnesium are added. The metal is tapped into bottom-pour ladles and teemed into cast-iron molds with cast-copper bases or stools to produce 4600-lb ingots, 18 by 18 by 40 in., which are treated with the electric-arc hot top as described previously.

Inconel may also be melted in electric-arc furnaces on a basic magnesite "bottom". The charges weigh about 9200 lb and consist of electrolytic nickel, low-carbon ferrochromium and clean Inconel mill scrap. The scrap and electrolytic nickel are charged first with about 2% nickel oxide. When the melt is fused, a slag consisting of about equal parts of fluorspar and cement clinkers is placed on the surface of the bath and through this slag the ferrochromium is added. The oxides in the slag are then reduced by the addition of aluminum chips and the temperature of the bath is raised to 2925 F. Small amounts of aluminum, titanium, boron and magnesium are added and the melts are tapped into bottom-pour ladles, teemed into 4600-lb ingots, 18 by 18 by 40 in., treated with the electric-arc hot top.

Melting of Monel. Monel matte, containing approximately 52% Ni, 25% Cu, 22% S and 1% Fe, is crushed, ground, roasted in an oxidizing atmosphere in mechanically rabbled Edwards-type "calcining" furnaces, and is thus converted to sulfur-free oxide. The hot oxide is mixed with low-sulfur charcoal as it leaves the calciners. Later it is mixed with more carbon, in the form of tar coke, and for melting is charged into acid-lined, open hearth furnaces, heated with natural gas. After melting, the Monel is duplexed for final refining into basic-lined, electric-arc furnaces of 20-ton capacity. The sulfur content of the Monel

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charges is reduced to approximately 0.005% by refining in these electric furnaces under carbide slags, consisting of approximately equal parts of lime and fluorspar with a small amount of carbon being added in the form of ground electrode dust. After the sulfur has been removed, the carbon content of the melts is adjusted to about 0.15% and the manganese content to about 1.00%. The melts are next deoxidized and "malleablized" by the addition of small amounts of silicon, phosphorus, titanium and magnesium. They are then tapped into bottom-pour ladles and teemed into cast-iron molds with cast-copper bases.

The standard molds for Monel are 14 by 14 by 60 in. long with a tile head about 5 in. long. The Monel ingots weigh about 3300 lb each, although larger ingots weighing as much as 14,000 lb can be cast where heavy plates or big forgings are to be produced. As with nickel, the metal in the heads of the Monel ingots is kept in the molten condition for some time by the use of an electric-arc hot top.

Rolling of Nickel Alloys. After they have solidified in the molds, nickel, Monel and Inconel ingots are stripped, cooled under a water spray and overhauled by milling ¼ to ⅜ in. of metal from each of the four surfaces. They are then overhauled further by chipping out any remaining surface defects with mechanical chipping machines or "billeteers". The ingots are next heated in furnaces fired with low-sulfur natural gas, and are then forged. If forgings are to be produced for subsequent machining, forging is the final hot working operation. When rolled or extruded products are to be produced, the ingots are forged to blooms and are again overhauled by chipping on billeteers to remove the last traces of surface defects which may have developed during forging. The blooms are reheated in furnaces fired with low-sulfur natural gas and are then hot rolled to billets or sheet bars on a 3-high, 24-in. reversing mill. The billets and sheet bars are again overhauled by chipping or grinding, and are finally hot rolled to rods, sheets, strip, shapes, or extruded into tubing shells.

Nickel is generally heated to 2300 F, Monel to 2150 F, and Inconel to 2300 F before forging or hot rolling. The finishing temperatures for hot working vary greatly with the size and shape of the product, but Monel and nickel can generally be hot worked at 1200 F or lower. Inconel is generally not hot worked below 1600 F.

For some applications, the nickel alloys may be shipped in the hot rolled condition, or they may be annealed, pickled and cold rolled or cold drawn to produce rods, sheets, strip, wire or tubing.

In addition to the standard grades of nickel, Monel and Inconel described above, a number of modifications of these alloys are produced also, including age hardenable alloys and other special materials. The melting and processing methods for these special alloys are generally similar to those employed for the standard grades of nickel, Monel and Inconel.

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The Hot Forging and Hot Bending of Nickel and Nickel Alloys

By W. F. Burchfield*

When correct procedures are followed, common nickel alloys are readily forged, either in dies or by hand methods, into almost any shape that can be forged in steel. However, since these materials are inherently stronger and stiffer than steel at the forging temperature, success in hot working operations depends more on having the proper conditions of heating. These conditions involve not only the temperature and duration of heating, but also the control of furnace atmosphere by correct combustion of suitable fuels.

The nominal compositions of the alloys discussed in this article are listed in Table I.

Table I. Chemical Compositions of Nickel Alloys

Material	Nominal Composition, per cent
Nickel	99+ Ni
Monel	67 Ni, 30 Cu, 1.5 Fe, 1 Mn
"K" Monel	66 Ni, 30 Cu, 3 Al
"Z" Nickel	94 Ni, 4.5 Al
"D" Nickel	95 Ni, 5 Mn
80 Ni—20 Cr	80 Ni, 20 Cr
Inconel	80 Ni, 15 Cr, 5 Fe
60 Ni—15 Cr	60 Ni, 15 Cr, 25 Fe
Hastelloy A	56 Ni, 22 Mo, 22 Fe
Hastelloy B	62 Ni, 32 Mo, 6 Fe
Hastelloy C	53 Ni, 19 Mo, 17 Cr, 6 Fe, 5 W

Fuels. The susceptibility of the nickel alloys to intergranular attack by sulfur at high temperatures necessitates the use of a fuel that contains very little sulfur.

Natural gas, almost free from sulfur and with a high Btu value, is the most desirable gaseous fuel. City gas, usually very low in sulfur, is also satisfactory, particularly for small furnaces where its good qualities justify the relatively higher cost per Btu. Two other excellent fuels are propane and butane, although butane must be preheated to gasify it before combustion. Propane in cylinders is convenient for occasional heating for forging, hot bending or riveting.

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Oil, the fuel most generally used in forge shops, should be purchased on a specification limiting the sulfur content to 0.5% max. The heavier varieties obtained under such a specification seldom exceed 0.2% S and the lighter distillates are virtually free from sulfur. Burners through which low-pressure air is supplied and utilized are superior to both the high-pressure air and the steam-injector types.

Solid fuels such as coal and coke are unsatisfactory because of the difficulty in maintaining proper heating conditions, inflexibility in the control of heat and the presence of sulfur in excessive amounts.

Heating Temperature and Time. Figure 1 shows the recommended temperature ranges for heavy forging, hot bending and "high-tensile" forging.

During the heating of nickel alloys, the furnace should be maintained at a temperature about 50 F higher than that at which the work is to be removed. In no instance should the work be at less than 2000 F when removed for heavy forging or severe bending.

These materials should not be held in the furnace longer than is necessary to heat the piece to the desired temperature, uniformly from surface to core. It is not possible to give a set of inflexible rules to govern the duration of heating, because furnaces and furnace operation may vary widely; however, Fig. 2 shows the approximate total time desirable between charging nickel alloys into a furnace at temperature and removing them for forging.

Furnace Atmosphere. The furnace atmosphere should be free from sulfur and always slightly reducing, with 2% or more of carbon monoxide. Although there is no maximum limit to the amount of carbon monoxide or free carbon that may be tolerated, the closer the atmosphere is to the neutral condition, the easier it is to maintain the required uniform temperature.

A most harmful condition is encountered when the atmosphere fluctuates between reducing and oxidizing. For this reason, the stack dampers should be closed wholly or partially, to force the gases out through any openings in the furnace and thus prevent the entrance of air.

It is important that complete combustion take place be-

fore the mixture of fuel and air comes in contact with the metal. If the furnace design prevents this condition, then steel plates should be placed so as to protect the nickel alloy from direct impingement of the flame.

thoroughly and uniformly heated, the bar is removed, water quenched or air cooled and bent cold through 180 deg. The absence of surface rupture at the bend indicates that the heating conditions are safe. If no surface ruptures occur on

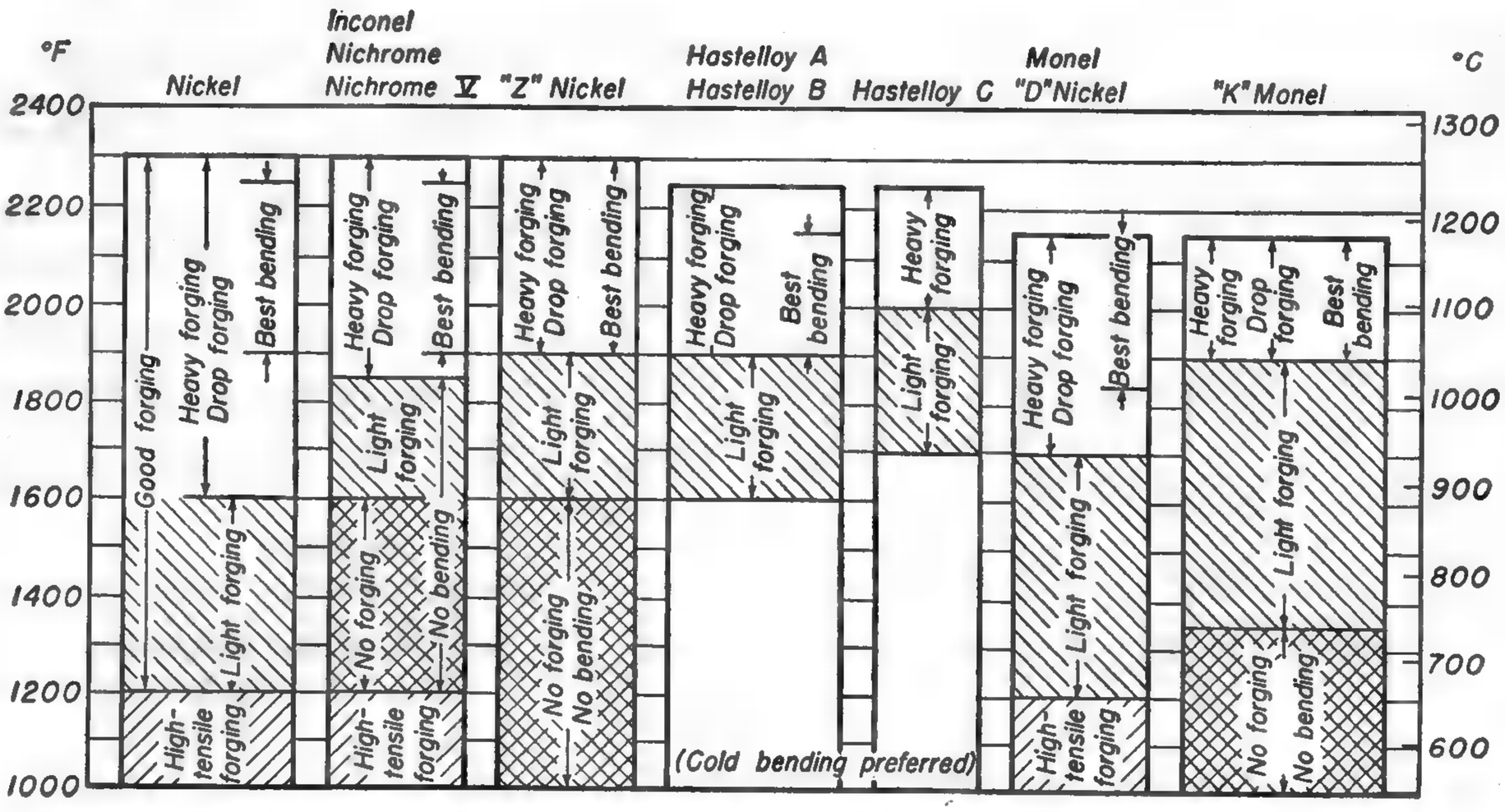

Fig. 1 Recommended temperature ranges for forging and bending nickel and nickel alloys

Quenching. Although it is not essential to cool rapidly or to quench most of the nickel alloys immediately after forging, this procedure is usually desirable when possible. "K" Monel and "Z" Nickel, which are precipitation hardening alloys, must be quenched, because if these alloys are allowed to cool slowly through their precipitation range (1100 to 900 F), they will harden to some extent in the center of the piece and may develop cracks. The Hastelloy alloys are also capable of age hardening, but the process is more sluggish than in "K" Monel and "Z" Nickel, and either quenching or air cooling may be employed. The quenching of alloy forgings that cannot be precipitation hardened, results in the following important advantages: (1) pickling is facilitated, particularly when the quenching bath contains 2% by volume of alcohol; (2) finished pieces can be removed more easily from around the hammer; (3) in forgings of large cross section, slightly higher mechanical properties can be obtained than would result from slow cooling.

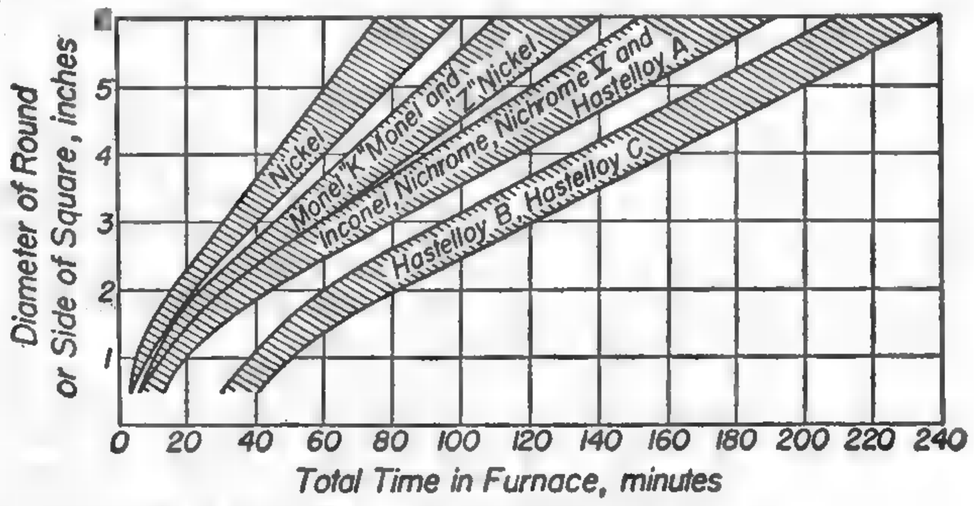

Fig. 2 Approximate duration of heating nickel and nickel alloys for forging

Checking Forging Conditions. After the furnace is at temperature and the furnace atmosphere is adjusted for a production run, it is advisable to make a pilot run for checking the hot forming setup. A small bar of the material to be forged (with oxide removed from the surface) may be placed in the furnace and brought up to temperature. When a second specimen, this time bent hot through 180 deg immediately after pulling, the temperature may be considered satisfactory for forging.

It is extremely important to prevent these nickel alloys from coming in contact with sulfurous atmospheres and with sulfur from other sources during forging or hot forming. Sulfur may be contained not only in the fuel but also in the cinder and slag that accumulate on the hearth. To prevent contact with this accumulation, the work material should be supported above the hearth on rails or other convenient shapes. Before the metals are heated, all sulfate salts, sludge and dirt remaining from a sulfuric acid pickling operation should be removed completely by washing. Marking paints are seldom suspected as sources of sulfur, yet they usually contain sulfide pigments that may lead to local but severe damage. Sand to be used in the bending of pipe should be of the washed variety, high in silica and as free as possible from pyrites and mineral sulfates.

Die Material. Alloy steel is essential to meet modern production requirements for die blocks.

Two widely used die block materials are: (1) Ni-Cr-Mo steel containing 0.40 to 0.60% C, 1.25 to 2% Ni, 0.5 to 0.8% Cr, and 0.25 to 0.35% Mo, and having a hardness ranging from Rockwell C 45 to 55, depending on the depth of the die depression; and (2) Cr-Mo steel containing 0.35 to 1.0% C, 5 to 5.25% Cr, and 1 to 1.75% Mo (sometimes containing also 1 to 1.5% W), and having a hardness ranging from Rockwell C 45 to 50.

In drop forging the nickel alloys, dies will remain serviceable while producing from 3000 to 10,000 pieces, depending on the size, shape and tolerance to be maintained.

Trimming dies for cold or hot trimming may be of 18-4-1 high speed steel containing 0.50 to 0.60% C and hardened to Rockwell C 58 to 60. Clearance for most hot trimming may be about $\frac{1}{16}$ in. *on the side,* and cutting edges are ground with considerable back rake.

Lubricants. The tendency to stick in the die is slightly greater in the nickel alloys than in carbon steel. Swabbing the dies with a mixture of sulfur-free grease and graphite (tallow and bone black) or grease of the type used in roll necks for hot rolling mills, insures proper clearing of the work material from the dies.

Annealing Nickel and Nickel Alloys

By W. A. Mudge*

ANNEALING involves a sequence of heating and cooling operations and usually implies slow cooling. Applied to metals and alloys, it is a process of heating at a predetermined temperature for a definite time, followed by cooling, to produce a change in mechanical properties. For some materials, such as steel, cooling must be slow; for others, such as nickel and copper, it may be either rapid or slow; for a few materials, such as the precipitation hardening alloys, cooling must be rapid.

For the nickel alloys, annealing is usually a complete or partial softening as a result of recrystallization; or, it may be a slight hardening, as a result of equalization of stress. The following are illustrations.

Soft Annealing (Annealing). Nickel and nickel alloys that have been hardened by cold working operations, such as rolling, deep drawing, spinning, severe bending and the like, require softening before cold working can be continued. The thermal treatment that will produce this condition is known as annealing, or soft annealing.

Temper Annealing (Partial Annealing). Work-hardened nickel materials may be heated at a temperature, and for a period, sufficient to accomplish partial softening only. This temper annealing, semi-annealing, or partial annealing is useful only for special processes.

Stress-Equalizing Annealing. Work-hardened nickel materials may be heated at a temperature that is too low to effect any softening, but that will equalize or homogenize stresses in the material and thereby increase mechanical properties. This is known as stress-equalizing annealing. The optimum temperature depends on the manner in which the metal or alloy has been work hardened. Cold worked metals require a lower temperature than hot worked metals. The thermal treatment produces a considerable increase in mechanical properties, especially in the proportional and elastic limits and in proof stress, without appreciable change in elongation and reduction of area. Often this thermal treatment is described incorrectly as normalizing.

The data for Monel (67% Ni, 30% Cu, 1.4% Fe, 1% Mn) in Table I illustrate the effects of these three thermal treatments.[1] Heating at 392 to 572 F produced stress-equalizing annealing with a large increase in proportional limit; heating at 752 to 1112 F gave temper annealing; and heating at 1382 F resulted in soft annealing.

Fuels. Nickel and nickel alloys are sensitive to attack by sulfur at annealing temperatures, and more so in reducing than in oxidizing atmospheres. An ideal fuel contains no sulfur, but such fuel is not available generally. Consequently care must be taken to effect combustion so as to eliminate or minimize the danger of sulfur embrittlement.

Electricity, natural gas and hydrocarbons, such as methane, propane, and butane, are ideal sources of heat. The gaseous fuels can be burned with incomplete combustion, thereby producing a satisfactory reducing atmosphere for bright annealing.

City gas, light distillate oils, and other liquid or gaseous fuels having a maximum sulfur content of 0.5% are suitable fuels when provisions are made in the design and construction of the furnace to effect complete combustion before the hot gases strike the metal.

Fuel oils, coal and coke, which contain more than 0.5% S, are not suitable fuels except when the metal is protected completely from contact with the products of combustion. Therefore such fuels can be used as a source of heat only in box or pot annealing methods, or for annealing baths of molten salts.

Bright Annealing. For soft annealing and for temper annealing nickel and the nickel alloys, the temperatures required are sufficiently high to cause slight surface oxidation unless a reducing atmosphere is provided. If oxidation is not important, the atmosphere need be sulfur-free only—though preferably not strongly oxidizing.

During annealing and subsequent cooling, a reducing atmosphere can be maintained as follows:

1 By regulating the fuel and air supplies so as to secure incomplete combustion and produce an atmosphere containing carbon monoxide or a mixture of carbon monoxide and hydrogen.

2 By introducing into the combustion chamber of the furnace a reducing gas such as hydrogen, with or without carbon monoxide, or a mixture of a reducing gas with an inert gas, such as hydrogen with nitrogen.

3 By burning charcoal in the furnace. Charcoal should always be prebaked for at least 3 hr at temperatures of 1200 to 1500 F to eliminate adsorbed moisture and carbon dioxide.

Bright annealing is more economical than oxidizing annealing, because it eliminates the expense of subsequent pickling[2] or grinding. For that reason, it is generally used for nonferrous materials. Typical bright-annealing atmospheres are described in Table II.[3]

The conditions for bright annealing should be maintained during heating, regardless of the method used for cooling. If facilities are available, nickel and the nickel alloys may be quenched in a 2% (by volume) solution of denatured alcohol. This will reduce the "oxide flash" formed by the oxygen of the air during the transfer from the furnace to the quenching tank.

Table I. The Effect of Annealing Temperature on the Mechanical Properties at Room Temperature of a Cold Drawn Monel Rod 1½ in. in Diam (20% reduction)

Temperature, deg Fahr, (3 hr)	Proportional Limit (0.00% offset), psi	Yield Point (0.5% elongation under load), psi	Tensile Strength, psi	Elongation in 2 in., per cent	Hardness, Rockwell B
None, as cold drawn ...	45,000	99,425	108,500	20.5	[illegible]
392	62,500	103,200	111,200	20.0	100
482	67,500	103,750	113,250	20.0	100
572	69,825	101,150	112,625	20.8	99
662	66,500	97,850	111,575	22.2	98
752	60,000	91,100	110,000	25.2	97
932	58,000	81,000	103,350	27.0	95
1112	52,500	73,125	99,250	30.8	91
1292	22,500	34,000	84,625	44.2	69
1382	20,000	33,750	83,625	43.5	66

The chromium oxide formed on Inconel cannot be reduced by quenching in alcohol. It can be removed best by pickling, according to the appropriate procedures described on page 1040.

Soft-Annealing Methods. The chemical compositions of nickel alloys are given in Table III. Annealing procedures are summarized in Table IV.

The differences in chemical composition among nickel and the nickel alloys require modifications in annealing temperatures as well as in furnace atmospheres. Nickel should be annealed at lower temperatures than Monel, and Nichrome or Hastelloy A requires a higher temperature. The precipitation hardening alloys must be cooled rapidly after annealing if maximum softness is desired.

Usually existing equipment must be used with or without modification, more often the latter. In such instances, control of temperature and atmosphere must be provided. If new equipment is to be added, it can be designed to produce the desired results.

Four soft-annealing methods in general commercial use are described in the following paragraphs.

Open Annealing. This method is used most often. The material to be annealed is heated at the selected temperature and protected from oxidation by the products of combustion in a fuel-heated furnace, or by a reducing gas introduced into an electric furnace. Temperature control is critical since the annealing period is short. During preliminary heating of the furnace, the burners may be adjusted to give optimum combustion; but, before charging, the air supply should be reduced to give the excess of reducing gases required. Also, the top vents or dampers should be closed or partially closed to give a positive gas pressure over the hearth and thereby prevent leakage of air.

Closed (Box) Annealing. Box or pot annealing requires more time than open annealing because of the lower temperatures used. Temperature control is less critical than in open annealing. In most instances, the weight of the container exceeds that of the work material; so the amount of fuel required, the heating time and the cost are greater than in open annealing. Small pressed parts, rivets,

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Table II. Atmospheres for Bright Annealing

Atmosphere	Nickel and Nickel-Copper Alloys	"K" Monel and "Z" Nickel	Alloys Containing Chromium and Molybdenum
1 Produced by incomplete combustion of natural gas or Generated separately by gas-cracking and introduced into annealing furnace	Satisfactory	(a)	(a)
2 Produced by incomplete combustion of city gas (water gas, not coke-oven gas)	Satisfactory	(a)	(a)
3 Hydrogen-nitrogen atmosphere from cracked ammonia	Satisfactory DP −30 C(b)	Satisfactory DP −50 C	Satisfactory DP −50 C
4 Hydrogen (tank or electrolytic)	Satisfactory DP −30 C	Satisfactory DP −50 C	Satisfactory DP −50 C

(a) Bright annealing is not possible. (b) Dew point (DP)

coiled wire and similar work are annealed in boxes because of greater ease in handling.

Bright annealing of nickel and the nickel-copper alloys is accomplished in boxes or pots by introducing an appropriate sulfur-free, reducing gas into the container during cooling. Annealing boxes can be made of a heat-resisting alloy steel or cast iron in a wide variety of shapes and sizes. The alloys that contain chromium or molybdenum cannot be bright annealed in boxes or pots, even if pure hydrogen is used.

After the work has been charged, the boxes should be luted with fire clay or sealed with sand or other suitable refractory material. A small quantity of charcoal, prebaked at 1200 to 1500 F for 3 hr to remove occluded gases, should be packed in the box at points where air could enter. Reducing gas is admitted to the box immediately when the box is withdrawn from the furnace, or when the burners are shut off. Following annealing, the flow of gas should be regulated to maintain a positive pressure within the box; if the gas is combustible, it will burn gently at all outlets.

Table III. Chemical Compositions of Nickel Alloys

	Percentage									
	Ni	Cu	Fe	Al	Mn	Cr	Mo	W	Si	C
Nickel	99+	...	...	...	...	...	...	...	...	...
"L" Nickel	99+	...	...	...	...	...	...	...	...	...
"D" Nickel	95	...	...	...	5	...	...	...	...	...
"Z" Nickel	94	...	...	4.5	...	...	...	...	...	...
Monel	67	30	1.5	...	1	...	...	...	...	...
"K" Monel	66	30	...	3	...	...	...	...	...	...
"KR" Monel	66	30	...	3	...	...	...	...	...	0.25
"S" Monel	63	30	2.0	...	0.5	...	...	...	4.0	0.1
80 Ni—20 Cr	80	...	...	...	...	20	...	...	...	...
Inconel	80	...	5	...	...	15	...	...	...	...
60 Ni—15 Cr	60	...	25	...	...	15	...	...	...	...
Illium G	58	6	6	...	1.2	22	6	...	0.6	...
Hastelloy A	56	...	22	...	...	...	22	...	...	...
Hastelloy B	62	...	6	...	...	...	32	...	...	...
Hastelloy C	53	...	6	...	...	17	19	5	...	...
Hastelloy D	85	3	...	...	...	...	...	...	10	...

Salt Bath Annealing. This method is used for special work with small parts. Inorganic salts, such as chlorides and carbonates of sodium, potassium and barium, which are relatively stable at temperatures considerably above their respective melting points, are fused in large metallic or refractory containers by any convenient source of heat. Steel pots are satisfactory containers when used at temperatures up to about 1300 F; at higher temperatures, heat-resisting Fe-Ni-Cr alloy pots or refractory containers should be used. Excessive fuming of the bath is an indication of its maximum usable temperature.

Particular care must be exercised to remove all traces of sulfur from the fused salts in order to prevent embrittlement of the work. This may be accomplished in 2 to 3 hr by adding to the fused salts a small amount (1 lb or more) of a 75 to 25 mixture (by volume) of powdered borax and powdered charcoal. If small test pieces of nickel strip or wire are not embrittled after 3 or 4 hr in the purified salt bath, the desulfurizing treatment has been sufficient.

The material to be annealed is placed in the molten salts and absorbs heat rapidly. After being annealed, the work metal is quenched in water to free it from particles of the salt mixture. The annealed material will not be bright and must be flash pickled.[2]

Electrical-Resistance Annealing. This also is a special method. When an electric current is passed through the material to be annealed, the material acts as a resistor and is heated rapidly.

The method has seldom been satisfactory. Temperature control is difficult unless the work material is uniform in cross section, and it is extremely difficult to provide a suitable reducing atmosphere for bright annealing. The results are generally irregular.

Temper Annealing. Temper or partial annealing is limited to light sections and is usually applied only to strip and wire. It has value for operations where fully annealed material is not required. Any of the aforementioned methods of annealing may be used, although the continuous method is best suited for the purpose. Careful regulation of the time at temperature is essential. The data in Table I illustrate the results obtainable.

Stress-Equalizing Annealing. Cold worked and hot worked nickel and nickel alloys require a low-temperature thermal treatment to develop the optimum combination of strength and ductility for each metal, and to insure against distortion and warping from subsequent machining. The proper temperature to be used depends on the nature of the preliminary fabrication or working.

Table IV. Annealing Conditions for Nickel and Nickel Alloys

Material	Soft Annealing: Open Annealing Temp, deg Fahr	Soft Annealing: Open Annealing Time, min	Soft Annealing: Closed Annealing Temp, deg Fahr	Soft Annealing: Closed Annealing Time, hr	Stress-Relief (Temper) Annealing Temp, deg Fahr	Stress-Relief (Temper) Annealing Time, hr	Stress-Equalizing Annealing Temp, deg Fahr	Stress-Equalizing Annealing Time, hr
Nickel and "L" Nickel	1500-1700	6-1[a, b, c]	1300-1400	3-1[a, b, c]	1000-1100	3-1[a, b, c]	525-600	3-1[a, b, c]
"D" Nickel	1600-1800	10-1[a, b, c]	1400-1500	3-1[a, b, c]	1000-1100	3-1[a, b, c]	525-600	3-1[a, b, c]
"Z" Nickel	1600-1900	6-1[c]	1500-1600	3-1[c]	1150-1200	1½[c]	525-600	3-1[a, b, c]
Monel	1600-1800	10-1[a, b, c]	1400-1500	3-1[a, b, c]	1000-1100	3-1[a, b, c]	525-600	3-1[a, b, c]
"K" Monel and "KR" Monel	1600-1800	10-1[c]	1500-1600	3-1[c]	1150-1200	1½[c]	525-600	3-1[a, b, c]
"S" Monel			1600	1[c]				
80 Ni—20 Cr Alloy and Inconel	1800-2000	15-2[a, b, c]	1600-1800	3-1[a, b, c]	1100-1300	3-1[a, b, c]	700-900	3-1[a, b, c]
60 Ni—15 Cr Alloy	1600-2000	15-2[a, b, c]	1600-1800	3-1[a, b, c]	1100-1300	3-1[a, b, c]	700-900	3-1[a, b, c]
Illium G			1700-1900	3-1[a, b]				
Hastelloy A & Hastelloy B	2100-2150	90-20[a, c]	1700-1900	3-1[c]				
Hastelloy C	2200-2250	180-40[a]	1700-1900	3-1[c]				
Hastelloy D			1700-1900	3-1[a, b]				

(a) Furnace Cool (b) Air Cool (c) Quench

Springs made from heavily cold drawn wire or cold rolled strip should be stress-equalized annealed after coiling. The preferred treatments are 1 hr at 575 F for nickel and nickel-copper alloys, and 1 hr at 850 F for the alloys that contain chromium or molybdenum.

Supplementary Items. *Pyrometry.* Accurate control of annealing temperature cannot be overemphasized. Satisfactory indicating, controlling, recording and controlling-recording pyrometers are available. Iron-constantan and chromel-alumel thermocouples should be changed every three months; noble metal thermocouples may be used as long as their accuracy is not impaired. All thermocouples should be checked daily for accuracy.

The Effect of Cold Work Previous to Annealing. The greater the amount of cold work to which the material has been subjected, the lower is the temperature required to produce the same degree of softness without increasing grain size, and the shorter is the time required at any one temperature. At 1200 F, for example, hard Monel that has been cold worked 40% softens more rapidly than half-hard Monel that has been cold worked 20%.

The amount of any type of previous cold work also has a critical influence on the ductility of nickel and nickel alloys after annealing. If only a small amount of cold work is done (for example, approximately 10% reduction) full ductility for deep drawing and spinning cannot be restored by annealing, even though the hardness is reduced to that of soft material. A minimum of approximately 20% of cold working is required between anneals to insure maximum ductility and softness following annealing.

The Effect of Rate of Cooling. Neither slow cooling, whether in or out of the furnace, nor rapid cooling by quenching, has any specific effect on the softness of the annealed, solid-solution nickel materials. Therefore, rapid cooling is preferable, both to economize time and to minimize the amount of oxidation. The age hardenable alloys must be cooled rapidly by quenching from their annealing temperatures.

Control of Grain Size and the Effect on Fabrication. Coarse-grained material is unsuitable for most cold working operations. A coarse grain in the high-nickel materials cannot be refined by thermal treatment. It can be removed only by cold working in excess of 50%, followed by soft annealing. Maximum workability is obtained with material that has been annealed without allowing appreciable grain growth to occur. The average grain diameter should not exceed 0.0025 in. (0.064 mm). This gives the best combination of ductility to permit extensive deformation, strength to withstand the action of the tools, and surface quality to facilitate polishing.

The Effect of Fluctuating Atmospheres During Annealing. If nickel and the nickel alloys are heated in atmospheres that fluctuate between oxidizing (excess of air) and reducing (excess of carbon monoxide or hydrogen), severe intercrystalline attack will occur with resulting embrittlement, even though the atmosphere is sulfur-free. This type of embrittlement can be prevented by maintaining a constant and sufficient excess of a reducing, gaseous atmosphere during heating and cooling. The alloys containing chromium or molybdenum are affected less than the nickel and nickel-copper alloys.

Dead-Soft Annealing. When the nickel alloys are annealed at higher temperatures and for longer periods, a condition commonly described as "dead-soft" is obtained, and hardness numbers will result that are 10 to 20% lower than those for the "soft" condition. This cannot be accomplished without increasing the grain size of the metal. Therefore, this treatment should be used only for those few purposes in which grain size is of little importance.

Torch Annealing. Some large equipment is hardened locally by the fabricating operations. If the available annealing furnace is too small to hold the work piece, the hardened sections can be annealed with the flames of oil or acetylene torches adjusted so as to be highly reducing. This method is not a good one for general use because it gives irregular and insufficient annealing, with heavily oxidized surfaces. However, if it is the only method available, heating must be gradual and can be facilitated by temporary brick construction to localize the heat and to permit higher temperatures to be attained. The work should be warmed gently at first, with sweeping motions of the torch, and should not be brought to the annealing temperature until sufficient preheating has been done to prevent cracking as a result of sudden release of stresses.

Protection From Contamination by Foreign Material. Many of the lubricants used for deep drawing and spinning contain sulfur or lead. Unless these elements are removed before annealing, they will cause embrittlement. Removal can be accomplished by washing with hot trisodium phosphate solution or with volatile, organic, grease-removing solvents such as carbon tetrachloride or trichlorethylene. Lubricants of any type should be entirely removed from the material before annealing. Paint marks also, and other adherent substances that may contain sulfur, lead or similarly harmful ingredients, should be removed by appropriate methods before annealing.

References

1 Peter R. Kosting, Stress-Relief Annealing of Monel Plate, Proc ASTM, 36, 222–30 (1936)

2 W. F. Burchfield, Pickling and the Removal of Oxide From Nickel and Nickel Alloys, p 1040 in this Handbook

3 W. A. Mudge, The Fabrication and Treatment of Nickel and High-Nickel Alloys, Trans Can Inst of Mining and Met, 46, 506–34 (1943)

The Age Hardening of Nickel Alloys

By W. A. Mudge*

THE addition of magnesium, beryllium, aluminum, silicon, titanium, and molybdenum to nickel and the high-nickel materials, separately or in combinations, results in alloys that show appreciable response to age hardening. The commercial alloys available are "K" Monel, "KR" Monel, "S" Monel, "Z" Nickel, Hastelloy A, Hastelloy B and Hastelloy C. The chemical compositions of these age hardening nickel alloys are given in Table I.

The age hardening treatments for these materials differ from those required for steels and for the aluminum-base alloys.[1] The nickel materials are soft when quenched from temperatures ranging from 1450 to 2225 F; however, they may be hardened by holding at temperatures of 1100 to 1600 F and then cooling. Quenching is not a prerequisite to aging; the alloys can be hardened from the hot worked and cold worked conditions, as well as from the soft condition. The temperatures used for the three nickel-molybdenum-base alloys are detrimental to corrosion resistance.

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Age hardening procedures are summarized in Table II.

Table I

Chemical Compositions of Age Hardening Nickel Alloys

	Percentage								
	Ni	Cu	Al	Si	Fe	Mn	Mo	Cr	W
"K" Monel	66	30	3	...	...	...	...	...	...
"KR" Monel	66	30	3	...	...	...	...	...	...
"Z" Nickel	94	...	4.5	...	...	...	...	...	...
"S" Monel	63	30	...	4.0	2.0	0.5	...	...	...
Hastelloy A	56	...	...	...	22	...	22	...	...
Hastelloy B	62	...	...	...	6	...	32	...	...
Hastelloy C	53	...	...	...	6	...	19	17	5

Nickel alloys are usually hardened in sealed boxes placed inside a furnace, although small horizontal or vertical furnaces without boxes may be used. The box or furnace should hold the parts loosely packed, yet afford a minimum of excess space. Electric furnaces provide the optimum

Table II. Age Hardening Treatments for Nickel Alloys

Material	Condition	Temp, deg Fahr	Time at Temp, hr	Cooling
"K" Monel and "KR" Monel	Soft: 140–180 Brinnell, 75–90 Rockwell B Moderate cold work: 175–250 Brinell, 8–23 Rockwell C Full cold work: 260–315 Brinell, 25–32 Rockwell C	1080–1100 1080–1100 980–1100	16 8–16(b) 6–10(b)	Not faster than 15°F per hr, down to 900 F.(a) Furnace cool or air cool below 900 F.
"Z" Nickel	Soft: 140–180 Brinell, 75–90 Rockwell B Moderate cold work: 200–300 Brinell, 15–31 Rockwell C Full cold work: 290–375 Brinell, 30–40 Rockwell C	1080–1100 1080–1100 980–1000	16 8–16(b) 6–8(b)	Not faster than 15°F per hr, down to 900 F.(a) Furnace cool or air cool below 900 F.
"S" Monel	As-cast: 275–350 Brinell Softened: 150–200 Brinell	1080–1100	4–6	Rate not important. Furnace cool or air cool.
Hastelloy A and B	Soft and as-cast: 90–235 Brinell	1375–1400	168	Air cool.
Hastelloy C	Soft: 160–215 Brinell	1575–1600	8–16	Air cool.

(a) The recommendations for slow cooling will apply only when maximum hardness is required. Where hardness slightly lower than the maximum obtainable is satisfactory, the cooling rate may be increased to from 25 to 50°F per hr.

(b) Longer time for softer material; shorter time for harder material.

temperature uniformity of ±10 F and the cleanliness required for this work. Gas-heated furnaces, particularly those of the radiant-tube type, can be made to give satisfactory results. It is difficult to obtain good results from oil heating, even with muffle furnaces. All lubricants should be removed from the work before hardening.

Because of the long time of aging and the difficulty of excluding air from the box or furnace, perfectly bright hardening cannot be accomplished commercially. For semibright hardening, dry hydrogen (dew point minus 50 C) or cracked and dried ammonia (dew point minus 50 C) should be used. When bright or semibright hardening is not required, other atmospheres may be used, such as nitrogen, cracked natural gas free from sulfur, cracked city gas, cracked hydrocarbons, or a generated gas. Freedom from gases that contain sulfur is necessary to avoid embrittlement of the alloy being treated.

Salt baths are used occasionally for small parts. The hardened material is never bright and must be flash pickled to restore the natural color. Inorganic salts are used, such as chlorides and carbonates of sodium and potassium, which are relatively stable at temperatures considerably above their respective melting points. It is extremely important that the salts be free from all traces of sulfur, or the result will be embrittlement of the work. Sulfur can be removed from fused salts by the procedure described on page 1032.

Reference

1 P. D. Merica, The Age Hardening of Metals, Trans AIME, 99, 13 (1932)

Joining Nickel and Nickel Alloys

By K. M. Spicer*

THE following joining processes used for steel are applicable, with slight modification, to nickel, Monel, "K" Monel, and Inconel:

Widely Used Processes	Less Widely Used Processes
Welding	Welding
Metal arc	Inert-gas-shielded arc
Oxyacetylene (gas)	Submerged melt
Atomic hydrogen arc	Carbon arc
Resistance	Furnace brazing
Silver brazing	Brass brazing
Soft soldering	

Only the first six processes have broad application to the high-nickel materials. Each produces very satisfactory joints. The choice among these processes is determined by the corrosive environment to which the equipment will be exposed, the thickness of material being joined, the design of the piece of equipment and the design of the individual joints in the equipment. The inert-gas-shielded arc and submerged-melt welding processes, furnace brazing, and copper and brass brazing are used for special purposes only. The oxyhydrogen flame is not suitable because of its low temperature. Hammer welding is not possible because union does not occur unless the metal melts. Carbon-arc welding has almost disappeared from the field since the advent of the improved electrodes now in use for metal-arc welding.

Good mechanical properties, strength and ductility are inherent in welded joints in all materials and no treatment, either thermal or chemical (passivation), is needed afterward or recommended to retain or restore resistance to corrosion. The as-welded joints are equal to the parent metal in strength and resistance to corrosion. If thermal treatment is necessary, it can be applied without harm to the welded structure.

Since the coefficients of expansion of the high-nickel materials are almost the same as that of steel, warping and buckling resulting from a welding operation will be essentially the same as with steel in the same construction.

Surface preparation of high-nickel materials before welding, as well as the jigs and clamps used, is also essentially the same as for high-quality steel welding.

Most work is done by metal-arc or oxyacetylene welding. The practice for sheet steel is an acceptable guide in selection of the proper method, not according to the composition of the material but according to the thickness, the design of the piece, and the design of the individual joint. Metal-arc welding, if applicable, will produce less buckling than gas welding.

Surface Preparation for Joining. Electrodes and the oxyacetylene welding wires and fluxes for nickel and nickel alloys were designed for use on clean metal, such as cold rolled sheet, pickled hot rolled plate or cold drawn rod. All oil, grease, paint, marking crayon or oxide must be removed from any area to be joined. To insure satisfactory welding of hot rolled plate, hot rolled bar stock, or material that has been hot worked otherwise in processing or fabrication, it is necessary first to remove the thin, dark-colored oxide film from the immediate vicinity of the area to be welded. This can be done either mechanically by such methods as machining, sandblasting, grinding, or rubbing by hand with abrasive cloth, or chemically by pickling. When hot rolled plate is beveled by machine in preparation for making a butt joint, no further cleaning is needed, because the clean metal surface is exposed on the face of the bevel. However, if an attachment must be made by fillet welding to the surface of a hot rolled plate not cleaned previously, the oxide must be removed, preferably by light grinding either with a disk, a solid grinding wheel of fine grit, or a roll-head wheel; otherwise, difficulty may be encountered.

The sand-cast surfaces of nickel, Monel and Inconel castings need to be removed only from the areas to be welded, either by rough grinding or by machine tools.

Arc Welding. Nickel and Monel can be arc welded in all positions with the same facility as steel. Inconel can be welded in any position, but it is preferable to place the work material in position for downhand or flat welding.

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In general, the lower limit of thickness of sheet for arc welding is set at 0.037 in. but, with modern welding equipment, thicknesses as light as 0.018 in. have been welded.

The shielded-arc, metal-arc electrodes for Monel and nickel have been designed for use with d-c motor generators and will produce satisfactory joints when so used. The electrodes designed for the welding of Inconel are intended to produce satisfactory welds with either alternating or direct current.

The proper diameter of electrode for a specific application is determined by the thickness of the material and the type of joint. Generally, the diameter of the electrode should be as nearly equal as possible to the thicknesses being joined.

Manipulation of the electrodes is similar to that for heavily flux-coated mild steel electrodes; that is, the electrode should be inclined about 20 deg in the direction of welding. This position is best suited for control of the molten flux. The arc should be slightly shorter than would be used for a steel electrode of the same diameter, and a weaving motion should be used to obtain proper width and contour in the weld. Welds should never be wider than three times the diameter of the core wire.

The heat from arc welding has no detrimental effect on the parent metal; only a slight grain enlargement occurs in a narrow band at the edge of the weld. The strength and ductility of the parent metal are not altered noticeably.

Oxyacetylene Welding. Good oxyacetylene welding can be accomplished in flat, vertical or overhead positions. In order to insure uniform resistance to corrosion without galvanic effects, the welding wires are of virtually the same composition as the material being welded. A slightly reducing (carburizing) flame with a small excess of acetylene is recommended for all materials. A soft flame is preferable to the harsh or wild flame that results if too small a tip is used.

The appearance of properly made gas welds is quite similar to that of good welds in steel. Puddling should be avoided and the welding should progress steadily, with the luminous cone of flame just touching the surface of the molten pool.

During welding, the end of the filler wire should always be kept well within the protecting envelope of flame to prevent oxidation of the hot wire.

Fluxes are necessary for all materials except nickel, and usually no detrimental effect on the parent metal would result from leaving on the flux after completion of welding; however, the flux is removed for the sake of appearance. Certain corrosive mediums and applications at high temperature (more than 1000 F) require removal of the flux.

Resistance Welding. When used for nickel alloys, the resistance methods—spot, seam and flash—are much the same as when used for steel. Adjustments in technique must be made to compensate for differences in electrical resistivity and thermal conductivity. Electrode pressure must be great enough to give intimate contact. Recommended conditions for spot and flash welding nickel, Monel and Inconel are given elsewhere.[1]

Silver Brazing. Silver-brazing alloys flowing at temperatures lower than 1400 F are best for joining the high-nickel materials. Appropriate compositions are those that melt and flow in the temperature range from 1140 to 1325 F. A suitable proprietary flux is used with brazing alloys. Borax and boric acid fluxes are not protective for silver brazing, because they are not fluid at the temperatures used. The spent flux that remains after a joint has been silver brazed, is removed by dissolving in hot or cold water.

Since the temperatures required for silver brazing are in the lower end of the range used for annealing nickel alloys, the softening effect is very slight. "Z" Nickel, "K" Monel, "KR" Monel and "S" Monel may be age hardened after silver brazing.

Brazing alloys that contain phosphorus, although excellent for brass and copper, are not recommended for the nickel alloys because of an embrittling effect of the phosphorus.

Soft Soldering. Soft soldering is limited to applications where resistance to corrosion is not an important factor. Soft solder is inherently weak, and usually the strength must depend on mechanical joints—riveted, lock-seamed, or spot-welded—with the soft solder acting only as a sealing medium. The process is ordinarily limited to joints in sheet metal that is not more than 0.062 in. thick, because other processes yield stronger joints in these and heavier gages.

Only those soft soldering fluxes known within the trade as "acid" fluxes are recommended for use with nickel and nickel alloys. Rosin is not suitable, because its cleaning action is too mild. The proprietary or "cut acid" fluxes commonly used for copper are adequate for the soft soldering of nickel and Monel, but a somewhat stronger flux is required with Inconel because of the chromium oxide film that forms during heating.

Strength of Welded Joints. Joints produced by the various arc methods are as strong as the parent metal, or stronger in most instances.[2] Arc welds in nickel, Monel and Inconel will meet all requirements of the ASME Unfired Pressure Vessel Code.

Average Mechanical Properties of Welded Joints

Material	Tensile Strength, psi	Minimum Percentage Elongation in Weld
	Arc Welded	
Nickel	70,000	30
Monel	79,500	30
Inconel	98,500	30
	Gas Welded	
Nickel	60,000	35
Monel	65,000	35
Inconel	75,000	35

Joints Between Dissimilar Metals. Joints between nickel alloys and dissimilar metals or alloys may be made by soft soldering, silver brazing or welding. The process selected depends on the conditions to be encountered in service. If a material can be soft soldered, silver brazed, or welded readily, then, provided other factors are equal, it can be joined to nickel, Monel or Inconel by one or more of these methods.

Metal-arc welding with high-nickel electrodes is used widely for joining nickel and the nickel alloys to other materials. In welding dissimilar joints, it is essential that penetration be kept to a minimum; therefore, excessive current densities and puddling must be avoided. Combinations of materials that have been joined successfully are too numerous for listing here, but complete information about the various combinations is available in publications of the producers of nickel alloys.

Hard Surfacing. A number of alloys that are resistant to abrasion and able to produce a hard surface, can be applied readily to the nickel alloys. The alloys that have acceptable resistance to corrosion are most generally used.[3]

When the facing materials are being applied, the temperature of the base metal should be only slightly higher than the melting point of the hard-surfacing alloy, in order to avoid boiling and the formation of holes in the facing overlay.

Overlaying Nickel Alloys on Ferrous Material. Nickel, Monel and Inconel arc-welding electrodes may be used for the application of facings or overlays of these materials on wrought iron, cast iron, or steel. This application is used generally where openings in lined vessels must be protected or faced with material similar to that used for the lining.

Care should be taken to avoid excessive penetration into the iron or steel, in order to prevent undue dilution of the high-nickel overlay.[3] Apart from this precaution, the use and manipulation of the electrodes is the same as in the arc welding of wrought forms made from nickel materials.

References

1 Recommended Practices for Resistance Welding (Tentative), AWS Bull CL 1-46T
2 "Welding Handbook", American Welding Society, chapter 24
3 "Welding Handbook", American Welding Society, chapter 15A

Machining Nickel and Nickel Alloys

By E. L. Fowler*

THE procedures for machining nickel and nickel alloys parallel the practices used conventionally for steel.

Cutting Materials. Tools made from high speed steel, cast cobalt-base alloys, and cemented carbide are recommended for machining wrought and cast nickel and nickel alloys.

Tool Design. To ensure a firm setup, sturdy tools and rigid machines should be used for machining these tough materials. Tools should be designed so as to provide maximum support for the cutting edge and minimum resistance to chip disposal. Front and side relief angles should be just large enough to prohibit drag. When possible the tool should have a lead angle (the side cutting edge angle of a lathe tool). Rake should be sufficient to permit free cutting and disposal of tough chips. Chip breakers are not essential for machining the cast materials.

Suggested designs for tools are shown in Fig. 1 to 20 inclusive. Lathe tools should be set up on the center line of the work with a minimum overhang from the tool holder.

Cutting Compounds. Tool life is lengthened and the finish of the work material is improved by the use of a cutting lubricant. Sulfurized mineral oil of the proper consistency is the lubricant generally recommended for machining nickel and nickel alloys with high speed steel and cast cobalt-base tools. Turpentine or gasoline is recommended for drilling holes smaller than $\frac{3}{32}$ in. in diam. Soluble oil in water is recommended as the lubricant when cemented carbide tools are being used.

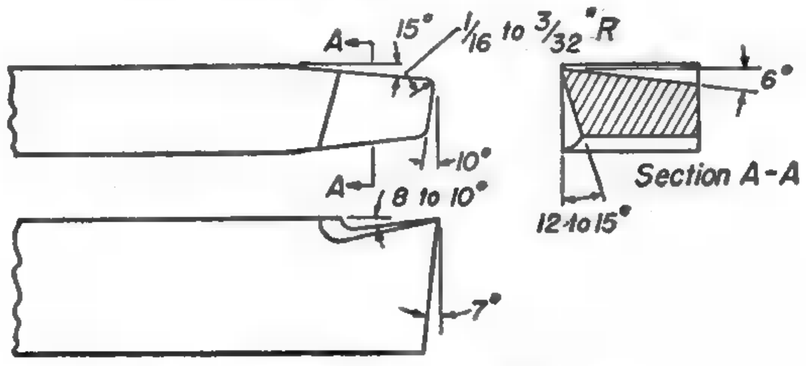


Fig. 1 Turning tool for medium work

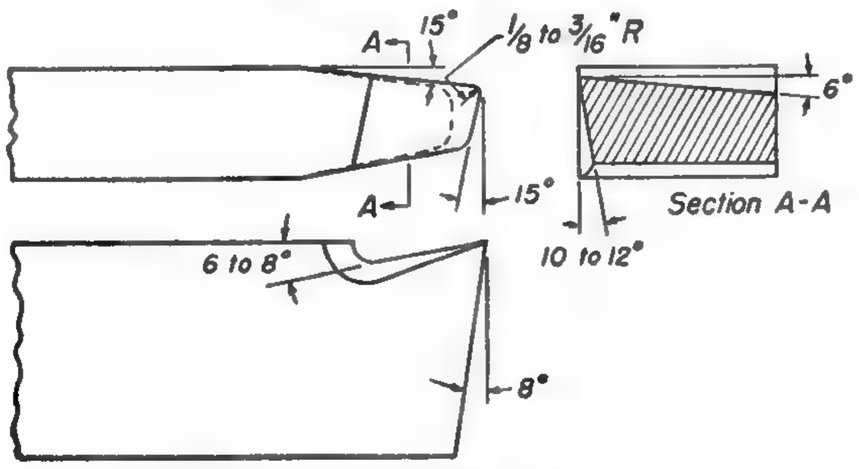


Fig. 2 Turning tool for heavy work(roughing)

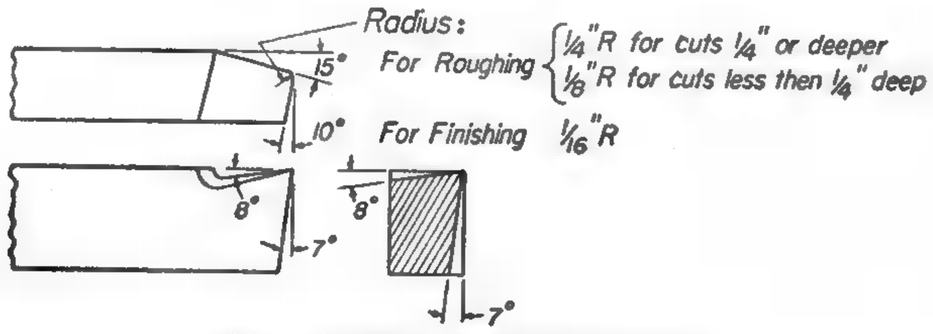


Fig. 3 General-purpose turning tool

Discoloration resulting from sulfur-bearing oil can be removed from machined parts by soaking the parts for 20 to 30 min in a cold 10% solution of sodium cyanide. *This solution is poisonous and should be handled with care.*

* Development and Research Division, The International Nickel Company, Inc., New York

All traces of the lubricant should be removed completely from machined parts that are to be subjected to high temperatures during subsequent fabrication or while in service.

Turning and Boring. The lathe setup for these operations is essentially the same as for steel. Speeds for boring should be slightly lower than those for turning, listed in Table I. Speeds and feeds for automatic screw machining are given in Table II. Representative tools for turning and boring are shown in Fig. 1 to 4 inclusive. Parting tools are illustrated in Fig. 5 and 6.

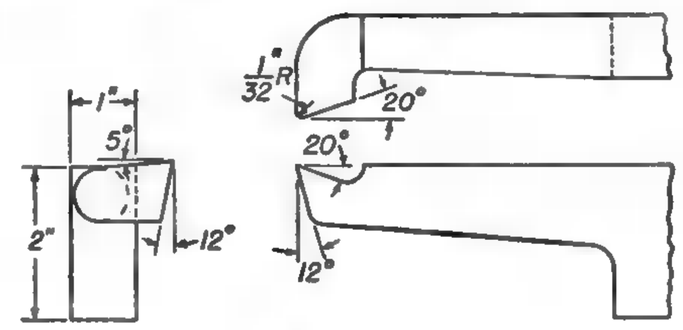


Fig. 4 Boring tool

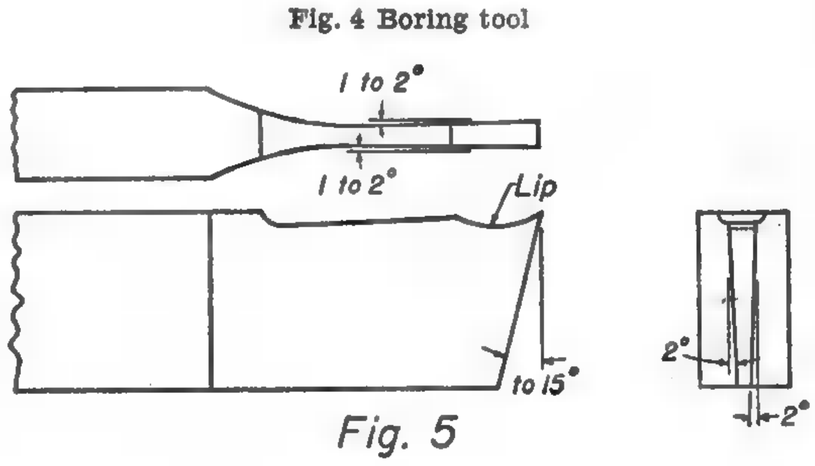


Fig. 5

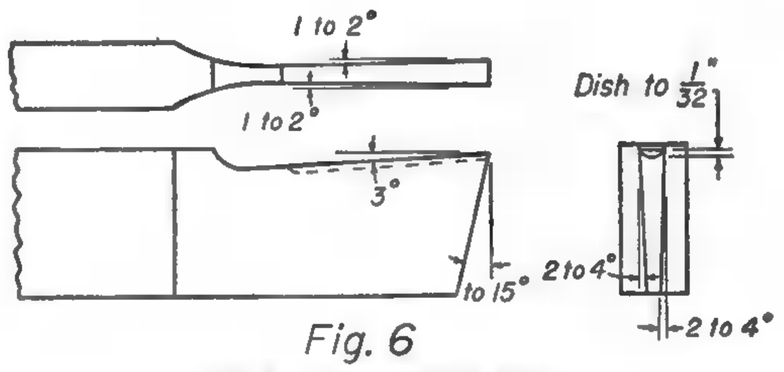


Fig. 6

Fig. 5 and 6 Parting tools

Drilling. Heavy-duty drills made from high speed steel are preferred. These drills should have heavy parallel webs and should be ground as shown in Fig. 7 to 9. Feeds and speeds for drilling are listed in Table I.

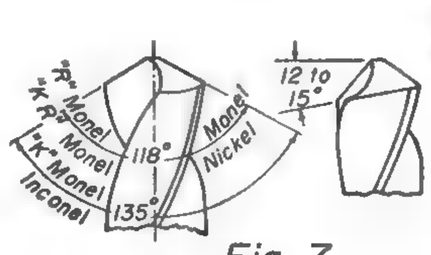


Fig. 7

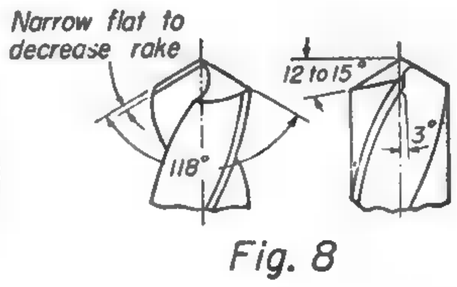


Fig. 8

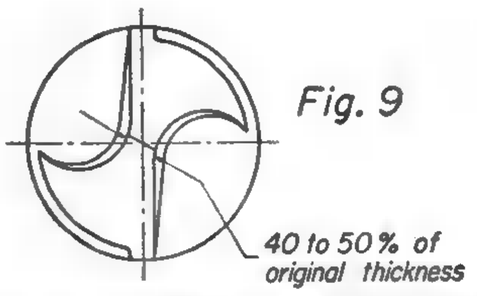


Fig. 9

Fig. 7 Standard angles for high speed steel drill
Fig. 8 Special grind for high speed steel drill for cast "S" Monel
Fig. 9 Drill grinds

Reaming. Reaming operations should not be "'pushed". High speed steel or carbide-tipped reamers are recom-

Table I. Range of Speeds for General Machining

Material	Speed, feet per minute — High Speed Steel Tools[a] — Turning[b]	Milling[c]	Drilling[d]	Tapping and Threading	Cemented Carbide Tools Turning	
			Wrought Alloys			
Monel	40 to 70	50 to 65	40 to 60	15 to 25	175 to 350	
"R" Monel	80 to 110	60 to 80	60 to 75	25 to 35	200 to 400	
"KR" Monel (unhardened)	40 to 70	50 to 65	40 to 60	15 to 25	125 to 350	
"K" Monel (unhardened)	35 to 50	30 to 45	20 to 30	10 to 15	150 to 325	
Inconel	30 to 45	30 to 45	30 to 45	10 to 15	100 to 200	
"Z" Nickel (unhardened)	30 to 45	30 to 45	20 to 30	10 to 15	100 to 250	
Nickel	40 to 70	■ to 65	40 to 60	15 to 25	200 to 350	
			Cast Alloys		Roughing	Finishing
Monel	40 to 50	40 to 50	40 to 70	15 to 25	175 to 275	225 to 325
"H" Monel	25 to 40	25 to 35	40 to 60	10 to 20	120 to 200	200 to 275
"S" Monel	13 to 35	15 to 25	20 to 30	8 to 12	75 to 125	125 to 175
Inconel	25 to 40	25 to 35	25 to 35	10 to 15	(e)	(e)
Nickel	50 to 60	40 to 60	50 to 90	15 to 25	200 to 300	300 to 350

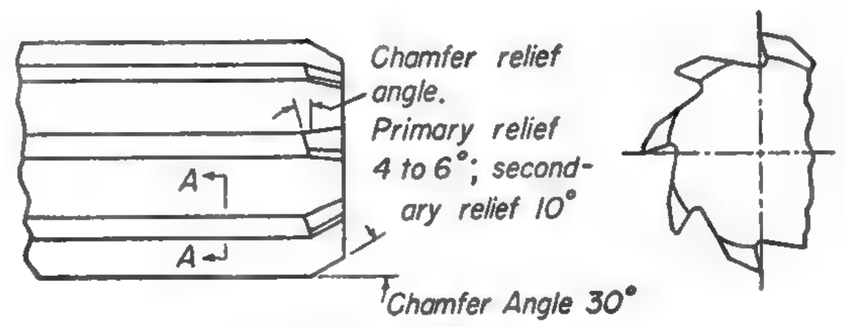
(a) Increase speeds approximately 25% when cast cobalt-base tools are being used.
(b) Feeds approximately 0.015 in. per revolution
(c) Feeds approximately 0.005 to 0.010 in. per tooth per revolution
(d) Use speeds on the minimum side of the range for drills larger than ¾ in. and conversely for drills of smaller diameter. Feed, in inches per revolution, should increase gradually with increase in diameter of drill. Feed for a 1/16-in. diam drill would be 0.001 in.; for a ¾-in. drill, 0.007 to 0.010 in.; and for larger drills, 0.010 to 0.015 in.
(e) Not determined. (Use speeds shown for "H" Monel.)

mended. These should be as short as possible. Spiral-fluted, side-cutting reamers cut more smoothly than straight-fluted reamers. Reamers should have narrow lands, only a few thousandths of an inch wide. End-cutting reamers that have a secondary chamfer relief angle between 2 and 5 deg from the end chamfer are helpful in obtaining a smooth finish. Data for grinding reamers are shown in Fig. 10. Feeds and speeds for reaming are listed in Table III.

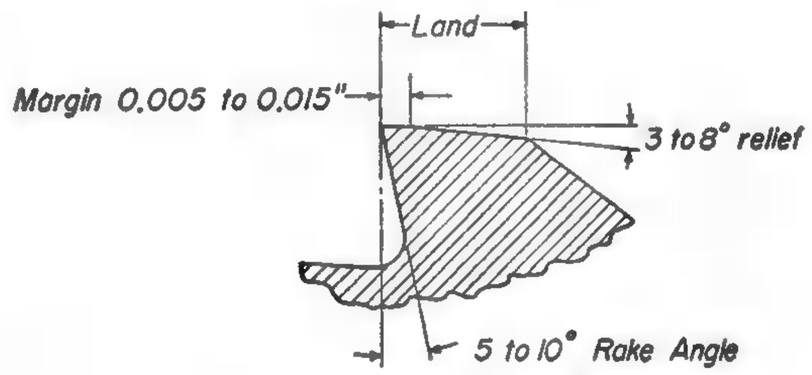
Table II. Feeds and Speeds for Automatic Screw Machining "R" Monel and "KR" Monel (Unhardened)

Tool and Operation	Width of Cut, inch	Feed, inch	Speed, ft per min — "R" Monel	"KR" Monel (unhardened)
Box Tool				
Roughing	1/32	0.006	100 to 125	60 to 80
	1/16	0.005	100 to 125	60 to 80
	⅛	0.004	100 to 125	60 to 80
Finishing	0.005	0.010	100 to 125	60 to 80
Cutting-Off Tool				
Circular Tool, Straight Tool	1/16 to ⅛	0.001	100 to 125	60 to 80
Stock less than ⅛ in. in diam	.....	0.0005	100 to 125	60 to 80
Forming Tool				
Circular	⅛ to ¼	0.0006	100 to 125	60 to 80
	⅜ to ½	0.0005	100 to 125	60 to 80
	⅝ to ¾	0.0004	100 to 125	60 to 80
	1	0.00025	100 to 125	60 to 80
Balance Turning Tool				
Turned diam less than 5/32 in.	1/32	0.006	100 to 125	60 to 80
	1/16	0.005	100 to 125	60 to 80
Turned diam more than 5/32 in.	1/32	0.012	100 to 125	60 to 80
	1/16	0.010	100 to 125	60 to 80

Tapping. Four-fluted plug or spiral-pointed taps made of high speed steel are recommended. These should have a 15-deg cutting rake angle and relief at least ⅔ the width of the land, in the angle of the thread and on the major diameter. Taps as short as possible should be used for machine tapping. Spiral-pointed taps are suggested for machine tapping through holes; plug taps are satisfactory for tapping blind holes. Skip-thread taps give excellent results in tapping holes 1¼ in. in diam or larger.



Point for end-cutting or side-cutting reamers



Tooth profile at A-A for side-cutting reamers

Fig. 10 Reamer

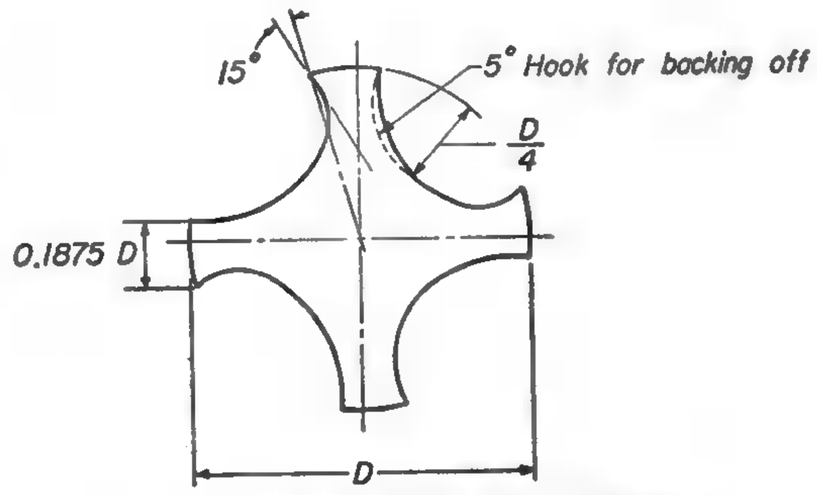


Fig. 11 Cross section of high speed steel tap

Table III. Feeds and Speeds for End-Cutting Reamers

Speed, ft per min — Monel "KR" Monel (unhardened) Nickel	"K" Monel (unhardened) Inconel	"R" Monel	Hole Diameter, inch	Feed per Revolution, inch	Material to be Removed, inch diam
25 to 35	10 to 15	30 to 40	⅛ to ¼	0.003 to 0.005	to 0.005
25 to 35	10 to 15	30 to 40	¼ to ½	0.005 to 0.009	to 0.008
20 to 30	10 to 15	30 to 40	½ to 1	0.009 to 0.020	to 0.012
15 to 20	10 to 15	25 to 35	1 to 2	1/32	1/64 to 1/32

In tapping, it is advantageous to make allowances for the toughness of the material by using a tap drill of slightly larger diameter than the standard commercial tap drill recommended for a specific thread. This practice eases the tapping operation and results in a thread of at least a 75% depth because the high ductility of these materials permits the metal to flow into the roots of the tap threads. A typical tap is shown in Fig. 11.

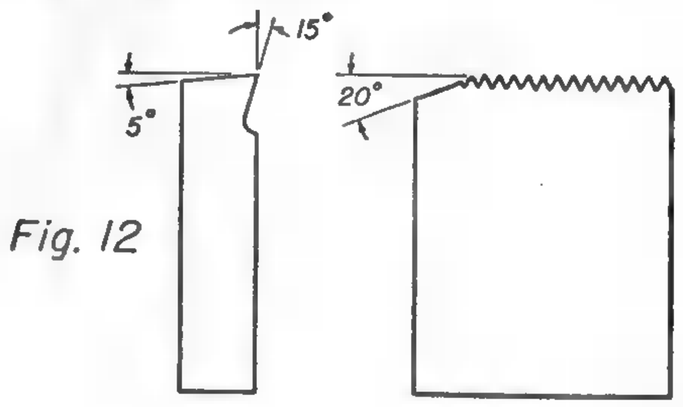


Fig. 12

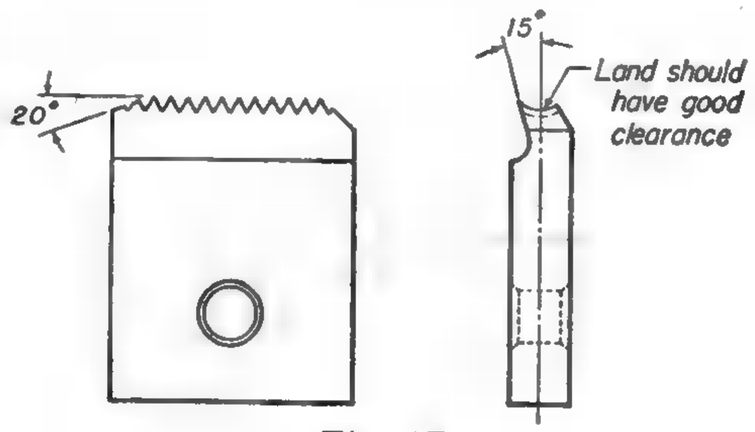


Fig. 13

Fig. 12 Thread chaser with milled type of insert
Fig. 13 Thread chaser with hobbed type of insert

Thread Chasing. Self-opening dies are preferred for thread chasing. Perfect threads can be cut with solid dies, but frequently dies are backed off before they are free and good threads are torn. The chasers should have a 15-deg rake, as shown in Fig. 12 and 13, with sufficient clearance from the cut edge to permit free cutting. A chaser-lead or throat angle of 20 deg is preferred to steeper angles. Threading speeds are listed in Table I.

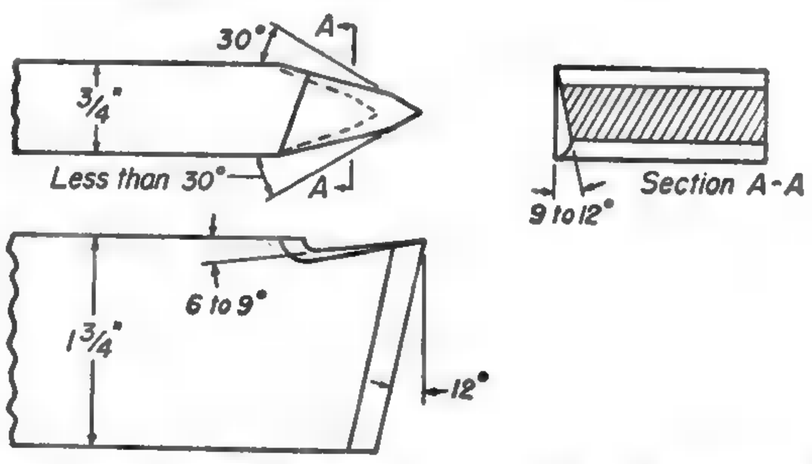


Fig. 14 Lathe threading tool for American National Form thread

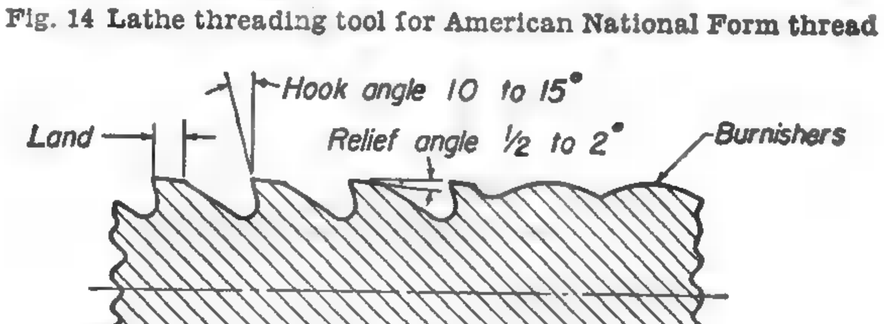


Fig. 15 Cross section of broach

Lathe Threading. The tool setup for machining threads is the same as for any other metal; that is, the tool is set straight into the metal on the cross feed with the compound set at half the included angle of the thread being cut. The depth of cut is fed with a compound feed. Figure 14 shows the recommended form of a lathe threading tool. Speeds for cutting acme threads should be about ⅔ as great as the threading speeds listed in Table I.

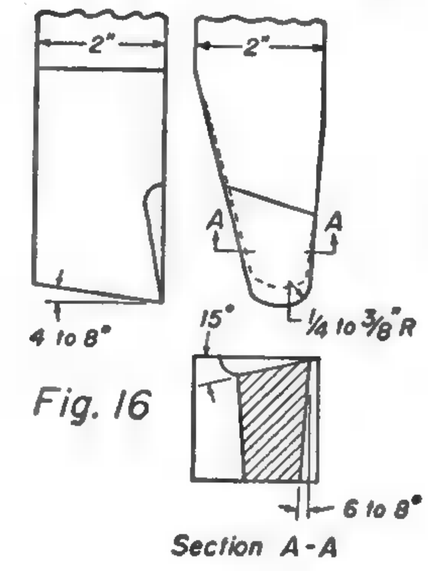


Fig. 16

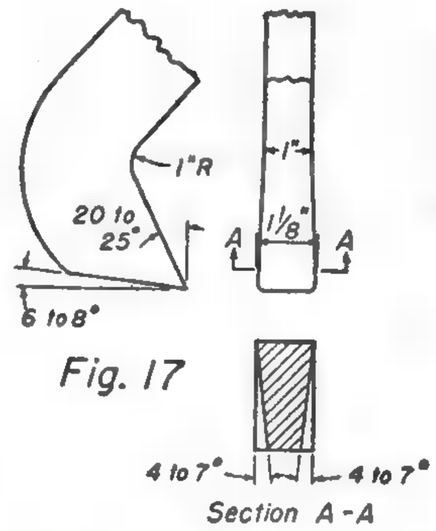


Fig. 17

Fig. 16 Roughing planer tool
Fig. 17 Finishing planer tool

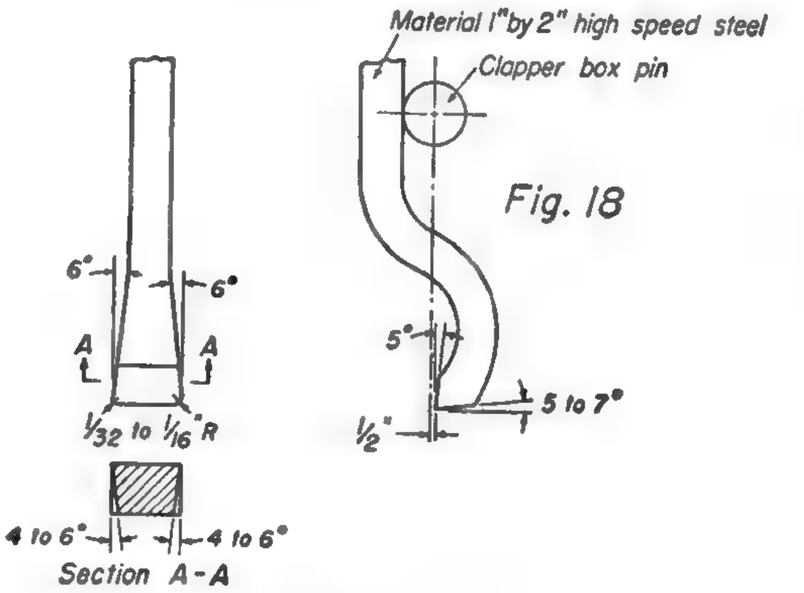


Fig. 18

Fig. 18 Broad-nose tool for finishing and parting work on deep section of planer

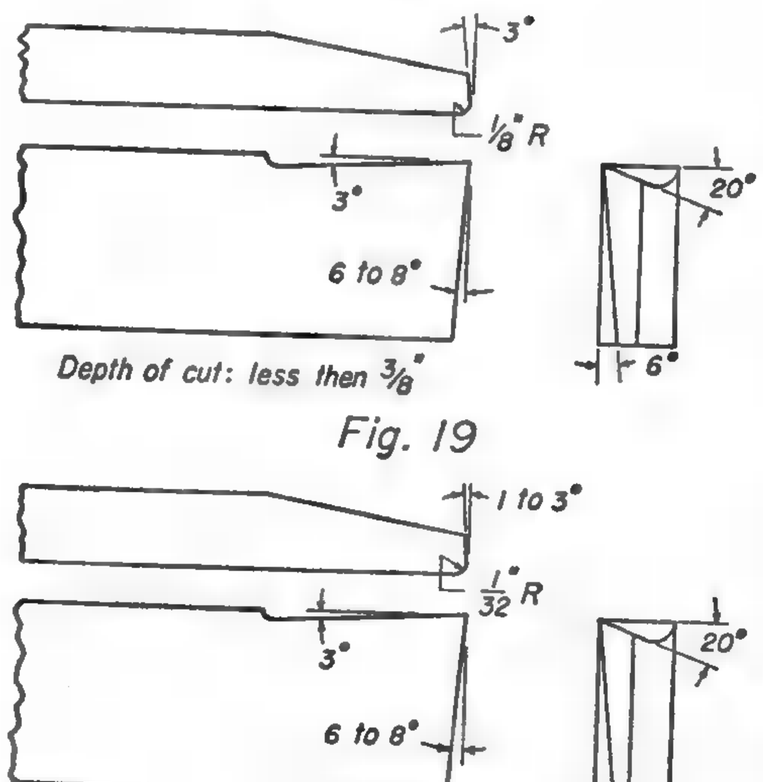


Fig. 19

Fig. 20

Fig. 19 Roughing shaper tool
Fig. 20 Finishing shaper tool

Cutting-Off Operations. Bar stock is cut on power hacksaws with heavy-duty, high speed steel hacksaw blades, having from 6 to 10 (raker-set) teeth per inch. The same type of saw, having from 14 to 18 (raker-set or wave-set) teeth per inch, is used for cutting off tubing that has a wall thickness of 1/16 in. or larger.

Table IV. Feeds and Speeds for Planing Heavy Work

	Speed, ft per min							
	Roughing Tool Fig. 16				Finishing Tool Fig. 17			Parting Tool Fig. 18
Depth of Cut, inch	1/16	1/8	1/4	3/8	0.020	0.014	0.010	0.005 to 0.010
Feed, inch	3/32	1/16	5/64	3/64	11/32	5/32	3/8	.....
Forged Monel } Forged Nickel }	25	25	25	25	25	35	30	30
Forged "K" Monel (unhardened) } Forged Inconel }	15	15	15	15	15	25	20	20

Nickel, Monel and unhardened "KR" Monel are cut off at 90 strokes per minute; Inconel and unhardened "K" Monel at 60 strokes per minute; and "R" Monel at 130 strokes per minute. High speed steel blades with 24 to 32 (wave-set) teeth per inch are used in hand hacksaws for cutting off thin-wall tubing.

Where abrasive cutoff wheels are used, aluminum oxide wheels, bonded with rubber or resin, are recommended.

Flexible-back saws of alloy steel in the saw manufacturers' "A" temper are recommended for band sawing. For band sawing nickel alloys less than ¼ in. thick, general saw velocities are 75 to 85 fpm for nickel, Monel, unhardened "KR" Monel and Inconel, and 110 fpm for "R" Monel. These speeds should be decreased for sawing material heavier than ¼ in.

Cutting-off lathes equipped with high-speed cutoff blades are operated at 50 to 60 fpm for Monel, unhardened "KR" Monel and nickel; 90 to 110 fpm for "R" Monel; and 35 to 45 fpm for unhardened "K" Monel and Inconel.

Figures 5 and 6 show suggested tool grinds for lathe parting tools.

Milling. Instead of curling, the milling chips from these materials break into fine shreds or powder. To facilitate chip disposal, the cutter should be ground with a 10 to 15-deg positive rake from the cutting edge. Coarse-tooth cutters are preferred. Plain or barrel milling cutters should be of the heavy-duty spiral-fluted type. Staggered, alternate-tooth cutters of opposite helix angle, or interlocking milling cutters are best for milling grooves. For narrow slotting, high speed steel slitting saws with alternately chamfered teeth are most satisfactory. Operating speeds for milling these materials with high speed steel cutters are listed in Table I. Complete data are not available concerning the milling of these materials with carbide tools; however, as a guide, "K" Monel has been milled with carbide tools at 425 fpm using a table feed at 12½ ipm. This particular job involved straddle-milling by a method of climb-milling with half-side milling cutters ground to a negative rake angle of 5 deg and a positive helix of 10 deg. No cutting lubricant was used.

Broaching. Broaches should be made of regular or super high speed steel. The latter type of steel affords longer service between regrinding operations. Broaches should be hardened and tempered to a hardness of about 64 Rockwell C. Depth of cut per tooth should be approximately 0.002 in. The broach should be designed so that at least two teeth are always working. Helical teeth afford the smoothest cutting. Chip breakers (nicked teeth) aid in chip control and lessen the cutting pressure per tooth. A suggested broach is shown in Fig. 15.

Planing. The setup for planing or shaping is the same as for mild steel. Roughing is usually done dry, but a cutting lubricant, used for finishing cuts and parting, improves surfaces.

Designs of planer tools are shown in Fig. 16 to 18 inclusive, and for shaper tools in Fig. 19 and 20. Table IV, which lists some feeds, cuts and speeds used on production jobs, will serve as a guide in setting up for planing.

Grinding, Polishing and Buffing Nickel and Nickel Alloys

By W. F. Burchfield*

THE wheels used for the precision grinding of nickel and nickel alloys should be sufficiently soft and the grinding conditions sufficiently severe to cause the abrasive in the wheel to wear off gradually, so as to present a continually new cutting edge. A suitable grinding compound correctly mixed must be used to obtain good finishing results and to maintain cool metal.

General recommendations in regard to wheels are as shown in Table I.

Metal Finishing. *The Grinding of Welds.* To grind welds on heavy plate where the finish is unimportant, either No. 14 grit or No. 24 grit rubber- or resinoid-bonded wheels should be used. On parts that are to be given a high finish later, finer grinding wheels, such as a No. 36 grit rubber-bonded or resinold-bonded wheel, are preferred.

Avoid overheating the welds in grinding. Excessively heated grinding wheels have been known to cause cracking of welds on thin sheets.

Polishing. This series of operations includes "roughing", "dry fining", "greasing" and "grease coloring"—all accomplished with roll-head wheels or abrasive belts. Economy in polishing is obtained only by the correct selection of wheels, abrasives, and operating speed, and above all, by the correct preparation of the wheels.

Cements as well as glue are used for making up roll-head wheels, and cements are especially employed for wheels up to No. 180 grit, inclusive.

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Abrasive belts on expanding drums or with back-stand idlers are also satisfactory for polishing.

Ordinarily there should be from 40 to 60 grit numbers between successive polishing operations. When preparing a surface for a buff finish, cross the scratches of the preceding coarser wheel to remove the coarser marks.

Buffing (Loose-Disk Buff). Buffing operations performed with a high-count muslin, loose-disk wheel include the "cutting down" from the polishing scratches preparatory to obtaining a mirror finish by color buffing. The selection of wheels is highly important for buffing. The pocket-type wheels that are made from high-count muslin sheeting hold the buffing compounds well and are also stiff enough to result in good cutting action. For the highest mirror finish, Canton flannel buffs charged with chromic oxide compound are used.

Tripoli compounds are used for cutting down, and unfused alumina (white) or chromic oxide (green) compounds are used for color buffing. Lime compounds, such as are used for buffing nickel plate, or rouge used for coloring brass, do not have sufficient cutting or coloring characteristics for nickel alloys and should not be used.

Satin Finish. One method of obtaining a satin finish is to polish with a grease wheel, usually No. 150 or No. 180 grit, and then grease color, using a pocket-type buff charged with fine emery paste. A second method is to polish with a grease wheel or to rub down the part by hand with No. 180 to 220 production paper and then brush with a Tampico wheel charged with fine emery paste; or if the area is large and flat, to spread a combination of

emery flour and oil over the surface and brush with a Tampico wheel.

Another method is to buff with a high-count muslin, loose-disk wheel charged with a greaseless compound. This compound is a moist mixture of glue and abrasive in stick form, which is charged on the wheel; it is obtainable in several grades. The compounds produce a satin finish.

Cleaning. The final operation in all finishing jobs where polishing and buffing compounds have been used, is to sprinkle Vienna lime ("whiting") over the article and rub clean with a soft rag. A Canton flannel rag should be used on a mirror finish.

Table I. Abrasive Wheels for Grinding Nickel

Grinding Operation	Abrasive[a]	Bond[b]
Cylindrical	Silicon carbide	Vitrified, resinoid or rubber
Surface (rotary and reciprocating)	Aluminum oxide	Vitrified
Centerless	Silicon carbide	Vitrified or resinoid

(a) Use silicon carbide for surface-reciprocating grinding Inconel.
(b) Wheels that are bonded with resinoid or rubber are preferred for fine finish grinding.

The following are data for internal grinding, cylindrical grinding and surface grinding:

Operation Data for an Internal Grinding Job

Material	Nickel, Monel and Inconel[a]
Wheel speed	3200 surface ft per min
Wheel size	1 in. diam by ¾ in. face by ¼ in. arbor hole
Wheel	Norton 3760–K5
Work speed	156 rpm
Traverse	40 in. per min
Rate of feed	0.0003 to 0.0004 in. per pass on diam
Grinding condition	Wet
Size of material	1 in. IPS

Operation Data for a Cylindrical Grinding Job

Material	Nickel, Monel, Inconel, "K" Monel and "Z" Nickel[a]
Machine	Norton 10 in. by 36 in. "A" type
Wheel	Norton 3760-J7
Wheel size	18 in. diam by ■ in. face by 5 in. arbor hole
Wheel speed	6000 surface ft per min
Work speed	88 rpm (work 2 in. diam)
Table traverse	Roughing, 90 ft per min Finishing, 63 to 77 ft per min
Feed per pass	Roughing, 0.001 to 0.0005 in. Finishing, 0.00025 in.
Wheel truing	Diamond, wet
Grinding condition	Wet

Operation Data for a Surface Grinding Job

	Work Motion — *Rotary*	*Work Motion* — *Reciprocating*
Machine	Pratt and Whitney vertical spindle	Norton No. 1, 6 in. by 8 in.
Wheel size	8 in. diam by 3 in. face by 4 in. arbor hole, P&W cup, ⅝ in. rim	8 in. diam by ½ in. face by 1½ in. arbor hole
Wheel speed	4200 surface ft per min	5000 surface ft per min
Table speed	50 rpm	400 in. per min
Cross feed	.....	0.050 in. every other cross stroke
Rate of down feed	Roughing 0.001 in. per rpm	Roughing, 0.001 in. per pass Finishing, 0.0005 in. per pass
Dressing	Huntington, fine	Diamond, fine
Grinding condition	Wet	Wet
	Wheels (Norton)	
Material		
Nickel	3860–K8BE	3860–18BE
Monel	3860–K8BE	3860–18BE
Inconel	3860–K8BE	3780–L5

(a) For chemical compositions of these alloys, see page 1029.

Pickling and the Removal of Oxide From Nickel and Nickel Alloys

By W. F. Burchfield*

THE same properties that make nickel alloys resistant to corrosion make the pickling of these alloys more difficult than that of iron, steel or copper alloys. In fact, because they resist attack by the usual commercial acids, nickel alloys are used for handling equipment and for tanks employed in pickling other materials.

Type of Oxide. Since the removal of oxides from nickel alloys is so difficult, it is important to consider the type of oxide formed. Light tarnish, resulting from thermal treatment at low temperature, is removed most easily. Reduced oxides, which result from heating in a reducing atmosphere, and either cooling in the reducing atmosphere or quenching in a 2% (by volume) solution of alcohol in water, are relatively easy to pickle provided they do not contain chromium oxide, which is almost irreducible in a controlled atmosphere. Heavy oxides produced in oxidizing atmospheres (and in alloys containing chromium) are the most difficult to pickle. Sulfur in any form is injurious to nickel alloys at elevated temperatures. Sulfurous atmospheres or sulfur contamination from residual lubricants, marking paints or roof spallings, will produce discoloration very difficult, if not impossible, to remove by pickling.

To obtain the best results and to reduce the cost of pickling, it is important to control the heating procedure, and thus to control the type of oxide formed, so as to minimize the amount and severity of pickle required.

Degreasing. Oils and greases must be removed prior to the pickling operations. Petroleum spirits, carbon tetrachloride, alkaline or vapor degreasers are used satisfactorily for degreasing nickel materials.

Pickling. Pickling formulas for the nickel alloys, together with the suggested containers and operating temperatures, are given below. In the preparation of these solutions, the ingredients should be added in the order given. All these solutions should be used only in a well-ventilated location since the fumes are noxious. Extreme care should be taken when handling and mixing these acids. *Hydrofluoric acid, either in liquid or gaseous form, will burn body tissue seriously and painfully. Sodium cyanide is a deadly poison.*

Table I gives recommended formulas for pickling four classes of material with three different oxide surfaces.

Table I. Numbers of the Pickle Formulas for Nickel and Nickel Alloys

Type of Finish	Light Tarnish	Reduced Oxide	Heavy Oxide
	Material[a]		
Nickel			
Nickel and "Z" Nickel	3	4	5, 5-3
Nickel-Copper			
Monel, "K" Monel, "R" Monel	1-2	4	5-6
Nickel-Chromium-Iron			
Inconel, Nichrome, Nichrome V, Illium G	7, 8-9	7, 8-9	7, 8-9
Nickel-Molybdenum			
Hastelloy A, B, C	4	4	4

(a) For chemical compositions of these alloys, see page 1029.

Neutralizing and Drying. After the final acid dip, parts should be rinsed in hot or cold water to remove the acid, then immersed in a cold, neutralizing bath, 1 to 2% by volume, of ammonia solution (4 to 8 fl oz commercial aqua ammonia per gallon of water). After neutralizing, the parts can be dried in sawdust or dipped in boiling water and dried in air.

Coppering. A copper flash will occur on Monel if iron is in contact with the Monel in an acid dip. Copper will also plate out on nickel and Inconel if the bath has become contaminated by the pickling of alloys containing copper. When coppering occurs, it can be removed by immersing

* Development and Research Division, The International Nickel Company, Inc., New York

the parts in ■ 4 to 5% ammonia solution (approximately 1 pint commercial aqua ammonia per gallon of water) at room temperature for about 1 min.

Discoloration From Sulfur Cutting Oil. Frequently sulfur-bearing cutting oil causes a brown discoloration on Monel when it is machined at high speeds. This discoloration can be removed easily with a solution of formula 10. *Remember that cyanide is a deadly poison; handle with care. Acid must not get into this solution or deadly hydrocyanic gas will be generated.*

Molten Salt Baths. The descaling of nickel and nickel alloys in certain molten salts is very satisfactory. These processes, discussed in the article on page 283 of this Handbook, accomplish the degreasing, reducing of oxide and removing of scale by immersion of the part in a molten salt bath for a period of 15 to 30 min followed by a quench in water. The surface obtained may be satisfactory for further processing, but usually subsequent acid dips are required to give the metal a bright finish. Nickel and nickel-copper alloys can be brightened in a hot solution (160 F) of 10% nitric acid for 1 to 2 min. Nickel-chromium-iron alloys can be brightened in a cold bath of nitric and hydrofluoric acids similar to formula 7, though not so strong. Nickel-molybdenum alloys can be brightened in a hot solution (190 F) containing 8% sulfuric acid plus 0.2 lb NaCl per gal of mixture.

Formula 1. Flash Pickle. Monel and "K" Monel. First Dip.

Water	1 gal	1000 cu cm
Nitric acid (38 Bé)	1 gal	1000 cu cm
Common salt (NaCl)	½ to ¾ lb	60 to 90 ■
Temperature	70 to 100 F	21 to 38 C
Time	Not more than 5 sec	
Container	Earthenware crocks, glass, or ceramic	
Procedure	Degrease, dip in acid, rinse in hot water (180 F), formula 2.	

Formula 2. Flash Pickle. Monel and "K" Monel. Second Dip.

Water	1 gal	1000 cu cm
Nitric acid (38 Bé)	1 gal	1000 cu cm
Temperature	70 to 100 F	21 to 38 C
Time	Not more than 5 sec	
Container	18-8 stainless steel, glass or ceramic	
Procedure	From rinse above, dip in acid, neutralize, dry.	

Formula 3. Flash Pickle. Nickle. Brightener After Formula 5.

Water	1 gal	1000 cu cm
Sulfuric acid (66 Bé)	1½ gal	1500 cu cm
Nitric acid (38 Bé)	2¼ gal	2250 cu cm
	Allow to cool and add:	
Salt	¼ lb	30 ■
Temperature	70 to 100 F	21 to 38 C
Time	5 to 20 sec	
Container	Earthenware crocks, glass, or ceramic	
Procedure	Degrease, warm in hot water, dip in acid, rinse, neutralize, dry.	

Formula 4. Removal of Reduced Oxide. Nickel, "Z" Nickel, Monel, "K" Monel, Hastelloy A, B and C.

Water	1 gal	1000 cu cm
Sulfuric acid (66 Bé)	¾ pt	95 cu cm
Sodium nitrate (crude)	½ lb	65 g
Common salt (NaCl)	1 lb	110 ■
Temperature	180 to 190 F	82 to 88 C
Time	30 to 90 min	
Container	Earthenware, glass, ceramic, wood for short time	
Procedure	Degrease, pickle, rinse in hot water, neutralize, dry. Pickling is facilitated by intermediate scrubbing with pumice or a fiber brush.	

Formula 5. Removal of Oxide Film or Scale. Nickel and "Z" Nickel, Monel and "K" Monel. First Dip.

Water	1 gal	1000 cu cm
Hydrochloric acid (20 Bé)	½ gal	500 cu cm
Cupric chloride	¼ lb	30 g
Temperature	180 F	82 C
Time	20 to 40 min	
Container	Earthenware, glass, ceramic, acid-proof brick	
Procedure	Monel: degrease, dip in acid, rinse in hot water, solution 6. Nickel: degrease, dip in acid, rinse in hot water, solution 3.	

Formula 6. Removal of Oxide Film or Scale. Monel and "K" Monel. Second Dip.

Water	1 gal	1000 cu cm
Sulfuric acid (66 Bé)	1/10 gal	100 cu cm
Sodium dichromate	1 1/10 lb	132 g
Temperature	70 to 100 F	21 to 38 C
Time	5 to 10 min	
Container	Earthenware, glass, ceramic or rubber	
Procedure	From solution 5 rinse, dip in acid, rinse in cold water, neutralize, dry.	

Formula 7. Removal of Oxide or Scale. Inconel, Nichrome, Nichrome V, Illium G.

Water	1 gal	1000 cu cm
Nitric acid (38 Bé)	1 gal	1000 cu cm
Hydrofluoric acid 40%	1¼ pt	150 cu cm
Temperature	70 to 100 F	21 to 38 C
Time	15 to 90 min	
Container	Carbon brick	
Procedure	Degrease, dip in acid, rinse in cold water, neutralize, dry.	

Formula 8. Reduced Oxide Only. Inconel, Nichrome, Nichrome V, Illium G. First Dip.

Water	1 gal	1000 cu cm
Sodium hydroxide (caustic soda)	18 oz	134 ■
Sodium carbonate (soda ash)	18 oz	134 g
Potassium permanganate (permanganate of potash)	7 to 11 oz	52 to 82 g
Temperature	180 to 190 F	82 to 88 C
Time	2 hr	
Container	Steel	
Procedure	Degrease, dip in alkali, to solution 9. These formulas work satisfactorily only when these materials have been heat treated in a strongly reducing atmosphere.	

Formula 9. Reduced Oxide Only. Inconel, Nichrome, Nichrome V, Illium G. Second Dip.

Water	1 gal	1000 cu cm
Sulfuric acid (66 Bé)	½ pt	63 cu cm
Copper sulfate or copper nitrate	1½ oz	12 g
Temperature	180 to 190 F	82 to 88 C
Time	1 hr	
Container	Wood, earthenware, glass, ceramic, acid-proof brick	
Procedure	From solution 8, dip in acid, rinse in cold water, neutralize, dry.	

Formula 10. Removal of Sulfur Discoloration. Monel.

Water	1 gal	1000 cu cm
Sodium cyanide	½ to 1 lb	60 to 120 g
Temperature	70 to 100 F	23 to 38 C
Time	5 to 30 min	
Container	Earthenware, glass, ceramic	
Procedure	Degrease, dip, rinse in hot or cold water, dry.	

The Resistance of Nickel and Nickel Alloys to Corrosion

By W. Z. Friend*

THIS article describes the resistance to corrosion of nickel, nickel-copper alloys, nickel-molybdenum-base alloys, nickel-chromium alloys, and the Ni-Cr-Cu-Mo alloy known as Illium.

Nickel. Nickel does not readily discharge hydrogen from any of the common reducing acids. A supply of some oxidizing agent, such as dissolved air, is necessary in order for corrosion to proceed. Reducing conditions usually retard corrosion of nickel, while oxidizing conditions accelerate corrosion. However, nickel has the ability to protect itself against certain forms of attack by the development of a corrosion-resisting, or passive, oxide film. Consequently, oxidizing conditions do not invariably accelerate corrosion.

Atmospheric Corrosion. Indoor exposure causes virtually

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no attack on nickel. Outdoors the rate of corrosion varies with atmospheric conditions; the rate is usually less than 0.0001 and never more than 0.001 ipy.* Sulfurous atmospheres are most corrosive. Marine atmospheres are scarcely more corrosive than suburban or rural atmospheres. Nickel is free from season cracking and other forms of stress corrosion in atmospheric exposure.

Waters. Nickel is highly resistant to corrosion by waters, such as distilled water, natural waters (including those containing hydrogen sulfide or free carbon dioxide) and sea water. In sea water, conditions of agitation or flow are favorable to nickel, whereas local attack may occur under barnacles or other attached solids in stagnant exposure.

Salt Solutions. Nickel resists corrosion by neutral and alkaline salt solutions, with rates usually less than 0.005 ipy. Nonoxidizing acid salts are only moderately corrosive, with rates seldom higher than 0.02 ipy. Oxidizing acid salts, such as ferric chloride, and mixtures of oxidizing salts with mineral acids, are likely to corrode nickel severely. So are oxidizing alkaline salts, such as hypochlorites, with which nickel should not be used when the available chlorine content exceeds 3 g per liter. Alkaline solutions containing hydrogen peroxide do not corrode nickel and are not decomposed by it.

Mineral Acids. Nickel is fairly resistant to sulfuric acid in concentrations of less than 80%. Corrosion rates vary from less than 0.005 ipy in acid free from air, to about 0.05 ipy in acid saturated with air at atmospheric temperatures. Nickel is rarely useful in contact with hot sulfuric acid solutions in concentrations greater than about 15%.

With cold hydrochloric (muriatic) acid the rates of attack vary, according to the air content and concentration of the acid, from 0.01 to 0.04 ipy, in dilute acid, to 0.06 to 0.08 ipy in concentrated acid. In hot acid, nickel is rarely useful in handling solutions containing more than 2% acid.

Nickel is not corroded appreciably by chlorinated solvents or mixtures of these with water.

Nickel is resistant to pure phosphoric acid, but is corroded severely by this acid when it contains oxidizing impurities, such as ferric compounds.

Nickel is corroded strongly by sulfurous acid, except the very dilute solutions used to preserve foods.

Strongly oxidizing acids, such as nitric, corrode nickel rapidly.

Organic Acids and Compounds. Organic acids are only moderately corrosive to nickel. Neutral and alkaline organic compounds have virtually no effect.

Alkalies. Nickel resists corrosion by the strongest alkalies. For example, in boiling 50% caustic soda, rates of corrosion are less than 0.001 ipy; and in concentrations greater than 75%, nickel is second only to silver in resisting attack. Anhydrous ammonia does not corrode nickel, but ammonium hydroxide is appreciably corrosive in concentrations greater than about 1%.

Wet and Dry Gases. No dry gases are actively corrosive to nickel at atmospheric temperature. Nitric oxide, chlorine and other halogens, sulfur dioxide, and ammonia are appreciably corrosive when mixed with water or condensed water vapor. Nickel is resistant to chlorine and hydrogen chloride at temperatures up to about 1000 F, and is not affected by steam within the range of temperatures commonly encountered.

When heated in oxidizing atmospheres, nickel forms a rather superficial, tightly adherent scale at temperatures lower than 1400 F. Resistance to excessive oxidation makes the metal especially useful in the temperature range from 2100 to 2300 F.

Nickel is not resistant to mixtures of nitrogen, hydrogen and ammonia at the temperatures and pressures encountered in the commercial process for the synthesis of ammonia. However nickel is useful under the conditions that obtain during the dissociation of ammonia in nitriding equipment, providing the temperature is not higher than about 1075 F.

At temperatures higher than 600 to 700 F, nickel is subject to both general and intergranular corrosion by compounds and gases that contain sulfur. The extent of this attack is less in an oxidizing environment containing SO_2 than in a reducing environment containing H_2S. The resistance of nickel to attack by sulfur is improved considerably by additions of manganese in amounts of 5% or less.

Nickel-Copper Alloys. The nickel-copper alloys that contain more than 50% Ni are benefited by the high degree of nobility of copper and by the ability of nickel to protect itself, frequently through the development of passive oxide films. Such alloys are, in general, more resistant than nickel under reducing conditions, and more resistant than copper under oxidizing conditions.

Atmospheric Corrosion. In indoor atmospheres these alloys remain substantially unchanged. In outdoor atmospheres they remain bright only in rural districts. In sulfurous atmospheres they gradually acquire a brownish or greenish tarnish but there is no destructive corrosion. Atmospheric corrosion tests have shown corrosion rates of less than 0.0001 ipy at all test locations.

Waters. The nickel-copper alloys have excellent resistance to distilled water and natural waters, both hard and soft. These alloys find their greatest usefulness in sea water under conditions of high velocity, where resistance to effects of impingement and cavitation are important. Stagnant exposure is less favorable, since pitting may be induced under marine organisms or other solids.

Salt Solutions. Neutral and alkaline salt solutions, including chlorides, carbonates, sulfates, nitrates, acetates and others, have a negligible corrosive effect on nickel-copper alloys, with corrosion rates usually less than 0.005 ipy. These alloys also have good resistance to nonoxidizing acid salt solutions, such as zinc chloride, ammonium sulfate, aluminum sulfate and others, and have rates of corrosion usually less than 0.02 ipy.

Oxidizing acid salts, such as ferric chloride, ferric sulfate, cupric chloride, cupric sulfate and mixtures of these salts with mineral acids, are likely to be severely corrosive, except in very dilute solutions. This is also true with alkaline hypochlorite solutions, where the limiting concentration of available chloride that can be handled safely is about 3 g per liter. Alkaline peroxide solutions are not corrosive to these alloys.

Mineral Acids. In sulfuric acid free from air at atmospheric temperature, corrosion of the nickel-copper alloys is virtually nil in all concentrations less than about 80%. In acid saturated with air, and in concentrations lower than 80%, maximum corrosion occurs with 5% acid at a rate of about 0.04 ipy. In 5% acid saturated with air, the temperature of most active corrosion is about 185 F where the corrosion rate is about 0.12 ipy. Boiling sulfuric acid may be handled in concentrations less than 20%.

In cold hydrochloric acid free from air, rates of corrosion range from about 0.005 ipy in 1% acid to 0.08 ipy in 20% acid. In cold acid saturated with air, corrosion rates vary from 0.04 ipy in 1% to 0.08 ipy in 10% concentrations. Rates are about 0.04 ipy in 5% acid at 160 F and 0.04 ipy in boiling 1% acid. There is no significant corrosion in mixtures of chlorinated solvents and water.

These alloys resist corrosion by hydrofluoric acid throughout a wide range of concentrations and temperatures. They resist pure phosphoric acid also, but may be corroded by impure solutions containing ferric salts.

Sulfurous acid and bisulfites are appreciably corrosive, except in very dilute solutions.

Oxidizing acids, such as nitric acid, are highly corrosive, except in concentrations less than 1%, at temperatures lower than 80 F.

Organic Acids and Compounds. Nickel-copper alloys show good resistance to corrosion by all the common organic acids, and are virtually free from corrosion by neutral and alkaline organic compounds, and fruit and other food acids.

Alkalies. Nickel-copper alloys are virtually completely resistant to most alkaline solutions, including concentrated caustic soda solutions at temperatures below the boiling point. In ammonium hydroxide solutions, these alloys may be used at concentrations less than 3% NH_3. Nickel-copper alloys are not corroded by anhydrous ammonia.

Wet and Dry Gases. No dry gases are actively corrosive at atmospheric temperatures. Nitric oxide, chlorine and other halogens, sulfur dioxide and ammonia are corrosive

* Ipy means the depth in inches to which uniform corrosion would penetrate during continuous exposure for one year.

in the presence of water. Nickel-copper alloys are resistant to chlorine at temperatures up to about 850 F.

These alloys are usefully resistant to steam within the range of temperatures and pressures commonly used. They resist atmospheric oxidation below about 1000 F.

In reducing sulfur atmospheres (hydrogen sulfide) nickel-copper alloys are subject to intergranular attack at temperatures higher than 700 F. These alloys are attacked by mixtures of nitrogen and hydrogen under the conditions of pressure and temperature in ammonia synthesis.

Resistance of Hastelloy Alloys to Corrosion. Hastelloy A (60% Ni, 20% Mo, 20% Fe) and Hastelloy B (65% Ni, 30% Mo, 5% Fe) were developed primarily to resist corrosion by hydrochloric acid, and the extent to which they do this is their most important property.

Hastelloy C (58% Ni, 17% Mo, 15% Cr, 5% W, 5% Fe) possesses an unusual degree of resistance to oxidizing solutions, especially to those containing chlorides, in addition to other corrosive chemicals. It is unique among alloys in its resistance to hypochlorite solutions and moist chlorine.

The most important property of Hastelloy D (85% Ni, 8 to 11% Si, 3% Cu) is its resistance to corrosion in concentrated solutions of sulfuric acid at elevated temperatures.

All these materials are virtually free from corrosion under such relatively mild conditions as exposure to the atmosphere, fresh water, salt water, and neutral and alkaline salts.

Hydrochloric Acid. Hastelloy A is usefully resistant to all concentrations of hydrochloric acid at room temperature and to unaerated solutions at temperatures lower than about 160 F. Rates of corrosion in unaerated acid are usually less than 0.03 ipy at this upper temperature limit.

Hastelloy B is notable for its unusually high resistance to corrosion in all concentrations of hydrochloric acid at temperatures as high as the boiling point. It is used in contact with wet hydrogen chloride gas. Its corrosion rate is only 0.023 ipy in 20% boiling acid, one of the most severely corrosive conditions.

Corrosion of Hastelloys A and B is considerably increased by the presence of oxidizing salts, such as ferric and cupric salts, in acid solutions, so caution should be used in such applications.

Hastelloy C resists all concentrations of hydrochloric acid at room temperature, and may sometimes be used at temperatures as high as 120 F.

Hastelloy D is moderately resistant, although the maximum temperature for its use is about 100 F.

Sulfuric Acid. Hastelloy A is usefully resistant to sulfuric acid in concentrations as great as 50% at temperatures as high as the boiling point, and to higher concentrations at temperatures lower than about 160 F.

Hastelloy B is more resistant than alloys A, C and D to boiling sulfuric acid in concentrations lower than about 60%, but is less resistant than alloy D to boiling acid at higher concentrations.

Hastelloy C is somewhat superior to alloy A in resistance to corrosion, although the same limitations apply to the use of both.

Hastelloy D is usefully resistant to all concentrations of sulfuric acid at temperatures as high as the boiling point. In boiling acid evaporated to fumes, the corrosion rate of Hastelloy D is about 0.05 ipy.

Nitric Acid and Oxidizing Acid Mixtures. Hastelloy C is resistant to dilute nitric acid below about 150 F, and to acid concentrations of more than 40% at room temperature only. In addition this alloy is resistant to mixtures of oxidizing acids, such as nitric and sulfuric; chromic and sulfuric; sulfuric and copper sulfate; sulfuric and dichromates, permanganates or persulfates; and similar combinations.

Hastelloys A, B and D are not recommended for service with nitric or other strongly oxidizing acids.

Organic Acids and Compounds. All these alloys are highly resistant to organic acids and to neutral and alkaline organic compounds.

Salt Solutions. Hastelloys A, B and C are resistant to acid chlorides, such as aluminum or ammonium sulfate, and to acid phosphates.

Hastelloy C is unusually effective in resisting solutions of such corrosive oxidizing salts as ferric chloride (below 160 F), and cupric chloride (below 100 F). At moderate temperatures, it also resists corrosion by mixtures of oxidizing salts such as chromates and nitrates in sulfuric and hydrochloric acid solutions.

Chlorine and Hypochlorites. Hastelloy C is one of the few metallic materials that has useful resistance to hypochlorites and other solutions containing free chlorine in appreciable concentrations, below about 100 F.

Wet and Dry Gases. Hastelloys A, B and D are resistant to progressive atmospheric oxidation and to oxidizing and reducing flue gases, at temperatures lower than about 1450 F. Hastelloy C is resistant to higher temperatures, about 1800 F. All alloys are resistant to ammonia, wet or dry.

Alloys C and D are resistant to wet hydrogen sulfide and to sulfur dioxide at less than about 160 F.

Nickel-Chromium Alloys. A number of available alloys contain from 60 to 80% Ni and from 13 to 20% Cr, with the remainder mostly iron. Because of their nickel base, these alloys are referred to as Ni-Cr alloys to distinguish them from the stainless steels, or iron-base Fe-Cr-Ni alloys. In addition, several grades of the hard surfacing material known as Colmonoy have a nickel base (from 68 to 85% Ni, depending on the grade), with chromium boride crystals as the other essential constituent.

The corrosion-resisting characteristics of these nickel-chromium alloys are somewhat similar. Their chromium content makes them superior to pure nickel under oxidizing conditions. The high nickel content enables them to retain considerable resistance under reducing conditions and in strongly alkaline solutions. As would be expected, the most significant differences in performance among alloys of this group occur, on the one hand, in highly oxidizing solutions, such as nitric acid solutions, where higher chromium contents are most effective; and, on the other hand, in reducing acids such as hydrochloric, where increased nickel content is usually beneficial.

Atmospheric Corrosion. The nickel-chromium alloys are resistant to all types of atmospheres, including rural, urban, industrial and marine. In rural and indoor atmospheres these alloys will remain bright indefinitely. In sulfurous industrial atmospheres there may be some tarnishing but no significant attack.

Waters. The nickel-chromium alloys are virtually free from attack by the most corrosive of natural waters and mine waters. They are moderately resistant to rapidly flowing sea water but, in quiet or stagnant exposure, may be subject to pitting where barnacles or other solids become attached to the metal surface. In marine atmospheres, these alloys are among the most resistant of commonly available materials.

Salt Solutions. Nickel-chromium alloys resist neutral and alkaline salt solutions well, with corrosion rates usually less than 0.001 ipy. In acid salt solutions, corrosion rates usually do not exceed 0.02 ipy, except with such oxidizing halogen salts as ferric chloride, cupric chloride, and mercuric chloride, which are severely corrosive in all but very dilute solutions. In hypochlorite solutions the use of these alloys is generally limited to available chlorine concentrations not exceeding 3 g per liter. In hot chloride solutions corrosion may sometimes be accompanied by pitting, although this tendency is considerably less than with iron-base Fe-Cr or Fe-Cr-Ni alloys.

Mineral Acids. The nickel-chromium alloys resist sulfuric acid solutions at atmospheric temperature. Corrosion rates vary from less than 0.005 ipy in solutions free from air, to 0.06 ipy in solutions saturated with air. Attack by strong hot solutions is usually severe. The addition of small amounts of oxidizing salts, such as ferric sulfate or cupric sulfate, to acid solutions, will increase the passivity range.

In hydrochloric (muriatic) acid, the usefulness of nickel-chromium alloys is limited to dilute solutions, less than 5% in concentration by weight, at atmospheric temperature. Corrosion is usually severe at elevated temperatures.

Nickel-chromium alloys resist both pure and impure solutions of phosphoric acid at moderate temperatures, but not hot concentrated solutions.

Sulfurous acid solutions are usually corrosive, especially when hot, but nickel-chromium alloys have good resistance to the very low sulfur dioxide concentrations used in food preservation.

The nickel-chromium alloys as a group are highly resist-

ant to strongly oxidizing acids such as nitric acid, at moderate temperatures. The higher the chromium content, the wider the range of concentrations and temperatures in which passivity exists. These alloys are generally inferior to the Fe-Cr-Ni and Fe-Cr alloys in solutions of hot nitric acid.

Organic Acids and Compounds. These alloys have generally good resistance to organic acids and to neutral and alkaline organic compounds. They are particularly effective in resisting fatty acids at elevated temperatures.

Alkalies. The nickel-chromium alloys resist corrosion by caustic alkalies and alkaline solutions in most concentrations and temperaures. They also resist all concentrations of ammonium hydroxide.

Wet and Dry Gases. The nickel-chromium alloys are completely resistant to all the common gases when dry, at or near atmospheric temperature. In the presence of moisture nickel-chromium alloys do not resist chlorine or other halogens, but are resistant to such gases as ammonia, nitric oxides and hydrogen sulfide. Inconel (80% Ni, 13% Cr, 6.5% Fe) is resistant to chlorine and hydrogen chloride at temperatures below about 1000 F.

These alloys are completely resistant to all mixtures of steam, air and carbon dioxide, and are especially useful in contact with steam at temperatures above 800 F. They also resist ammonia, nitrogen and hydrogen as encountered in nitriding operations.

Inconel resists progressive oxidation at temperatures below 2000 F. In oxidizing sulfur atmospheres such as sulfur dioxide, the safe operating temperature limit is about 1500 F. In reducing sulfur atmospheres such as hydrogen sulfide, the safe upper limit is about 1000 F.

Corrosion Resistance of Illium. Illium (56% Ni, 22% Cr, 6% Cu, 6% Mo, 1% W) was originally developed as a material resistant to both sulfuric and nitric acids over a wide range of concentration and exposure conditions. It is superior in applications under highly oxidizing conditions, such as exposure to nitric acid, and has limited applications in hydrochloric acid and acid chlorides. This material is virtually free from corrosion under such relatively mild conditions as exposure to the atmosphere, to fresh water, salt water, and to neutral and alkaline salts.

Mineral Acids. Illium is usefully resistant to sulfuric acid under virtually all conditions of concentration, aeration, agitation and temperature. Tests in boiling 25% sulfuric acid have indicated a rate of corrosion of 0.017 ipy. Illium has been found useful for parts of pumps and other equipment handling chamber-process acid containing oxidizing nitrogen compounds.

Illium is resistant to hydrochloric acid in concentrations as high as 15% at atmospheric temperature, but is not recommended for use with more concentrated acid or with hot dilute solutions. Illium is highly resistant to attack by phosphoric acid and is especially useful when the acid contains fluorides or oxidizing impurities. It possesses useful resistance to sulfurous acid solutions, especially where both sulfuric and sulfurous acids are present, and is highly resistant to hydrogen sulfide and solutions containing this gas.

Oxidizing Acids. Illium resists all concentrations of nitric acid at all temperatures. Tests in boiling 25% acid indicated corrosion rates of less than 0.01 ipy, and in cold concentrated acid, less than 0.001 ipy. Illium also resists oxidizing acid mixtures such as nitric and sulfuric; chromic and sulfuric, sulfuric and copper sulfate; sulfuric and dichromates, permanganates, and persulfates.

Organic Acids and Compounds. Illium is highly resistant to organic acids and to neutral and alkaline organic compounds.

Salt Solutions. Illium is highly resistant to acid phosphates and to acid sulfates, such as aluminum and ammonium sulfate. It also resists such highly corrosive chemicals as ferric chloride and ferric sulfate, and mixtures of oxidizing salts such as chromates and nitrates, in acid solutions.

The Metallography of Nickel and Nickel Alloys

By David I. Sinizer*

In preparing specimens of nickel and nickel alloys for metallographic examination, it is important to prevent working of the surface, and care should be taken to avoid pitting and loss of inclusions.

Grinding and Polishing. Specimens to be polished should be about ½ to 1 in. sq, with the thickness somewhat less, to prevent rocking during preparation. Smaller specimens may be mounted in lucite, bakelite or mechanical clamps of various kinds. Materials used in mechanical clamps should be similar to the sample in order to prevent abnormal etching effects. Woods metal or babbitt mounts are unsatisfactory because of their etching behavior at the interfaces between sample and mounting material.

The specimen is first faced, if necessary, by filing or coarse grinding on a rotating stone, using light pressure and water lubrication to prevent surface distortion. The flat surface thus obtained is further ground on dry abrasive disks, using successively finer grits on several wheels rotating at 300 to 600 rpm. In general, a succession of emery or carborundum disks, of 180, 240, 320 and 400 grits, provide a satisfactory surface for further polishing. Specimens should be turned 90 deg as they proceed to each successive disk, in order to remove scratches from the previous operation. The specimen should be ground on each disk only long enough to remove scratches from the previous operation. Dry grinding on the last abrasive paper is the most critical step, because the wet polishing time is governed by the depth and uniformity of the scratches produced here. To prevent loss of inclusions from some alloys, it is advisable to use a well-worn or graphited paper for the final grinding step, and to omit the wet polishing on the coarse alumina wheel. Frequently, finishing by hand on the final abrasive papers keeps the specimen flatter, reduces surface distortion, and prevents pitting in later stages of preparation.

The specimens are then coarse polished on a wheel covered with flat silk crepe, revolving at about 300 rpm, and using levigated alumina (such as Fishers' No. 3) in water. This polishing is done at 90 deg to the scratches produced by the last grinding disk. Before final polishing, both specimen and hands should be carefully washed free from grit. Final polishing is done with extremely fine relevigated alumina, such as Rite-Tonnerde No. 3, on a wheel covered with flat silk crepe and rotating at about 300 rpm. At this stage the sample is rotated slowly on the wheel, opposite to the direction of wheel rotation. The specimen may be turned in the fingers through 90 deg a few times during the polishing operation. Disturbed metal on the polished surface may frequently be removed by repeated light etching and repolishing.

Preparation of Specimens for Macroscopic Examination. The surface to be etched for macroscopic examination may be prepared by surface grinding to a fine finish, or by polishing with 180-grit and 240-grit carborundum paper. Finer polishing is not necessary, but the finer the surface before etching, the better will be the final result. With finer surfaces, less drastic macro-etching is required to reveal the metal structure.

Etching for Metallographic and Macroscopic Examination. Etchants commonly used for metallographic examination of nickel and nickel alloys are listed in Table I. Representative microstructures obtained with various etchants are shown in Fig. 1 through 6.

Etchants commonly used for macroscopic examination of nickel and nickel alloys are shown in Table II.

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Table I. Etchants for Metallographic Examination of Nickel and Nickel Alloys

Etchant	Composition	Directions for Use	Applications
Carapella's Reagent	Ferric chloride ..... 5 g Concentrated hydrochloric acid.. 2 ml Ethyl alcohol .....99 ml	Swab lightly or immerse with gentle agitation. Use covered dish to cut down evaporation. Time varies from 2 to 3 sec to several minutes, depending on alloy.	General use for nickel and nickel-copper alloys (Monel). Excellent definition of grain boundary and structural detail. Removes flowed metal easily. Develops grain contrast in Monel. (See Fig. 1)
Cyanide-persulfate	Equal volumes of 10% sodium cyanide and 10% ammonium persulfate	Use freshly mixed solutions. Swab or immerse for 5 to 90 sec. *Caution: Use a hood. Poisonous fumes are released when solutions are mixed.*	General use on nickel alloys, when desired to reveal the structure without removing finely dispersed inclusions such as graphite or nickel sulfide. (Fig. 2 and 3)
Modified Aqua Regia	Concentrated hydrochloric acid..10 ml Concentrated nitric acid..... 2 ml	Swab for 5 to 30 sec immediately after mixing. Use fresh white nitric acid.	General use on nickel-chromium-iron alloys such as Inconel. May pit specimens if not used fresh. Shows grain boundaries and carbides. (See Fig. 4)
Oxalic acid	10% oxalic acid solution in water	Etch anodically at 6 v for 5 to 15 sec. Four dry cells in series may be used.	Grain boundary etch for nickel-chromium alloys. (See Fig. 5)
Sodium cyanide	10% sodium cyanide solution in water	Etch anodically at room temperature at 5 to 6 v for 3 min. Voltage across cell is critical. Adjust current for proper voltage.	Carbides in nickel-chromium alloys. Longer etching, up to 20 min, will reveal general structure but oxalic acid is preferable for general structural detail. (See Fig. 6)
Monel Contrast Solution	Chromic acid ..... 3 g Concentrated nitric acid.....10 ml Ammonium chloride ..... 3 g Water .....90 ml	Immerse or swab specimen for 10 to 60 sec.	Grain contrast for measurement of grain size.

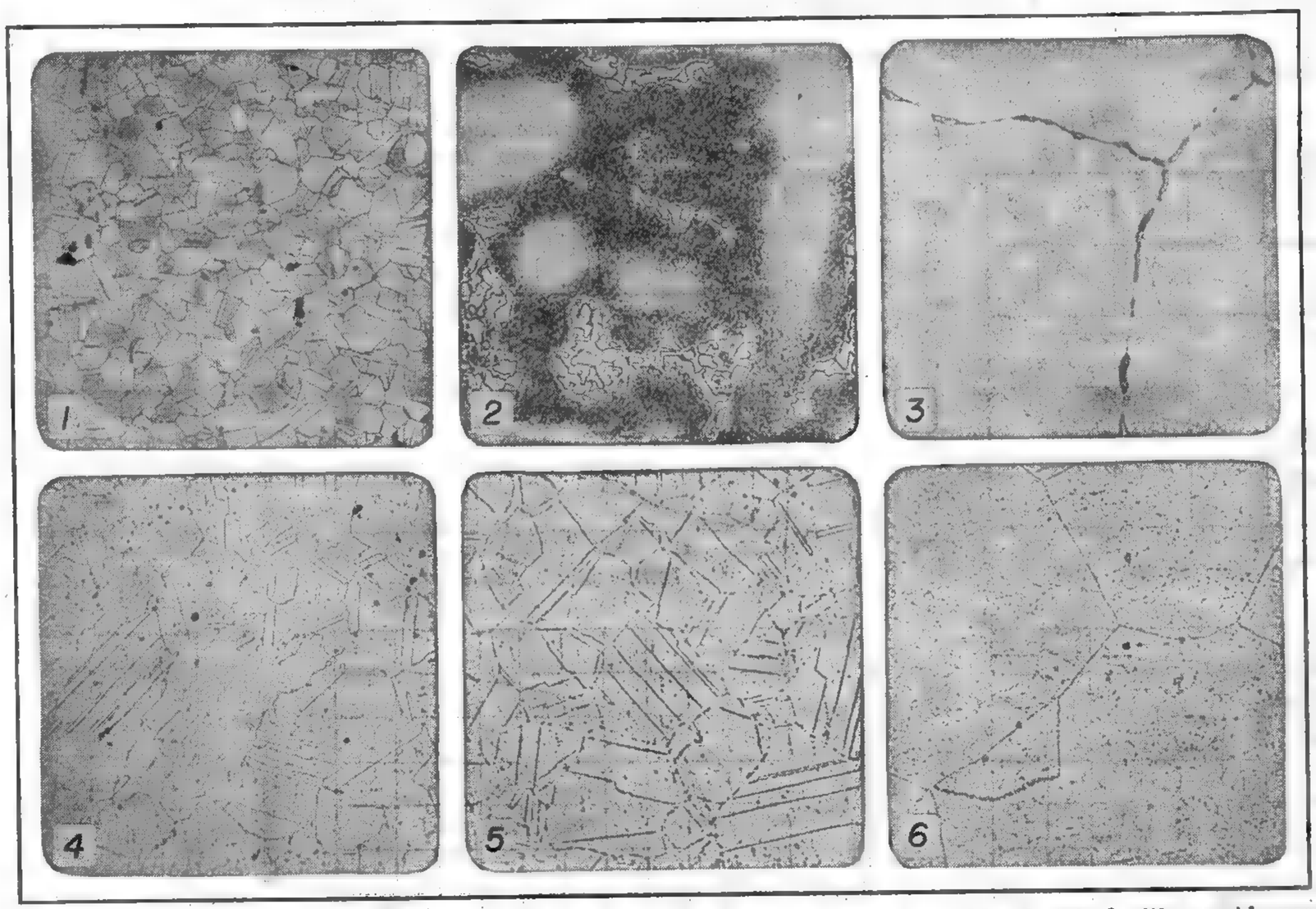


Fig. 1 Wrought Monel etched in Carapella's reagent (× 250). Fig. 2 Age hardened cast silicon Monel etched with cyanide-persulfate (× 250). Fig. 3 Sulfide inclusions in nickel etched lightly with cyanide-persulfate (× 1000). Fig. 4 Alloy 80-20 nickel-chromium etched in modified aqua regia (×250). Fig. 5 Alloy 35-15 nickel-chromium etched electrolytically in oxalic acid (× 250). Fig. 6 Carbides in Inconel etched electrolytically in sodium cyanide (× 250). Original magnifications are indicated. All micrographs were reduced to four-fifths size in making the engravings reproduced here.

Table II. Macro-Etchants for Nickel and Nickel Alloys

Etchant	Composition	Directions for Use	Applications
Nitric acid	Concentrated nitric acid	Use clear white acid to avoid staining. Immersing specimen 3 to 5 min is sufficient for structure. Longer etching required to reveal porosity or forging flow lines.	General structural detail in nickel and nickel-copper alloys. Surface and subsurface cracks; porosity; dendritic structure of cast alloy; forging flow lines. Light etching will reveal sulfur embrittlement. Monel weld deposits.
Marble's Reagent	Copper sulfate ..... 20 g Concentrated hydrochloric acid.100 ml Water .....100 ml	Immerse for 3 to 10 min.	Structure of nickel-chromium-iron alloys. Porosity; surface and subsurface cracks.
Aqua Regia	Concentrated nitric acid..... 25 ml Concentrated hydrochloric acid. 75 ml	Immerse for 3 to 10 min. Prolonged etching may pit specimen.	General use on nickel-chromium and nickel-chromium-iron alloys

PROPERTIES OF NICKEL AND NICKEL ALLOYS

Nickel (99.95 Ni+Co)

COMPILED BY E. M. WISE*

A *1 Common name.* **Pure Nickel (electrolytic)**

B *1 Typical uses.* Alloying additions, electronic devices, protective coatings

2 Precautions in use. Do not heat above 320 C (600 F) in sulfidizing atmospheres.

C *1 Density* at 25 C (77 F). 8.902 g per cu cm (0.322 lb per cu in.)

D *1 Melting point.* 1455 C (2651 F)

4 Boiling point. Approx 2730 C (4950 F)

6 Thermal expansion 0 to 100 C (32 to 212 F). 0.0000133 per °C. *See* Fig. 1 for temperature dependence.

11 Specific heat at 100 C (212 F). 0.1123 cal per g; at 500 C (932 F) 0.1265 cal per g

12 Specific heat versus temperature. See Fig 2.

13 Latent heat of fusion. 73.8 cal per g

16 Thermal conductivity at 25 C (77 F). 0.22 cal/sq cm/cm/°C/sec; at 100 C (212 F) 0.198; at 300 C (572 F) 0.152; at 500 C (932 F) 0.148

E *1 Volume conductivity* referred to standard copper. 25.2%

2 Electrical resistivity at 20 C (68 F). 6.84 microhm-cm

5 Temperature coefficient of electrical resistivity 0 to 100 C (32 to 212 F). 0.0069 microhm-cm per °C (Fig. 3)

9 Contact potential versus platinum 0 to 100 C (32 to 212 F). 1.485 mv

F *1 Reflectivity.* 0.64 at $\lambda = 5500$ A

5 Emissivity. 0.355 at $\lambda = 6500$ A (unoxidized)

G *Magnetic Properties. See* Fig. 4, 5, 6, 7 and 8.

8 Magnetostriction. -32×10^{-6} cm per cm per gauss

9 Magnetic transformation temperature. 353 C (665 F)

Effect of alloying additions. *See* Fig. 8.

J *1 Crystal structure.* Face-centered cubic; $a = 3.5167$ kX at 20 C (68 F)

K *Mechanical properties.*

Modulus of elasticity. See Fig 9.

Hardness versus annealing temperature. See Fig 10.

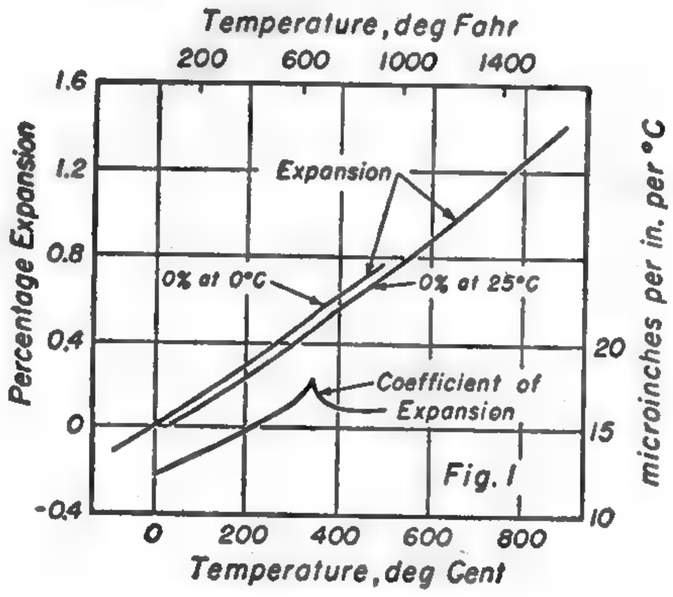
Tensile strength (annealed). 46,000 psi

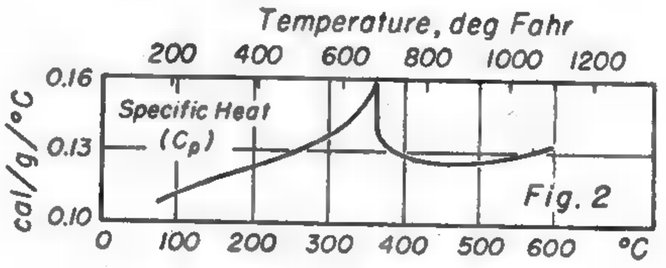
Yield strength (annealed). 8500 psi

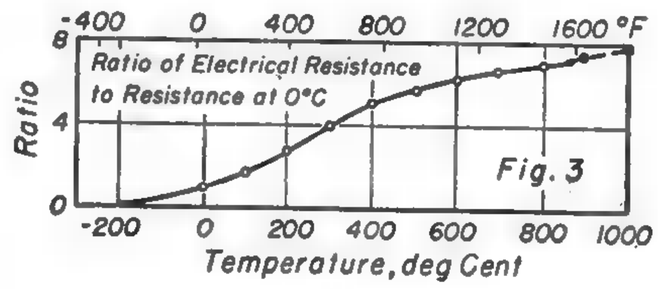
Elongation (annealed). 30%

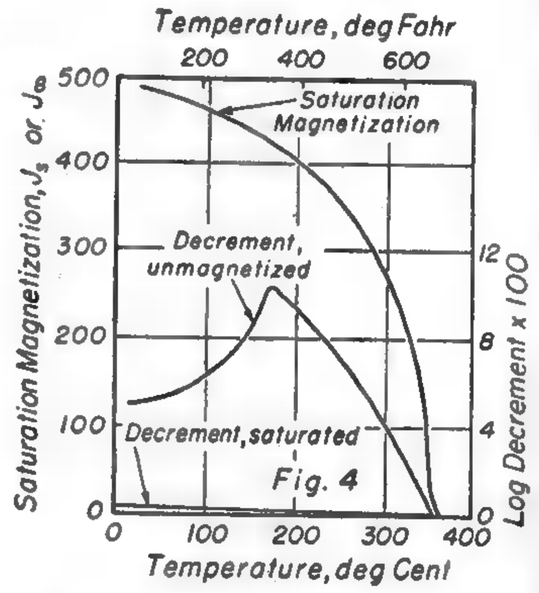
* Development and Research Division, The International Nickel Company, Inc., New York

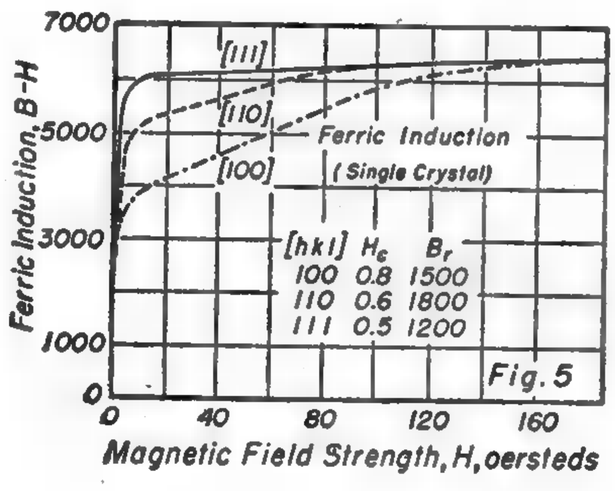
Reference. E. M. Wise and R. H. Schaefer, The Properties of Pure Nickel, Metals & Alloys, 16, 424 (1942). This paper contains 39 references.

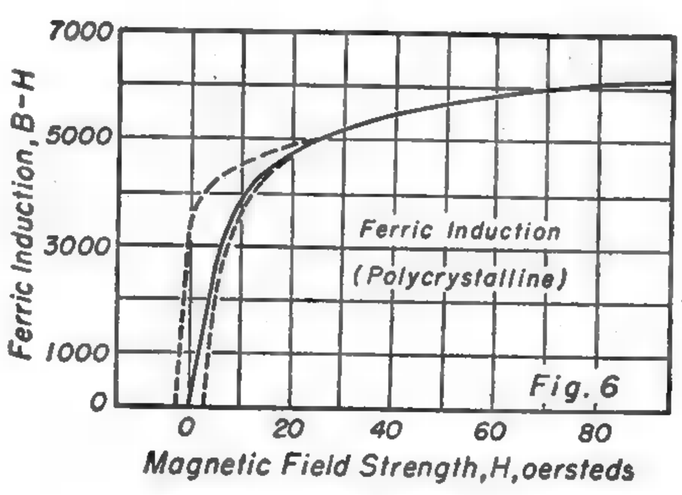


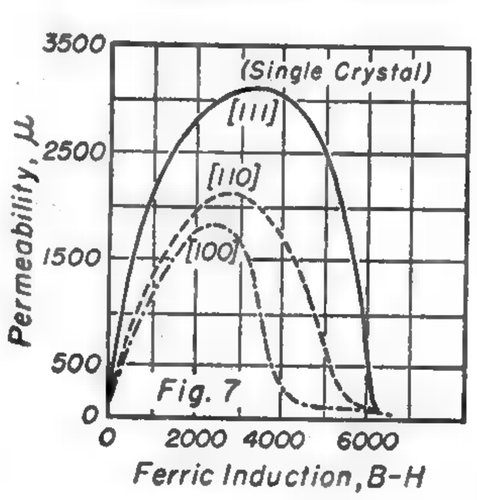


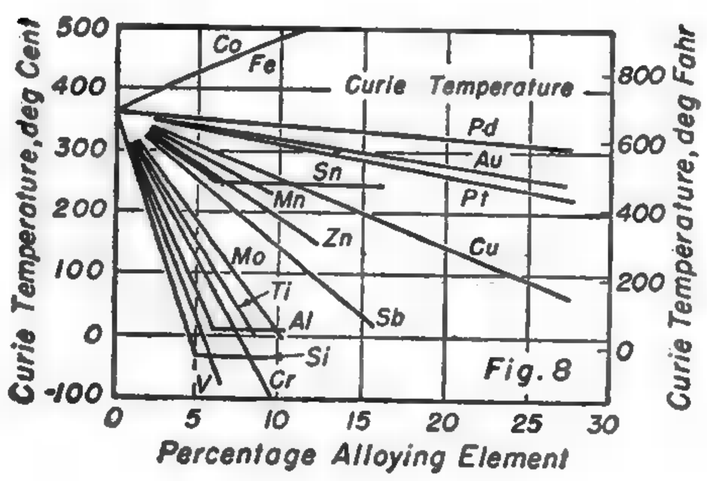


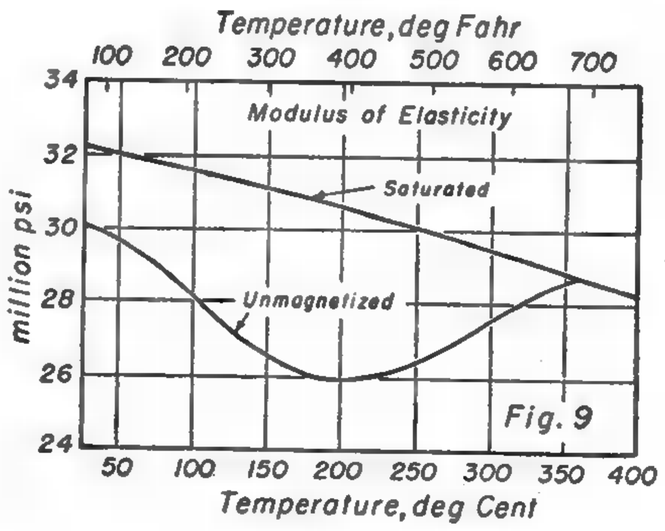


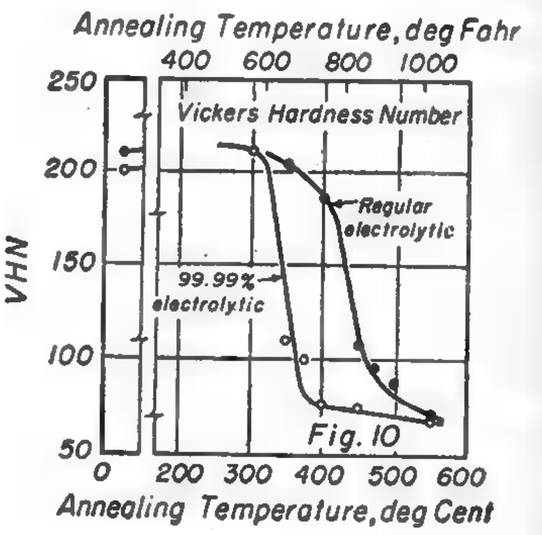












Nickel (99.4 Ni + Co)

COMPILED BY G. F. GEIGER*

A *2 Trade name.* "A" Nickel*
3 ASTM numbers. B 160–41T, B 161–41T, B 162–41T, and B 163–41T
B *1 Typical uses.* Chemical industry, production of caustic soda, nickel plating, heat-resisting articles
C *1 Density* at 20 C (68 F). 8.885 ■ per cu cm (0.321 lb per cu in.)
D *1 Liquidus temperature.* 1446 C (2635 F)
2 Solidus temperature. 1435 C (2615 F)
6 Thermal expansion 25 to 100 C (77 to 212 F). 0.0000133 per °C
11 Specific heat 0 to 100 C (32 to 212 F). 0.13 cal per ■
13 Latent heat of fusion. 73 cal per ■
16 Thermal conductivity 0 to 100 C (32 to 212 F). 0.145 cal/sq cm/cm/°C/sec (420 Btu/sq ft/hr/°F/in.)
19 Recrystallization temperature. 600 C (1112 F)
E *1 Volume conductivity* referred to standard copper. 18%
2 Electrical resistivity at 20 C (68 F). 9.5 microhm-cm
5 Temperature coefficient of electrical resistivity 20 to 100 C (68 to 212 F). 0.00474 microhm-cm per °C
Electrical resistivity versus temperature. See Fig. 1.

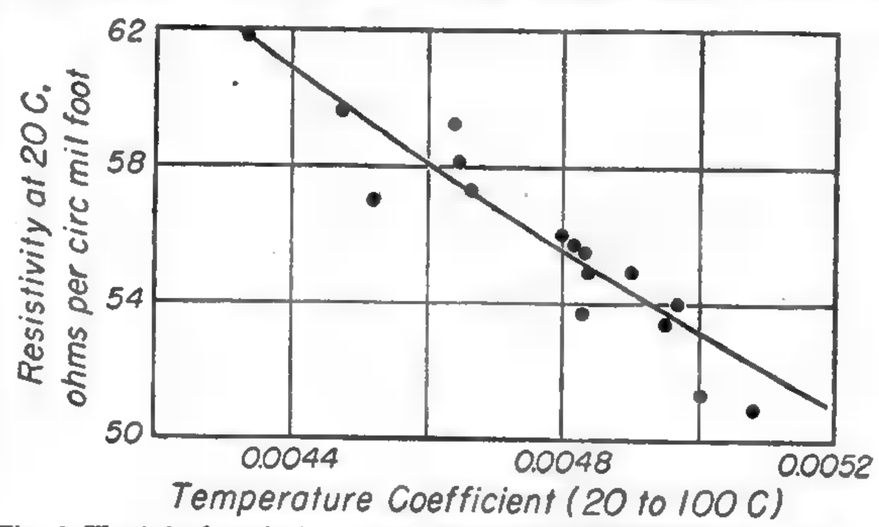


Fig. 1 Electrical resistivity and temperature coefficient of "A" Nickel

G *3 Initial permeability.* 110 gausses
Maximum permeability. 600 gausses
4 Coercive force. 3.4 oersteds
5 Saturation magnetization (*B-H*). 6100 gausses
7 Hysteresis loss at saturation. 3000 ergs per cu cm per cycle
9 Magnetic transformation temperature. 360 C (680 F)
K *Mechanical properties. See* Table I.
Modulus of elasticity. Sand cast, 21,500,000 psi; annealed, 30,000,000 psi
Charpy. Annealed, 222 ft-lb; hot rolled 197 ft-lb; cold drawn, 195 ft-lb; sand cast, 60 ft-lb
Izod. Annealed, hot rolled, or cold drawn, 120 ft-lb; sand cast, 85 ft-lb
Strength in double shear. Annealed, 52,300 psi; ½ hard, 57,550 psi; hard, 75,300 psi
Endurance limit for 100,000,000 cycles. Annealed, 24,000 psi; hot rolled, 30,000 psi; cold drawn, 42,500 psi
6 Minimum creep rate at 400 C (750 F). Hot rolled, 10,000 psi, 1% per 10,000 hr; at 425 C (800 F). Cold drawn, 24,000 psi, 1% per 10,000 hr
M *Composition limits.* Wrought products: 99% Ni min; 0.25% Cu max; 0.5% Fe max; 0.35% Mn max; 0.5% Si max; 0.2% C max; 0.02% S max

Table I. Tensile Properties and Hardness of Nickel (99.4 Ni + Co)

Condition	Yield Strength (0.20% offset), 1000 psi	Tensile Strength, 1000 psi	Elongation in 2 in., per cent	Reduction of Area, per cent	Bhn	Rockwell B
Rod and Bar						
Cold drawn						
Annealed	10-30	50-80	50-35	75-60	90-120	40-65
As drawn.....	40-90	65-115	35-15	70-50	125-230	70-100
Hot rolled	15-45	55-80	65-30	75-60	90-120	40-65
Forged	20-80	65-105	40-25	70-50	90-200	40-95
Cold Drawn Wire						
Annealed	10-30	50-80	50-30	.....	.....	.....
No. 1 temper...	75-90	90-105	20-5	.....	.....	.....
Regular temper.	90-130	105-140	15-4	.....	.....	.....
Spring	130-155	135-165	10-2	.....	.....	.....
Hot Rolled Plate						
Annealed	10-30	50-80	50-35	.....	90-120	40-65
As rolled	20-75	70-100	45-30	.....	100-200	50-100
Standard Cold Rolled Sheet						
As rolled	15-45	55-80	50-35	.....	.....	40-70
Special Cold Rolled Sheet and Strip						
Annealed	10-30	50-80	50-35	.....	.....	40-70
Hard sheet	70-105	90-115	15-2	.....	.....	92 min.
Full hard strip..	70-115	90-130	15-2	.....	.....	96 min.
Cold Drawn Tubing						
Annealed	10-30	50-80	50-35	.....	.....	40-65
As drawn.....	50-80	70-95	35-15	.....	.....	80-100
Sand Castings						
As cast.....	25	53	25	.....	100	.....

N *2 Casting temperature range* (sand). 1510 to 1595 C (2750 to 2900 F)
3 Alloying. Add silicon and manganese as metals.
4 Preferred deoxidizer. Magnesium
5 Type of flux. Lime-fluorspar
6 Precautions in melting. Do not superheat.
7 Hot working temperature. 650 to 1260 C (1200 to 2300 F)
9 Annealing temperature. 650 to 760 C (1200 to 1400 F)
10 Maximum reduction between anneals. 90%
11 Suited to forming by all methods of hot and cold working.
12 Precautions in forming. Do not heat in sulfidizing atmospheres.
17 Joining.
Soft solder with Pb-base and Sn-base alloys, acid flux.
Silver solder with phosphorus-free silver brazing alloys, fluoride flux, reducing flame.
Braze with phosphorus-free and lead-free alloys, fluoride flux, reducing flame.
Oxyacetylene weld with nickel, no flux, reducing flame.
Metal-arc weld with nickel, proprietary flux.
Resistance welding. All methods are satisfactory.

* Nominal composition includes 0.2% Mn, 0.15% Fe, 0.1% Cu, 0.1% C, 0.05% Si, 0.005% S.

Reference. E. M. Wise and R. H. Schaefer, The Properties of Pure Nickel—II, Metals & Alloys, 16, 891 (1942)

95 Ni – 4.5 Mn

COMPILED BY W. A. MUDGE*

A *2 Trade name.* "D" Nickel
B *1 Typical uses.* To provide improved resistance to attack by sulfur compounds at elevated temperatures in both oxidizing and reducing atmospheres; spark plug wires.
2 Precautions in use. Do not use above 540 C (1000 F) in sulfidizing atmospheres.

* Development and Research Division, The International Nickel Company, Inc., New York

C *1 Density* at 20 C (68 F). 8.78 ■ per cu cm (0.317 lb per cu in.)
D *11 Specific heat* 0 to 100 C (32 to 212 F). 0.13 cal per g
16 Thermal conductivity 0 to 100 C (32 to 212 F). 0.115 cal/sq cm/cm/°C/sec
E *2 Electrical resistivity* at 20 C (68 F). 14 microhm-cm
G *9 Magnetic transformation temperature.* 352 C (665 F)
K *Mechanical properties.* Hot rolled: tensile strength 86,000 psi; yield strength (0.2% offset) 34,000 psi;

elongation 40%; reduction of area 60%; Brinell hardness number 147; Rockwell hardness B 70; modulus of elasticity 30,000,000 psi; torsional breaking strength 68,000 psi; torsional yield strength 26,000 psi; angle of twist 380 deg per in.; shear 2.70 in. per in.; ratio of torsional breaking strength to tensile strength 0.79.

M *Composition limits.* The alloy usually contains approximately 0.15% Fe; 0.10% C; 0.05% Cu; 0.05% Si and 0.005% S in addition to 4.5% Mn. A similar alloy having the trade name **"E" Nickel** contains 2% Mn.

N 1 *Melting temperature range.* Approx 1430 C (2600 F)
2 *Casting temperature range* (ingot). Approx 1565 C (2850 F)
3 *Alloying.* Add Mn as the metal when Ni is molten.
4 *Preferred deoxidizer.* Magnesium
5 *Type of flux.* Lime-fluorspar, reducing
6 *Precautions in melting.* Do not overheat.
7 *Hot working temperature range.* 650 to 1175 C (1200 to 2150 F)
9 *Annealing temperature.* 760 to 815 C (1400 to 1500 F)
10 *Maximum reduction between anneals.* 85%
11 *Suited to forming* by all methods of hot and cold working.
17 *Joining.*
Soft solder with Pb-base or Sn-base alloys, acid flux.
Silver solder with phosphorus-free silver alloys, fluoride flux, slightly reducing flame.
Braze with phosphorus-free and lead-free alloys, standard brazing flux, slightly reducing flame.
Oxyacetylene weld with "D" Nickel, fluoride-base flux, slightly reducing flame.
Resistance welding. All types are satisfactory.

94 Ni – 4.5 Al

COMPILED BY W. A. MUDGE*

A 2 *Trade name.* **"Z" Nickel**
B 1 *Typical uses.* For industrial applications that demand high strength and high resistance to corrosion, especially in large sections; pump rods; springs; shafts.
2 *Precautions in use.* Do not use above 320 C (600 F) in sulfidizing atmospheres.
C 1 *Density* at 20 C (68 F). 8.26 g per cu cm (0.298 lb per cu in.)
D 1 *Liquidus temperature.* 1446 C (2635 F)
2 *Solidus temperature.* 1435 C (2615 F)
6 *Thermal expansion* 0 to 100 C (32 to 212 F). 0.0000130 per °C (0.0000072 per °F)
11 *Specific heat 0 to 100 C* (32 to 212 F). 0.13 cal per g
E 2 *Electrical resistivity* at 20 C (68 F). 43.3 microhm-cm
G *Magnetic properties.* Nonmagnetic or very slightly magnetic in the soft condition. Slightly magnetic when age hardened.
K *Mechanical properties. See* Tables I and II.
L 2 *Radiography.* Technique similar to that for steel; voltage to be increased 15%.
N 1 *Melting temperature.* 1435 to 1445 C (2615 to 2635 F)
2 *Casting* (ingot). 1565 to 1620 C (2850 to 2950 F)
4 *Preferred deoxidizer.* Magnesium
5 *Type of flux.* Lime-cryolite
7 *Hot working temperature.* 700 to 1175 C (1300 to 2150 F)
9 *Annealing temperature.* 870 C (1600 F) for 1 hr, followed by quenching in water.
10 *Maximum reduction between anneals.* 85%
11 *Suited to forming* by all types of hot working and cold working methods.
15 *Heat treatment.*

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hr	Atmosphere	Cooling
To soften	870	1600	½	Reducing	Quench in water
To harden	595	1100	8 to 16	Reducing	Cool in furnace

16 *Standard finishes.* Hot rolled, cold drawn, or cold rolled. Mill products are given all finishes.
17 *Joining.*
Soft solder with Pb-base or Sn-base solder, acid flux.
Silver solder with phosphorus-free silver alloys, fluoride flux, slightly reducing flame.
Braze with phosphorus-free and lead-free alloys, fluoride-base flux, slightly reducing flame.
Oxyacetylene weld with "Z" Nickel, fluoride flux, slightly reducing flame.
Metal-arc weld with "Z" Nickel, fluoride flux, direct current.

* Development and Research Division, The International Nickel Company, Inc., New York

Table I. Tensile Properties and Hardness of 94 Ni – 4.5 Al

Condition	Tensile Strength, 1000 psi	Yield Strength (0.20% offset), 1000 psi	Elongation in 2 in., percentage	Reduction of Area, percentage	Brinell Hardness (3000 kg)	Rockwell Hardness
Cold Drawn Rod and Bar						
Annealed	30 to 60	90 to 120	50 to 25	65 to 45	140 to 180	B 75 to 90
As drawn	50 to 130	100 to 150	35 to 15	60 to 40	175 to 300	C 8 to 31
As drawn, age hardened	120 to 150	160 to 190	20 to 7	30 to 15	300 to 380	C 31 to 40
Hot Rolled Rod and Bar						
As rolled	35 to 85	90 to 120	50 to 25	65 to 45	150 to 225	C 0 to 18
As rolled, age hardened	120 to 140	160 to 180	20 to 10	30 to 15	300 to 350	C 31 to 38
Cold Drawn Wire						
Annealed	30 to 60	90 to 120	40 to 25	.....	.....	.....
Annealed, age hardened	.....	160 to 190	15 to 7	.....	.....	.....
Spring, as drawn	.....	150 to 200	5 to 2	.....	.....	.....
Spring, age hardened	.....	190 to 250	10 to 5	.....	.....	.....
Cold Rolled Strip						
Soft	30 to 60	90 to 120	50 to 25	.....	.....	B 75 to 90
Soft, age hardened	.....	150 to 190	20 to 10	.....	.....	C 30 to 40
½ hard	.....	130 to 155	15 to 3	.....	.....	C 25 to 34
½ hard, age hardened	.....	160 to 210	20 to 7	.....	.....	C 33 to 42
Full hard	.....	155 to 190	10 to 2	.....	.....	C 30 to 40
Full hard, age hardened	.....	180 to 230	15 to 5	.....	.....	C 36 to 46

Table II. Some Mechanical Properties of 94 Ni – 4.5 Al

Condition	Modulus of Elasticity, psi	Charpy, ft-lb	Izod, ft-lb	Shear Strength, psi	Endurance Strength 10^8 cycles, 1000 psi	Compressive Yield Strength (0.01% offset), psi	Compressive Yield Strength (0.2% offset), psi
Hot rolled	30,000,000	240+	120+	67,500	53.5	40,000	51,000
Hot rolled and age hardened	.....	36	25	116,000	52.0	126,000	148,000
Cold drawn	.....	190	120+	89,000	52.5 to 54.5	67,000	103,000
Cold drawn and age hardened	.....	41	25	104,000	53.5 to 65.5	140,000	166,000

97 Ni – 1.5 Si

COMPILED BY W. A. MUDGE*

A *1 Common name.* **Cast Nickel***

B *1 Typical uses.* Cast nickel has resistance to corrosion similar to that of wrought nickel and is useful for applications in equipment handling corrosives such as caustics, and when it is necessary to avoid contamination of a product with such metals as copper and iron. Resistance to galling under faulty lubrication can be provided by adjustment of the minor elements, including carbon.

C *1 Density* at 20 C (68 F). 8.34 ■ per cu cm (0.301 lb per cu in.)

5 Solidification shrinkage. 0.25 in. per ft

D *6 Thermal expansion* 25 to 100 C (77 to 212 F). 0.0000130 per °C (0.0000072 per °F)

E *2 Electrical resistivity* at 20 C (68 F). 21 microhm-cm

G *Magnetic properties.* Slightly magnetic at room temperature. Magnetic properties decrease with increasing silicon content.

K *Mechanical properties.* Sand cast: tensile strength 45,000 to 60,000 psi; yield strength (0.05% elongation under load) 20,000 to 30,000 psi; elongation in 2 in. 30 to 15%; Brinell hardness number 80 to 125; modulus of elasticity 21,500,000 psi; Charpy 60 ft-lb; Izod 90 to 75 ft-lb; compressive yield strength (0.00% offset) 10,000 psi, (0.01% offset) 14,000 psi, (0.2% offset) 23,000 psi.

N *1 Melting temperature range.* 1345 to 1425 C (2450 to to 2600 F)

2 Casting temperature range (sand). 1510 to 1595 C (2750 to 2900 F)

4 Preferred deoxidizer. Magnesium

16 Standard finishes. Machined or sandblasted.

17 Joining.
Soft solder with Pb-base or Sn-base alloys, acid flux.
Silver solder with phosphorus-free silver alloys, fluoride flux, slightly reducing flame.
Braze with phosphorus-free and lead-free alloys, fluoride-base flux, slightly reducing flame.
Oxyacetylene weld with nickel, fluoride flux, slightly reducing flame.
Metal-arc weld with nickel; fluoride flux; direct current.

* Nominal composition includes 0.50% Mn, 0.50% C, 0.30% Cu, 0.25% Fe, 0.015% S.

67 Ni – 30 Cu – 1.4 Fe – 1 Mn – 0.15 C – 0.1 Si – 0.01 S

COMPILED BY E. R. PATTON*

A *2 Trade name.* **Monel†**

3 ASTM numbers. B 127–41T, B 163–41T, B 164–41T, B 165–41T

4 Government numbers. QQ-N-281, Am 1, Cl A; Navy 46M7g, Cl A; 44T38; QQ-R-571, Type F (gas-welding wire); Navy 46R1, Grade 1, Cl F (gas-welding wire); Navy 17E4A (metal-arc electrode)

5 Other designations. ASME SB-127, SB-163, SB-164, SB-165

6 Foreign equivalents. British DTD-192, DTD-10B, DTD-196, DTD-200A, DTD-204A

B *1 Typical uses.* Used where high strength and resistance to corrosion are required. Widespread and diversified uses in chemical, pharmaceutical, marine, power, electrical, oil refinery, laundry, textile, pulp and paper equipment; and for household and architectural applications where appearance is a factor. Useful against many commonly encountered corrosives, such as sea water, dilute sulfuric acid, and strong caustic solutions.

2 Precautions in use. Not suitable in sulfidizing atmospheres at temperatures above 370 C (700 F). Does not oxidize at a destructive rate below approximately 540 C (1000 F) in sulfur-free atmospheres, and for some purposes may be used up to 820 C (1500 F). The scale formed is adherent. Sulfur compounds in the atmosphere lower the safe limit of temperature. Not useful in highly oxidizing acids such as nitric and nitrous, ferric salts in acid solutions, stannic and mercuric salts, alkaline hypochlorite solutions in concentrations greater than 3 grams of available chlorine per liter, in sulfur-bearing gases above about 370 C (700 F), and in molten metals such as lead, tin, zinc, aluminum and in molten sulfur.

Furnace atmospheres for heating for hot working or for open annealing should be sulfur-free and slightly reducing with 2% or more of carbon monoxide; sulfur should not exceed 0.5% and preferably should not exceed 0.2%. Avoid fluctuating or marginal atmospheres, that is, reducing to oxidizing to reducing.

C *1 Density* at 20 C (68 F). 8.84 g per cu cm (0.319 lb per cu in.)

D *1 Melting temperature.* 1300 to 1350 C (2370 to 2460 F)

6 Thermal expansion. See Fig. 1.
0 to 100 C. 0.0000140 per °C
77 to 212 F. 0.0000078 per °F

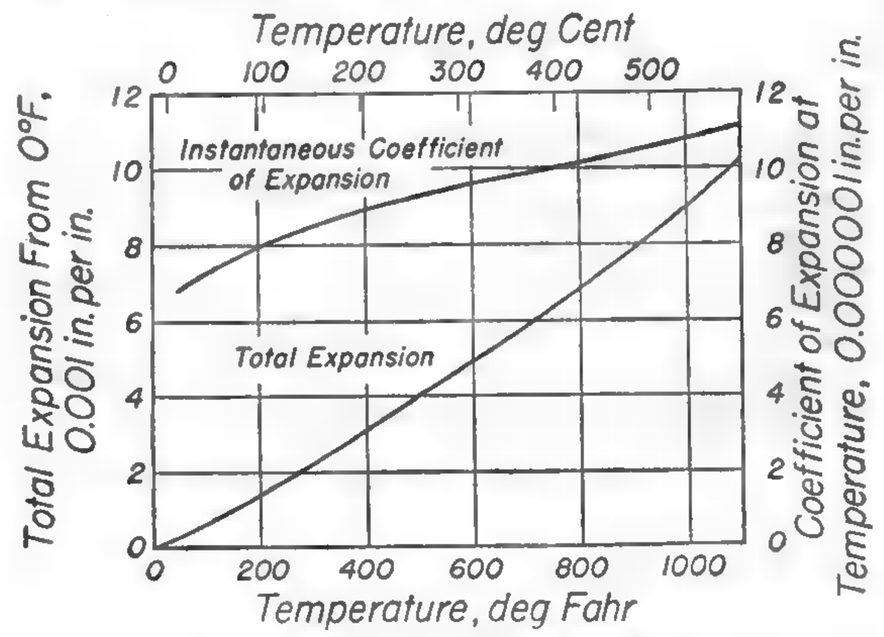


Fig. 1 Thermal expansion of Monel

11 Specific heat at 1260 C (2300 F). 0.127 cal per ■

13 Latent heat of fusion. 68 cal per g

16 Thermal conductivity 0 to 100 C (32 to 212 F). 0.062 cal/sq cm/cm/°C/sec

19 Recrystallization temperature.
660 C (1220 F) for 10% reduction
600 C (1112 F) for 50% reduction

E *1 Volume conductivity* referred to standard copper. 3.58%

2 Electrical resistivity at 20 C (68 F). 48.2 microhm-cm (290 ohms per cir mil-ft)

5 Temperature coefficient of electrical resistivity. 20 to 100 C (68 to 212 F). 0.0011 microhm-cm per °C (0.0019 microhm-cm per °F)

F *4 Color.* White. *See* reference 1.

G *Magnetic properties. See* reference 2.

1 Influence of treatments. Alloying elements, other than cobalt and iron, in solid solution in nickel, lower the Curie temperature. Sufficient copper is present in

* Development and Research Division, The International Nickel Company, Inc., New York

† This alloy is also made in a free-cutting grade ("R" Monel) that contains 30% Cu, 1.7% Fe, 1.1% Mn, 0.1% C, 0.05% Si, 0.035% S.

Table I. Tensile Properties and Hardness of 67 Ni – 30 Cu

Condition	Tensile Strength, 1000 psi	Yield Strength (0.2% offset), 1000 psi	Proof Stress (0.01% offset), 1000 psi	Elongation in 2 in., percentage	Reduction of Area, percentage	Brinell Hardness (3000 kg)	Rockwell Hardness Number
Rod and Bar							
Annealed	70 to 85	25 to 40	20 to 30	50 to 35	75 to 60	110 to 140	B 60 to 75
Hot rolled	80 to 95	40 to 65	30 to 55	45 to 30	75 to 60	140 to 185	B 75 to 90
Forged	75 to 110	40 to 85	25 to 65	40 to 20	70 to 60	140 to 220	B 75 to 98
Cold drawn, as drawn	85 to 125	55 to 120	45 to 95	35 to 10	70 to 50	160 to 250	B 85 to C 23
Cold drawn, No. 1 temper (less than ½ in.)	95 to 110	50 to 85	.....	20 to 5	.....	.....	.....
Cold Drawn Wire							
Annealed	70 to 85	25 to 40	.....	50 to 30	.....	.....	.....
No. 1 temper	95 to 110	50 to 85	.....	20 to 5	.....	.....	.....
Regular temper	110 to 140	85 to 130	.....	15 to 4	.....	.....	.....
Spring temper (less than $\frac{5}{16}$ in. diam)	140 to 170	130 to 160	.....	10 to 2	.....	.....	.....
Hot Rolled Plate							
Annealed	70 to 85	25 to 45	20 to 30	50 to 30	.....	110 to 140	B 60 to 75
As rolled	80 to 110	40 to 90	25 to 70	45 to 20	.....	140 to 220	B 75 to 98
Cold Rolled Sheet and Strip							
Annealed sheet and strip	70 to 85	25 to 45	.....	50 to 30	.....	.....	B 61 to 73
Standard cold rolled sheet	70 to 85	25 to 45	.....	50 to 30	.....	.....	B 61 to 73
No. 35 sheet	78 to 85	45 to 65	.....	40 to 20	.....	.....	B 74 to 89
¼ hard strip	78 to 85	45 to 65	.....	40 to 20	.....	.....	B 74 to 82
Hard sheet	100 to 120	90 to 110	.....	15 to 2	.....	.....	B 94 min
Full hard strip	100 to 140	90 to 130	.....	15 to 2	.....	.....	B 98 min
Seamless Drawn Tubing							
Annealed	70 to 85	25 to 45	.....	50 to 30	.....	.....	B 60 to 75
As drawn	90 to 125	60 to 120	.....	20 to 10	.....	.....	B 90 to 105 C 8 to 23

Table II. Some Mechanical Properties of 67 Ni – 30 Cu

Form and Condition	Rockwell Hardness Number	Modulus of Elasticity, psi	Charpy (V-Notch), ft-lb	Izod, ft-lb	Endurance Strength 100,000,000 cycles, psi
Cast	B 70 to 80	26,000,000	70	80 to 65	.....
Rod, annealed	B 60 to 75	26,000,000	215	120 to 90	31,000 to 36,000
Rod, hot rolled	B 75 to 90	26,000,000	220	120 to 100	39,000 to 44,000
Forged	B 75 to 98	26,000,000	200	115 to 75	.....
Cold drawn, as drawn	B 85 to C 23	26,000,000	150	115 to 75	39,500 to 47,500

Table III. Results of Tension and Tension-Impact Tests on 67 Ni – 30 Cu

Condition	Impact Tests: Brinell Hardness	Impact Tests: Tension Impact, ft-lb	Impact Tests: Reduction of Area, percentage	Impact Tests: Elongation in 3.5 in., percentage	Tension Tests: Tensile Strength, psi	Tension Tests: Reduction of Area, percentage	Tension Tests: Elongation in 2 in., percentage
Cold drawn	199	96(a)	63.7	15.0	92,250	66.4	27.0
Annealed	123	129(a)	68.0	29.5	78,350	65.9	44.0

(a) Proportional limit

Monel to lower the Curie temperature considerably, so that although Monel is usually slightly magnetic at room temperature, it will become nonmagnetic when warmed mildly. Monel that contains about 1.25% Si is nonmagnetic at room temperature; a silicon content of 4% lowers the Curie temperature to approximately minus 57 C (minus 70 F). The magnetic characteristics of Monel are not affected greatly by cold work or thermal treatment.

2 *Magnetic susceptibility.* Slightly magnetic at room temperature.

3 *Magnetic permeability.* 2000 to 10,000 cgs. Some weakly magnetic alloys have high B at very low H and consequently a high permeability.

5 *Saturation magnetization.* 1000 to 2000 gausses at 200 oersteds

9 *Magnetic transformation temperature.* 43 to 60 C

J 1 *Crystal structure.* Face-centered cubic; $a = 3.541$ kX

Table IV. Tensile Properties of Large, High-Tensile Forged Rods of 67 Ni – 30 Cu
(Average of tests on each end of 17 rods, 9⅝ in. diam by 22 ft long by 6000 lb)

	Yield Strength,(a) (0.00% offset), psi	Proof Stress (0.01% offset), psi	Yield Strength (0.20% offset), psi	Tensile Strength, psi	Elongation in 2 in., percentage	Reduction of Area, percentage
Longitudinal	55,700	62,000	70,100	95,300	33.5	70.6
Transverse	54,400	60,900	69,600	93,800	28.2	53.0

(a) Proportional limit

Table V. Effect of Orientation of Test Specimen Relative to Direction of Forging
(67 Ni – 30 Cu, high-tensile forged rods)

Angle of Test Specimen, degrees	Tensile Properties: Proof Stress (0.01% offset), psi	Tensile Properties: Yield Strength (0.20% offset), psi	Tensile Properties: Tensile Strength, psi	Tensile Properties: Elongation in 2 in., percentage	Tensile Properties: Reduction of Area, percentage	Impact, ft-lb: Standard Izod	Impact, ft-lb: Standard Charpy	Impact, ft-lb: Round Izod(a)
0 (longitudinal)	55,750	61,875	89,060	35.6	67.5	>120	220	103(b)
15	54,200	61,000	88,025	37.8	67.6	>120	210	101(b)
30	54,100	60,650	86,325	36.3	68.7	116	205	90(b)
45	55,000	62,050	88,125	35.5	66.5	111	175	84(b)
60	55,800	63,400	89,875	30.0	59.4	99	150	69(b)
75	54,500	63,350	90,750	27.8	52.9	91	133(b)	65(b)
Transverse	53,800	62,950	91,000	26.5	53.7	84	128(b)	64(b)

(a) Dimensions were: diam 0.500 in.; notch angle 60 deg and 0.01-in. radius in bottom of notch; notch depth 0.075 in.; distance of notch from end of specimen 1.125 in.; root diam 0.350 in.

(b) Indicates a completely broken test specimen; all other test specimens were broken incompletely.

Condition	Rockwell Hardness	Tensile Strength, psi	Deflection at Maximum Strength, in.	Maximum Shear Strength, psi
Soft	B 61	69,800	0.08	49,200
½ hard	B 89	76,800	0.06	54,700
Hard	B 100	116,100	0.03	65,200

Form and Condition	Yield Strength (0.0% offset), psi	Tensile Strength, psi	Endurance Strength 100,000,000 cycles, psi
Strip, annealed	21,400	73,700	24,500
Strip, full hard	58,200	122,800	37,750

Condition	Brinell Hardness	Torsion Impact, ft-lb	Ft-lb per sq in.	Angle of Twist, degrees
Cold drawn	199	39	788	98.0
Hot rolled	145	34	694	101.5
Annealed	123	30	599	102.0

Condition	Apparent Corrosion-Fatigue Limit (10^8 cycles), psi In Air	In Fresh Water	In Brackish Water
Annealed	36,000	21,000 to 24,000	20,000 to 22,000
Cold worked	50,000	21,000 to 24,000	20,000 to 22,000

K *Mechanical properties.* *See* Tables I to V.
Shear modulus. 9,500,000 psi
6 *Creep properties.* *See* Fig. 2, 3 and 4.
10 *Short-time, high-temperature properties.* *See* Fig. 5.
L 2 *Radiography.* The procedure is similar to that for steel with approximately 15% increase of current.

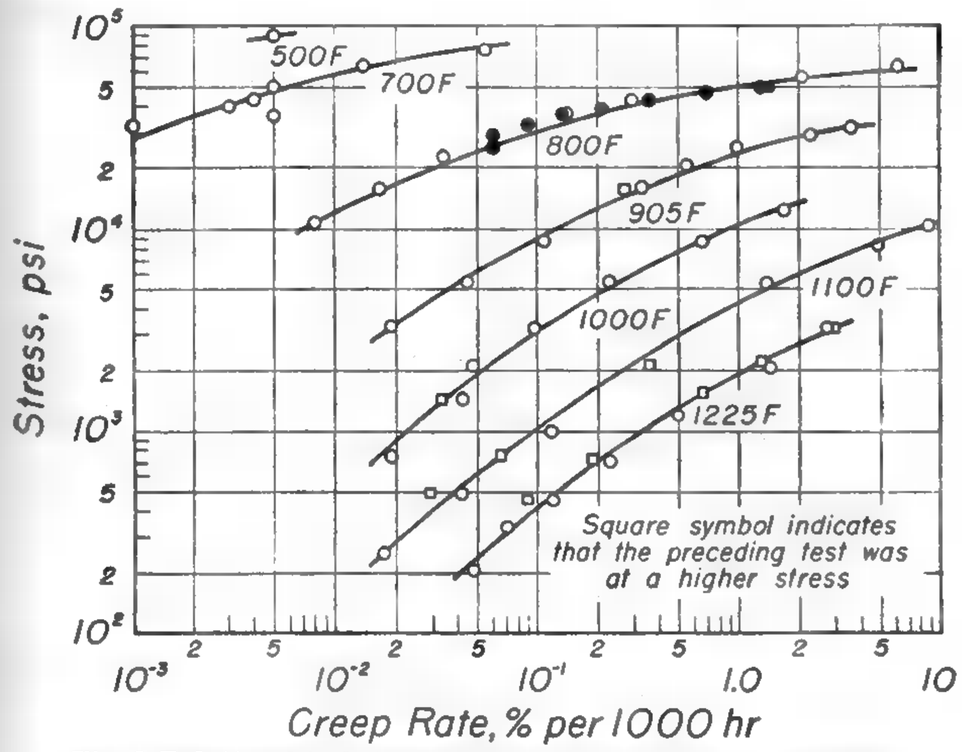


Fig. 2 Relationship between stress and creep rate at various temperatures (Bennett and McAdam[3])

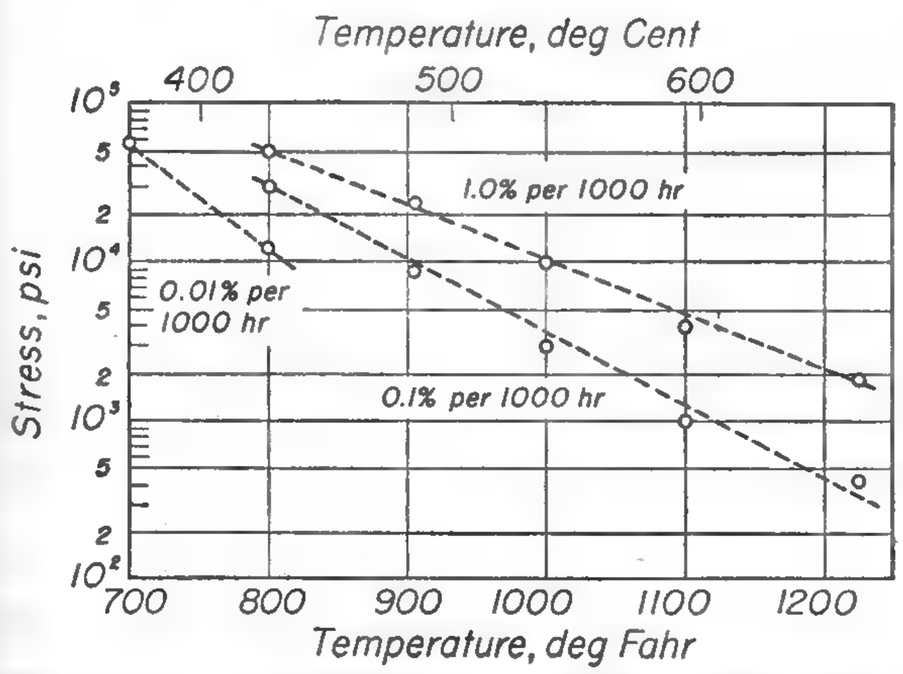


Fig. 3 Relationship between temperature and the stress required to produce certain creep rates, as derived from Fig. 2 (Bennett and McAdam[3])

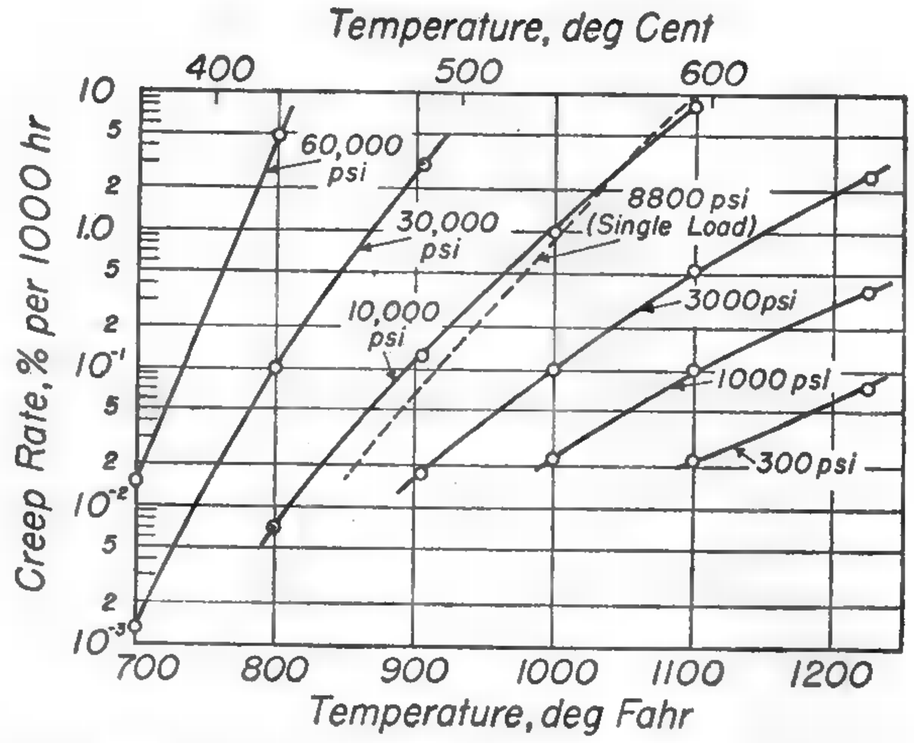


Fig. 4 Relationship between temperature and creep rate for various stresses, as derived from Fig. 2 (Bennett and McAdam[3])

M *Composition limits* (specifications: QQ-N-281; Navy 46M7g; ASTM B 164–41T; B 127–41T; B 165–41T; B 163–41T; ASME SB-164; SB-127; SB-165; SB-163).

Nickel[a]	63.0 to 70.0	Carbon	0.30 max
Iron	2.50 max	Silicon	0.50 max
Aluminum	0.50 max	Sulfur	0.02 max
Manganese	2.00 max	Copper	remainder

(a) Includes a small amount of cobalt

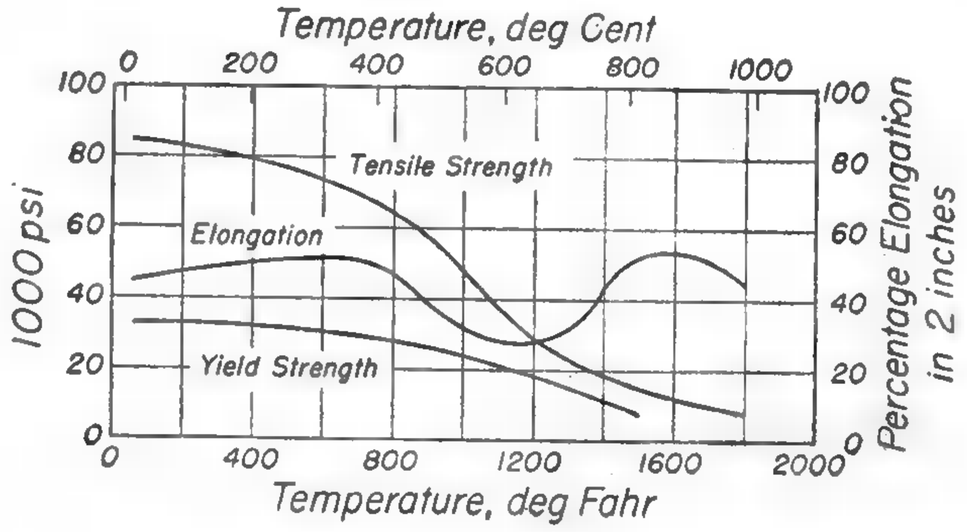


Fig. 5 Tensile properties of hot rolled Monel at elevated temperatures

N 1 *Melting temperature range.* 1300 to 1350 C (2370 to 2460 F)
2 *Casting temperature range* (sand). 1480 to 1565 C (2700 to 2850 F)
4 *Preferred deoxidizer.* Magnesium

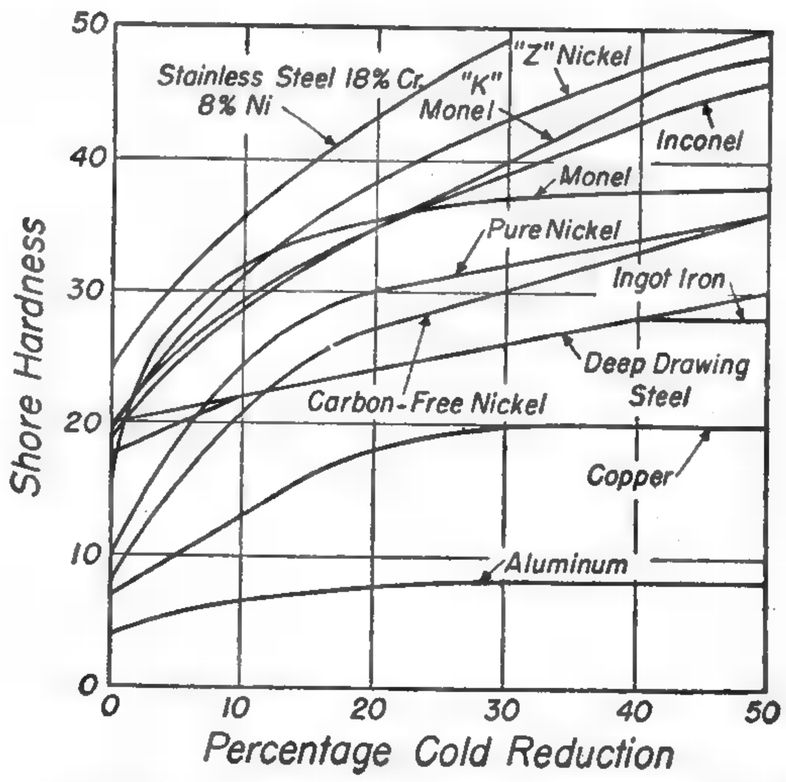


Fig. 6 Increase in hardness of various metals with cold working

7 *Hot working temperature range.*
Best bending, 1010 to 1177 C (1850 to 2150 F)
Heavy and drop forging, 926 to 1177 C (1700 to 2150 F)
High-tensile forging, 538 to 649 C (1000 to 1200 F)
8 *Shortness range.* 650 to 925 C (1200 to 1700 F)
Light forging only may be performed in this range.
9 *Annealing.* See the article on page 1031.
10 *Maximum reduction between anneals.* Up to 90% for cold rolling or cold drawing; deep drawing, up to 40% for first draw, 25% for next and 10 to 15% for subsequent reductions; spinning, up to 50% reduction. For increase in hardness with cold work, *see* Fig. 6.
12 *Precautions in forming.* The alloy should be degreased thoroughly after forming, before thermal treatment, to remove sulfur-bearing lubricants. Likewise similar precautions should be taken against contamination from "Kirksite" dies on parts formed by drop hammer. Coarse-grained materials are unsuitable for most cold forming operations, particularly for heavy cold work.
16 *Standard finishes.* Forgings: as forged, rough-turned, or finish-machined. Mill products: all types of finish.
17 *Joining.*
Rivet compositions. Soft Monel rivets
Soft solder with 50-50 or 60-40 Sn-Pb, tinned surfaces preferred, cut-acid or proprietary flux. Do not use rosin.
Silver solder with phosphorus-free low-melting-point silver alloys; neutral or slightly reducing flame.
Braze with naval brass or tobin bronze. Brazing with brass or bronze is not used frequently, since the resistance to corrosion of the bronze joints is less than that of Monel; oxyacetylene welding or silver brazing is preferred.
Oxyacetylene weld with "40" Monel gas welding rod, "1" gas welding and brazing flux, slightly reducing flame.
Resistance welding. See reference 4.
Metal-arc weld with 130X Monel electrodes
Submerged-melt weld with suitable electrodes

References

1 Kihlgren, Pilling and Wise, Trans AIME, 117, 284 (1935)
2 Michels and Strigland, Physica, 8, 53 (1941)
3 Bennett and McAdam, J Research Nat Bur Standards, 28, 433 (1942)
4 Hess and Muller, Welding J, 20, 4175 (1941); 22, 5325 (1943)

63 Ni – 32 Cu – 1.6 Si – 1.5 Fe – 0.15 C

COMPILED BY W. A. MUDGE*

A 2 *Trade name.* **Cast Monel**
4 *Government number.* QQ-C-551; Navy 46M1
B 1 *Typical uses.* For industrial applications that demand high strength, pressure tightness, and high resistance to destructive chemical action or mechanical wear.
C 1 *Density* at 20 C (68 F). 8.63 g per cu cm (0.312 lb per cu in.)
5 *Solidification shrinkage.* 0.25 in. per ft
D 6 *Thermal expansion* 25 to 100 C (77 to 212 F). 0.0000129 per °C (0.0000072 per °F)
E 2 *Electrical resistivity* at 20 C (68 F). 53.3 microhm-cm
G 1 *Influence of treatments.* Slightly magnetic at 25 C
K *Mechanical properties.* Sand cast, as cast: tensile strength 65,000 to 90,000 psi; yield strength 32,000 to 40,000 psi; elongation in 2 in. 45 to 25%; Brinell hardness number 125 to 150; modulus of elasticity 18,500,000 psi; Charpy 70 ft-lb; Izod 80 to 65 ft-lb; compressive yield strength (0.00% offset) 19,000 psi, (0.01% offset) 23,000 psi, (0.2% offset) 29,000 psi.
M *Composition limits.* Sand cast (QQ-C-551 and Navy 46M1): 60.0% Ni min; 23.0% Cu min; 3.5% Fe max; 0.5% Al max; and 2.0% max for C plus Si.
N 1 *Melting temperature range.* 1315 to 1345 C (2400 to 2450 F)
2 *Casting temperature range.* 1480 to 1565 C (2700 to 2850 F)
4 *Preferred deoxidizer.* Magnesium
16 *Standard finishes.* Machined or sandblasted.
17 *Joining.*
Soft solder with Pb-base or Sn-base alloys, acid flux.
Silver solder with phosphorus-free silver alloys, fluoride flux, flame slightly reducing.
Braze with phosphorus-free and lead-free alloys, fluoride-base flux, flame slightly reducing.
Metal-arc weld with Monel, fluoride flux, and direct current.

66 Ni – 29 Cu – 2.75 Al – 0.9 Fe – 0.75 Mn – 0.50 Si – 0.15 C – 0.005 S

COMPILED BY W. A. MUDGE*

A 2 *Trade name.* **"K" Monel***
4 *Government numbers.* QQ-N-286, Navy 46N5
B 1 *Typical uses.* For industrial applications that demand high strength and high resistance to corrosion, especially in large sections; nonmagnetic parts for aircraft, pump rods, springs, shafts, valve stems.
2 *Precautions in use.* Do not use above 315 C (600 F) in sulfidizing atmospheres.
C 1 *Density* at 20 C (68 F). 8.47 ■ per cu cm (0.306 lb per cu in.)
D 1 *Liquidus temperature.* 1349 C (2460 F)
2 *Solidus temperature.* 1316 C (2400 F)
6 *Thermal expansion* 25 to 100 C (77 to 212 F). 0.0000140 per °C (0.0000078 per °F)
11 *Specific heat* 25 to 399 C (77 to 750 F). 0.127 cal per ■
16 *Thermal conductivity* 0 to 100 C (32 to 212 F). 0.045 cal/sq cm/cm/°C/sec (130 Btu/sq ft/in./°F/hr)
E 2 *Electrical resistivity* at 20 C (68 F). 58.3 microhm-cm
5 *Temperature coefficient of electrical resistivity* 20 to 100 C (68 to 212 F). 0.00018 microhm-cm per °C
G *Magnetic properties.* Nonmagnetic to minus 150 F
3 *Maximum permeability.* 1.0015 cgs (air, 1.02 max)
9 *Magnetic transformation temperature.*
minus 101 C (minus 150 F), age hardened
minus 129 C (minus 200 F), soft
I 1 *General resistance to corrosion.* Good resistance to dilute mineral acids, salt water, and steam. Not resistant to oxidizing acids.
K *Mechanical properties. See* Table I.

* Development and Research Division, The International Nickel Company, Inc., New York

* This alloy is also made in a free-cutting grade ("KR" Monel) that contains 29% Cu, 2.75% Al, 0.9% Fe, 0.85% Mn, 0.5% Si, 0.3% C, 0.005% S.

Condition	Modulus of Elasticity, psi	Charpy, ft-lb	Izod, ft-lb	Shear Strength, psi	Endurance Strength 100,000,000 cycles, psi
Hot rolled	26,000,000	170	120+	65,300	38,500 to 45,500
Hot rolled and age hardened	.....	61	40	96,475	45,000 to 53,000
Cold drawn	.....	71	56	71,000	40,500 to 43,500
Cold drawn and age hardened	.....	42	26	98,750	42,000 to 53,000

Table I. Tensile Properties and Hardness of 66 Ni–29 Cu –2.75 Al

Condition	Proof Stress (0.01% offset), 1000 psi	Yield Strength (0.20% offset), 1000 psi	Tensile Strength, 1000 psi	Elongation in 2 in., percentage	Reduction of Area, percentage	Brinell Hardness (3000 kg)	Rockwell Hardness Number
Cold Drawn Rod and Bar							
Annealed	.....	40 to 60	90 to 110	45 to 35	70 to 50	140 to 180	B 75 to 90
Annealed, age hardened	70 to 100	90 to 110	130 to 150	30 to 20	50 to 30	240 to 280	C 21 to 28
As drawn	.....	70 to 100	100 to 135	35 to 13	65 to 45	175 to 260	C 8 to 26
As drawn, age hardened	80 to 125	100 to 130	140 to 170	30 to 15	50 to 25	265 to 320	C 27 to 33
Hot Rolled Rod and Bar							
As rolled	.....	40 to 90	90 to 120	45 to 25	70 to 50	140 to 240	B 75 to C 18
As rolled, age hardened	80 to 110	100 to 120	140 to 160	30 to 20	50 to 25	265 to 300	C 27 to 31
Forged Rod and Bar							
As forged	.....	40 to 90	90 to 120	40 to 25	65 to 40	140 to 240	B 75 to 100
As forged, age hardened	80 to 115	100 to 125	140 to 165	30 to 20	50 to 25	265 to 310	C 25 to 32
Cold Drawn Wire							
Annealed	.....	40 to 60	90 to 110	45 to 30	.....	.....	.....
Annealed, age hardened	.....	90 to 110	130 to 150	30 to 15	.....	.....	.....
Spring	.....	130 to 155	145 to 175	4 to 2	.....	.....	.....
Spring, age hardened	.....	150 to 175	160 to 200	8 to 3	.....	.....	.....
Cold Rolled Strip							
Soft	.....	50 to 65	90 to 105	45 to 25	.....	.....	B 75 to 85
Soft, age hardened	.....	90 to 110	130 to 150	25 to 10	.....	.....	C 20 to 30
Half hard	.....	85 to 105	125 to 145	20 to 5	.....	.....	C 15 to 28
Half hard, age hardened	.....	110 to 130	150 to 180	15 to 3	.....	.....	C 28 to 35
Full hard	.....	105 to 120	145 to 165	8 to 2	.....	.....	C 25 to 32
Full hard, age hardened	.....	125 to 145	170 to 200	10 to 2	.....	.....	C 33 to 40

Condition	Yield Strength (0.01% offset), psi	Yield Strength (0.2% offset), psi
Hot rolled	34,000	40,000
Hot rolled and age hardened	96,000	121,000
Cold drawn	55,000	76,000
Cold drawn and age hardened	102,000	121,000

2 Directional properties. Age hardened forging (10.5 in. diam by 74.5 in. long): tensile strength, parallel to direction of rolling 152,800 psi; perpendicular to direction of rolling 151,350 psi; elongation, parallel to direction of rolling 23.1%, and perpendicular to direction of rolling 20.6%

6 Minimum creep rate.
at 482 C (900 F). 45,000 psi, 1% in 10,000 hr
at 538 C (1000 F). 21,000 psi, 1% in 10,000 hr

M *Composition limits.*

Designation	Ni min	Ni max	Cu min	Al min	Al max	Fe max	Si max	Mn max	C max
QQ-N-286	63.0	70.0	remainder	2.0	4.0	2.0	1.0	1.0	0.25
46N5	63.0	70.0	remainder	2.0	4.0	2.0	1.0	1.0	0.25

N *1 Melting temperature.* 1315 to 1350 C (2400 to 2460 F)
2 Casting (ingot). 1455 to 1510 C (2650 to 2750 F)
3 Alloying. Add aluminum as metal when Ni-Cu base has melted.
4 Preferred deoxidizer. Magnesium.
5 Type of flux. Lime-cryolite
7 Hot working temperature range. 730 to 1175 C (1350 to 2150 F)
8 Shortness range. 540 to 730 C (1000 to 1350 F)
9 Annealing temperature. 870 C (1600 F) for 1 hr, followed by quenching in water.
10 Maximum reduction between anneals. 85%
11 Suited to forming by all methods of hot and cold working.
15 Heat treatment.

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hr	Atmosphere	Cooling
To soften	872	1600	½	Reducing	Quench in water
To harden	593	1100	8 to 16	Reducing	Furnace cool

17 Joining.
Soft solder with Pb-base or Sn-base alloys, acid flux.
Silver solder with phosphorus-free silver alloys; fluoride flux, slightly reducing flame.
Braze with phosphorus-free or lead-free alloys, standard brazing flux, slightly reducing flame.
Oxyacetylene weld with "K" Monel, fluoride flux, slightly reducing flame.
Resistance welding. All types satisfactory
Metal-arc weld with "K" Monel, fluoride flux, direct current.

63 Ni – 30 Cu – 4 Si – 2 Fe

COMPILED BY W. A. MUDGE*

A *2 Trade name.* "S" Monel
4 Government numbers. Navy 46N7, class B; AAF 11084, grade 2

B *1 Typical uses.* For industrial applications that demand high strength, pressure tightness, and high resistance to destructive chemical action and to galling; particularly suitable for valve seats, and sliding or other moving elements.

C *1 Density* at 20 C (68 F). 8.36 g per cu cm (0.302 lb per cu in.)
5 Solidification shrinkage. 0.25 in. per ft

D *6 Thermal expansion.*

Temperature, deg Cent	Temperature, deg Fahr	Coefficient of Expansion, per °C	Coefficient of Expansion, per °F
21 to 100	70 to 212	0.0000122	0.0000068
21 to 316	70 to 600	0.0000148	0.0000082
21 to 454	70 to 850	0.0000151	0.0000084
21 to 538	70 to 1000	0.0000157	0.0000087

E *2 Electrical resistivity* at 20 C (68 F). 63.3 microhm-cm

G *Magnetic properties.* Nonmagnetic at room temperature
9 Magnetic transformation temperature. minus 57 C (minus 70 F)

K *Mechanical properties. See* Table I.

Temperature, deg Cent	Temperature, deg Fahr	Brinell Hardness
	As cast	
Room	Room	321
371	700	321
427	800	311
482	900	311
538	1000	321
566	1050	355
593	1100	293

M *Composition limits* (sand-cast samples). *See* Table II.

N *1 Melting temperature.* 1260 to 1290 C (2300 to 2350 F)
2 Casting temperature. 1455 to 1540 C (2650 to 2800 F)
4 Preferred deoxidizer. Magnesium

* Development and Research Division, The International Nickel Company, Inc., New York

Table I. Mechanical Properties of 63 Ni–30 Cu–4 Si–2 Fe

Condition	Tensile Strength, psi	Yield Strength, psi	Elongation in 2 in., percentage	Brinell Hardness Number	Modulus of Elasticity, psi	Charpy, ft-lb	Izod, ft-lb	Compressive Yield Strength (0.00% offset), psi	Compressive Yield Strength (0.01% offset), psi	Compressive Yield Strength (0.20% offset), psi
Sand cast, as cast	110,000 to 145,000	80,000 to 115,000	4 to 1	275 to 350	21,000,000	4	9 to 3	65,000	80,000	111,000
Quenched	.....	.....	.....	225 to 260	20,500,000	..	....	30,000	41,000	61,000
Aged	110,000 to 145,000	80,000 to 115,000	4 to 1	300 to 375	21,500,000	..	5 to 1	67,000	91,000	125,000

15 Heat treatment.

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hr	Atmosphere	Cooling
To soften	871	1600	1	Air	Air cool to 650 C (1200 F) quench in water
To harden	593	1100	4 to 6	Air	Air or furnace

16 Standard finishes. Machined or sandblasted.

17 Joining.

Soft solder with Pb-base or Sn-base solder, acid flux.
Silver solder with phosphorus-free silver alloys, fluoride flux, slightly reducing flame.
Braze with phosphorus-free and lead-free alloys, fluoride-base flux, slightly reducing flame.

Table II. Composition Limits of 63 Ni–30 Cu–4 Si–2 Fe

Designation	Ni min	Ni max	Cu min	Cu max	Mn min	Mn max	Si min	Si max	Fe max	Al max	C max
Navy 46N7, class B	62	68	remainder		0.5	1.0	3.0	5.0	3.0	0.5	0.3
AAF 11084, grade 2	64	68	28	31	...	1.5	3.5	4.5	3.5	...	0.2

57 Ni – 20 Mo – 20 Fe

COMPILED BY BURNHAM E. FIELD*

A *2 Trade name.* **Hastelloy A**

B *1 Typical uses.* This alloy is resistant to hydrochloric acid and to other nonoxidizing acids and salts, such as phosphoric acid, sulfuric acid up to 50% concentration, aluminum chloride, cuprous chloride, and similar reducing chloride salts.

2 Precautions in use. This alloy is not recommended for use in contact with strongly oxidizing acids or salts, or for strongly aerated conditions. It is not recommended for use in boiling hydrochloric acid and seldom for temperatures above 75 C (170 F).

C *1 Density* at 25 C (77 F). 8.80 g per cu cm (0.318 lb per cu in.)

5 Solidification shrinkage. 2%

D *1 Liquidus temperature.* 1330 C (2425 F)

2 Solidus temperature. 1300 C (2370 F)

3 Minimum "burning" (liquation) temperature. 1230 C (2250 F)

6 Thermal expansion
0 to 100 C (32 to 212 F). 0.0000110 per °C
0 to 1000 C (32 to 1832 F). 0.0000154 per °C

11 Specific heat. 0.094 cal per g

16 Thermal conductivity at 25 C (77 F). 0.04 cal/sq cm/cm/°C/sec

E *1 Volume conductivity* referred to standard copper. 1.4%

2 Electrical resistivity at 25 C (77 F). 126.7 microhm-cm

5 Temperature coefficient of electrical resistivity 20 to 800 C (68 to 1472 F). zero

F *4 Color.* Silvery

G *3 Magnetic permeability.* 5 cgs

I *1 General resistance to corrosion.* This alloy should not be held in the range 500 to 800 C (930 to 1470 F) unless subsequently annealed, since these temperatures are likely to cause higher rates of corrosion. Severe hot or cold working should be followed by full annealing.

2 Resistance to specific agents. See next column.

* Manager, Union Carbide and Carbon Research Laboratories, Inc., Niagara Falls, N. Y.

Corrosive Agent	Resistance
Acetone	Resistant
Acid acetic	Resistant
Acid butyric	Resistant
Acid carbonic	Resistant
Acid citric	Resistant
Acids fatty	Resistant
Acid formic	Resistant
Acid hydrochloric All strengths at temp up to 170 F	Resistant
Acid hydrofluoric At room temperature	Resistant
Acid lactic	Resistant
Acids mixed	Severe general attack
Acid nitric	Severe general attack
Acid oxalic	Resistant
Acid phosphoric	Resistant
Acid salts Reducing salts only, up to 170 F	Resistant
Acid sulfuric Any strength 160 F, up to 50% boiling	Resistant
Acid tartaric	Resistant
Air Up to 1350 F	Resistant
Alcohol ethyl	Resistant
Alcohol methyl	Resistant
Alcohols higher	Resistant
Aluminum sulfate	Resistant
Ammonia	Resistant
Ammonium chloride	Resistant
Ammonium nitrate	Resistant
Ammonium sulfate	Resistant
Bleaching solutions	Severe general attack
Bromine	Severe general attack
Calcium chloride	Resistant
Carbon dioxide	Resistant
Carbon tetrachloride	Resistant
Chlorine	Severe general attack
Copper sulfate (cuprous only)	Resistant
Dyestuffs Consult manufacturer	Resistant
Ferric chloride	Severe general attack
Foodstuffs	Resistant
Formaldehyde	Resistant
Fruit products	Resistant
Hydrogen sulfide Sulfide film forms	Resistant
Iodine	Moderate general attack
Magnesium chloride	Resistant
Magnesium sulfate	Resistant
Milk	Resistant
Mineral oils	Resistant
Motor fuel	Resistant
Oxygen	Resistant
Petroleum products	Resistant
Phenols	Resistant
Photographic solutions	Resistant
Potassium chloride	Resistant
Potassium hydroxide	Resistant
Potassium nitrate	Severe general attack
Refrigerants	Resistant
Sodium carbonate	Resistant
Sodium chloride Discolors	Resistant
Sodium hydroxide	Resistant
Sodium nitrate	Severe general attack
Sodium sulfate	Resistant
Sugar	Resistant
Sulfur	Resistant
Sulfur dioxide	Severe general attack
Tanning solutions	Severe general attack
Water chlorinated	Severe general attack
Water distilled	Resistant
Water rain	Resistant
Water sea	Moderate pitting attack

Table I. Mechanical Properties of 57 Ni–20 Mo–20 Fe

Form	Section, in. diam	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 in., percentage	Reduction of Area, percentage	Rockwell Hardness Number	Brinell Hardness Number	Modulus of Elasticity, 10^6 psi	Charpy, ft-lb	Izod, ft-lb
Sand cast	0.505	69 to 77.5	42.5 to 45	8 to 12	16 to 18	B 85 to 94	155 to 200	.....	.....	25 to 35
Annealed	0.505	110 to 120	47.0 to 52	40 to 48	40 to 54	B 94 to 97	200 to 215	27	37 to 38	62 to 77
Precision cast	0.250	.....	.....	.....	.....	B 80 to 85	.....	.....	.....	.....

J *1 Crystal structure.* Face-centered cubic alpha
K *Mechanical properties. See* Tables I, II and III.

Temperature, deg Cent	500	700	900	1000
Short-time tensile strength, 1000 psi	90	55	40	23

6 Creep rate at 900 C (1652 F). 1500 psi, less than 1% per year

Table II. Strength, Elongation and Reduction of Area at Elevated Temperatures
(Precision-cast specimens, 0.250-in. diam)

Temperature, deg Cent	Temperature, deg Fahr	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 in., percentage	Reduction of Area, percentage
20	70.....	75.0 to 80.0	43.8 to 48.4	10 to 20 16 avg	11 to 30 24 avg
540	1000.....	63.0 to 72.0	.....	15 to 30 24 avg	12 to 30 22 avg
650	1200.....	57.7 to 66.0	.....	20 to 28 24 avg	12 to 26 20 avg
815	1500.....	41.0 to 52.0	.....	11 to 27 18 avg	11 to 22 15.8 avg

Table III. Tensile Properties for Rolled and Annealed Forms at Subzero Temperatures

Temperature, deg Cent	Yield Strength, psi	Tensile Strength, psi	Charpy, ft-lb	Elongation in 2 in., percentage	Reduction of Area, percentage
−50.....	59,000	125,000	37	52	49
−100.....	61,000	130,000	36	49	49
−200.....	70,000	149,000	35	51	48

N *1 Melting temperature.* 1595 to 1650 C (2900 to 3000 F)
2 Casting temperature (chill). 1450 C (2650 F)
7 Hot working temperature range. 1035 to 1230 C (1900 to 2250 F)
8 Shortness range. 600 to 870 C (1110 to 1600 F)
9 Annealing temperature. 1175 C (2150 F)
11 Suited to forming by forging; hot rolling into bars, strip, plate, sheet and rod; welding; drawing into wire; cold rolling; deep drawing; spinning; hot extrusion; machining.
12 Precautions in forming. In hot forming, temperatures from 600 to 850 C (1110 to 1560 F) should be avoided. In cold forming frequent annealing should be employed, since the alloy work hardens rapidly.
15 Heat treatment.

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Cooling
Full anneal to produce softness, machinability, and good corrosion resistance	1150 to 1180	2100 to 2150	⅓ to 1½	Rapidly in air or water
Stabilizing anneal to reduce loss of corrosion resistance because of exposure to 650 to 1040 C (1200 to 1900 F)	1050 to 1065	1925 to 1950	2 to 4	In air
Hardening anneal to produce maximum hardness	745 to 760	1375 to 1400	168	In air

16 Standard finishes. Castings are sandblasted; forgings are sandblasted or pickled; and mill products are hot rolled, annealed or pickled.
17 Joining.
Rivet compositions are not recommended.
Oxyacetylene welding with Hastelloy B rods; usually no flux; neutral flame.
Carbon-arc welding is not recommended.
Resistance welding. All types satisfactory.
Metal-arc welding. Use specially coated Hastelloy B rods, with reversed polarity. Arc is choked short. Avoid overheating weld.

62 Ni – 30 Mo – 5 Fe

COMPILED BY BURNHAM E. FIELD*

A *2 Trade name.* **Hastelloy B**
B *1 Typical uses.* This alloy is resistant to hydrochloric acid in all concentrations up to the boiling point. It is also resistant to other nonoxidizing acids and salts, such as phosphoric acid, sulfuric acid up to 50% concentration, cuprous chloride, and similar reducing chloride salts.
2 Precautions in use. This alloy is not recommended for strongly oxidizing acids or salts.
C *1 Density* at 25 C (77 F). 9.24 g per cu cm (0.334 lb per cu in.)
5 Solidification shrinkage. 2%
D *1 Liquidus temperature.* 1350 C (2460 F)
2 Solidus temperature. 1320 C (2410 F)
3 Minimum "burning" (liquation) temperature. 1230 C (2250 F)
6 Thermal expansion
0 to 100 C (32 to 212 F). 0.0000100 per °C
0 to 1000 C (32 to 1832 F). 0.0000146 per °C
11 Specific heat. 0.091 cal per ■
16 Thermal conductivity at 25 C (77 F). 0.027 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 1.3%
2 Electrical resistivity at 25 C (77 F). 135 microhm-cm
F *4 Color.* Silvery
G *3 Magnetic permeability.* 4 cgs
I *1 General resistance to corrosion. See* 57 Ni – 20 Mo – 20 Fe.
2 Resistance to specific agents. Ratings listed for 57 Ni – 20 Mo – 20 Fe apply also to this alloy.
K *Mechanical properties. See* Tables I, II and III.

* Manager, Union Carbide and Carbon Research Laboratories, Inc., Niagara Falls, N. Y.

Table I. Strength, Elongation and Reduction of Area at Elevated Temperatures
(Precision-cast specimen, 0.250-in. diam)

Temperature, deg Cent	Temperature, deg Fahr	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 in., percentage	Reduction of Area, percentage
20	70.....	80.0 to 84.0	56.5 to 61.5	9.5 to 15 11.9 avg	10 to 20
540	1000.....	74.5 to 80.0	.....	13 to 17 15 avg	11 to 19
650	1200.....	62.9 to 68.7	.....	10 to 25 15 avg	10 to 30
815	1500.....	55.4 to 61.4	.....	11 to 30 19 avg	10 to 30

Compressive strength:
Proportional limit. 25,000 to 36,000 psi
Yield strength (0.2% offset). 61,000 to 68,000 psi

Temperature, deg Cent	500	700	900	1000
Short-time tensile strength, 1000 psi	115	85	50	25

Table II. Mechanical Properties of 62 Ni – 30 Mo – 5 Fe

Form	Section, in. diam	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 in., percentage	Reduction of Area, percentage	Rockwell Hardness	Brinell Hardness Number	Modulus of Elasticity, 10^6 psi	Charpy, ft-lb	Izod, ft-lb
Sand cast	0.505	75.0 to 82.0	55 to 57	6 to 9	10 to 13	B 92 to 99	190 to 230	.....	.....	11 to 16
Rolled and annealed..	0.505	130 to 140	60 to 65	40 to 45	40 to 45	B 96 to 100	210 to 235	30.75	58 to 62	68 to 78
Precision cast.....	0.250	.....	.....	.....	.....	B 92 to 99	.....	.....	.....	.....

N *1 Melting temperature.* 1600 to 1650 C (2900 to 3000 F)
2 Casting temperature (chill). 1450 C (2650 F)
7 Hot working temperature range. 1035 to 1250 C (1900 to 2250 F)
8 Shortness range. 600 to 870 C (1110 to 1600 F)
9 Annealing temperature. 1175 C (2150 F)
Forming and heat treatment. Same as for 57 Ni – 20 Mo – 20 Fe
16 Standard finishes. Castings are sandblasted. Forgings are either sandblasted or pickled. Mill products are hot rolled, annealed, or pickled.
17 Joining.
Oxyacetylene welding with Hastelloy B rods; usually no flux.
Carbon-arc welding is not recommended.

Table III. Tensile Properties for Rolled and Annealed Forms at Subzero Temperatures

Temperature, deg Cent	Yield Strength, psi	Tensile Strength, psi	Elongation in 2 in., percentage	Reduction of Area, percentage	Charpy, ft-lb
—50	59,000	142,000	66	54	49
—100	61,000	144,000	63	53	53
—200	83,000	172,000	58	45	53

Resistance welding. All types satisfactory.
Metal-arc welding. Use specially coated Hastelloy B rods with reversed polarity. Arc is choked short. Avoid overheating weld.

58 Ni – 17 Mo – 15 Cr – 5 W – 5 Fe

COMPILED BY BURNHAM E. FIELD*

A *2 Trade name.* **Hastelloy C**
B *1 Typical uses.* This alloy is resistant to oxidizing agents such as wet chlorine, ferric chloride, nitric acid, hydrochloric and sulfuric acids at moderate temperatures or under oxidizing conditions. It has excellent resistance to acetic acid, sea water and many corrosive organic acids and salts.
2 Precautions in use. Except for weak solutions, this alloy is not recommended for use above 50 C (120 F) in nitric and hydrochloric acid and salt combinations.
C *1 Density* at 25 C (77 F). 8.94 g per cu cm (0.323 lb per cu in.)
5 Solidification shrinkage. 2%
D *1 Liquidus temperature.* 1305 C (2380 F)
2 Solidus temperature. 1270 C (2320 F)
3 Minimum "burning" (liquation) temperature. 1245 C (2275 F)
6 Thermal expansion
0 to 100 C (32 to 212 F). 0.0000113 per °C
0 to 1000 C (32 to 1832 F). 0.0000153 per °C
11 Specific heat. 0.092 cal per g
16 Thermal conductivity at 25 C (77 F). 0.03 cgs
E *1 Volume conductivity* referred to standard copper. 1.3%
2 Electrical resistivity at 25 C (77 F). 133.0 microhm-cm
5 Temperature coefficient of electrical resistivity 20 to 800 C (68 to 1472 F). Zero
F *4 Color.* Silvery
G *3 Magnetic permeability.* 4 cgs
I *1 General resistance to corrosion.* Hastelloy C should not be held for long periods of time in the range 500 to 800 C (932 to 1472 F) unless subsequently annealed, as these temperatures are likely to cause higher corrosion rates of the alloy. Severe hot or cold working should be followed by full annealing.
2 Resistance to specific agents. Except for the following, the ratings listed for 57 Ni – 20 Mo – 20 Fe apply also to this alloy. *See* Table I.
J *1 Crystal structure.* Face-centered cubic alpha
K *Mechanical properties. See* Tables II, III and IV.

Temperature, deg Cent	500	700	900	1000
Short-time tensile strength, 1000 psi	94	75	42	22

Compressive strength:
Proportional limit. 41,000 psi
Yield strength (0.2% offset). 75,000 to 79,000 psi

* Manager, Union Carbide and Carbon Research Laboratories, Inc., Niagara Falls, N. Y.

Table I. Corrosion Resistance of 58 Ni – 17 Mo – 15 Cr – 5W – 5 Fe

Corrosive Agent	Resistance
Acid hydrochloric	Resistant Any strength, up to 120 F
Acids mixed	Resistant Up to 120 F
Acid nitric	Resistant Up to 40%, 150 F; above 40%, room temperature
Acid salts	Resistant Consult manufacturer
Air	Resistant Up to 2000 F
Bleaching solutions	Resistant
Bromine	Resistant
Chlorine	Resistant Excellent resistance to wet chlorine at room temp
Copper sulfate	Resistant
Ferric chloride	Resistant Up to 160 F
Hydrogen sulfide	Resistant
Iodine	Resistant
Potassium nitrate	Resistant
Sodium chloride	Resistant Excellent resistance
Sodium nitrate	Resistant
Sulfur dioxide	Resistant Excellent resistance
Tanning solutions	Resistant
Water chlorinated	Resistant
Water sea	Resistant Excellent resistance
Rayon hardening baths (viscose)	Resistant Excellent resistance

This alloy also has good resistance to chromic acid, the permanganates, the persulfates and to sulfuric acid solutions that contain these salts.

Table II. Strength, Elongation and Reduction of Area at Elevated Temperatures
(Precision-cast specimens, 0.250-in. diam)

Temperature, deg Cent	Temperature, deg Fahr	Tensile Strength, psi	Yield Strength, psi	Elongation in 2 in., percentage	Reduction of Area, percentage
20	70	76.7 to 88.5	44.5 to 56.4	▮ to 12 10 avg	9 to 15 12 avg
540	1000	63.0 to 73.0	.....	10 to 17 12 avg	10 to 20 15 avg
650	1200	56.2 to 62.2	.....	10 to 16 15 avg	10 to 20 16 avg
815	1500	50.0 to 61.0	.....	11 to 28 18.2 avg	10 to 20 15 avg

Table III. Tensile Properties for Rolled and Annealed Forms at Subzero Temperatures

Temperature, deg Cent	Yield Strength, psi	Tensile Strength, psi	Elongation in 2 in., percentage	Reduction of Area, percentage	Charpy, ft-lb
— 50	65,000	134,000	38	33	25
—100	79,000	143,000	25	25	22
—200	96,000	160,000	24	22	27

Table IV. Mechanical Properties of 58 Ni – 17 Mo – 15 Cr – 5 W – 5 Fe

Form	Section, in.	Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in ▮ in., percentage	Reduction of Area, percentage	Rockwell Hardness	Brinell Hardness Number	Modulus of Elasticity, 10^6 psi	Charpy, ft-lb	Izod, ft-lb
Sand cast	0.505	72 to 80	45 to 48	10 to 15	11 to 16	B 89 to 97	175 to 215	.....	.....	9 to 14
Annealed plate ...	0.25	115 to 128	55 to 65	25 to 50	.....	B 84 to 95	160 to 210	28.5	21 to 23	34 to 40
Precision cast	0.250	.....	.....	.....	.....	B 90 to 95	.....	.....	.....	.....

N 7 *Hot working temperature range.* 1035 to 1205 C (1900 to 2200 F)
8 *Shortness range.* 650 to 925 C (1200 to 1700 F)
9 *Annealing temperature.* 1220 C (2225 F)
11 *Suited to forming* by hot rolling into plate, sheet, bar and rod; welding; drawing into wire; cold rolling and deep drawing; spinning; machining.
15 *Heat treatment.* See table at right.
16 *Standard finishes.* Castings are sandblasted. Forgings are either sandblasted or pickled. Mill products are hot rolled, annealed, or pickled.
17 *Joining.*
Oxyacetylene welding with Hastelloy C rods; Cromaloy flux; and neutral flame.
Carbon-arc welding is not recommended.

Purpose	Temperature, deg Cent	Temperature, deg Fahr	Time, hours	Cooling
Full anneal to produce softness, machinability, and good corrosion resistance	1205 to 1220	2200 to 2225	2 to 3	Rapidly in air
Stabilizing anneal to reduce loss of corrosion resistance because of exposure to 650 to 1040 C (1200 to 1900 F)	1120 to 1135	2050 to 2075	2 to 4	In air
Hardening anneal to produce maximum hardness	860 to 870	1575 to 1600	16	In air

Resistance welding. All types satisfactory.
Metal-arc welding. Use specially coated Hastelloy C rods with reversed polarity. Arc is choked short. Avoid overheating weld.

85 Ni – 10 Si – 3 Cu

COMPILED BY BURNHAM E. FIELD*

A 2 *Trade name.* **Hastelloy D**
B 1 *Typical uses.* This alloy is resistant to all concentrations of hot sulfuric acid. It is also resistant to hydrochloric acid under mild conditions and to other nonoxidizing acids and salts. It has excellent wearing properties and freedom from galling against both soft and hard alloys.
2 *Precautions in use.* This alloy is not recommended for use under oxidizing conditions at elevated temperatures. The alloy has low impact strength.
C 1 *Density* at 25 C (77 F). 7.8 g per cu cm (0.282 lb per cu in.)
5 *Solidification shrinkage.* 2%
D 1 *Liquidus temperature.* 1120 C (2050 F)
2 *Solidus temperature.* 1110 C (2030 F)
6 *Thermal expansion*
0 to 100 C (32 to 212 F). 0.0000110 per °C
0 to 1000 C (32 to 1832 F). 0.0000181 per °C
11 *Specific heat.* 0.109 cal per g
16 *Thermal conductivity* at 25 C (77 F). 0.05 cal/sq cm/cm/°C/sec
E 1 *Volume conductivity* referred to standard copper. 1.5%
2 *Electrical resistivity* at 25 C (77 F). 113 microhm-cm
5 *Temperature coefficient of electrical resistivity* 20 to 800 C (68 to 1472 F). Virtually zero.
F 4 *Color.* Silvery with copper tinge

* Manager, Union Carbide and Carbon Research Laboratories, Inc., Niagara Falls, N. Y.

I 1 *General resistance to corrosion.* The resistance of this alloy to corrosion is not affected greatly by previous exposure to heat.
Resistance to specific agents. This alloy is resistant to iodine, it is somewhat less resistant to hydrochloric acid, sulfuric acid, and to reducing acid salts than is 57 Ni – 20 Mo – 20 Fe. The other ratings listed for 57 Ni – 20 Mo – 20 Fe apply also to this alloy.
J 1 *Crystal structure.* Alpha and silicide phases
K *Mechanical properties*

Form	Section, in. diam	Tensile Strength, 1000 psi	Modulus of Elasticity, 10^6 psi	Transverse Breaking Test, 1-in. cross section, 12-in. span
Sand cast	0.505	36 to 40.5	28.85	Breaking load 5000 psi Deflection 0.07 to 0.08 in.
Precision cast	0.250	39 to 45	.....	.....

Elongation and reduction of area, zero; Rockwell C 50 to 55; modulus of rupture, 78,000 psi.

N 11 *Suited to forming* by casting and welding; limited machining with tungsten carbide and grinding.
15 *Heat treatment.* To toughen and soften to some extent: 1050 to 1065 C (1925 to 1950 F), 2 to 4 hr, cool slowly in furnace.
16 *Standard finishes.* Castings are sandblasted.
17 *Joining. Oxyacetylene welding* with Hastelloy D rods; slight excess acetylene flame.

80 Ni – 14 Cr – 6 Fe

COMPILED BY W. A. MUDGE*

A 2 *Trade name.* **Inconel**
3 *ASTM number.* B 163-41T, B 166-41T, B 167-41T, B 168-41T
4 *Government number.* AN-N-4, AN-QQ-N-268, AN-QQ-N-271, AN-WW-T-831, AN-WW-T-833
5 *Other designations.* AMS 5540, 5580, 5665, 5683
B 1 *Typical uses.* For industrial applications that demand good strength, high resistance to corrosion, and excellent resistance to oxidation at high temperatures.

* Development and Research Division, The International Nickel Company, Inc., New York

2 *Precautions in use.* Do not use above 815 C (1500 F) in sulfidizing atmospheres.
C 1 *Density* at 20 C (68 F). 8.51 g per cu cm (0.307 lb per cu in.)
D 1 *Liquidus temperature.* 1425 C (2600 F)
2 *Solidus temperature.* 1395 C (2540 F)
6 *Thermal expansion* 20 to 100 C (68 to 212 F). 0.0000115 per °C (0.0000064 per °F)
11 *Specific heat* 25 to 100 C (77 to 212 F). 0.109 cal per g
16 *Thermal conductivity* 0 to 100 C (32 to 212 F). 0.036 cal/sq cm/cm/°C/sec (104 Btu/sq ft/in/°F/hr)
E 2 *Electrical resistivity* at 20 C (68 F). 98.1 microhm-cm

Table I. Some Mechanical Properties of Inconel

Form	Modulus of Elasticity, psi	Charpy, ft-lb	Izod, ft-lb	Shear Strength, psi	Endurance Strength 100,000,000 cycles, psi	Compressive Yield Strength (0.01% offset), psi	Compressive Yield Strength (0.2% offset), psi
Annealed	31,000,000	230	120+	60,800	31,000 to 45,000	23,000	28,000
Hot rolled	.....	191	110	.....	38,000 to 51,000	31,000	42,000
Cold drawn	.....	151	85	66,250	40,000 to 51,000	90,000	105,000

5 Temperature coefficient of electrical resistivity. 20 to 500 C (68 to 932 F). 0.000125 microhm-cm per °C
F *4 Color.* White
G *1 Influence of treatments.* Nonmagnetic at 25 C
3 Maximum permeability. 1.005 cgs (air, 1.02 max)
9 Magnetic transformation temperature. minus 40 C
I *1 General resistance to corrosion.* Good, not affected by stress.
K *Mechanical properties. See* Table I.

Condition	Yield Strength (0.20% offset), 1000 psi	Tensile Strength, 1000 psi	Elongation in 2 in., percentage	Brinell Hardness (3000 kg)	Rockwell Hardness
Cold Drawn Rod and Bar					
Annealed	25 to 50	80 to 100	50 to 35	120 to 170	B 65 to 85
As drawn	70 to 125	95 to 150	30 to 15	180 to 290	C 8 to 30
Hot Rolled Rod and Bar					
As rolled	35 to 90	85 to 120	45 to 30	140 to 210	B 75 to 95
Annealed	25 to 50	80 to 100	50 to 35	120 to 170	B 65 to 85
Forged	35 to 90	85 to 120	45 to 20	140 to 210	B 75 to 95
Cold Drawn Wire					
Annealed	25 to 50	80 to 105	50 to 25	.....	.....
Regular temper	115 to 165	130 to 175	12 to 3	.....	.....
Spring	150 to 175	165 to 185	10 to 2	.....	.....
Hot Rolled Plate					
Annealed	30 to 60	80 to 110	50 to 35	120 to 170	B 65 to 85
As rolled	45 to 95	100 to 140	40 to 20	160 to 240	B 85 to 100
Standard Cold Rolled Sheet and Strip					
Annealed	30 to 45	80 to 100	50 to 35	.....	B 65 to 85
Hard sheet	90 to 125	125 to 150	15 to 2	.....	C 21 to 26
Full hard strip	120 to 160	145 to 170	10 to 2	.....	C 27 min
Cold Drawn Tubing					
Annealed	30 to 50	80 to 100	50 to 35	.....	B 65 to 85
As drawn	65 to 140	110 to 160	20 to 2	.....	C 8 to 35

6 Creep strength of hot rolled rod.[1]

deg Fahr	900	1000	1100	1200	1300	1400	1500	1600	1800
1000 psi[a]	39	22	11	5.5	3.0	1.8	1.1	0.71	0.33

(a) Creep strength for secondary creep rate of 1% in 10,000 hr

L *2 Radiography.* Technique similar to that for steel; voltage increased 5%.
M *Composition limits* (ASTM B 163, B 166, B 167, B 168; AMS 5540, 5580, 5665, 5683; AN-N-4, AN-QQ-N-268, AN-QQ-N-271, AN-WW-T-831, and AN-WW-T-833). All forms: 75.0% Ni min; 12.0 to 15.0% Cr; 9.0% Fe max; 0.5% Cu max; 1.0% Mn max; 0.5% Si max; 0.15% C max; 0.02% S max.
N *1 Melting temperature.* 1395 to 1425 C (2540 to 2600 F)
2 Casting (ingot). 1540 to 1600 C (2800 to 2900 F)
3 Alloying. Add chromium as Fe-Cr when nickel is molten.
4 Preferred deoxidizer. Magnesium
5 Type of flux. Lime-fluorspar
7 Hot working temperature. 870 to 1260 C (1600 to 2300 F)
8 Shortness range. 650 to 870 C (1200 to 1600 F)
9 Annealing temperature. 870 C (1600 F) for 3 hr, to 980 C (1800 F) for 7 to 15 min.
10 Maximum reduction between anneals. 85%
11 Suited to forming by all types of hot and cold working.
17 Joining.
Soft solder with lead-base or tin-base solder, acid flux.
Silver solder with phosphorus-free silver alloys, fluoride flux, slightly reducing flame.
Braze with phosphorus-free and lead-free alloys, fluoride-base flux, slightly reducing flame.
Oxyacetylene welding with Inconel, fluoride flux, slightly reducing flame.
Resistance welding. All types are satisfactory.
Metal-arc welding with Inconel, fluoride flux, direct or alternating current.

Reference

1 B. B. Betty and W. A. Mudge, Some Engineering Properties of Nickel and High-Nickel Alloys, Mech Eng, 67, 123 (1945)

78 Ni – 13.5 Cr – 6 Fe – 2 Si

COMPILED BY W. A. MUDGE*

A *2 Trade name.* **Cast Inconel**
B *1 Typical uses.* For industrial applications that demand high strength, pressure tightness, and high resistance to destructive chemical action, mechanical wear and oxidation at elevated temperatures.
C *1 Density* at 20 C (68 F). 8.3 g per cu cm (0.30 lb per cu in.)
5 Solidification shrinkage. 0.25 in. per ft
D *6 Thermal expansion* 25 to 100 C (77 to 212 F). 0.0000115 per °C (0.0000064 per °F)
F *4 Color.* White
G *1 Influence of treatments.* Nonmagnetic at 25 C
9 Magnetic transformation temperature. minus 101 C (−150 F)
I *1 General resistance to corrosion.* Similar to wrought Inconel
K *Mechanical properties.* Sand cast, as cast: tensile strength 70,000 to 95,000 psi; yield strength 30,000 to 45,000 psi; elongation in 2 in. 30 to 10%; Brinell hardness number 160 to 190; modulus of elasticity 22,700,000 psi; Charpy 60 ft-lb; Izod 85 to 70 ft-lb; compressive yield strength (0.00% offset) 17,000 psi, (0.01% offset) 23,000 psi, (0.2% offset) 36,000 psi.
M *Nominal composition.* Sand cast: 77.50% Ni, 13.50% Cr, 6.0% Fe, 0.25% Cu, 0.80% Mn, 2.0% Si, 0.2% C, and 0.01% S.
N *1 Melting temperature range.* 1370 to 1400 C (2500 to 2550 F)
2 Casting temperature range (sand). 1540 to 1620 C (2800 to 2950 F)
4 Preferred deoxidizer. Magnesium
16 Standard finishes. Machined or sandblasted.
17 Joining.
Same as for wrought Inconel.

* Development and Research Division, The International Nickel Company, Inc., New York

58 Ni – 22 Cr – 6 Cu – 6 Mo – 6 Fe

COMPILED BY T. E. JOHNSON*

A *2 Trade name.* **Illium "G"**†
B *1 Typical uses.* A machinable, corrosion-resistant alloy used in resisting the attack of sulfuric, nitric, phosphoric acids, mixed acids, and salt and acid mixtures. Useful as a heat-resistant alloy where severe corrosion is encountered. Especially resistant to sea water and saline atmospheres.
2 Precautions in use. In general, not recommended where acids of the halogens are encountered; for instance, in hydrochloric acid and wet chlorine gas.
C *1 Density.* 8.58 ▮ per cu cm (0.31 lb per cu in.)
5 Solidification shrinkage (cast). $\frac{5}{16}$ in. per ft
D *2 Solidus temperature.* 1300 C (2370 F)
3 Minimum "burning" (liquation) temperature. 1200 C (2100 F)
16 Thermal conductivity at 21 C (70 F). 0.029 cal/sq cm/cm/°C/sec

* Plant Engineer, Burgess-Parr Company, Freeport, Ill.

† The nominal composition of this alloy includes also 1.2% Mn, 0.6% Si and 0.2% C.

F *1 Reflectivity.* 76% in white light

I *1 General resistance to corrosion.* Pitting type of corrosion is encountered when the metal is immersed in dilute solutions of halogen acids. Corrosion in nitric, sulfuric and phosphoric acids increases with temperature.

2 Resistance to specific agents. See Table I.

K *Mechanical properties.* Sand cast: tensile strength 60,000 to 73,000 psi; elongation 9.5 to 4.0%; reduction of area 11 to 8%; Brinell hardness number 160 to 210; modulus of elasticity 26,680,000 psi; Charpy 40 to 3 ft-lb.

L *1 Metallography.*
Polishing, same as for Inconel
Etching for grain size. Immersion in aqua regia
Etching for microstructure. 5% sulfuric acid, electrolytically

N17 *Joining.*
Soft solder with tin solder; non-acid flux.
Oxyacetylene welding with Illium rod, reducing flame.

Table I. Resistance to Corrosion of 58 Ni – 22 Cr – 6 Cu – 6 Mo – 6 Fe

The following code indicates relative ratings on the basis of resistance to corrosive attack in the various solutions listed. Data are compiled from results obtained in service and those from controlled laboratory tests.

R—Recommended for use, quantitative test not furnished
A—Not more than 0.004 in. penetration per annum
B—0.004 to 0.015 in. penetration per annum
A and B ratings are less than 1 mg per sq cm per day
C—0.015 to 0.050 in. penetration per annum, approx 1 to 3 mg per sq cm per day
D—0.050 to 0.125 in. penetration per annum
E—More than 0.125 in. penetration per annum
N—Not recommended for use, quantitative tests not furnished

Corrosive Agent	Rating
Acid acetic	
conc, boiling	A
5%, boiling	A
Acid arsenic	
75 to 90% soln, conc by boiling, boiling	A
Acid boric	
"liquor" at 150 F	A
Acid butyric	
80% at 70 F	A
Acid chromic	
50%, boiling	E
varying, pump handling 1.5 to 36% acid, 70 F	R
Acid citric	R
Acids fatty	R
Acid formic	
80%, boiling	A
25% at 70 F	A
Acid hydrochloric	
conc at 100 F	E
conc at 70 F	E
10%, aerated at 100 F	C
10% at 70 F	A
7% at 120 F	E
7% at 70 F	B
1%, wash liquor	R
conc fumes at 113 F	A
Acid hydrofluoric	
anhydrous at 70 F	A
anhydrous, plus 77% by vol 98% H_2SO_4, 70 F	A
5% at 70 F	A
Acid hydrofluosilicic	
8% at 85 F	A
Acid lactic	
10% at 160 F	A
Acid malic at 70 F	A
Acid oleic	
commercial at 70 F	A
Acid oxalic	
15%, boiling	B
8% at 70 F	A
Acid picric, conc at 70 F	A
Acid pyrogallic	
30% at 70 F	A
Acid, pyroligneous, pure	
tar removed at 70 F	A
Acid sludge, refinery waste	
37% H_2SO_4 at 160 F	B
25% H_2SO_4 at 140 F	A
Acid sulfuric (fuming)	
100% at 125 F	R
Acid sulfuric mixtures with:	
acetic anhydride, equal parts with 98% H_2SO_4 at 250 F	C
chlorine, 63% H_2SO_4, saturated with chlorine at 104 F	C
copper sulfate, 50%, equal parts with 25% H_2SO_4, boiling	B
copper sulfate, 10%, equal parts with 25% H_2SO_4, boiling	B
copper sulfate, 5%, equal parts with 25% H_2SO_4, boiling	B
ferrous sulfate, saturated, equal parts with 25% H_2SO_4, boiling	B
ferrous sulfate, 10%, equal parts with 10% H_2SO_4, boiling	A
ferrous sulfate, 5%, equal parts with 25% H_2SO_4, boiling	A
hydrochloric acid, conc; 5.8% soln containing 1.8% H_2SO_4, 70 F	C
nitric acid, 25%, equal parts with 25% H_2SO_4, boiling	B
nitric acid, 10%, equal parts with 25% H_2SO_4, boiling	B
nitric acid, conc; 7.5% of soln with 92.5% conc H_2SO_4 at 54 F	A
potassium dichromate, 5%, equal parts with 25% H_2SO_4, boiling	E
potassium permanganate, 5%, equal parts with 25% H_2SO_4, boiling	B
sodium dichromate, 45%; 23% of soln with 77% of 78% H_2SO_4, 21 F	E
sodium sulfate, 10%, equal parts with 25% H_2SO_4, boiling	B
sodium sulfate, 5%, equal parts with 25% H_2SO_4, boiling	B
Acid sulfurous	
0.75% at 175 F	A
Acid tartaric, 25%, 70 F	A
Acid tetraphosphoric	A
Aluminum sulfate, H_2SO_4	
boil of clay, 300 F	E
effluent from clay boil at 210 F	A
Ammonia at 70 F	A
Ammonium bromide	
30% at 120 F	A
Ammonium carbonate	
25% at 70 F	A
Ammonium chloride	
30% at 330 F	A
Ammonium hydroxide, conc, still soln at 70 F	A
conc, agitated soln at 70 C	B
Ammonium sulfide	
saturated at 70 F	A
Bromine, moist	N
dry	R
aqueous solns	E
Calcium hypochlorite, 2% available Cl_2, 70 F	C
Carbon tetrachloride	
boiling	A
saturated with free sulfur, boiling	A
plus 3% by vol bromine, boiling	E
Chlorine, moist, 200 F	E
dry	R
Chrome tanning soln,	
conc at 76 F	A
Copper sulfate	
25% at 70 F	A
Ethyl acetate, crude, 167 F	B
distillation, 212 F	B
Ferric chloride	
43% at 176 F	E
Ferrous sulfate	
See H_2SO_4 mixtures	
Formaldehyde, 40%, 70 F	A
Fruit juices	R
Gasoline	
with H_3PO_4, SiO_2 and steam in vapor phase in polymerization tower, 500 F	A
Hydrogen peroxide	R
Hydrogen sulfide gas at 1300 F	N
Iodine	
aqueous soln evaporated, boiling	N
Lithopone sludge	R
Magnesium citrate	R
Mercury at 70 F	A
See Note 1.	
Nickel plating soln	R
Nitre cake soln, 15% H_2SO_4	R
Phosphate rock acidulation, hot gases (SO_2, SO_3, CO_2) at 150 F	B
Pickling solns, 10 to 12% H_2SO_4	R
spent soln	A
water wash-tank solns	A
Potassium aluminum sulfate	
30% at 250 F	B
15% at 70 F	A
Potassium dichromate	
5% at 70 F	A
See also H_2SO_4 mixtures.	
Potassium hydroxide	
30%, boiling	A
Potassium permanganate	
2% at 70 F	A
See also H_2SO_4 mixtures.	
Rayon, viscose process coagulating bath	A to R
Sewage, meter parts	R
Silver nitrate	
50% at 120 F	A
Sodium acid fluoride, saturated soln containing HF at 120 F	C
Sodium acid sulfate	
24% at 104 F	A
pump in service, 150 F	R
Sodium aluminum sulfate	
strong crude, 70 F	A
Sodium chloride	
saturated at 70 F	C
16%, salt spray test	A
conc, kept alkaline with NaOH at 140 F	A
36%, plus traces of free chlorine, 122 F	B
Sodium hydroxide	
70% at 194 F	A
5% at 100 F	A
Sodium hypochlorite	
15% available Cl_2, 87 F	E
5% at 70 F	N
bleaching soln, 77 F	D
Sodium metaphosphate	
1.3%, boiling	A
Sodium nitrate	
40% at 70 F	A
Sodium sulfide	
8% at 70 F	R
Sodium thiosulfate	
commercial	R
Stannic chloride, 24%, 70 F	B
Sulfonation process (petroleum products)	R
Sulfur (molten), 350 F	A
See Note 2.	
Sulfur dioxide in sulfur burner at 1800 F	N
plus SO_3 and CO_2 gases at 150 F	B
Urea, under 1125 psi pressure at 318 F	A
Vegetable juices	R
Water mine (acid)	R
Water sea, Gulf of Mexico	A
Yeast wort at 94 F	A
Zinc chloride, from shorted dry cells at 70 F	A

NOTE 1. *Mercury.* In common with other complex alloys, this alloy may take up mercury through some intergranular capillarity. This tendency prevents use of the alloy for thermometer bulbs, where exact volumes and dimensions must be kept.

NOTE 2. *Molten sulfur.* Test conducted in molten sulfur indicates that this alloy, unlike many other corrosion-resistant alloys, does not gain in weight or dimensions from immersion in the fluid over long periods of time.

80 Ni – 20 Cr

COMPILED BY W. A. GATWARD*

A *3 ASTM number.* B 82-46
B *1 Typical uses.* Heating elements
2 Precautions in use. Avoid sulfur atmospheres at high temperatures, especially reducing atmospheres.
C *1 Density.* 8.4 g per cu cm (0.30 lb per cu in.)
D *6 Thermal expansion.* 70 to 1000 C (158 to 1832 F). 0.0000176 per °C
11 Specific heat. 0.107 cal per g
16 Thermal conductivity at 100 C (212 F). 0.134 watts per sq cm per cm per °C
E *1 Volume conductivity* referred to standard copper. 1.6%
2 Electrical resistivity at 20 C (68 F). 107.9 microhm-cm
5 Temperature coefficient of electrical resistivity 20 to 100 C (68 to 212 F). 0.000219 per °C
I *1 General resistance to corrosion.* This alloy is especially resistant to oxidation up to 1200 C (2200 F). It is subject to corrosion in sulfur atmospheres and in some corrosive atmospheres at 925 C (1700 F).
K *Mechanical properties.*

Condition	Tensile Strength, psi	Elongation, percentage	Reduction of Area, percentage	Rockwell Hardness	Modulus of Elasticity, psi
Annealed	95,000	25 to 35	55	B 85 to 90	31,000,000
Hard	165,000	0 to 1	0 to 1	B 100 to 105	.....
Extra spring..	200,000	0	0	.....	.....

M *Composition Limits* (ASTM B 82–46). *Components:* 77 to 79% Ni; 19 to 20% Cr; *impurities:* 1.0% max Fe; 2.5% max Mn; 0.25% max C; 0.75 to 1.5% Si; 0.03% max S.
N *1 Melting temperature.* 1400 C (2550 F)
7 Hot working temperature range. 1200 C (2200 F)
9 Annealing temperature. 870 to 1040 C (1600 to 1900 F)
10 Reduction between anneals. 65%
11 Suited to forming by hot and cold bending, cold drawing and rolling.
15 Heat treatment. Annealing only
17 Joining. This alloy can be soldered with soft and silver solders, brazed, and welded by oxyacetylene, carbon-arc and resistance welding processes.

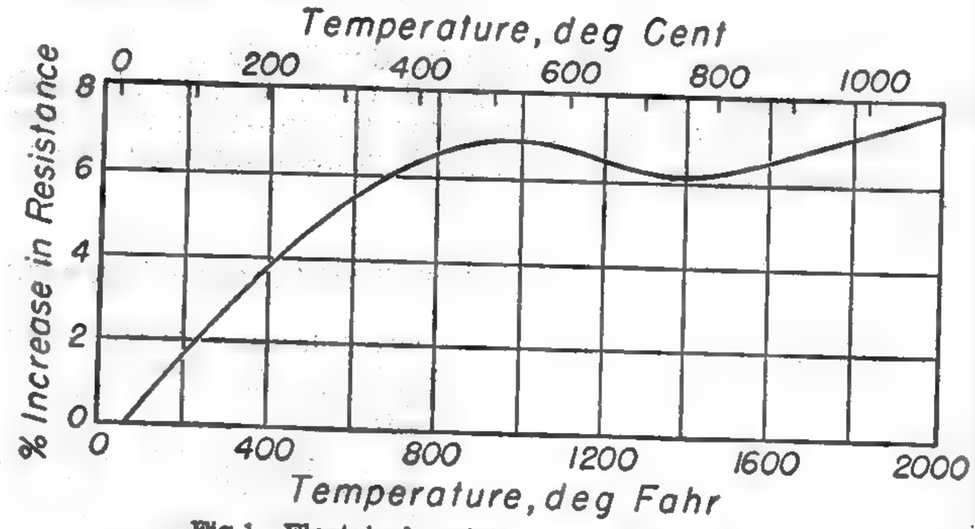


Fig. 1 Electrical resistivity of 80 Ni – 20 Cr

* Hoskins Manufacturing Company, Detroit

60 Ni – 24 Fe – 16 Cr

COMPILED BY J. M. LOHR*

A *3 ASTM number.* B 83-46
B *1 Typical uses. Heat resistant* elements for heating devices such as toasters, percolators, waffle irons, flat irons, ironing machines, heater pads, hair dryers, permanent waving equipment, hot water heaters, carburizing and annealing containers for sheet metal. *Electrical* usage in high-resistance rheostats for radio and moving-picture equipment, oxidized wire with high resistance coating for close-wound rheostats, potentiometers, and thermocouples. *Corrosion-resistant* usage in dipping baskets for acid pickling and cyanide hardening, automatic pickling-machine parts, filters, enameling racks, containers for molten salts.
C *1 Density* at 20 C (68 F). 8.247 g per cu cm (0.298 lb per cu in.)
5 Solidification shrinkage. 2.0%
D *6 Thermal expansion* 20 to 1000 C (68 to 1832 F). 0.000017 per °C
11 Specific heat at 20 C (68 F). 0.107 cal per g
16 Thermal conductivity at 20 C (68 F). 0.0325 cgs

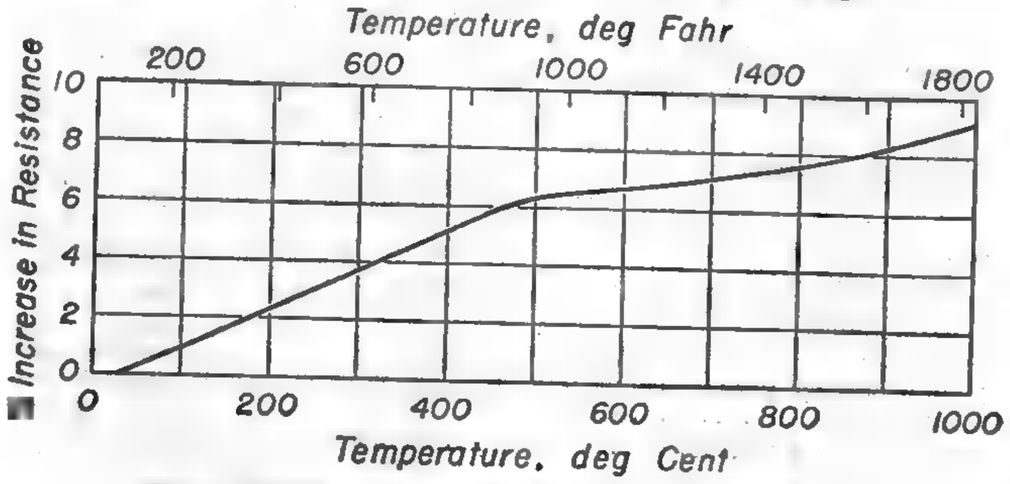


Fig. 1 Electrical resistivity of 60 Ni – 24 Fe – 16 Cr

* Driver-Harris Company, Harrison, N. J.

E *1 Volume conductivity* referred to standard copper. 1.5%
2 Electrical resistivity at 20 C (68 F). 112 microhm-cm
5 Temperature coefficient of electrical resistivity 20 to 100 C (68 to 212 F). 0.00017 per °C. *See* Fig. 1 for electrical resistivity versus temperature.
I *2 Resistance to specific agents.*

Corrosive Agent	Resistance
Acid acetic	Resistant
Acid hydrochloric	Moderate general attack
Acid lactic	Resistant
Acid nitric	Resistant
Acid phosphoric	Moderate general attack when hot
Acid sulfuric	Resistant
Air	Resistant
Alcohol ethyl	Resistant
Alcohol methyl	Resistant
Ammonia	Resistant
Ammonium nitrate	Resistant
Carbon dioxide	Resistant
Carbon tetrachloride	Resistant
Copper sulfate	Moderate intergranular attack
Foodstuffs	Resistant
Fruit products	Resistant
Hydrogen sulfide	Severe general attack when hot
Milk	Resistant
Mineral oils	Resistant
Motor fuel	Resistant
Oxygen	Resistant
Petroleum products	Resistant when cold
Photographic solutions	Resistant
Potassium hydroxide	Resistant
Potassium nitrate	Resistant
Sodium carbonate	Resistant
Sodium hydroxide	Resistant
Sodium nitrate	Resistant
Sugar	Resistant
Sulfur	Severe general attack when hot
Sulfur dioxide	Severe general attack when hot
Water distilled	Resistant
Water rain	Resistant

J *1 Crystal structure.* Face-centered cubic
K *Mechanical properties.* See Tables I and II.
L *1 Metallography.*[1] Polishing with emery paper to 000 levigated alumina to finish. Etching, grain size, Marble's reagent or aqua regia conc (3 HCl, 1HNO_3); sometimes less HCl, and sometimes diluted down to 50% water depending on worked or annealed condition. Etching for microstructure, same. This material often finishes polishing with cold worked film obscuring true structure, hence must be repolished on last

Table I. Tensile Properties and Hardness of 60 Ni – 24 Fe – 16 Cr

Form	Tensile Strength, psi	Elongation, percentage	Reduction of Area, percentage	Rockwell Hardness
Sand cast	65,000	2	2	C ▮
Annealed	105,000	30	47	B 83

stage and re-etched. This is common to other stainless austenitic materials. Usual method of reporting grain size, grains per sq mm.

3 Corrosion test commonly used.[2] Both weight and electrical resistance changes are criteria in the Strauss test.

4 Mechanical tests. See reference 3.

M *Composition limits* (ASTM specification B 83–46).

Table II. Strength and Elongation of 60 Ni – 24 Fe – 16 Cr at Elevated Temperatures
(approximate values)

Temperature, deg Fahr	Cast Samples: Tensile Strength, psi	Cast Samples: Elongation, percentage	Wrought Samples: Tensile Strength, psi	Wrought Samples: Elongation, percentage
68	65,000	2	105,000	30
1000	47,000	2.1	52,500	12
1200	42,700	2.3	38,000	13
1400	37,000	2.5	28,500	23
1600	22,000	3.7	19,000	32
1800	15,000	6.0	9,000	45

Components: 57% min Ni plus Co; 14 to 18% Cr, remainder Fe; *impurities*: 3% Mn max, 0.75 to 1.5% Si, 0.25% C max, 0.03% S max.

N *1 Melting temperature range.* 1510 to 1540 C (2750 to 2800 F)

2 Casting temperature range (sand and ingot). 1510 to 1540 C (2750 to 2800 F)

7 Hot working temperature range. 980 to 1260 C (1800 to 2300 F)

9 Annealing temperature. 650 to 1100 C (1200 to 2000 F)

10 Maximum reduction between anneals. 75% in area

11 Suited to forming by hot and cold rolling, forging, drawing, pressing, and bending.

16 Standard finishes. Castings are sandblasted, forgings pickled, and mill products are given various finishes.

17 Joining.

Soft solder with 50 Pb – 50 Sn; HCl plus Zn flux.

Silver solder with low melting point solder, borax flux, neutral flame.

Braze with low brass, borax flux.

Oxyacetylene welding with 60/16 Nichrome rod, no flux, neutral or carburizing flame.

References

1 J. R. Vilella, Polishing and Etching of Iron-Chromium and Iron-Nickel-Chromium Alloys, Proc ASTM, 34, Part 1, 193, (1934)

2 J. J. B. Rutherford and R. H. Aborn, A Quantitative Method for the Estimation of Intercrystalline Corrosion in Austenitic Stainless Steels, Trans AIME, 100, 293 (1932)

3 ASTM Standards, Part I-B, Non-Ferrous Metals, 1946, p 220

35 Ni – 50 Fe – 15 Cr

COMPILED BY J. M. LOHR*

B *1 Typical uses.* This alloy has an exceptionally high temperature coefficient of resistance for an alloy of its class. It has excellent resistance to oxidation at temperatures up to 815 C (1500 F). It is also used for heavy-duty rheostats and low-priced electrical appliances. Also for resistors used in the presence of cracked gas atmospheres.

C *1 Density* at 20 C (68 F). 7.95 g per cu cm (0.287 lb per cu in.)

5 Solidification shrinkage. 2.0%

D *6 Thermal expansion* 20 to 500 C (68 to 932 F). 0.0000158 per °C

11 Specific heat at 20 C (68 F). 0.110 cal per g

16 Thermal conductivity at 20 C (68 F). 0.031 cal/sq cm/cm/°C/sec

E *1 Volume conductivity* referred to standard copper. 1.7%

2 Electrical resistivity at 20 C (68 F). 100 microhm-cm

5 Temperature coefficient of electrical resistivity 20 to 500 C (68 to 932 F). 0.00031 per °C. *See* Fig. 1 for electrical resistivity versus temperature.

I *1 Resistance to specific agents. See* corresponding section for 60 Ni – 24 Fe – 16 Cr.

J *1 Crystal structure.* Face-centered cubic

K *Mechanical properties.* See Tables I and II.

L *Testing Methods. See* 60 Ni – 24 Fe – 16 Cr.

N *1 Melting temperature range.* 1525 to 1550 C (2775 to 2825 F)

2 Casting temperature range (sand and ingot). 1525 to 1550 C (2775 to 2825 F)

7 Hot working temperature range. 980 to 1260 C (1800 to 2300 F)

9 Annealing temperature. 650 to 1100 C (1200 to 2000 F)

Table I. Mechanical Properties of 35 Ni – 50 Fe – 15 Cr

Condition	Tensile Strength, psi	Elongation, percentage	Reduction in Area, percentage	Rockwell Hardness
Sand cast	62,000	2	2	C 18
Annealed	102,000	30	45	B ▮

* Driver-Harris Company, Harrison, N. J.

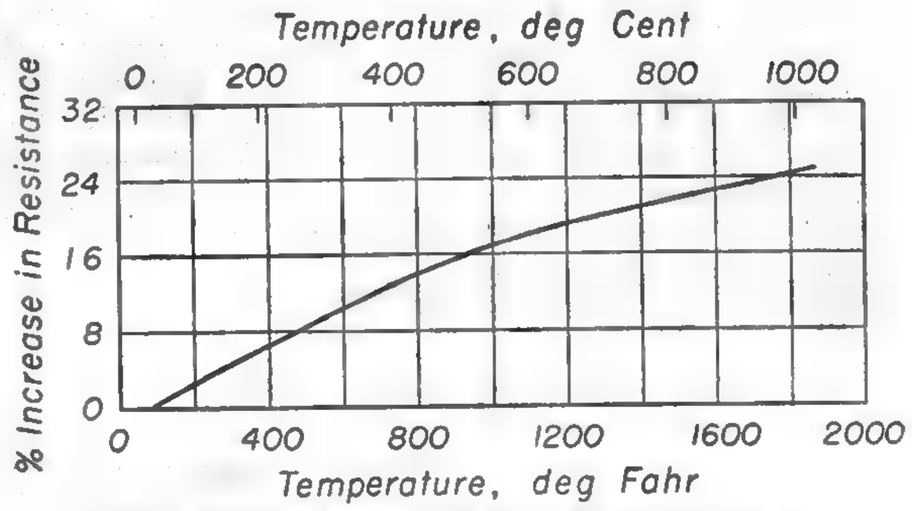


Fig. 1 Electrical resistivity of 35 Ni – 50 Fe – 15 Cr

10 Maximum reduction between anneals. 75%

11 Suited to forming by hot and cold rolling, forging, drawing, pressing, and bending.

16 Standard finishes. See 60 Ni – 24 Fe – 16 Cr.

17 Joining.

Soft soldering, silver soldering and brazing. Use same methods as for 60 Ni – 24 Fe – 16 Cr.

Oxyacetylene welding with 35/16 Nichrome rod; no flux; neutral or carburizing flame.

References. Same as for 60 Ni – 24 Fe – 16 Cr.

Table II. Tensile Strength and Elongation of 35 Ni – 50 Fe – 15 Cr at Elevated Temperatures
(approximate values)

Temperature, deg Fahr	Cast Samples: Tensile Strength, psi	Cast Samples: Elongation, percentage	Wrought Samples: Tensile Strength, psi	Wrought Samples: Elongation, percentage
68	62,000	2	102,000	32
1000	43,000	4	50,000	22
1200	36,000	6	36,000	20
1400	34,000	8.5	26,500	26
1600	19,000	20	17,500	28
1800	12,000	25	8,500	30

45 Ni – 55 Cu

COMPILED BY G. C. STAUFFER* AND W. A. GRAHAM*

A *1 Common name.* **Constantan**

B *1 Typical uses.* This alloy has about the highest electrical resistivity, the lowest temperature coefficient of resistance, and the highest thermal emf against platinum of any of the copper-nickel alloys. Because of these properties it is used for electrical resistors and thermocouples. This alloy is ordinarily used in the wrought condition, but is also used in the form of castings.

2 Precautions in use. Maximum temperature for use as a resistor, 500 C (930 F); maximum temperature for thermocouple use, 900 C (1650 F).

C *1 Density.*
Wrought: 8.9 g per cu cm (0.32 lb per cu in.)
Cast: 8.6 g per cu cm (0.31 lb per cu in.)

5 Patternmaker's shrinkage. ¼ in. per ft

D *1 Liquidus temperature.* 1290 C (2355 F)

2 Solidus temperature. 1220 C (2230 F)

6 Thermal expansion.

20 to 100 C (68 to 212 F). 0.0000149 per °C
20 to 500 C (68 to 932 F). 0.0000163 per °C
20 to 1000 C (68 to 1832 F). 0.0000188 per °C

11 Specific heat. 0.094 cal per g

16 Thermal conductivity. 0.0546 cal/sq cm/cm/°C/sec

E *2 Electrical resistivity.* 49 microhm-cm
Specific resistance. 294 ohms per cir mil-ft
231 ohms per sq mil-ft

5 Temperature coefficient of electrical resistivity.
Wrought: 20 to 100 C (68 to 212 F). ±0.00002
20 to 500 C (68 to 932 F). ±0.000025
Cast: 0 to 150 C (32 to 302 F). ±0.0001

The change in resistance with temperature may be either positive or negative, depending on small variations in composition and on variations in the amount of cold working. In any case, the change is small. The above values are averages for the various temperature ranges.

9 Thermal emf. The basic alloy is modified by additions of manganese and iron to give somewhat varied emf as specified by manufacturers of pyrometers. The following representative values, obtained by the National Bureau of Standards, establish the shape of the curve of emf versus temperature.

Emf of Constantan versus Platinum, Cold Junction at 0 C (32 F)†

deg Fahr	Millivolts	deg Fahr	Millivolts
−300	+5.02	+800	−17.41
−200	+3.73	900	−19.97
−100	+2.24	1000	−22.55
0	+0.57	1100	−25.15
+100	−1.27	1200	−27.77
200	−3.26	1300	−30.39
300	−5.39	1400	−32.99
400	−7.64	1500	−35.58
500	−9.98	1600	−38.14
600	−12.40	1700	−40.66
700	−14.88	1800	−43.13

K *Mechanical properties. Wrought alloy*: tensile strength 60,000 psi, annealed; tensile strength 135,000 psi, cold worked.
Cast alloy: tensile strength (0.505-in. test specimens cast in green sand mold) 55,000 psi; yield strength (0.2% offset) 21,000 psi; elongation in 2 in. 32%; reduction of area 4%; Brinell hardness number (500-kg load, 10-mm ball) 75 to 85; Rockwell hardness (100-kg load, $\frac{1}{16}$-in. ball) B 48 to 54; shear strength 43,000 psi; Charpy impact resistance (10-by-10-mm specimen) approx 30 ft-lb.

N *2 Casting temperature.* 1350 C (2460 F) minimum

3 Alloying. Pure copper and nickel are melted together, usually in an arc furnace.

4 Preferred deoxidizer. Magnesium

6 Precautions in melting. Add deoxidizer just before pouring.

12 Precautions in casting. The rate of filling the mold should be controlled by the size of the runner and not by varying the rate of pouring.

* Driver-Harris Company, Harrison, N. J.
* Westinghouse Electric Corporation, Buffalo, N. Y.

† Research Paper 1080, National Bureau of Standards

OTHER NICKEL ALLOYS

60 Ni – 28 Fe – 12 Cr
ACI Alloy Type HW
See "Heat-Resistant Castings", pages 576 and 577.

67 Ni – 17 Cr – 16 Fe
ACI Alloy Type HX
See "Heat-Resistant Castings", page 577.

73 Ni – 15 Cr – 7 Fe – 2.5 Ti – 1 Cb
Inconel "X"
See "Wrought Heat-Resisting Alloys", pages 566 to 569.

42 Ni – 22 Co – 18 Cr – 13 Fe – 2.5 Ti
K-42-B (Type 5)
See "Wrought Heat-Resisting Alloys", pages 566 to 569.

Magnetically Soft Nickel Alloys
See pages 587 to 595.

Nickel and Nickel-Alloy Clad Steels
See pages 547 and 548.

Low-Expansion Alloys
See pages 601 to 605.

Iron-Nickel Alloys
See pages 587, 599 and 601.

TIN AND TIN ALLOYS

Prepared under the chairmanship of

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The Tin Industry

BY ERWIN VOGELSANG*

ALTHOUGH the entire world production of tin is small in tonnage, the uses of this metal are of maximum importance and are more widely spread industrially than those of almost any other metal.

Tin is derived from cassiterite (SnO_2), a mineral found in nearly all parts of the world, but with commercially important deposits in comparatively few localities. The most important tin mines are located in Malaya, Bolivia, the Netherlands' East Indies, Siam, China, the Belgian Congo and Nigeria. These areas account for more than 90% of the world's tin output. Thus far, no commercial deposits of tin have been found in the United States.

Tin deposits are of two different kinds, which may be described as *vein* or *lode* deposits and *alluvial* or *placer* deposits. The ores from lode deposits contain approximately 2 to 4% Sn, and the placer gravels contain approximately ½ to 3 lb of cassiterite per cubic yard. Bolivian mines are almost entirely in vein formations, whereas mines in other areas are mainly placer deposits.

The vein deposits are extracted by usual deep-mining methods and are concentrated by various mechanical methods to produce aggregates that contain from 18 to about 65% Sn. The placer deposits are mined by dredging, hydraulic sluicing, and other more primitive hand methods, and produce a concentrate containing 70% Sn or more.

Table I shows the different smelting and refining companies that produced tin before and during World War II, and gives names and approximate compositions of the various brands produced by each company. One important addition to the list is the smelter of Tin Processing Corporation at Texas City, Texas, which was built in 1941 and started operations in the spring of 1942. This smelter, financed by the United States government, has the greatest capacity of any existing smelter. Depending on the type of ore available, its capacity is from 40,000 to 45,000 tons per year on a mixture of low-grade and high-grade concentrates, and would be from 75,000 to 80,000 tons if only high-grade ores were treated.

Some of the plants listed in Table I were closed during the war and may not be reopened.

The principal markets for tin are in London and New York. Tin is usually marketed in the form of pigs, bars or ingots weighing between 7 and 100 lb, or in large blocks weighing between 300 and 400 lb. The price has fluctuated between wide extremes. During the period from 1931 to 1941 the price of Straits tin at New York varied from a low of 18.35 cents to a high of 63.50 cents per lb. Between September 1941 and November 1946 the maximum price at New York was set by the Office of Price Administration at 52.00 cents per pound. With the ending of price controls, the Reconstruction Finance Corporation, as the distributor for almost all the tin sold in the United States, set the price at 70.00 cents per pound, in line with the price established by the British Ministry of Supply. In April 1947, along with the increased costs of foreign concentrates, the Reconstruction Finance Corporation raised the price to 80.00 cents per pound.

A classification of the various uses of virgin tin consumed in the United States is shown below for both the war and prewar periods. These figures have been computed from records of the Bureau of Mines and the War Production Board.

	Avg 1938 to 1941, percentage of total	Avg 1942 to 1945, percentage of total
Tin plate and terneplate	50.2	46.8
Solder	15.7	14.7
Babbitt	6.4	7.9
Brass and bronze	7.3	20.7
Foil	3.5	0.5
Collapsible tubes	5.1	0.9
Chemicals	0.2	0.1
Tin oxide	1.0	<0.1
Tinning (other than tin plate)	3.6	5.0
White metal	1.5	<0.1
Type metal	0.2	0.1
Pipe and tubing	1.2	0.3
Galvanizing	1.3	<0.1
Miscellaneous	2.8	3.0
	100.0	100.0

* Chief, Tin, Lead and Zinc Section, Office of Materials Distribution, Department of Commerce, Washington, D. C.

Table I. Principal Tin Smelters and Refiners and Typical Compositions of Their Brands

	Sn	Sb	As	Pb	Bi	Cu	Fe	Ag	■	Co	Ni + Co	Cd
American												
Tin Processing Corporation, Texas City, Tex.												
Longhorn 3-Star	99.880	0.037	0.020	0.020	0.004	0.025	0.004	0.0005	0.005	....	0.005	trace
Metal & Thermit Corporation, New York												
M. & T. Refined	99.978	0.006	trace	0.0055	0.0005	0.0009	0.009	nil	nil	nil	nil	nil
The Vulcan Detinning Co., Sewaren, N. J.												
Vulcan's Electrolytic	99.9966	0.0005	trace	0.0005	0.0002	0.0002	0.0020	trace	nil	nil	nil	nil
English												
Consolidated Tin Smelters, Ltd.												
Mellanear L. & F. (Com.)	99.103	0.227	0.070	0.316	0.087	0.156	0.007	0.009	nil	0.016	0.007	0.002
Mellanear Refined	99.841	0.030	0.016	0.052	0.020	0.025	0.007	0.001	nil	0.006	0.002	nil
Mellanear (Guar. 99.9%)	99.920	0.007	0.023	0.025	0.003	0.012	0.006	nil	nil	nil	0.004	nil
Cornish Refined	99.808	0.039	0.018	0.059	0.029	0.033	0.006	0.001	nil	0.005	0.002	nil
Capper, Pass & Sons, Ltd.												
Chempur	99.9919	0.003	nil	0.0027	0.0006	0.0005	0.0013	nil	trace	....	....	....
Eastern Smelting Company, Ltd.												
E. S. Coy (Penang)	99.904	0.002	0.035	0.028	0.008	0.008	0.008	nil	0.005	....	0.002	nil
Straits Trading Company, Ltd.												
Straits Trading (Sing.)	99.895	0.004	0.031	0.029	0.007	0.025	0.009	nil	nil	....	trace	nil
British Tin Smelting Co., Ltd.												
Hawthorne Refined	99.891	0.010	0.029	0.028	0.004	0.028	0.010	nil	nil	nil	trace	nil
Dutch												
N. V. Hollandsche Metallurgische Bedrijven												
Banka	99.9701	0.0022	0.002	0.0128	0.0011	0.0028	0.009	....	....	....	....	....
Billiton	99.934	0.018	0.018	0.019	0.001	0.003	0.007	nil	nil	nil	nil	nil
Dutch L. & F.	99.100	0.289	0.089	0.412	0.014	0.082	0.014	nil	nil	nil	nil	nil
Tulip Refined	99.870	0.041	0.031	0.038	0.003	0.008	0.009	nil	nil	nil	nil	nil
Australian												
O. T. Lempriere & Company	99.897	0.018	0.027	0.030	0.002	0.023	0.002	trace	nil	nil	0.001	nil
Sidney Smelting Company												
Pyrmont	99.938	0.017	0.019	trace	nil	0.022	trace	nil	0.004	....	....	....
Belgian												
Cie Miniere du Haut Katanga												
Katanga	99.966	nil	0.006	0.012	trace	0.013	0.003	nil	nil	nil	nil	nil
Chinese												
Ping Kwei Mining Administration												
P. K. M. A.	99.89	0.01	0.02	0.05	0.015	0.005	0.003	0.0005	nil	....	0.001	nil
Yunnan Tin Corp.												
Y. T. C.	99.17	0.01	0.04	0.61	0.03	0.13	0.003	0.0009	nil	nil	0.001	nil

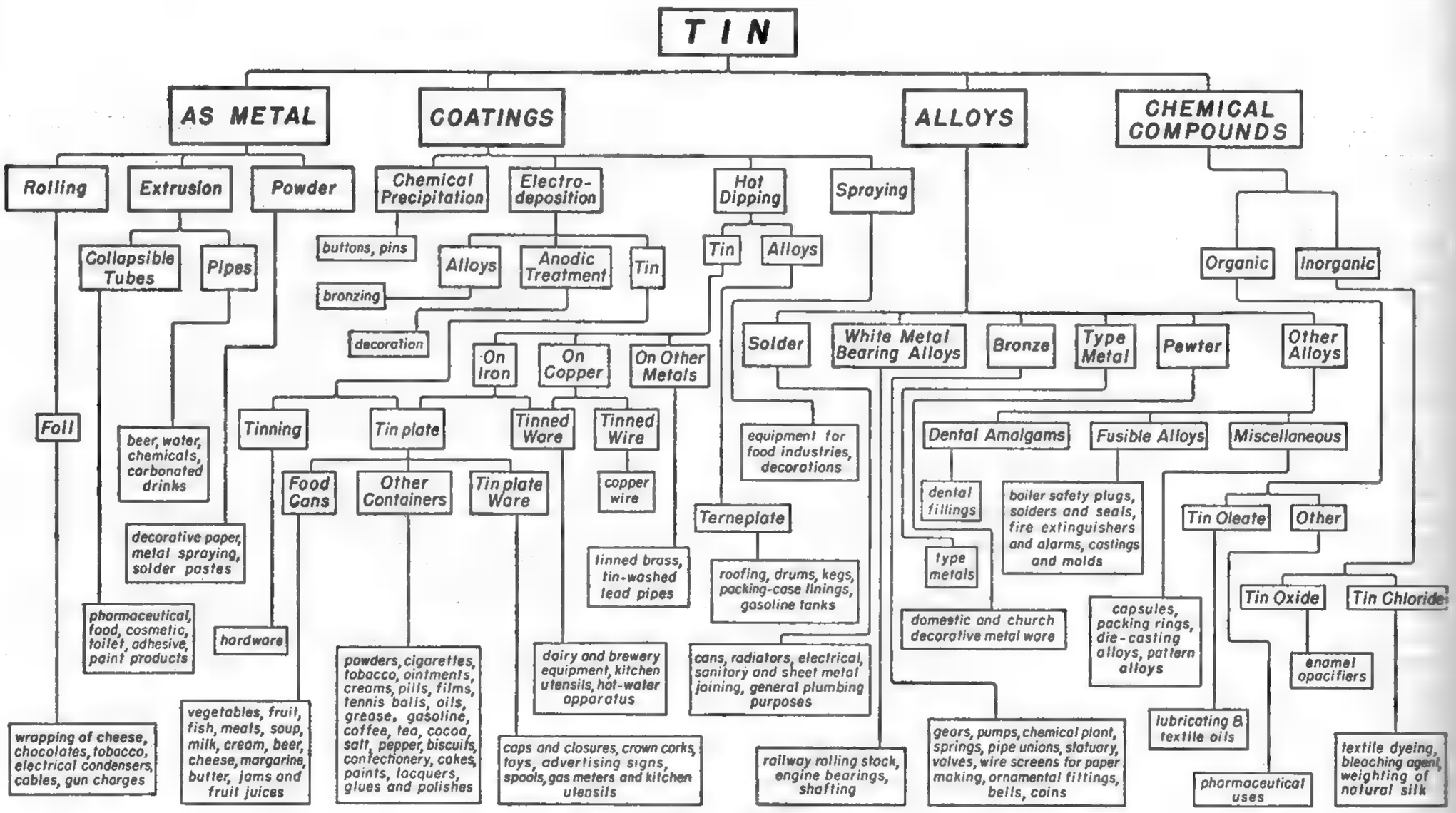

Fig. 1 The uses of tin in peacetime

The major application of tin is as a coating for steel (tin plate), which, in the form of the tin can, serves as the most efficient container for the preservation of perishable foods. Before World War II, all tin plate was produced by the hot dip method, with a coating of approximately 1½ lb Sn per base box of 112 plates, 14 in. by 20 in. With the new electrolytic method, ■ coating of any desired thickness may be applied—for example, 1/10 lb Sn per base box, or more. Although such a thin coating is not practicable for packaging wet food, the coating of ½ lb Sn per base box is used to can many wet food products. The thin-coated plate will eventually find many uses for packaging dry food and products other than food when a strong, serviceable container is required. As a packaging medium, tin is also important in the form of foil and collapsible tubes, although these uses have been greatly curtailed in recent years in favor of lead or aluminum.

A second major application of tin is as an alloying element. Tin is alloyed with copper to produce the various tin brasses and bronzes; with lead to produce solder; with

antimony, copper or lead to form babbitts, type metals, cast alloys and pewterware.

Figure 1 outlines the applications of tin, tin compounds and tin alloys during peacetime.

During the period between 1931 and 1940, world consumption of virgin tin varied between 107,400 and 169,500 long tons per year, and consumption in the United States varied between 35,477 and 93,885 long tons per year. No figures for world consumption have been available since 1940. However, during 1941, consumption in the United States was controlled by the War Production Board, and later by the Civilian Production Administration according to conservation orders. This control was intended to protect the tin required by the United States during the war and reconversion, and to ensure an orderly liquidation of reserves until the world supply and demand should balance once more.

Many of the physical and mechanical properties of tin and tin alloys are listed in the data sheets on pages 1070 to 1076. Other articles discuss specific applications of tin, such as the tinning of steel (page 709) and the use of tin alloys as bearing materials (page 745).

The Casting of Tin and Tin Alloys

By C. H. Hack*

COMMERCIALLY PURE TIN is seldom used as a casting metal, but alloyed with other metals for strength and hardness, it finds wide use in industry. The alloying elements most commonly used are antimony and copper. In varying proportions, these are added to tin for producing babbitt metals, pewter and novelty jewelry, principally as die castings and permanent mold castings.

Tin and the tin alloys lend themselves to all types of casting. At normal casting temperatures, the attack on iron is negligible; therefore these metals can be melted in an ordinary iron kettle. The casting methods depend largely on the article and its intended purpose. Casting methods are listed below, with several applications.

Gravity Casting. Both permanent and impermanent molds are used for gravity casting. Where only a few castings are wanted, impermanent plaster of Paris molds are used. Since these are very fragile, they usually serve for only one casting. The tin alloy is simply poured in, allowing sufficient head, which is cropped off later.

Where a large number of castings is required, permanent molds of bronze or iron are used, the former for ornamental designs. A hot mold is used and after casting the alloy, the shrinkage is confined to the gate end by spraying water on the outside near the bottom.

A common alloy used for gravity castings is pewter or britannia metal, 4 to 7% Sb, 1 to 2% Cu, and the remainder tin. This class of alloy is also cast in iron molds as slabs or ingots, which are later rolled out into sheet. The sheet is sold commercially in various gages and sizes for spinning or hammering later into articles of commerce—generally vases, bowls, trays and such. Because of its toxicity a considerable proportion of lead is undesirable in articles that come in contact with food.

The largest use for the tin alloys is in bearings. Gravity casting is one method of manufacturing a bonded steel-backed bearing. In such a bearing, the tinned bearing shell constitutes the outer part of the mold. A hollow mandrel is used, with an outside diameter such that when it is placed concentric with the shell, it will give a cast bearing lining much greater than required, thus affording ample metal for later machining. Provisions should be made for a fair-sized head at the pouring end to provide for the shrinkage. Half-bearings may be lined singly, in either a vertical or a horizontal position, but they are generally lined with two halves together vertically. In casting such bearings certain rules should be followed:

1 The tin or solder bonding alloy on the shell should be molten at the time of casting.
2 The shrinkage should be controlled in a way that will make it take place at the gate; otherwise holes will be present throughout the cast lining. To prevent this, the mandrel should be approximately 100 F hotter than the shell; also, the top should be hotter than the bottom. After casting the bearing, the application of a fine spray of water to the outside of the mold, first at the bottom and then progressing to the top, helps to keep the shrinkage at the gate.

If these simple rules are followed, the finished bearing should be well bonded and free from porosity.

Slush Casting. This type of casting is used for ornamental ware. The alloy—generally britannia metal—is cast in a cold bronze mold of the desired shape and design. A few seconds after casting, when the alloy has solidified against the inside of the mold, the mold is inverted to allow the metal that is still molten to run out.

Centrifugal Casting. This method, which is being used increasingly, is ideally suited to the manufacture of bearings in quantity production. In centrifugal casting, a steel cylinder is cleaned, pickled and tinned with either pure tin or a tin-lead solder. After tinning, the cylinder is immediately placed between heated end-plates in a machine very similar to a lathe. One of the end-plates has a hole in it, through which the bearing metal is poured into the shell by means of a trough. For a guide to the proper casting temperature, see Table I. Immediately after being cast, the bearing cylinder is revolved at a speed that depends on the diameter. As an example, for a 4-in. diam, a speed of 650 to 750 rpm is used. At this speed, all the molten metal is thrown evenly toward the inside wall. After approximately 5 sec, a fine water spray is directed against the outside of the revolving cylinder. This practice not only confines the shrinkage to the desired place, but also brings about rapid solidification before segregation can take place. The casting is then cut lengthwise, machined and finished as two half bearings.

Die Casting.* Because of the relatively low melting temperature of tin and tin alloys, they can be cast in dies made from cold rolled steel or 0.20 to 0.50% C steel. It is good practice to put some lubricant, such as lard oil, on a new die, until a natural oxide forms on the metal from use. No fluxes are used on the metal in the die-casting machine. Finely powdered talc, sometimes used as a mechanical covering over the metal bath in the machine, not only prevents excessive oxidation but also acts as an insulator. A good operating temperature for die casting is 50 to 100 F above the liquidus. Pressures from

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* For illustrations of die-casting machines, see page 1078.

Table I. Tin-Base Bearing Alloys (Babbitt Metal) [a]

ASTM Alloy Grade	Composition, percentage [b]					Melting Point,		Liquefaction Temperature,		Pouring Temperature,	
	Sn	Sb	Cu	Pb	As	deg Fahr	deg Cent	deg Fahr	deg Cent	deg Fahr	deg Cent
1	91	4.5	4.5	0.35 [c]	0.10 [c]	433	223	700	371	825	441
2	89	7.5	3.5	0.35 [c]	0.10 [c]	466	241	669	354	795	424
3	83.3	8.3	8.3	0.35 [c]	0.10 [c]	464	240	792	422	915	491
4	75	12	3.0	10	0.15 [c]	363	184	583	306	710	377
5	65	15	2.0	18	0.15 [c]	358	181	565	296	690	366

(a) Physical and mechanical properties for some of these alloys are given in the data sheets for tin alloys in this Handbook (pages 1074 and 1075). *See also* appendix to ASTM Tentative Specification B 23–46T.

(b) ASTM Tentative Specification B 23–46T. Iron content, 0.08% max; zinc and aluminum, none

(c) Maximum

250 to 1500 psi are used, depending on the type of machine; 350 psi is a fair average. A 10-lb casting is about the maximum weight made; however, the castings produced in greatest number weigh 1 lb or less.

Table II. Tin Alloys Used in Die Casting[a]

Alloy No.	Composition, percentage[b] Tin	Lead	Antimony	Copper	Approx Melting Range, deg Fahr
1	92	..	5.5	2.5	430 to 590
2[c]	91	..	4.5	4.5	433 to 680
3	90.5	..	8	1.5	435 to 480
4[d]	86	..	7.5	6.5	460 to 670
5	83.3	..	8.3	8.3	464 to 792
6[e]	82	..	13	5	460 to 650
7	79	5	9	7	440 to 610
8[f]	65	18	15	2	358 to 565
9	61.5	25	10.5	3	397 to 540
10	61	30	6	3	368 to 450
11	60	35	5	....	355 to 380
12[g]	59.5	26	9.5 to 11.5	3.25	.....

(a) Physical and mechanical properties for some of these alloys are given in data sheets on pages 1074 to 1076. *See also* references 1 and 2.
(b) Permissible percentages of impurities, according to the ASTM standards, are a maximum of 0.35 Pb, 0.08 Fe, 0.08 As, 0.01 Zn, and 0.01 Al with a maximum of 0.15 As, in alloy 8 (ASTM Alloy Grade No. 3, B 102)
(c) ASTM B 102–44, Alloy Grade No. 1; similar to ASTM B 23 (White Metal Alloys) Grade No. 1; and to SAE No. 10 standard specification
(d) Similar to SAE No. 11
(e) ASTM B 102–44, Grade No. 2
(f) ASTM B 102–44, Grade No. 3; similar to ASTM B 23, Grade No. 5
(g) SAE No. 12

The shrinkage of tin-base die castings is small, and dimensional specifications can be held closely. The U. S. Army specification permits only ±0.0005 in. per linear inch variation for tin-base die castings, as compared with ±0.0025 in. for aluminum-base die castings. The figures show that tin alloys can be used where close tolerances are essential. Speedometer parts and parts wherein the wall thickness is only $\frac{1}{32}$ in. are die cast. Also threads up to 32 per inch can be die cast.

The fins and risers are easily removed from these die castings, which seldom need finishing and are easily buffed and coated. Self-threading screws are frequently used.

Most of these die castings are used because of the close dimensions to which they can be cast and because of their bearing properties. Die castings are also used in connection with certain types of food-handling equipment.

For compositions and melting ranges, see Table II.

Tin-base alloys are also widely used in costume jewelry and such pieces as ornamental handles for tableware. These are cast by gravity or are cast centrifugally in rubber molds. The molds, which may be used for 500 to 2000 castings, are made by pressing rubber around the model and then vulcanizing.

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The Working and Joining of Tin

By Bruce W. Gonser*

THE SOFTNESS and plasticity of tin make it adaptable to all types of cold working where high tensile strength is not required. For such operations as making wire, tin is better suited to extrusion than to wire drawing. Alloying elements are commonly added to provide greater hardness and strength, or to improve bearing qualities or resistance to corrosion. Working at slightly elevated temperatures is also possible, and is sometimes desirable with tin-base alloys, but the heat generated in cold working is usually sufficient to assure easy working after the operation has once been started.

General Working Properties. Pure tin work-hardens to such a slight extent that for practical purposes it is considered not to harden with cold work. Since tin anneals at room temperature, heating for the purpose of softening is unnecessary unless restoration of the original hardness is required at once.

Certain impurities affect the hardness of tin, and some make it amenable to permanent work hardening. Bismuth, in amounts greater than a few tenths of a per cent, is particularly effective in hardening tin permanently; copper and cadmium are also effective, although increased hardness with cadmium gradually decreases during a period of many months. Aluminum and arsenic, even in amounts smaller than 0.1%, harden tin, but are undesirable additions. Small amounts of antimony have little effect on the hardness of cast tin, but when several per cent of antimony is present not only is the hardness as cast increased, but with moderate cold rolling, as in a reduction of 10 to 30%, further permanent work hardening is obtainable. As a result of severe cold working, however, the metal may become softer than the hardness as cast—or at least there is less immediate hardening—and the metal may self-anneal at room temperature to less than the hardness as cast.[1,2] This softening by severe cold work can be overcome and the original hardness may be regained by annealing at 225 C (437 F).

The addition of 0.05% Te or more to tin has been found to improve greatly the resistance to creep and to be effective also in increasing the work hardenability; the tensile strength may be twice that of pure tin after 50% reduction by cold rolling.[3] More severe cold work is less effective.

The tensile properties of cold worked tin and tin alloys are influenced considerably by the grain size of the metal. For example,[4] in pure tin an increase in tensile strength from 1150 to 2300 psi has been noted, without decrease in elongation, as the number of grains in the cross section of rolled specimens was increased from 1 to 20. With finer grain sizes, elongation was found to increase, but there was only a slight increase in tensile strength. Tin alloys containing antimony and cadmium behaved similarly, increasing from 1800 to 3300 psi in tensile strength with 1% Sb and from 1250 to 3100 psi with 1% Cd, as the grains in the cross section of the specimen increased from 1 to 20.

Cold Rolling. Tin is easily cold rolled with heavy reductions and with no need for annealing. Thus, the Brinell hardness of pure tin may increase from 4 or 5 in a cast slab to 10 as a result of cold reduction, but rolling can be continued down to the thinnest foil.

Ordinarily, two strips of foil are rolled simultaneously so that some slip can take place between the strips; otherwise irregularity in roll bearings could cause wrinkles and tears. In rolling tin, solder and other tin alloys to foil, lubricants may vary with different plant practices, but tallow and paraffin are generally used for coarse reductions in heavy mills; and for rolling the very light gages, a light petroleum oil is used, to which an unsaturated oil is added, such as rapeseed or linseed oil. A few per cent of antimony added to the tin gives a much stronger foil. Condenser foil of adequate strength may be rolled commercially 0.00025 in. thick from an alloy containing 83% Sn, 15% Pb, 2% Sb. This is sometimes used in preference to less expensive aluminum foil because of solderability and a tendency toward "self healing" by local melting if short circuit occurs. The eutectic alloy of tin and zinc

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(8% Zn) rolls readily to foil thinness and has a tensile strength several times that of pure tin.[5] Such tin-zinc foil, 0.0015 in. thick, has been used successfully in England for milk-bottle caps. Aluminum, even when present in amounts of only 0.1 or 0.2%, is a particularly undesirable impurity in tin foil, and care is required for preventing contamination of scrap tin foil that is to be remelted.

Composite tin-lead slabs can be cold rolled to produce a firmly adherent tin surface, suitable for making slugs for tin-coated lead collapsible tubes. The surfaces forming the metal interface should be clean and free from lubricant. A convenient method is to roll two sheets of tin together, separate them, and use the inner, freshly disrupted surface for contact with the lead.

Extrusion. Tin and tin alloy pipe, wire, and ornamental shapes are commonly made by extrusion, with equipment and procedure similar to those used for comparable lead products. Most important of these are various solders that may be extruded in solid or flux-cored wire, or in ribbon or angular shapes. Tin alloys are extruded usually at elevated temperatures, but considerably below the melting range. As an example, in making ornamental shapes from pewter alloys (britannia or white metal), billets 2½ in. in diam by 8 in. long are commonly extruded in a 250-ton horizontal rod-press at a temperature of 60 to 65 C (140 to 150 F), with pressures from 40,000 to 100,000 psi.[6] Speeds as low as 10 to 20 fpm are needed to prevent checking of the edges when white metal is being extruded, but 30 fpm is common for tin-lead solders. The extruded white metal shapes or "mounts" are frequently beaded or embossed by passing the uniform shape through a pattern roll.

The manufacture of collapsible tubes provides the best example of simplicity in impact extrusion. The general mechanism is approximately the same as that for lead, as described on page 949. Tin that contains 0.25 to 0.5% Cu as ■ hardener, is rolled to requisite thinness; then round slugs are stamped from the slab. After tumbling with a small amount of lubricant, the slugs are impact-extruded into tubes that have walls as thin as 0.004 in. The pressure required is about 50,000 lb for 1-in. tubes of 0.004-in. sidewall. Vertical presses of 60-ton capacity are standard for producing the most common sizes of tubes. The pressure of extrusion depends particularly on the sidewall thickness. The operation is substantially cold working, although after a few extrusions the dies become warm. A lubricant is needed that is both effective and compatible with coating enamels, such as vegetable shortening or olive oil. Tin-coated lead tubes are made similarly. As with some severely cold rolled tin alloys, tin-copper tubes produced by impact extrusion gradually increase in hardness during a period of several months by aging at room temperature.

Spinning. Pewter, or tin containing from 5 to 15% Sb and 3% Cu or less, is easily worked into utilitarian and artistic forms by spinning, as well as by forming in other ways. Although soft, pewter retains sufficient strength and ductility to permit drastic forming. The modern pewter or britannia metal remains bright after long exposure to the atmosphere, whereas the lead-containing pewter of colonial days tends to darken rather rapidly. Both types spin well, but care is needed for applying pressure cautiously in order to avoid rupture while the metal is being stretched. Fairly heavy stock should be used, since it can be spun down to any shape. An even thickness can be maintained without difficulty, and no annealing is required. Several compositions of pewter soften under severe work, but some hardening may be secured by heating the spun or beaten product to 150 to 200 C (300 to 390 F). Tallow or soap-oil mixtures are commonly used as lubricants.[7]

Working at Elevated Temperature. Tin softens with a rise in temperature (*see graphs,* page 1071); however, both tin and tin alloys cold work so easily that they seldom need to be heated. Tin that contains impurities may become embrittled at elevated temperature.[8] Intergranular fracture may result from impurities that form low-melting eutectics or solid solutions with tin. Thus, the presence of 0.005% Cu will cause tin to fracture easily at 5 C (9 F) below the melting point of tin, and the effect of only 0.001% Cu is detectable. The temperature to fracture is lowered by 12 C (22 F) when 0.02% Ag is added to tin as cast, or 0.04% Ag is added after long annealing. Addition of 0.5% Pb may cause tin as cast to fracture at 183 C (361 F).

Joining Tin Parts. Parts made from tin and tin alloys are joined most readily by soldering with ■ low-melting solder. Care must be taken not to overheat the joint members, since the fusion point of the tin or tin alloy may be only a little higher than that of the solder. The eutectic tin-lead solder (63% Sn) is frequently used.

For pewter, a composition similar to that of the base metal, or even pure tin may be desired to give a matching color. Tin-lead-bismuth solders can be used where color is not important. Rosin and olive oil are sufficiently strong fluxes, but a flux of 10 drops HCl in 1 oz glycerin is frequently used in the soldering of pewter. Parts to be joined should be made to fit well before soldering, and only enough solder should be used to fill the joint. A light flame is more convenient to use than a soldering bit and ordinarily entails less danger of local overheating.

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Tin Coatings and the Resistance of Tin to Corrosion

By Bruce W. Gonser*

TIN COATINGS are applied to ferrous materials and copper alloys in order to increase the resistance to corrosion. The coating of ferrous materials with tin by hot dipping, and the manufacture of electrolytic tin plate, are discussed in the article on page 709 in this Handbook. The present article describes the hot tinning of nonferrous objects, and the application of tin coatings by hot dipping and by other methods.

The resistance of tin to corrosion in the atmosphere and in aqueous mediums is summarized briefly here. More specific information concerning the resistance of tin to commonly encountered corrosive agents is included in the compilation of the properties of tin, on page 1072.

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Tin Coatings

Tin-coated copper is used for dairy and refrigeration equipment, as well as for containers and conveyers of food and beverages. Tin-coated copper tubing is useful for handling natural fresh waters that are very soft or that contain large percentages of dissolved carbon dioxide and oxygen. As a coating on copper wire and cable, tin arrests corrosion caused by sulfur in rubber insulation.

The Hot Tinning of Nonferrous Articles.[1] Copper and bronzes other than aluminum bronze are coated by hot tinning in about the same manner as ferrous articles. Ordinarily there is less difficulty in preparation, because copper objects are less likely to be coated with oil or grease. Pickling is done best by dipping the work for 2

to ▮ min in cold 15% nitric acid by volume, or in a hot solution containing 10% sulfuric acid and 2% nitric acid. After washing and immersion in a flux solution that has a zinc chloride base (for example, 3 lb zinc chloride, 0.3 lb ammonium chloride per gal of water) the articles are tinned and the surplus tin is removed by wiping or shaking.

The reaction between copper and molten tin is much more rapid than that between iron and tin; hence, the tin bath quickly becomes contaminated with copper. This contamination can be minimized by keeping the temperature of the tin bath low, preferably 250 C (480 F) and leaving the copper in the molten tin no longer than is absolutely necessary. Ordinarily only one pot of tin is used, since a double immersion merely prolongs the time of contact between tin and copper, and the only flux is that carried by the article being dipped. When large, heavy copper-base articles are to be tinned, they should be preheated after fluxing, to shorten the time of tinning.

If the tin bath or the liquid film of tin on the copper contains much more than 0.7% Cu (the eutectic alloy), enough crystals of intermetallic compound, η, are precipitated during cooling, to make the tin pasty and slow in draining. The excess of tin is commonly removed from copper articles by hand wiping with a cloth pad. It may be necessary to reheat the surface—for example, with a gas flame—to ensure smoothness after wiping. If the temperature exceeds about 280 C (545 F) during wiping, the result may be a yellowish cast to the tin and dark streaks from the wiping cloth.

So that excess copper can be removed from the tin bath, the tin should be cooled at frequent intervals, nearly to the solidification point, thus permitting crystals of η to settle to the bottom as a sludge, from which copper can be removed readily. It is not good practice to attempt to tin iron and copper articles in the same pot, since the copper picked up by the molten tin causes the coating on iron to be dull or spangled.

Brass is hot tinned by the same method as copper. Zinc dissolved from the brass adds another undesirable constituent to the tin. The zinc forms an oxide dross that remains on the surface of the bath and adheres to the articles being tinned, thus making ▮ good finish more difficult to secure. Also, the tin becomes less fluid and does not drain so well; consequently it is preferable to tin brass by electrodeposition. Aluminum bronze and other copper alloys that contain aluminum have been hot tinned successfully after heavy electroplating with copper, but electrodeposition of tin seems to be a preferred method.

Large articles that cannot be immersed easily in a tinning bath, or vessels that require a tin lining only, may be hot tinned by wiping, a method used particularly for copper and copper alloys. After being cleaned and pickled, the article is heated moderately above the melting point of tin, finely powdered ammonium chloride flux is scattered over the surface, and then solid tin is rubbed quickly over the surface. Where feasible, a little molten tin is poured into a recess of the surface and is flushed around with a wiping pad. For tinning copper sheet on one side only, the reverse side is coated with whitewash (slaked lime); then molten tin is poured over the sheet, on a heated table, which slopes to permit drainage.

Electrotinning. Miscellaneous articles are commonly electrotinned[2] in ▮ bath of 9 to 16 oz per gal sodium stannate, 1.5 to 2.5 oz per gal free caustic soda, and (optionally) 2.5 to 5 oz per gal sodium acetate, at a cathode current density of about 15 amp per sq ft, and at a temperature of 75 C (165 F). In this bath it is necessary to cover the tin anodes with a film by subjecting them temporarily to a relatively high current density in order to prevent formation of stannous tin. The film is maintained by removing the anodes whenever the current through the bath is stopped; otherwise, the filming treatment must be repeated. A modified bath of this nature, containing copper cyanide, is used in plating bronze for hard, white decorative coatings or for stop-off in nitriding.

An acid bath (13.5 oz total sulfuric acid per gallon; 4.8 oz tin, dissolved anodically, per gallon; 16 oz cresol sulfonic acid per gallon; 0.3 oz gelatin per gallon; and 0.015 oz beta naphthol per gallon) is also used successfully for general electrotinning. This bath tolerates a higher current density, operates at room temperature, and the anodes are not filmed. Both electrolytes have excellent throwing power and are used in barrel plating small articles.

Other Methods. Small copper and brass parts, such as pins, screws, hooks and eyes, and parts for switches, are commonly tinned by replacement or immersion. A number of hot tin-salt solutions are used, such as 4 to 30 ▮ per liter of stannous chloride in a saturated solution of potassium acid tartrate; ▮ dilute solution of stannous chloride containing 25 g per liter of ammonium alum; or an alkaline bath containing 15 g per liter stannous chloride, 18 g per liter sodium hydroxide, and 7 g per liter sodium cyanide. More rapid deposition takes place in a cold bath of 50 ▮ per liter sodium cyanide, 5 ▮ per liter hydrous stannous chloride, and 5.6 g per liter caustic soda. A tin thickness of 0.000004 in. can be deposited on copper in 5 min with this solution.[3]

Molten anhydrous stannous chloride, preferably diluted with other inert salts that have low melting points, forms an excellent bath for tinning copper alloys and steel very rapidly. This coating is deposited at ▮ temperature sufficiently high to form a hard alloy coating. Similarly, tin alloy coatings can be applied by "stannizing", that is, heating the articles to be tinned, in volatilized stannous or stannic chloride and hydrogen.[4]

Tin powder in a convenient flux-lacquer suspension is sometimes painted over parts to be tinned, and is then heated above the melting point by means of a torch. Wiping is usually necessary to secure reasonably good distribution. Tin is easily sprayed, also, from wire, molten metal, or powder.

Resistance to Corrosion

Tin retains its brightness well during atmospheric exposure, both indoors and outdoors. The gain in weight from tarnishing indoors has been reported as 0.004 mg per sq dm per day for tin, compared with 0.019 mg for cadmium.[5] In ASTM 10-yr exposure tests, the average gains in weight for commercial 99.85% Sn panels were 0.007, 0.067, and 0.11 mg per sq dm per day at rural, industrial and marine locations, respectively, and respective losses in tensile strength were 19, 23.5, and 30%.[6] The rusting of tin cans, often attributed to corrosion of the tin coating, is caused by iron rust that mushrooms through pinholes in the coating. In detinning, virtually as much tin is recovered from a moderately rusty can as from one that has no rust.

In aqueous mediums, tin reacts with both strong acids and strong bases, but is relatively resistant to nearly neutral solutions. Corrosion is greatly accelerated by the presence of oxygen. Normally, tin is coated with a thin invisible film of stannic oxide, which may be removed by acids or alkalies, or may be penetrated locally so that pits develop. Corrosion by pitting is more common in nearly neutral solutions than corrosion by general attack. Distilled or fresh water attacks tin negligibly, although in some hard waters, precipitated carbonate may cause localized water-line pitting. The addition of 5% Sb to the tin has prevented such localized attack by hard water.[7]

When tin is used as a protective coating over a base metal, as on tin plate or tinned copper, corrosion is usually localized at pinholes through the coating. Tin is not electroprotective to steel under oxidizing conditions; but, under some nonoxidizing conditions, the potential of the tin-iron couple reverses, which accounts for the fact that tin does prevent exposed iron from corroding.[8] The best example is on the inside of tinned cans, where partial vacuum and the presence of dilute organic acids prevent appreciable attack by many foods, even though the tin coating is porous. The presence of stannous ions, resulting from slight attack on the tin coating, also aids in inhibiting an attack on exposed iron by many foodstuffs.[9]

Rusting of tin plate or tin cans during outdoor exposure may be prevented, or at least greatly delayed, by a treatment with a hot alkaline phosphate-dichromate solution (0.20 lb crystalline trisodium phosphate per gallon, 0.08 lb sodium dichromate per gallon, 0.20 lb caustic soda per gallon, and 0.03 lb wetting agent per gallon) for

a few seconds at 60 to 85 C (140 to 185 F).[10] This solution has been effective in treating electrolytic tin plate of 0.5 lb per base box coating weight, as well as in treating more heavily coated, hot dipped tin plate. Evidently the action is on the tin coating, since the same treatment has no apparent effect in preventing the formation of rust on untinned steel.

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The Metallography of Tin and Tin Alloys

By C. H. Hack* and Frances H. Clark*

THE PREPARATION of tin and tin alloys for metallographic examination requires good technique and care because of the softness and ease of formation of flowed metal on the surface of the specimens. In general, the procedure for preparation is identical with that outlined on page 955 for lead and lead alloys. The harder alloys are more easily prepared than the softer ones.

The specimens may be surfaced initially by filing, or machining on a lathe, using a sharp tool that has a sharp rake, and then by grinding on abrasive papers of decreasing fineness. If a microtome is available, it may be used advantageously in minimizing the amount of subsequent polishing. However, if a microtome is used, a check should be made to see that it possesses three requisite properties, namely, sufficient rigidity, a properly sharpened knife, and such adjustments that cuts of 2 microns in thickness may be made. If a microtome is not available, a good substitute can be made by attaching a microtome knife to the front end of the supporting arm of a milling machine. The specimen is clamped in a vise attached to a slide rest (similar to the type used for a lathe) mounted on the moving bedplate at a slightly inclined angle. Settings for cuts as thin as 1 micron may then be made by turning the screw of the slide rest. A final microtoming with cuts of 1 to 2 microns is best for tin and tin alloys.

When preparing thin sections, such as tin coatings on metals or thin sections of babbitt linings, for metallographic examination, it is generally necessary to mount the section in some molding medium. Waxy materials sometimes used have a disadvantage in that they clog the polishing papers and soften in alcoholic etching agents or in solvents used for drying. Likewise, fusible alloys used for mounting clog the polishing papers, and are usually attacked more readily than the specimen by the etching reagent. Acid-hardened bakelite is being used successfully for mounting.[7] For this procedure 10 ml of a bakelite acid-hardening solution is added to 100 ml of the bakelite resin, and the two are mixed thoroughly. The mixture is then poured into the mold containing the specimen and is heated to between 40 and 45 C, when the bakelite begins to harden. It is then heated further at 60 C for 1 to 1½ hr, until the mixture has set hard. Bubbling and too rapid hardening may take place if the temperature applied is too high; therefore, it is desirable to use the lower temperature (40 C) for setting the resin, and then to apply a higher temperature (60 C) for hardening. Just enough material should be mixed for the immediate work, because the mixture hardens while aging at room temperature. One of the advantages of the acid-hardened bakelite is that it does not require high temperatures and pressures.

Polishing. If the specimen has been machined on a lathe, the polishing should be started on 0 abrasive paper, with subsequent polishing on 00 and 000 abrasive paper, all three lubricated with paraffin dissolved in kerosene (100 g of paraffin in 200 ml of kerosene). After being polished on each paper, the specimen should be washed first in warm kerosene to remove the grit and paraffin,

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Table I. Etching Reagents for Tin and Tin Alloys

No.	Etching Reagent	Composition	Remarks	Use
1	Nital	HNO_3 ..... 2 to 5 ml C_2H_5OH .... 95 to 98 ml	Swab or immerse for several minutes.	Tin-cadmium or tin-iron alloys
2	Potassium dichromate	Acidified dilute solution	.....	Tin-cadmium alloys
3	Mixed acids in glycerol[1] (*A*)	HNO_3 .....1 part $HC_2H_3O_2$ .....1 part Glycerol .....8 parts	Immerse ½ to 10 min at 38 to 42 C.	(*A*) Tin-lead alloys
	(*B*)	HNO_3 .....1 part $HC_2H_3O_2$ .....3 parts Glycerol .....5 parts	Same as for (*A*) above	(*B*) Pure tin
4	Hydrochloric acid (*A*)	HCl (conc)	Immerse for several seconds.	To remove surface flow
	(*B*)	HCl .....10 to 20 ml H_2O .....90 to 80 ml	Immerse ½ to 5 min following (*A*).	Follow (*A*)
	(*C*)	HCl .....10 ml H_2O .....90 ml	Electrolytic etch at low current density	Tin-iron alloys
5	Ferric chloride	$FeCl_3$ .....10 g HCl ..... 2 ml H_2O .....95 ml	Immerse ½ to 5 min at room temperature.	Micro-etching tin-rich babbitt metal
6	Nitric acid[5]	HNO_3 ..... 5 ml C_2H_5OH (abs) ....95 ml	.....	Pure tin
7	Picric acid and nitric acid[6]	Alcoholic solution	.....	Tin-iron alloys
8	Ammonium polysulfide[2]	Concentrated solutions	Immerse 20 to 30 min at room temperature.	Macro-etching of tin-rich babbitt metals
9	Ammonium persulfate	$(NH_4)_2S_2O_8$ ..... 5 ml H_2O .....95 ml	Blackens out the tin or tin alloy, leaving the compound as a bright contrasting layer.	Tin coatings on steel
10	Acetic acid	$HC_2H_3O_2$ .....50 ml H_2O .....50 ml H_2O_2 .....1 drop	.....	Soldered joints

Solutions of silver nitrate or 10% nitric acid plus 5% chromic acid are also used occasionally.

and then with soap and water to remove the kerosene.[3] Thereafter the specimen may be etched with HCl (10 to 20%) or any other suitable etching reagent, in order to remove any metal that may have flowed on the polished surface.[4] A specimen that has been finished by microtoming may be polished on 000 paper to remove any scratches left by the microtome blade.

The specimen is then polished on a rotating wheel covered with broadcloth. The polishing mixture—usually a suspension of levigated alundum* (grain size 600) in a soap solution—may be prepared as follows: 5 g alundum grain is added to 300 ml water. This mixture is agitated thoroughly and allowed to stand for 15 min, when the supernatant suspension is decanted. To the decanted suspension 40 g soap is added and the mixture is heated until the soap dissolves. Because this mixture is nearly solid at room temperature, it should be used warm. When poured on the polishing wheel, this polishing material forms a gelatinous mass, viscous enough not to be thrown off the wheel at 120 rpm.[3] The final steps of preparation consist in polishing on a good grade of silk velvet, on which the mixture of soap and alundum grain is used. Then the specimen is etched and polished alternately until the true structure is revealed.

In one successful method, the specimen is microtomed, then etched rather deeply and polished on a wheel covered with silk velvet, on which magnesium oxide and water are used without addition of soap. The specimen is then washed thoroughly in running water, etched and dried. Further light polishings and etchings may be performed if necessary. This method saves considerable time.

When the specimen is being prepared for examination at ■ high magnification, the following procedure may be used:[3] A 4-in. circle of wool broadcloth is cemented onto a metal lap. The cloth is moistened with water and a 30 to 40% solution of sodium hydroxide, heated to 50 C. The cloth is washed off after two minutes and is charged with a paste of relevigated alumina in water. The fibers of the cloth are softened by this procedure and a satisfactory final polish can be obtained.

As already mentioned, the structure of pure tin is likely to be distorted by mechanical polishing, even on fine abrasive paper. Such polishing often produces twinning to a considerable depth. A paper by P. A. Jacquet[9] tells in detail how to polish tin specimens electrolytically without mechanical preparation.

Etching. The reagents listed in Table I have been used successfully for etching the tin alloys indicated.

* Finer abrasives, such as alumina or magnesium oxide, may be used, although these have been reported as producing excessive burnishing action and relief polishing.[3]

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PROPERTIES OF TIN AND TIN ALLOYS

COMPILED BY JOHN L. EVERHART

Battelle Memorial Institute

Pure Tin

A *1 Designations.* Straits tin (Grade A tin) has a minimum purity of 99.8% and must meet definite specifications limiting some individual impurities. Most of the tin sold is in this classification. A few brands have been consistently more pure than 99.98%, and may be considered "pure tin". A number of other brands normally have contained more than 99.90% Sn. For specific information concerning the chemical compositions of twenty brands of commercial tin, the reader may refer to the article entitled, "The Tin Industry", page 1063.

Many of the properties listed here for pure tin were determined on tin of 99.95% purity. More recent work has been with Chempur tin of 99.9918% purity, containing 0.0031 Sb; 0.0025% Pb; 0.0004% Bi; 0.0004% Cu; 0.0016% Fe; 0.0002% S; no As, Ag or Co. Small amounts of copper increase the hardness of tin; traces of iron change the color of the metal.

B *1 Typical uses.* Electrotinning, chemical compounds

C *1 Density* at 1 C (33.8 F). 5.765 g per cu cm (0.208 lb per cu in.) α tin[8]
at 15 C (59 F). 7.2984 g per cu cm (0.2637 lb per cu in.) β tin[9]

2 Density versus temperature.[10] *See* Fig. 1.

5 Solidification shrinkage.[11] 2.7%

6 Transformation volume change. 27% expansion, tetragonal to cubic, during cooling below 13.2 C (55.8 F)

7 Specific volume.[41,42]

Temperature, deg Cent	20	409	474	523	574	602	648
Temperature, deg Fahr	68	768	885	973	1065	1116	1198
Specific Volume, cu cm per g..	0.1395	0.1462	0.1473	0.1479	0.1486	0.1490	0.1499

D *1 Melting point.*[12] 231.9 C (449.4 F)

Effect of pressure on melting point.[37]

Pressure, atmospheres	500	750	1000	1490	2000
Temperature, deg Cent	232.26	233.09	233.89	235.47	237.18
Temperature, deg Fahr....	450.07	451.56	453.00	455.85	458.92

4 Boiling point.[40] 2270 C (4120 F)

Critical pressure and temperature.[39] 650 atmospheres, 3730 C (6730 F)

Vapor pressure.[40]

Temperature, deg Cent.....	1932	2056	2163	2270
Temperature, deg Fahr	3510	3733	3925	4120
Vapor pressure, atmospheres.....	0.1	0.25	0.50	1.0

5 Transformation temperature (cooling).[13] 13.2 C (55.8 F)
$\beta \rightarrow \alpha$

6 Thermal expansion (polycrystalline) (linear)[14,35] 0 to 100 C (32 to 212 F). 0.000023 per °C; −163 to +18 C (−261 to +64 F). 0.000016 per °C; white tin 20 to 231 C (68 to 448 F). 0.000023 to 0.000024 per °C; gray tin −163 to +18 C (−261 to +64 F). 0.0000053 per °C.

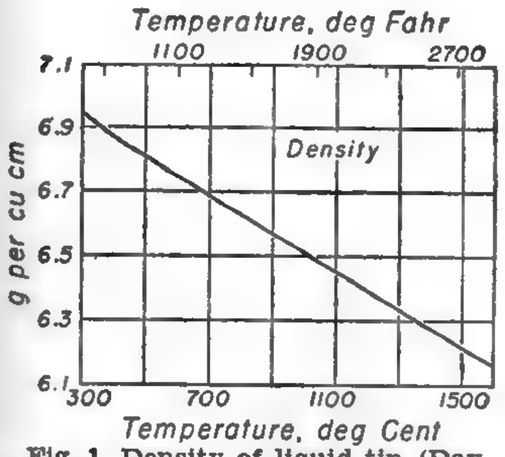

Fig. 1 Density of liquid tin (Day, Sosman and Hostetter[10])

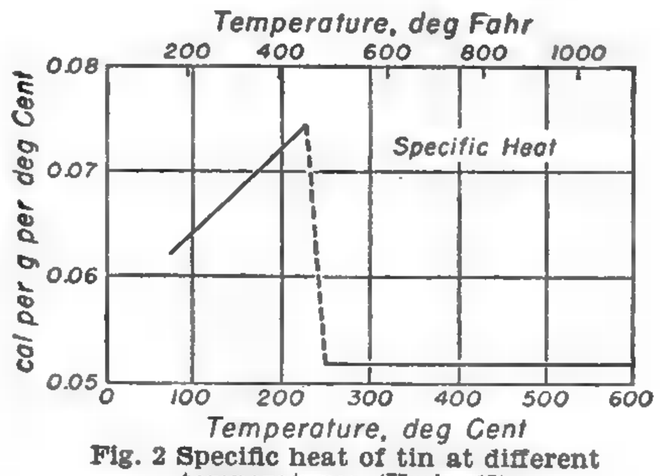

Fig. 2 Specific heat of tin at different temperatures (Umino[17])

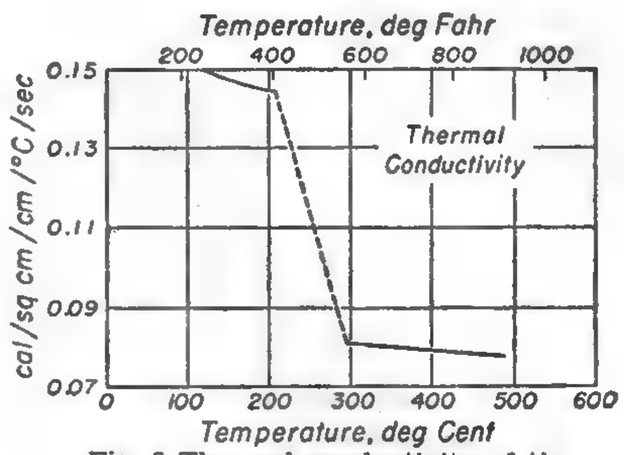

Fig. 3 Thermal conductivity of tin at different temperatures (Konno[19])

(cubic)[10,36] 232 to 396 C (450 to 745 F). 0.000000106 per °C
232 to 1600 C (450 to 2912 F). 0.000000100 per °C

7 Thermal expansion along a axis[15] at 20 C (68 F). 0.0000305 per °C

8 Thermal expansion along b axis[15] at 20 C (68 F). 0.00001545 per °C

11 Specific heat 0 to 100 C (32 to 212 F). $0.0534 + 0.0000348t$ cal per ■ for β tin[11]
8 to 13 C (45 to 55 F). 0.0493 ± 0.0002 for α tin[16]

12 Specific heat versus temperature.[17] *See* Fig. 2.

13 Latent heat of fusion.[50] 14.5 cal per g

14 Latent heat of transformation (cooling).[11] 4.46 cal per g

15 Latent heat of vaporization.[49] 570 cal per ■ at 2270 C

16 Thermal conductivity[11] at 0 C (32 F). 0.16 cgs

17 Thermal conductivity versus temperature.[19] *See* Fig. 3.

E *1 Volume conductivity* referred to standard copper. 15.0%

2 Electrical resistivity[11] (polycrystalline) at 20 C (68 F). 11.5 microhm-cm

3 Electrical resistivity along a axis[15] at 20 C (68 F). 14.30 microhm-cm
Electrical resistivity along b axis[15] at 20 C (68 F). 9.90 microhm-cm

4 Electrical resistivity (liquid)[20] at 231.9 C (449.4 F). 48.1 microhm-cm

5 Temperature coefficient of electrical resistivity[21] 0 to 100 C (32 to 212 F). 0.00447 microhm-cm per °C

6 Temperature coefficient of electrical resistivity along ■ axis[15] 0 to 100 C (32 to 212 F). 0.00447 per °C
Temperature coefficient of electrical resistivity along b axis[15] 0 to 100 C (32 to 212 F). 0.00469 per °C

10 Electrochemical equivalent[22]
(valence 2). 0.61505 mg per coulomb
(valence 4). 0.30752 mg per coulomb

11 Electrolytic solution potential versus hydrogen.[23]
Sn/Sn^{++} 0.1359 volts; Sn/Sn^{++++} 0.158 volts

14 Hydrogen overvoltage[24] 0.73

15 Hall effect.[25] 4 kilogauss; R = minus 0.2×10^{-4} volt-cm per ampere-gauss at room temperature

16 Supraconductive at 3.71 K[11]

F *1 Reflectivity.*[9,26]

54%, at λ = 1,000A	81%, at λ = 7,000A
72%, at λ = 4,000A	85%, at λ = 12,000A

2 Refractive index.[27] 1.48 at 5890 A, sodium light

4 Color.[9] White, with slightly bluish tinge

5 Emissivity.[9] 0.04 at 50 C (122 F)

G *2 Mass magnetic susceptibility.*[46] minus 0.25×10^{-6} cgs

H *1 Velocity of sound* (solid).[28] 8672 ft per sec;
(liquid).[28] 4249 ft per sec

I *Chemical Properties. See* data sheet for 99.8% Sn.

J *1 Crystal structure.*[47]

Phase	Type	*a*, kX	*c*, kX
■	Cubic	6.46[11]	.....
β	Tetragonal	5.8195	3.1750[30]

Under certain specific conditions at low temperature, tin can transform from the normal tetragonal metal (white tin) to a cubic form (gray tin) that has entirely different properties. Since this transformation is accompanied by a change in density from 7.30 to 5.75, the resultant expansion causes disintegration of the metal to coarse powder or to local "warts".

The equilibrium temperature of transformation is 13.2 C (55.8 F). However, there is a marked lag or undercooling before the transformation occurs, and even under very favorable conditions a much lower temperature is needed to produce gray tin. The maximum velocity of transformation is at about minus 40 C (minus 40 F). It is very difficult to initiate the change, and even after the transformation has started, the rate is slow. For example, 500 hr is required for the change to progress a distance of 1 mm in a specimen at minus 10 C (plus 14 F) in high-purity (Kahlbaum) tin, or 800 hr is required in Banka tin. Inoculation, or contact with gray tin, greatly speeds the start of transformation, and has been an important aid in experimental work on the formation of gray tin.

Many factors influence this transformation besides temperature. Most of the common impurities in tin greatly delay or, for practical purposes, inhibit the change. Bismuth is particularly potent in this respect; the addition of 0.1% Bi is sufficient to assure that no change occurs under any conditions that are likely to be encountered. Antimony and lead are also strong inhibitors of the change; gold, silver, and nickel are somewhat less effective. On the other hand, zinc, aluminum, magnesium, cobalt, manganese, and tellurium accelerate the transformation; fortunately, these elements are seldom present in commercial grades of tin. The probability of transformation is increased and the velocity of the change is accelerated greatly by drastic working of the tin, but this effect is removed by annealing the metal at an elevated temperature. Repeated transformation of the same tin to the gray form, then back to the white form, facilitates the change.

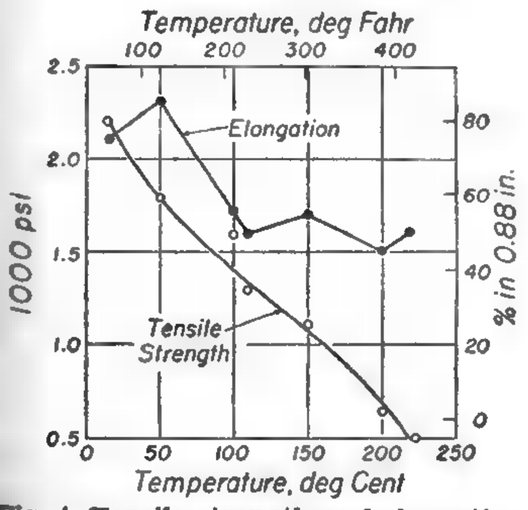

Fig. 4 Tensile strength and elongation of tin (Homer and Plummer[44])

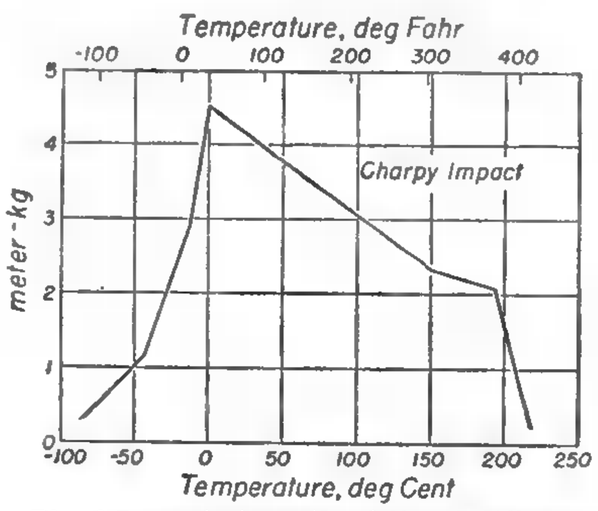

Fig. 5 Impact strength of tin at different temperatures (Greaves and Jones[45])

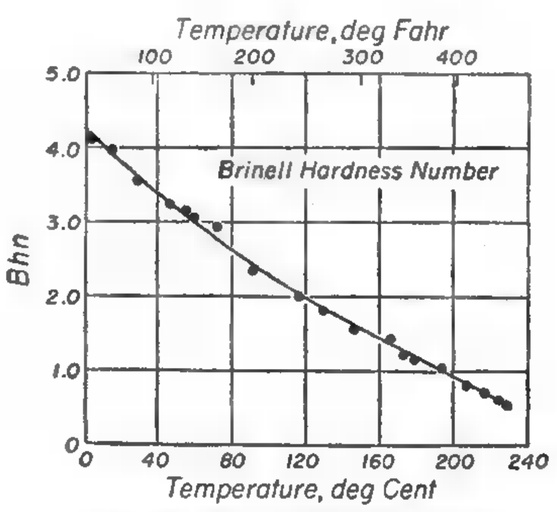

Fig. 6 Brinell hardness of tin (5-mm ball, 10-kg load, 180 sec) (Homer and Plummer[48])

Gray tin is of no commercial importance, since it does not exist in massive form or at normal working temperatures. If formed, it is readily converted to massive white tin by melting, or to white tin powder by heating. Fears of the failure of fabricated products made of block tin or of high-tin alloys at low temperatures, or of the disintegration of tin in storage, are largely unfounded, because of the inhibiting effect of the common impurities, and the difficulty in initiating the transition. Authenticated instances of the transformation taking place under natural conditions are rare. No solder or tin article containing more than 5% Pb has been found that has shown signs of transformation. As a precaution, however, the absence of aluminum and zinc should be assured, and 0.1% Bi (or at least 1 or 2% Sb or Pb) should be added to tin that is to be refrigerated continuously for long periods.

The existence of "gamma tin", a brittle modification that is sometimes mentioned in technical literature, has been rather well disproved.[48] Abrupt changes in some properties at elevated temperatures are ascribed more accurately to the presence of impurities.

K *Mechanical properties.*

Form	Tensile Strength, psi	Elongation, percentage	Brinell Hardness Number	Modulus of Elasticity, 10^6 psi	Izod, ft-lb	Shear Strength, psi
Cast	3100	55 (4 in.)	5.3	6.0 to 6.5	14	2900
Chill cast	2100	69 (2 in.)	...	...	...	...
Sheet, annealed (0.1 in. thick)	2400	96	...	...	...	...
Foil	2200	..	...	...	...	...

All forms: *Modulus of elasticity* at 225 C, 1,500,000 psi (437 F)
Cast: *Poisson's ratio.* 0.33
Modulus of rigidity. 2,400,000 psi

6 Creep at room temperature for wire (0.1 in. diam).

Applied stress, psi.....	75	155	230	310	390	540	775
Time, days	28	28	28	28	28	28	3
Elongation, %	0	0	0.78	3.0	8.5	10.5	failed

Creep at room temperature of rolled strip (0.1 in. thick)

Stress, psi	160	195	325	400	470	610	1025
Time, days	551	551	173	79	21	4.6	0.5
Elongation, %....	3.5	7.0	101 failed	132 failed	119 failed	105 failed	78 failed

Effect of temperature on mechanical properties.[44,45] Fig. 4, 5 and 6.

7 Viscosity (liquid)[33] at 300 C. 0.0168 poise

8 Surface tension (liquid)[34] at 231.9 C. 662 dynes per cm

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Tin (99.8 Sn)

A *1 Common name.* **Straits Tin**
2 Trade name. **Grade A**
4 Government number. Federal QQ-T-371, Grade A (99.75%)
6 Foreign equivalents. German DIN 1704, Grade A2 (99.75%)

B *1 Uses.* Foil, collapsible tubes, powder, tin plate, pipe

I *2 Resistance to specific agents.*

Corrosive Agent	Resistance	Remarks
Acid acetic	Slight general attack	Increased by air
Acid butyric	Resistant	.....
Acid citric	Moderate attack	At water line
Acids fatty	Moderate general attack	.....
Acid hydrochloric	Severe general attack	In presence of air
Acid hydrofluoric	Severe general attack	In presence of air
Acid lactic	Moderate general attack	Increased by air
Acid nitric	Severe general attack	.....
Acid oxalic	Moderate general attack	Most corrosive of common organic acids
Acid phosphoric	Resistant	.....
Acid salts	Severe general attack	In presence of air
Acid sulfuric	Severe general attack	Increased with concentration and in presence of air
Acid tartaric	Slight general attack	.....
Air	Resistant	.....
Ammonia	Resistant	.....
Bromine	Severe general attack	.....
Carbon tetrachloride	Resistant	.....
Chlorine	Severe general attack	.....
Iodine	Severe general attack	.....
Milk	Resistant	.....
Motor fuel	Resistant	.....
Petroleum products	Resistant	.....
Potassium hydroxide	Severe general attack	Increased by air
Sodium carbonate	Slight general attack	.....
Sodium hydroxide	Severe general attack	Increased by air
Water distilled	Resistant	.....
Water sea	Resistant	.....

Notes. Tin reacts with both strong acids and strong alkalies but is relatively resistant to nearly neutral solutions. Oxygen greatly accelerates corrosion in aqueous solutions.

In general, with mineral acids the rate of attack increases with the temperature and concentration.

Dilute solutions of weak alkalies have little effect on tin, but strong alkalies are corrosive even in cold dilute solutions.

Salts with an acid reaction attack tin in the presence of oxidizers or air.

Tin resists soft tap waters but is slightly attacked near the water line by hard tap waters.

K *Mechanical properties.*

Form	Section, inch	Tensile Strength, psi	Yield Strength (0.2% offset), psi	Elongation, percentage	Vickers Pyramid Hardness
Cast	....	2100	....	55 (4 in.)	...
Sheet, annealed 1 hr at 370 F	0.040	2200	1300	45 (2 in.)	7.2
Sheet, cold rolled 30% reduction	0.040	2800	2000	35 (2 in.)	8.4
Foil	0.0016	2000	....	6.5	...

Cast: Modulus of elasticity 6,000,000 psi; *Izod* 14 ft-lb; *Shear strength* 2,900 psi; *Poisson's ratio* 0.33.

M *Composition limits* (Federal specification QQ-T-371) *Component:* Sn 99.75% min; *impurities:* 0.10% Pb max, 0.10% Sb max, zinc none, 0.10% As max, copper none, 0.10% Cr max, 0.01% S max, 0.01% Fe max, 0.01% Bi max.

Reference

"Mechanical Properties of Metals and Alloys", Nat Bur Standards Circular C 447, 1943

99.6 Sn – 0.4 Cu

A *1 Common name.* **Hard Tin**

B *1 Typical uses.* Collapsible tubes and foil

D *1 Liquidus temperature.* 230 C (446 F)
2 Solidus temperature. 227 C (441 F)

I *2 Resistance to specific agents.* Resistant to attack by foodstuffs, medicinal products, cosmetics and artist's colors.

K *Mechanical properties.* Tensile strength of 0.1-in. strip: (annealed 3 hr at 100 C) 3300 psi; (annealed 3 hr at 200 C) 3100 psi; (hard—80% reduction) 4000 psi. Collapsible tube, impact extruded, 0.004-in. wall: 21 bends over 90-deg jaws (1000-g load). A tube 1-in. in diam, with 0.004-in. wall, burst under an internal pressure of 46 psi.

N *Working data.* Although copper dissolves readily in tin at temperatures of 600 C (1112 F) or higher, the alloy is usually prepared by the addition of a master alloy, such as a 10% Cu alloy. For the manufacture of collapsible tubes, the alloy is cast into slabs, ⅝ to ¾ in. thick and rolled cold to the desired thickness. Blanks are punched from the strip, and the tubes are formed by impact extrusion.

Reference. D. Hanson, E. J. Sandford and H. Stevens, Some Properties of Tin Containing Small Amounts of Silver, Iron, Nickel or Copper, J Inst Metals, 55, 115 (1934)

95 Sn – 5 Sb

A *1 Common name.* **Antimonial Tin Solder**

B *1 Typical uses.* Solder for electrical equipment, joints in copper tubing, cooling coils for refrigerators. High-tin solder is used for joining parts of electrical apparatus because this solder has somewhat higher electrical conductivity than high-lead alloys. High-tin solder is also used where lead may be a hazard—for instance, in contact with foodstuffs. Because of their higher melting points, the tin alloys that contain 5% Sb or 5% Ag, are suitable for use at higher temperature than the tin-lead alloys.

D *1 Liquidus temperature.* 240 C (464 F)
2 Solidus temperature. 233 C (452 F)

E *1 Volume conductivity* referred to standard copper. 11.9%
2 Electrical resistivity at 25 C (77 F). 14.5 microhm-cm

I *2 Resistance to specific agents.* Resistant to SO_2.

K *Mechanical properties.* Cast: tensile strength 5900 psi; elongation in 4 in. 38%; Izod 20 ft-lb; shear strength 6000 psi.
Soldered copper joint: tensile strength 14,200 psi; shear strength 11,100 psi.
The mechanical properties of solder metal are not so indicative of the value of the material as the strength of joints produced with them. Tension and shear tests[3,4,5] have been used in evaluating the strength of joints and, in general, the thinner the layer of solder metal, the stronger the joint. Although the references do not deal with the specific alloys under discussion here, they should be referred to for details of the testing methods that have been used. Other properties, such as those involved in "spreading tests",[3] "wetting tests",[6] and the capillary rise of solder between strips of the metal to be soldered,[5] are beyond the scope of these data sheets and reference should be made to the original articles.

N *17 Joining.* For the joining of copper alloys and low-carbon steel, zinc chloride and zinc-ammonium chloride can be used as fluxes with all four of the tin-base solders. The excess flux should be removed because the residue is corrosive. A number of proprietary organic-base fluxes are suitable also, and are stated to leave noncorrosive residues. Rosin fluxes may be used with the high-tin Sn-Pb alloys but are not satisfactory for the antimony and silver solders. A flux containing zinc-ammonium chloride, stannous chloride, and free hydrochloric acid is suitable for joints of copper alloy, low-alloy steels, stainless steels and cast iron with tin solders. The flux residue is corrosive and should be removed. These solders are not suitable for joining magnesium and aluminum alloys.

References

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95 Sn – 5 Ag

A *1 Common name.* **Tin-Silver Solder**

B *1 Typical uses.* Solder for electrical work and high-temperature service. *See* 95 Sn – 5 Sb.

D *1 Liquidus temperature.* 245 C (473 F)
2 Solidus temperature. 221 C (430 F)

E *1 Volume conductivity* referred to standard copper 16.6%
2 Electrical resistivity at 0 C (32 F). 10.4 microhm-cm
5 Temperature coefficient of electrical resistivity 0 to 100 C (32 to 212 F). 0.00423 microhm-cm per °C

K *Mechanical properties.* Sheet, aged 14 days at room temperature, in 0.040-in. section: tensile strength 4600 psi; yield strength 3600 psi; elongation in 2 in. 49%. Soldered copper joint: tensile strength 14,000 psi; shear strength 10,600 psi. *See also* 95 Sn – 5 Sb.

N *Working data. See* 95 Sn – 5 Sb.

References. *See* 95 Sn – 5 Sb.

70 Sn – 30 Pb

A *1 Common name.* **Soft Solder**
3 ASTM number. B 32–46T, grades 70A, 70B
4 Government number. Federal QQ-S-571a, Grade F
B *1 Typical uses.* Joining and coating of metals. *See* 95 Sn – 5 Sb.
C *1 Density.* 8.32 ■ per cu cm (0.300 lb per cu in.)
D *1 Liquidus temperature.* 192 C (378 F)
2 Solidus temperature. 183 C (361 F)
6 Thermal expansion 15 to 110 C (59 to 230 F). 0.0000216 per °C
E *1 Volume conductivity* referred to standard copper. 11.8%
2 Electrical resistivity. 14.6 microhm-cm
K *Mechanical Properties.* Cast: tensile strength 6800 psi; Brinell hardness number 12. *See* 95 Sn – 5 Sb.
M *Composition Limits* (ASTM specification B 32–46T, grades 70A and 70B). *Tin Content,* permissible variations in minimum. Fabricated metal: nominal content minus 1.50% in random sample; nominal content minus 1.00% in composite sample. Cast metal: nominal content minus 1.00% in composite sample. *Impurities* (*max*). Grade 70A: 0.12% Sb, 0.25% Bi, 0.08% Cu, 0.02% Fe, 0.005% Zn, 0.005% Al, 0.08% total others. Grade 70 B: same except 0.50% Sb max.
N *Working data. See* 95 Sn – 5 Sb.

References

J. G. Thompson, Properties of Lead-Bismuth, Lead-Tin, Type Metal and Fusible Alloys, J Research Nat Bur Standards, 5, 1085 (1930)
ASTM Standards, Part I-B Nonferrous metals, 1946, p 618
See also 95 Sn – 5 Sb.

63 Sn – 37 Pb

A *1 Common name.* **Soft Solder**
2 Trade name. **Eutectic Solder**
3 ASTM number. B 32 – 46T. Similar to grades 60A and 60B
B *1 Typical uses.* Solder for electrical work. *See* 95 Sn – 5 Sb.
C *1 Density.* 8.42 ■ per cu cm (0.304 lb per cu in.)
D *1 Melting point.* 183 C (361 F)
6 Thermal expansion 15 to 110 C (59 to 230 F). 0.0000247 per °C
15 Thermal conductivity 0 to 180 C (32 to 356 F). 0.12 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 11.9%
2 Electrical resistivity. 14.5 microhm-cm
K *Mechanical Properties.* Cast: tensile strength 7500 psi; elongation in 4 in. 32%; Brinell hardness number 14; Izod 15 ft-lb; shear strength 6200 psi. Soldered copper joint: tensile strength 29,000 psi; shear strength 8000 psi. *See also* data sheet for 95 Sn – 5 Sb.
6 Minimum creep rate at room temperature. 335 psi, 0.0001 in. per in. strain per day
at 80 C (176 F). 68 psi, 0.0001 in. per in. strain per day
7 Viscosity (liquid) at 280 C (536 F). 0.0133 poise
8 Surface tension (liquid) at 280 C. 490 dynes per cm
M *Composition Limits* (ASTM Specification B 32–46T). *Tin content,* permissible variations in minimum percentage.

Form	Random Sample (spot sample)	Composite Sample
Fabricated metal	nominal minus 1.50	nominal minus 1.00
Cast metal	.....	nominal minus 0.50

Impurities, as specified for grades 60A and 60B.

Form	Sb max	Bi max	Cu max	Fe max	Zn max	Al max	Total Others max
Grade 60 A	0.12	0.25	0.08	0.02	0.005	0.005	0.08
Grade 60 B 0.50		0.25	0.08	0.02	0.005	0.005	0.08

N *Working data. See* 95 Sn – 5 Sb.

References

Solder, International Tin Research and Development Council, Bull 2 (1935)
"Mechanical Properties of Metals and Alloys", Nat Bur Standards Circular C 447, 1943
S. J. Nightingale and O. F. Hudson, "Tin Solders", BNFMRA, Research Monograph No. 1, 2d Ed, 1942
See also 95 Sn – 5 Sb.

50 Sn – 50 Pb

See PROPERTIES OF LEAD ALLOYS, page 964.

91 Sn – 4.5 Sb – 4.5 Cu

A *1 Common name.* **Tin Babbitt**
3 ASTM number. B 23-46T, Alloy No. 1; B 102-44, Alloy No. 1
4 Government number. Federal QQ-M-161, Grade No. 1; Navy 46M2, No. 1
5 Other designations. SAE 10; AMS 4800
B *1 Typical uses.* Bearings, die castings. *See* "Bearing Materials", page 745 in this Handbook.
C *1 Density.* 7.34 g per cu cm (0.265 lb per cu in.)
D *1 Liquidus temperature.* 371 C (700 F)
2 Solidus Temperature. 223 C (433 F)
K *Mechanical Properties.* Chill cast: tensile strength 9300 psi; Brinell hardness number 17; modulus of elasticity 7,300,000 psi; endurance limit at 20,000,000 cycles 3800 psi. *See* Table I.
M *Composition Limits* (ASTM Specifications B 23 and B 102). Chill cast. *Components:* 90 to 92% Sn, 4 to 5% Sb, 4 to 5% Cu. *Impurities* (*max*): 0.35% Pb, 0.08% Fe, 0.10% As, zinc none, aluminum none. Sand cast (B 23): same composition limits except 0.08% Bi max. Die cast (B 102): same composition limits except 0.08% As max; also 0.01% Zn max and 0.01% Al max.
N *2 Casting temperature* (chill). 441 C (825 F)

Table I. Mechanical Properties of 91 Sn – 4.5 Sb – 4.5 Cu

Temperature, deg Cent	Temperature, deg Fahr	Compressive Yield Strength (0.125% set), psi	Compressive Yield Strength (0.3% set), psi	Compr Strength (25% set), psi	Izod, ft-lb	Brinell Hardness Number
		Chill Cast				
20	68	4400	6300	12,800	2.5	17
60	140	....	5200	....	...	..
100	212	2600	....	6,900	3.0	8
150	302	....	....	....	3.3	..
200	392	....	1000	....	2.3	..

Reference. H. K. Hershman and J. L. Basil, White Metal Bearing Alloys, Mechanical Properties at Different Temperatures and Service Tests, J Research Nat Bur Standards, 10, 1 (1933)

89 Sn – 7.5 Sb – 3.5 Cu

A *1 Common name.* **Tin Babbitt**
3 ASTM number. B 23–46T, Alloy No. 2
4 Government number. Federal QQ-M-161, Grade No. 2
5 Other designations. SAE 110
B *1 Typical uses.* Bearings.
See article "Bearing Materials", page 745.
C *1 Density.* 7.39 g per cu cm (0.267 lb per cu in.)
D *1 Liquidus temperature.* 354 C (669 F)
2 Solidus temperature. 241 C (466 F)
K *Mechanical properties.* Chill cast: Brinell hardness number 24 (at 68 F), 12 (at 212 F). Cast from 600 F into mold at 300 F: Brinell hardness number 24; endurance limit for 2×10^7 cycles, 4800 psi; tensile strength 12,600 psi. Cast from 750 F into mold at 212 F: Brinell hardness number 22; modulus of elasticity 7,600,000 psi; yield strength (proportional limit) 1460 psi. Also *see* Table I.
M *Composition limits.* (ASTM Specification B 23–46T, Grade 2). Sand cast: *components,* 88 to 90% Sn, 7 to 8% Sb, 3 to 4% Cu; *impurities,* 0.10% As max, 0.08% Fe max, 0.35% Pb max, zinc none, aluminum none, 0.08% Bi max.

Table I. Mechanical Properties of 89 Sn – 7.5 Sb – 3.5 Cu

Temperature, deg Cent	Temperature, deg Fahr	Compr Yield Strength (0.125% set), psi	Compr Strength (25% set), psi	Tensile Strength, psi	Elongation $4\sqrt{\text{area}}$, percentage	Reduction of Area, percentage
		Chill Cast				
20	68	6100	14,900	11,200	18	25
49	120	....	....	9,200	24	27
100	212	3000	8,700	6,500	23	28
149	300	....	.....	4,000	32	38
175	345	....	.....	2,900	38	44

N *2 Casting temperature* (chill). 424 C (795 F)

References

"Mechanical Properties of Metals and Alloys", Nat Bur Standards Circular C 447, 1943
L. W. Cuthbertson, The Elastic Properties of Some Antifriction Alloys at Room and at Elevated Temperatures. International Tin Research and Development Council, Series A, No. 84 (1939)
Bearing Materials, in this Handbook, page 745.

83.4 Sn – 8.3 Sb – 8.3 Cu

A *1 Common name.* **Tin Babbitt**
3 ASTM number. B 23–46T, Alloy No. 3
4 Government number. Federal QQ-M-161, Grade No. 3
B *1 Typical uses.* Bearings.
See article "Bearing Materials", page 745.
C *1 Density.* 7.46 g per cu cm (0.269 lb per cu in.)

Table I. Mechanical Properties 83.4 Sn – 8.3 Sb – 8.3 Cu

Temperature, deg Cent	Temperature, deg Fahr	Compressive Yield Strength (0.125% set), psi	Compressive Yield Strength (0.3% set), psi	Compr Strength (25% set), psi	Izod, ft-lb	Brinell Hardness Number
			Chill Cast			
20	68	6600	8000	17,000	0.9	27
60	140	....	6800	....	1	..
100	212	3100	5100	9,900	1	14
150	302	....	....	....	1.1	..
200	392	....	1000	....	0.7	..

D *1 Liquidus temperature.* 422 C (792 F)
2 Solidus temperature. 240 C (464 F)
K *Mechanical properties.* Chill cast: Brinell hardness number 27. Die cast: tensile strength 10,000 psi; elongation 1%; Brinell hardness number 30. *See* Table I.
M *Composition limits* (ASTM Specification B 23–46T, grade 3). Sand cast, chill cast. *Components:* 82.5 to 84.5% Sn, 7.5 to 9.0% Sb, 7.5 to 9.0% Cu. *Impurities (max):* 0.35% Pb, 0.08% Fe, 0.10% As, 0.08% Bi, 0.005% Zn, 0.005% Al.
N *2 Casting temperature* (chill). 491 C (915 F)

References

H. K. Hershman and J. L. Basil, White Metal Bearing Alloys: Mechanical Properties at Different Temperatures and Service Tests, J Research Nat Bur Standards, 10, 1 (1933)
"Mechanical Properties of Metals and Alloys", Nat Bur Standards Circular C 447, 1943
Bearing Materials, in this Handbook, page 745.

65 Sn – 18 Pb – 15 Sb – 2 Cu

A *1 Common name.* **Tin Babbitt**
3 ASTM number. B 23-46T, Alloy Grade 5; B 102-44, Alloy No. 3

Table I. Mechanical Properties of 65 Sn – 18 Pb – 15 Sb – 2 Cu

Temperature, deg Cent	Temperature, deg Fahr	Brinell Hardness Number	Compressive Yield Strength (0.125% set), psi	Compr Strength (25% set), psi
		Chill Cast		
20	68	22.5	5000	15,000
100	212	10	2100	6,700

B *1 Typical uses.* Bearings, die castings
See article "Bearing Materials", page 745.
C *1 Density.* 7.75 g per cu cm (0.280 lb per cu in.)
D *1 Liquidus temperature.* 296 C (565 F)
2 Solidus temperature. 181 C (358 F)
K *Mechanical properties. See* Table I.
M *Composition limits.* (ASTM Specifications B 23–46T, B 102-44). *See* Table II.
N *2 Casting temperature* (chill). 366 C (690 F)

References

ASTM Standards, Part I-B, Nonferrous Metals, 1946, p 211, 614
Bearing Materials, in this Handbook, page 745.

Table II. Composition Limits of 65 Sn – 18 Pb – 15 Sb – 2 Cu

Form	Designation	Components: Sn min	Sn max	Sb min	Sb max	Pb min	Pb max	Cu min	Cu max	Impurities: Fe max	As max	Zn max	Al max
Sand cast	B 23	64	66	14	16	17	19	1.75	2.25	0.08	0.15	none	none
Chill cast	.....	64	66	14	16	17	19	1.75	2.25	0.08	0.15	none	none
Die cast	B 102	64	66	14	16	17	19	1.5	2.5	0.08	0.15	0.01	0.01

92 Sn – 8 Zn

A *1 Common name.* **Tin Foil**
B *1 Typical uses.* Foil for packaging food products
D *2 Solidus temperature.* 199 C (390 F)
16 Thermal conductivity 0 to 200 C (32 to 392 F). 0.14 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 14.2%
2 Electrical resistivity. 12.1 microhm-cm
I *2 Resistance to specific agents.* Immersion and bottle-capping tests with milk showed that this alloy is only slightly soluble and has no effect on the milk.[2]
K *Mechanical properties.* Foil: tensile strength 8700 psi; yield strength 6000 psi; elongation 40%. Bending properties are important in connection with the use of foil. Chalmers and Seddon[1] have investigated the force-deformation-time characteristics of various foils using static and dynamic bend tests in an attempt to determine the stiffness. Reference should be made to their paper for details of these tests.
N *Working data.* Rolled to foil satisfactorily.

References

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92 Sn – 8 Sb

A *1 Common name.* **White Metal**
B *1 Typical uses.* Castings for costume jewelry.
D *2 Solidus temperature.* 246 C (475 F)
E *1 Volume conductivity* referred to standard copper. 11.1%
2 Electrical resistivity at 25 C (77 F). 15.48 microhm-cm
K *Mechanical properties.*

Form and Condition	Section, in.	Tensile Strength, psi	Elongation, percentage	Brinell Hardness Number	Izod, ft-lb	Shear Strength, psi
Chill cast, tested 2 months after casting	2 by ½	7200	....	20	..	..
Chill cast, annealed at 225 C	2 by ½	6500	50	17	..	..
Cast	....	....	....	..	22	6700
Annealed sheet	0.1	6700	70 (2 in.)	..	..	..
Sheet, quenched from 220 C	0.1	7400	28 (2 in.)	..	..	..
Sheet, aged 150 C	0.1	8800	28 (2 in.)	..	..	..
Wire, extruded	0.14	8500	63	..	..	..
Wire, extruded, and annealed 24 hr at 225 C	0.14	7800	10	..	..	..

Effect of rolling on hardness. The alloy hardens at first on cold rolling; the maximum hardness is reached at a reduction of about 40 to 45%. Further working causes progressive softening until at about 80% reduction, the hardness approaches that of the cast alloy. Annealing at 200 to 225 C (392 to 437 F) causes the severely worked alloy to harden slightly.
6 Creep tests. Creep tests[4] conducted at room temperatures [9 to 27 C (48 to 81 F)] on rolled material (0.1 in. thick), yielded the following results:

Stress, psi	1400	1200	1100	1000	900	800	600	400
Time, days	19	54	71	155	198	360	339[a]	337[a]
Final extension, %	66	54	37	42	49	98	4.12[a]	1.06[a]

(a) These specimens did not fracture.

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1 D. Hanson and W. T. Pell-Walpole, A Study of the Mechanical Properties of Tin-Rich Antimony-Tin Alloys, J Inst Metals, 63, 87 (1938)
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3 "Mechanical Properties of Metals and Alloys", Nat Bur Standards Circular C 447, 1943
4 D. Hanson and E. J. Sandford, The Creep of Tin and Tin Alloys, Part I, Tech Pub International Tin Research Development Council, Series A, No. ■ (1936)

91 Sn – 7 Sb – 2 Cu

A *1 Common name.* **Pewter, Britannia Metal**
Pewter consists essentially of tin hardened by the addition of antimony and copper. Although a wide range of compositions has been called pewter, the usual modern alloys contain from 90 to 95% Sn, 1 to 3% Cu and the remainder antimony. Britannia metal, so called because it was first made in Great Britain, contains from 91 to 92% Sn. Although some pewter contains lead as an alloying constituent, a considerable portion of lead is undesirable in containers for foods. Lead also may impart a dullness to the ware.
B *1 Typical uses.* Vases, candlesticks, tea and coffee services and book ends.
D *1 Liquidus temperature.* 295 C (563 F)
2 Solidus temperature. 244 C (471 F)
I *1 General resistance to corrosion.* Hoar[1] found that pewter tarnishes in soft water with the production of a visible film of interference-tint thickness. In hard water there was no tarnishing, but localized attack at the water line and sometimes elsewhere occurred if a chalky deposit was formed from the water. Pewter is attacked by dilute hydrochloric and citric acids in the presence of air.
K *Mechanical properties.* See Table I.
Erichsen value, depth in mm: annealed, 9.6; cold rolled to 32% reduction, 11.6
N *2 Working data.* Plaster-of-Paris molds are used if only one casting is required.[4] Bronze is generally used for permanent molds. The permanent mold is heated to the same temperature as the pewter. Hollow objects may be made by using bronze cores, or by slush casting.
11 Suited to forming by rolling, hammering or spinning.
17 Joining. Pewter is readily soldered. Suitable solders[5] are: 50% Sn, 25% Pb, 25% Cd; 50% Sn, 25% Sb, 25% Cd; and 45% Sn, 27.5% Pb, 27.5 Bi.

Table I. Mechanical Properties of Pewter

Form and Condition	Section, in.	Tensile Strength, psi	Elongation in 2 in., percentage	Brinell Hardness Number	Modulus of Elasticity, psi
Chill cast	0.75	....	..	23.8	7,700,000
Sheet, annealed 1 hr at 400 F, air cooled[2,3]	0.241	8600	40	9.5	.....
Sheet, cold rolled 32% reduction	0.241	7600	50	8.0	.....

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3 B. Egeberg and A. B. Smith, Effect of Heat Treatment on Properties and Microstructure of Britannia Metal, Trans AIME, Inst Metals Div, 490 (1930)
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ZINC AND ZINC ALLOYS

Prepared under the chairmanship of

E. H. KELTON

The New Jersey Zinc Company (of Pa.)

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The Zinc Industry

BY R. K. WARING*

THE principal ores of zinc are the sulfide, blende; the silicate, willemite; and the oxides, franklinite and zincite. The sulfide is the most widely distributed and is today the principal source of zinc. Sulfide deposits of commercial importance occur in many parts of the world. Large deposits of willemite and franklinite have been found only in New Jersey.

Manufacture.[1] The sulfide ore is first concentrated, usually by flotation. The concentrate is roasted in the presence of air, yielding zinc oxide and sulfur dioxide, which is usually converted to sulfuric acid.

Several processes are in use for producing metallic zinc from the roasted ore. The oldest is the horizontal retort process, developed in Belgium about 1806 and first used in the United States in 1859, at Bethlehem, Pa. In this process, ore mixed with coal is charged by hand into small horizontal retorts that are heated from the outside. The temperature necessary to reduce the zinc oxide to metallic zinc is above the boiling point of zinc, thus producing zinc vapor. Each retort has a condenser attached to it in which the vapor condenses. The molten zinc is tapped at intervals. When a large part of the zinc has been reduced, the charge is removed. A complete cycle usually takes 24 hours.

In recent years a new process has been developed in which the ore and coal are briquetted and charged into large vertical retorts, built of refractories with good heat conductivity and heated externally by gas. The charge moves continuously down through the retort and the zinc vapor passes in a continuous stream into a condenser. In another type of process using a vertical retort, the heating is done internally by passage of electric current through the charge.

The third commercially important method of producing zinc is by the electrolytic process, in which the roasted ore is dissolved in sulfuric acid. The resulting zinc sulfate solution is purified and the zinc is plated out by electrolysis. Very careful control of the purity of the solution is essential to successful operation.

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In the retort process, the purity of the product depends largely on the impurities in the ore, and can be controlled to a limited extent by the initial removal of objectionable impurities from the ore. In order to produce zinc of the high purity required for some purposes, a refining process has been developed recently in which the impure zinc is subjected to fractional distillation in a rectifying column. A large tonnage of zinc that has a purity of 99.99+% is now produced by this process. Zinc of similar purity is also produced by an electrolytic process, in which the high purity is attained by chemical purification of the zinc sulfate electrolyte.

Grades. The recognized commercial grades of zinc in the United States have been specified by the American Society for Testing Materials,[2] as follows:

Grade	Composition, max %				
	Pb	Fe	Cd	Al	Sum of Pb,Fe,Cd
(1a) Special High Grade	0.006	0.005	0.004	none	0.010
(1) High Grade	0.07	0.02	0.07	none	0.10
(2) Intermediate	0.20	0.03	0.50	none	0.50
(3) Brass Special	0.60	0.03	0.50	none	1.0
(4) Selected	0.80	0.04	0.75	none	1.25
(5) Prime Western	1.60	0.08	...	...	...

The amount and kind of impurities in the metal have an important influence on the physical and chemical properties of zinc and zinc alloys.

Uses. The consumption of zinc in the United States during 1946 is given in Table I,[3] according to uses.

Galvanizing, which constitutes the largest use of zinc, is done either by dipping the iron in molten zinc or by electroplating. Hot dip galvanizing employs chiefly the less pure grades of zinc. For some applications, such as wire, which must stand bending without flaking of the coating, High Grade or Special High Grade zinc is used. In electrogalvanizing, the zinc may be obtained either from zinc anodes or by direct solution from ore and subsequent purification of the electrolyte. High Grade and Special High Grade zinc are used to a large extent for anodes in the method mentioned first. The life of gal-

vanized material is proportional to the thickness of the coating and recent developments in both electrogalvanizing and hot dip galvanizing have been toward the application of heavy coatings that will withstand deformation without peeling. See the article "Zinc Coatings", page 712.

Table I. Consumption of Zinc in the United States, 1946

Purpose		Tons
Galvanizing (total)		319,189
Sheets	113,760	
Tubes	61,449	
Wire	43,829	
Wire cloth	100,151	
Shapes		
Brass making		147,355
Die castings		205,353
Rolled zinc		92,294
Other purposes		26,213
Total		790,404

All grades of zinc are used to some extent in brass. The grade used has considerable influence on the properties of the brass. The manufacture, properties and use of brass are discussed in the COPPER SECTION of this Handbook.

All grades of zinc are used for rolling. In general, the presence of natural impurities or added metals increases the hardness and stiffness of rolled zinc. Special combinations of lead, iron and cadmium are used to control the chemical characteristics of zinc for dry batteries and photoengraving. Rolled zinc is discussed in greater detail in the article "Working of Zinc and Zinc Alloys", page 1082.

The use of zinc-base alloys for die casting has become important in recent years and is increasing rapidly; for this work, it is essential to use Special High Grade zinc. Zinc die castings are discussed in the next article.

Other forms of zinc include zinc oxide and zinc sulfide, widely used in paint and rubber, and zinc dust, used as a pigment in priming paints for metal and as a reducing agent in chemical processes.

References

1 Metallurgy of Lead and Zinc, Trans AIME, 121 (1936)
2 ASTM Standard Specifications for Slab Zinc (Spelter) (B 6-46)
3 Yearbook of the American Bureau of Metal Statistics, 1946, p 64

Casting and Production of Zinc Alloys

BY G. L. WERLEY*

IN the production of zinc alloy castings, the process of die casting is most widely used. Sand casting is employed for producing stamping dies from zinc-base alloys and certain articles are made by slush casting or by the use of permanent molds. Because it is generally more important, die casting is discussed here in considerably greater detail than is gravity casting.

Die Casting

Process. Die casting is the art of producing accurately dimensioned castings repeatedly by forcing molten metal under pressure into metal dies.

The die-casting machine consists of a melting pot, a means for forcing the alloy into the die, and a mechanism for opening, closing and locking the die. When the melting pot is an integral part of the die-casting machine,

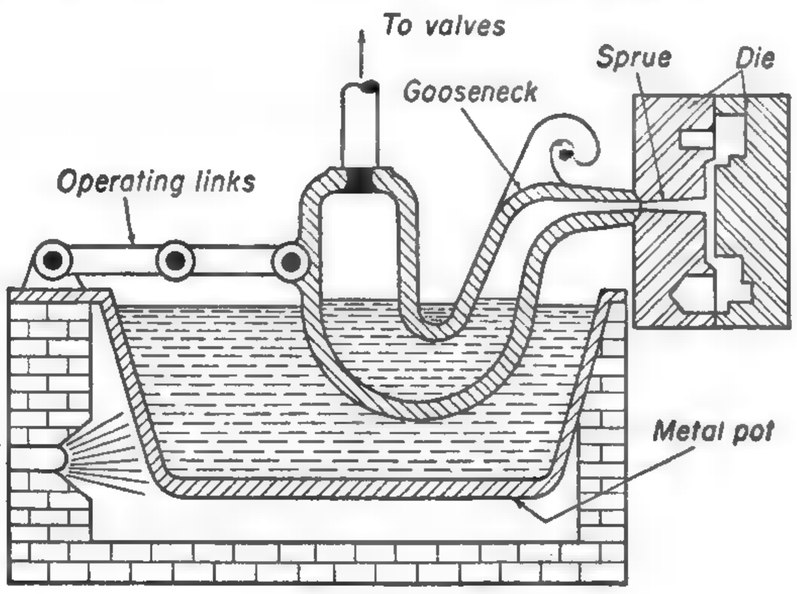

Fig. 1 Diagram showing arrangement of an air-injection machine that has a horizontal nozzle in position for filling a die by air pressure without a plunger

the injection cylinder automatically fills with alloy prior to each cast, regardless of whether the machine is designed for direct operation of air pressure on the metal (air gooseneck machine, Fig. 1) or for air or liquid operation of a plunger (plunger machine, Fig. 2). In another type, known as a "cold chamber" machine (Fig. 3) the melting furnace is a separate unit from which the alloy must be ladled into the cold pressure chamber prior to each operation (shot) of the machine, unless the equipment includes an automatic feeding device.

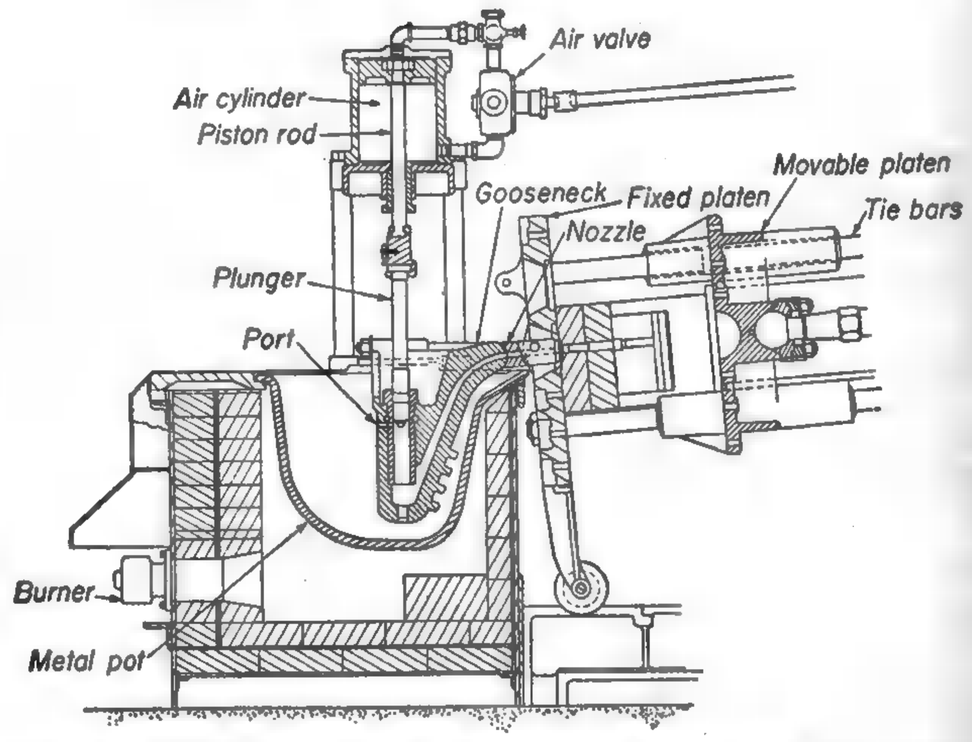

Fig. 2 Portion of a modern machine for die casting zinc alloy, showing a vertical plunger arranged for air operation

The zinc die-casting alloys can be cast in all three types of machines, but economical practice dictates the use of the plunger type.

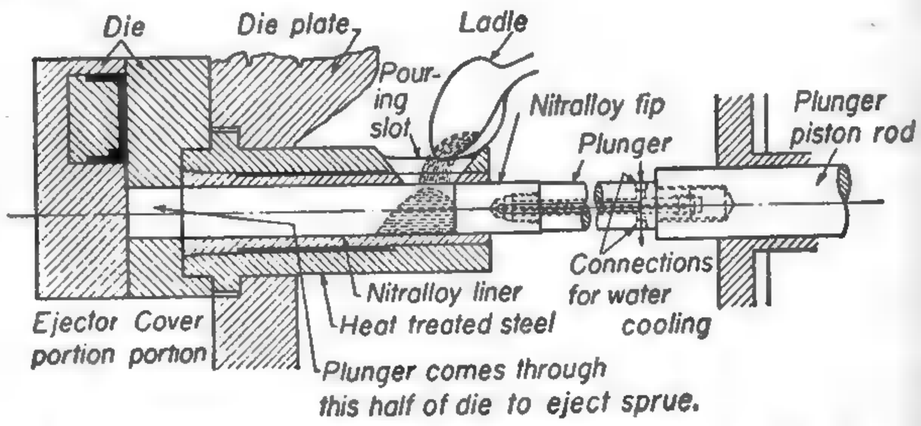

Fig. 3 Sectioned diagram showing the die, cold chamber, and horizontal plunger (in charging position) of a modern cold chamber type of die-casting machine

Alloys. The zinc alloys are low in cost of metal per casting, are easy to die cast, are cast at low temperatures,

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have strengths greater than all but the copper alloys, lend themselves to casting within close dimensional limits, permit the thinnest sections yet produced, and are machined at a minimum cost. Resistance to surface corrosion is adequate for a wide range of applications. Prolonged contact with moisture results in the formation of white corrosion products, but surface treatments can be applied that will prevent the formation of such products to a great extent. There are three standard zinc alloys for die casting. Specifications for these alloys have been adopted by the American Society for Testing Materials (Alloys XXI, XXIII and XXV) and by the Society of Automotive Engineers (Alloys 921, 903 and 925, respectively). *See* Table I. Only two of these alloys (ASTM XXIII and XXV or SAE 903 and 925) are in common use.

Table I
Designation and Composition of Zinc Die-Casting Alloys

	Designation		
ASTM Number	XXI	XXIII	XXV
Government Number	.....	QQ-Z-363	QQ-Z-363
SAE Number	921	903	925
Trade Name	Zamak-2	Zamak-3	Zamak-5
Foreign Equivalents	Mazak-2, Gomak-2	Mazak-3, Gomak-3	Mazak-5, Gomak-5
	Composition, percentage		
Aluminum	3.5 to 4.5	3.5 to 4.3	3.5 to 4.3
Copper	2.5 to 3.5	0.1 max	0.75 to 1.25
Magnesium	0.02 to 0.10	0.03 to 0.08	0.03 to 0.08
Lead, maximum	0.007	0.007	0.007
Cadmium, maximum	0.005	0.005	0.005
Tin, maximum	0.005	0.005	0.005
Iron, maximum	0.100	0.100	0.100
Zinc (Special High Grade)	Remainder	Remainder	Remainder

ASTM Alloys XXIII and XXV are alike in chemical composition except that XXIII is free from copper while XXV contains 1% Cu. Both alloys are quite similar in properties and can be used interchangeably.

Alloying. The use of virgin metals is always desirable in the manufacture of the zinc die-casting alloys, in order to meet the prescribed limits of composition, although secondary materials are equally satisfactory if they are of uniform and suitable composition.

The equipment required for the manufacture of the zinc alloys consists of cast-iron melting pots, a small refractory pot for melting the copper-aluminum hardener, instruments for recording temperature, scales, pouring ladles, skimmers and molds. Three alloying pots are desirable so that virgin alloy can be held in one until it has been analyzed, while the next heat of alloy is being prepared in the second pot. The third pot is used exclusively for the remelting of sprues and rejected castings.

It is advisable to prepare alloys on a 24-hr basis, since this not only increases the hourly output of the plant but decreases the overhead and increases the life of both the refractory and the iron pots. The following is an ideal alloying practice for ASTM XXIII, assuming the use of a 2000-lb pot: For the first cycle, 500 lb of Special High Grade zinc is placed in the cast-iron pot. When the molten zinc reaches a temperature of about 500 C (932 F), 75¼ lb of ingot aluminum is stirred into the melt. After all the aluminum has dissolved, the remainder of the Special High Grade zinc charge (1259 lb) is added. When the temperature again reaches 475 C, the pot is skimmed and 3/4 lb Mg is added. The magnesium, having a specific gravity of only 1.74, must be held under the surface to prevent loss by oxidation. The melt should be stirred thoroughly after the magnesium is added; then the skimmings should be carefully removed again. The skimmings are iron-aluminum compounds of low density, together with some products of oxidation that will eventually rise to the surface. Inadequate skimming is responsible for the appearance of some surface defects, such as hard spots in the die castings. The use of a flux is not advised because it removes the magnesium from the alloy. After the alloy has been skimmed, it is ready for transfer to the pouring ladles. When the ladles are filled with about 50% of the alloy from the pot, they can be pushed aside and poured as soon as the second cycle of alloying has been started.

The second cycle of alloying is started by adding 37½ lb Al to the heel in the alloying pot. After the aluminum has dissolved, 877 lb of Special High Grade zinc is added. When the alloy reaches 475 C, the melt is thoroughly skimmed and 6 oz Mg is added. Again after thorough stirring and skimming, the melt is ready to be poured in preparation for the next alloying cycle.

The procedure for preparing ASTM XXV is identical with that described above for ASTM XXIII, except that all the alloying ingredients are added at one time, as a molten alloy hardener, to the heel in the alloying pot. The hardener—80% Al, 0.8% Mg, with the remainder copper—is melted and kept molten in a refractory crucible.

Die Casting. The temperature of the metal in the die-casting pot should never exceed 425 C, because coarse-grained castings of low shock resistance will result. The preferred range is 390 to 415 C, and many companies operate successfully within the still narrower limits of 390 to 405 C. Supplying liquid alloy to the die-casting machines eliminates a remelting cost, but it is more important that enough alloy can be supplied in this manner to keep die-casting machines operating uninterruptedly and with the metal temperature more closely controlled.

While there is a preferred range of temperatures for the dies used in producing die castings with the best surface finish, soundness and mechanical properties, few die casters use equipment to control the temperature accurately. Although such control is desirable in order to keep the number of rejected castings at a minimum, it is not an absolute requirement, because run marks appear on the castings when the die temperature is too low, and pits, blisters and similar surface blemishes develop at excessive die temperatures. A good range of temperatures for dies is 150 to 220 C.

Aside from the temperatures of metal and dies, the third major factor in the production of die castings is the pressure applied on the metal. The pressure should not be less than 1500 psi. Lower pressures will result in some porosity in the castings. Higher pressures are advantageous at times, but generally there is little to be gained by using pressures above 2500 psi. The velocity with which the metal enters the die is controlled by the pressure and the die design. The optimum velocity may differ for each casting and the only way it can be determined is by trial and error.

Inspection and Control. Inspection in the die-casting plant is usually confined to a visual examination of each casting for surface finish, disfiguring flaws and cracks; and to such gaging as may be needed to insure that the dimensions are within the required limits. Since there are no well-established standards for surface smoothness, the usual practice is for the die caster to submit sample castings which, if satisfactory, serve as reference standards for future shipments.

At present it is becoming general practice to analyze chemically each lot of alloy, to conduct some mechanical tests and to X-ray castings made in new dies until, by die changes, the porosity in critical sections has been climinated.

Important dimensions are usually checked and approved by the customer when the die is first put into service. Thereafter, dimensions are unlikely to change significantly unless some part of the die is subject to unusual wear or must be replaced.

Stabilization. Aging changes produce a maximum shrinkage of 0.0007 in. per in. for ASTM Alloy XXIII and 0.0009 in. per in. for ASTM Alloy XXV. About two thirds of the shrinkage occurs in 4 to 5 weeks; the remainder takes place over a period of years. Since these changes can be accelerated by annealing treatments at low temperatures, it is customary to use one of the following heat treatments when castings are required to maintain rigid dimension tolerances: (*a*) 3 to 6 hr at 100 C, (*b*) 5 to 10 hr at 85 C, (*c*) 10 to 20 hr at 70 C.

Castings given one of the above treatments will show an additional shrinkage, on aging, which is equal to about one third of that which occurs on untreated castings.

Assembly. All die castings have at least a light flash at the die parting, and those requiring movable cores will have some flash around the cores. Flash is also formed around ejector pins at the points at which they make

contact with the casting. The most common method of removing flash at the die parting is to force a shaving die over the casting. Flash in holes is usually removed by close-fitting punches. Other flash removal is effected generally by filing, grinding or using other cutting tools. Castings that are to be plated and must therefore be made unusually smooth often require grinding and polishing at the parting line, and sometimes on other surfaces.

Although it is often cheaper to cut threads than to cast them, in many pieces making a cast thread is more economical. Male threads are usually made with a parting parallel to the axis; this leaves a flash at the parting. The flash can be removed with a shaving tool in some instances, but in others it is necessary to perform a chasing operation.

Zinc die castings are invariably cast within quite close dimensional limits, but some machining is commonly required in addition to removal of flash, even though it may consist only of such simple operations as punching, drilling, reaming or tapping of holes. However, in general, only very light cuts are required, and the work can always be done at high speeds because of the excellent machining qualities of these alloys.

Zinc die castings can be soldered or welded, but ordinarily neither process is used except in special assembly applications or in repair work.

Soldered joints have low strength. Soldering with the usual soft solder is possible only on nickel-plated surfaces. A more satisfactory procedure is to use a soldering alloy of 82.5% Cd and 17.5% Zn, applied without a flux.

Flame welding is best done by means of a reducing flame and welding rods made from the same alloy as the die casting. Since zinc die castings have a low melting point, the flame must be held almost parallel to the casting.

In recent years, a pulsation welding technique has been developed to a point where it may be used in assembly work.

Finishing. Many of the finishes applied to other types of metal products can be applied also to die castings, although some differences in formulation are desirable, as well as occasional differences in the method of application. The types of finishes applicable to zinc die castings are as follows: (1) mechanical — buffing, polishing, brushing and tumbling; (2) electrodeposited — copper, nickel, chromium, brass, silver, and black nickel; (3) chemical — chromate, phosphate, molybdate, and black nickel; (4) organic — enamel, lacquer, paint, and varnish; (5) plastic.

Mechanical Finishes. Zinc die castings can be given mechanical finishes rather easily but, unless the surface is protected, tarnishing will occur more quickly and be more noticeable than on untreated parts. For this reason, mechanical finishes are seldom used on zinc die castings, except as a preparatory step for other types of finishes.

Electrodeposited Coatings. While virtually all metals capable of electrodeposition can be applied to zinc die castings, coatings of nickel, or of copper and nickel, finished with a thin layer of chromium, are used on a very large scale. Plated coatings are most commonly applied for decorative purposes, but they also improve resistance to corrosion and to abrasion. For increasing such resistance, direct chromium deposits are generally applied, 0.0002 in. or more in thickness. All plated coatings are somewhat porous, and when moisture penetrates through the pores, some corrosion of the base metal usually results. If the plated coatings are too thin, this corrosion will destroy the appearance in a short time; therefore the satisfaction and useful life to be expected from such coatings depends on the thickness of the deposit and the method of application. The American Society for Testing Materials has adopted specifications covering three classes of commercial coatings for zinc die-casting alloys; namely, for mild, ordinary, and severe exposures.

Chemical Treatments. Although chemical treatments sometimes take the place of other applied finishes, they are more often applied as a base for enamels and lacquers. Certain treatments are used alone as a means for inhibiting corrosion.

Organic Finishes. A great many organic finishes are available, each offering some particular advantage, such as color, hardness, gloss, adhesion and weathering. Since improvements in formulation are constantly being made, it is best to select a finish for a particular purpose by consultation with an experienced manufacturer of finishes.

Most modern finishes are baked for greater durability and adhesion. When finishes are baked on zinc alloy die castings, the properties of the castings may be adversely affected, if the castings are heated for more than 1/2 hr at 220 C; 1 hr at 190 C; 2 hr at 165 C; or 3 hr at 150 C. If the casting is copper-nickel-chromium-plated and then given a baked finish, the maximum temperature that can be used without blistering is 125 C.

Plastic Finishes. Some die castings, especially hardware for the interior of automobiles, radio grilles and instrument panels, have been used in large quantities with plastic finishes. Such finishes are often applied by repeated dipping into nitrocellulose or ethyl cellulose solutions, or by spraying with either type of solution. These finishes are several times as thick as other organic coatings and differ from similar base lacquers not only in thickness but in composition. Another type of finish is an injection molding of cellulose-acetate or acetate-butyrate plastics over a die-cast core. This gives the appearance of plastic molding but is combined with the strength of the die-cast core.

Application. Zinc die castings are used chiefly in the following applications:

Automotive Industry. The automotive industry uses by far the largest number of die castings. Some of the most important die castings for mechanical parts made of zinc alloy include the carbureter, bodies for fuel pumps, parts for windshield wipers, speedometer frames, horns, heaters, and parts for hydraulic brakes. Parts that perform both structural and decorative functions include grilles for radiators and radios, lamp and instrument bezels, hubs for steering-wheels, brackets, horn rings, exterior and interior hardware, instrument panels and body molding.

Electrical Industry. In the electrical industry, there is probably a larger diversity of die castings than in the automotive industry, because of the range of different products manufactured. Die castings are employed for numerous parts of washing machines, oil burners, stokers, motor housings, vacuum cleaners, electric clocks, kitchen equipment and utensils.

Business Machines and Other Light Machines. Die castings are used successfully in business machines and light machines of all types; for example, in typewriters, recording machines, picture projectors, vending machines, accounting machines, cash registers, cameras, slicing machines, garbage disposers, gasoline pumps, hoists and drink mixers.

Tools. Increasing quantities of tools are being made with die-cast parts. The die castings are not hard enough to serve as cutters, but steel elements are often cast in place as parts of the tools, thus saving appreciable assembly costs. Die castings are not limited to portable tools but are also used on such large equipment as drill presses and lathes.

Building Hardware, Padlocks, Toys and Novelties. These items constitute the other major uses of die castings. They consume about 10 to 20% of the total production of die castings made of zinc alloy.

Corrosion Resistance. The resistance of zinc die castings to atmospheric corrosion is similar to that of rolled zinc and galvanized iron.

In applications where die castings are used in recirculated water lines, the addition of 0.1 to 0.3% of sodium dichromate or of 1% of borax to the water greatly reduces the corrosion rate of the die castings. In general, the attack of water on zinc castings reaches a minimum under mildly alkaline conditions.

The use of zinc die castings in continuous contact with steam is not recommended; but with hot water, as in plumbing hardware, their use is satisfactory, if inserts are used on critical parts in contact with the water.

The corrosion of zinc die castings, as a result of contact with various other liquids, gases or solids, does not follow any general rules, and individual service trials are usually necessary.

Engineering Design. Engineering design involves two problems, namely, the design of the die and the design of the castings. Since the manufacturer of the castings is responsible for the design of the die and also should be consulted on the design of the casting, the following discussion of this subject is intended merely to list some of the necessary considerations rather than to explain them.

Die Design. In die design, after the parting line and the general die construction have been planned, it is highly important to gate and vent the casting cavity properly. The gates and vents, as thick as can be tolerated, must be placed at their proper positions. In addition, large overflow wells should be connected to the cavity at the vent end of the die and at other points where there is a likelihood of trapping air. Since the loss of metal is small during the remelting of overflow wells, the cost of such wells is small, considering the improved quality. In most instances a saving actually results, because overflow wells accomplish a vast reduction in the percentage of rejected castings. Gates, vents, and overflow wells, considered collectively, have more influence than any other factor in the production of uniform high strength, good surface finish and soundness in die castings.

Design of Die Castings. The rules for designing die castings have many exceptions, but the following principles generally assist in arriving at a design that is both rational and helpful in attaining low cost: (1) Keep sections at a minimum thickness and use ribs for strengthening purposes where necessary. Make a gradual transition when section thicknesses vary. Use cores to keep sections uniform and fillets to avoid sharp corners. (2) Cast studs or bosses for economical fastening aids. Bosses are stronger than threaded studs. (3) Avoid plain flat surfaces when such areas must be cast smooth for finishing purposes. (4) Allow ample drafts on cavity walls and on cores, and never specify closer tolerances than are essential. (5) Employ inserts whenever their use attains results that cannot be realized at equal cost by other means. (6) Take advantage of the ductility of zinc alloys by designing parts for bending or forming after casting.

In designing zinc alloy die castings to withstand constant loads, it must be borne in mind that these alloys do not have recognized elastic moduli or yield strengths. Hence, standard engineering formulas used in calculating cross sections of elastic materials cannot be used for zinc alloys. However, data developed from creep tests have been compiled and may be applied with satisfactory results. See "Creep Data on Die-Cast Zinc Alloy", Trans AIME, **161**, 466 (1945).

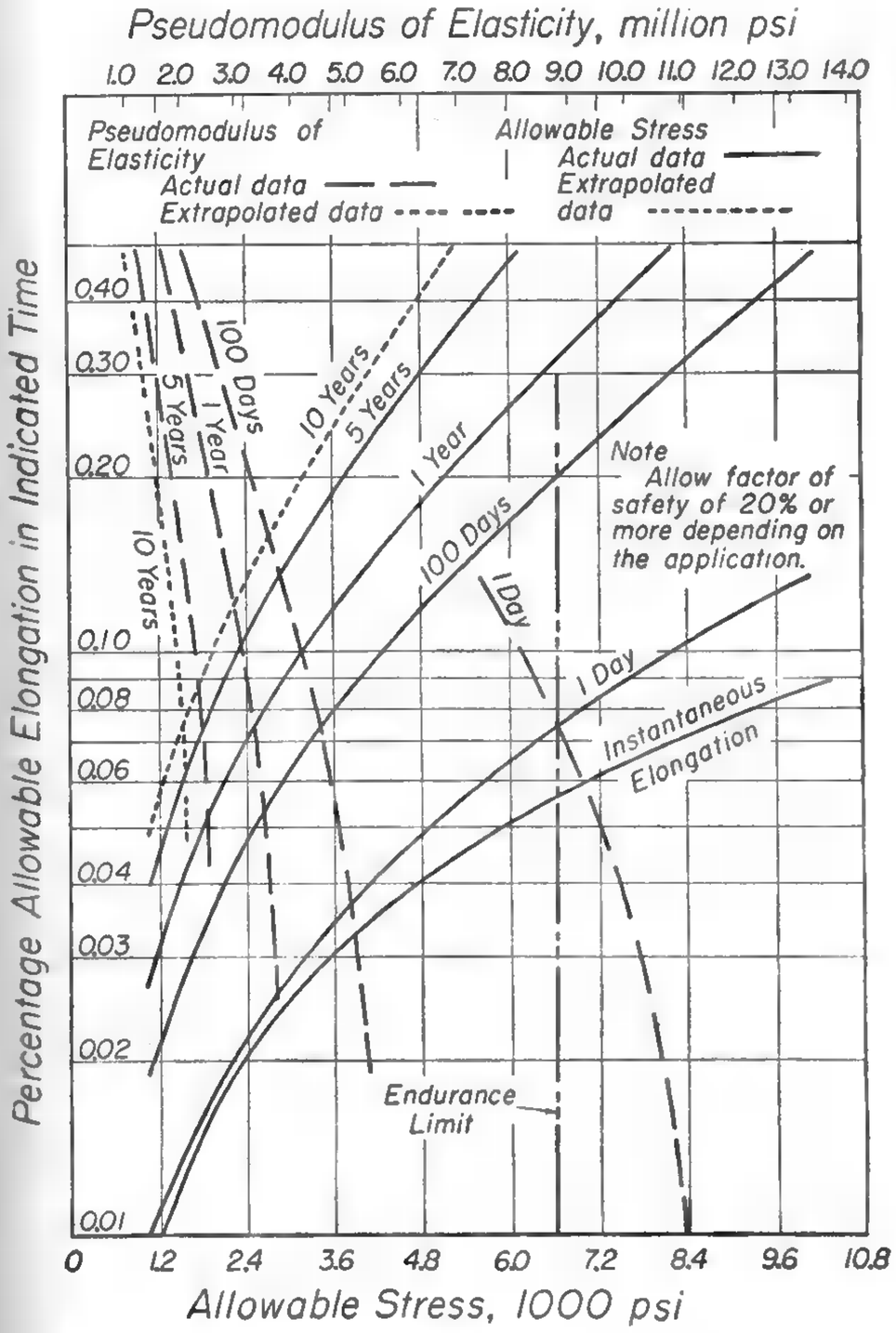

Fig. 4 Transverse creep characteristics of alloys XXIII and XXV at 25 C

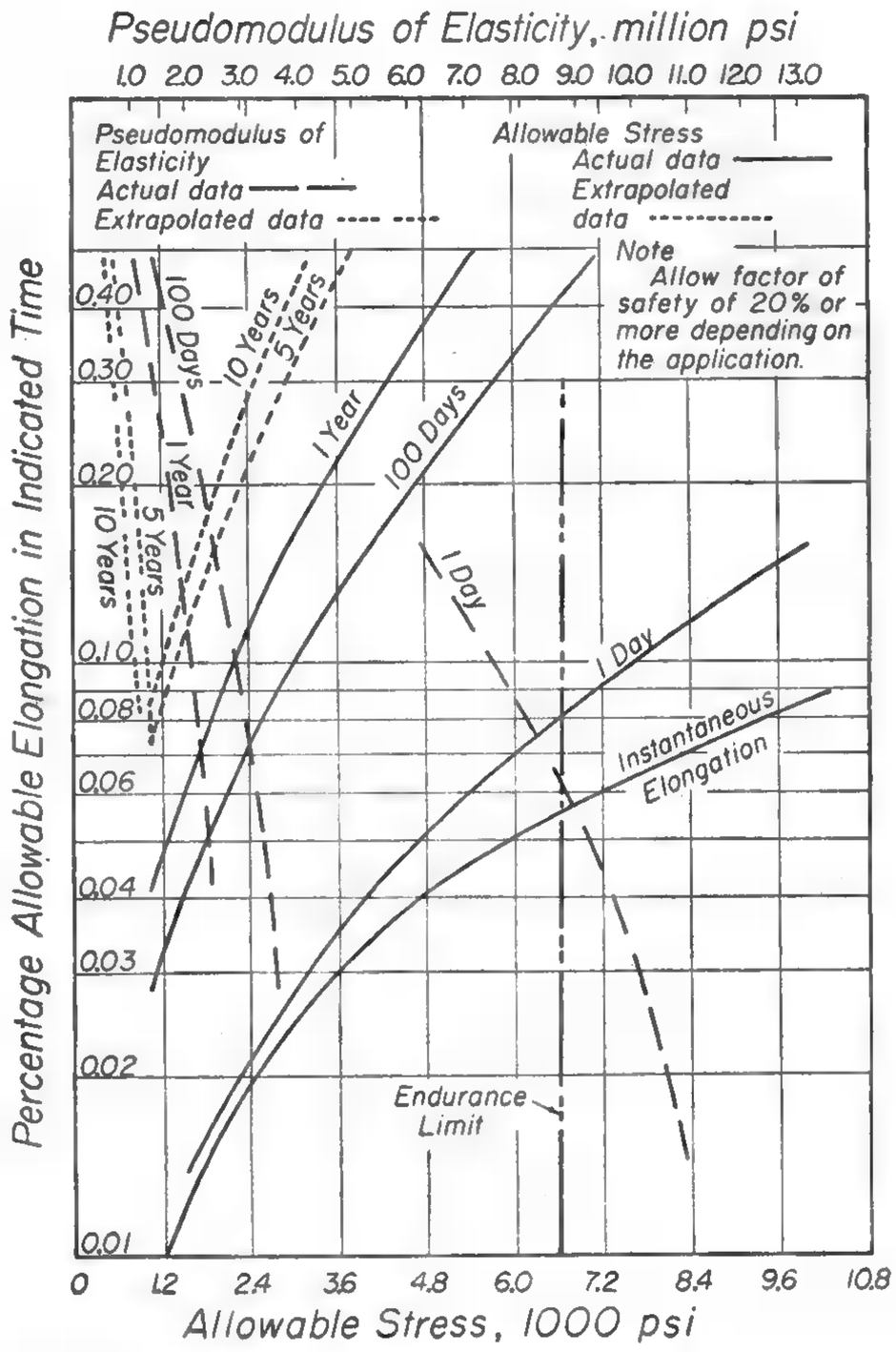

Fig. 5 Tension creep characteristics of alloys XXIII and XXV at 25 C

The creep characteristics of zinc die-casting alloys subjected to constant transverse loads may be calculated from the graph shown in Fig. 4. The method of using this graph follows. Determine the percentage of elongation that is permissible in the particular beam member in some definite period of time — for instance, 5 years.

In applications involving beams, the following approximate formulas have been found useful in determining the relations between the deflection and the elongation in the outer fiber of such members:

(1) For cantilever beams $e = \frac{150dt}{L^2}$

(2) For simple beams (concentrated load) $e = \frac{600dt}{L^2}$

where e = percentage of elongation in outer fiber of the beam
d = deflection of the beam, inches
t = thickness of the beam, inches
L = length of the beam, inches

Find this percentage of elongation on the ordinate and move across the chart horizontally until the chosen time curve is intercepted. From this point, move vertically down to the abscissa, which will indicate the permissible stress. For ordinary applications, a factor of safety of 20% is usually applied. Thus, if the permissible stress for the particular application is 2500 lb, the cross section would be designed to yield a stress of not more than 2000 lb.

The graph also shows curves of pseudomodulus. These are not true elastic moduli but the instantaneous moduli calculated from the stress-strain curves of Fig. 4 at any particular time. These values have been found useful in engineering calculations. They may be employed in standard engineering formulas instead of the true modulus, provided it is understood that the value applies only for one particular load and one particular time at the temperature specified.

Figure 4 contains a curve labeled "instantaneous elongation". This is simply the stretch that takes place immediately upon application of the load and is similar to "initial stretch" or "initial elongation", terms applied by other investigators. In this instance, the elongation is largely elastic and hence recoverable by unloading. Curves labeled "1 day", "100 days" and so on, include this "instantaneous elongation"; hence they show total deformation, part of which is elastic.

In the graph, the vertical line indicating the endurance limit is at 6600 psi. Thus, if the particular application involves cyclic loading, a working stress of 6600 psi should not be exceeded.

Zinc and zinc alloys are influenced in their creep properties by temperature. The degree of this effect may be estimated approximately by the following empirical formula derived from temperature studies:

$$S_T = \frac{(S_{25} \times 28)}{T}$$

where S_T = permissible stress at any temperature from 25 to 100 C
S_{25} = permissible stress at 25 C
T = given temperature in °C

Thus, it will be seen that for an increase of 31°C in temperature above 25 C, the permissible stress is reduced by about half. It may be noted that zinc alloy die castings are not suggested for uses involving continuous stress at temperatures above 100 C.

The chart in Fig. 4 deals only with deformation in bending. Similar data for tension stresses are shown in Fig. 5.

Gravity Casting

Stamping Dies, Uses, Alloys. Sand-cast stamping dies made from wooden or plaster patterns, for drop-hammer forming, are used in the fabrication of aluminum, magnesium, zinc, stainless steel and other sheet materials.

Unalloyed zinc was first used but later zinc alloys were found to be superior. The alloys with the greatest hardness and strength are the best.

ASTM Alloys XXI and XXV are the alloys used for drop-hammer work, and they produce from 10 to 50 times as many stampings as were obtained from unalloyed zinc.

Since many of these dies are now being stored for the manufacture of replacement parts, ASTM Alloy XXV with its greater dimensional stability may prove to be a more desirable alloy than XXI, even though slightly fewer stampings can be made before failure.

Slush and Permanent Mold Casting. The slush casting of zinc alloys is discussed in the article on page 741 in this Handbook. The same alloys are used for casting in permanent molds, and the process is similar to slush casting except that the mold is not inverted after filling, and hence the castings are solid instead of hollow.

Working of Zinc and Zinc Alloys

By E. H. Kelton*

WROUGHT zinc and zinc alloys may be obtained in the form of rolled strip and sheet, extruded rod and shapes, and drawn rod and wire. These metals have desirable resistance to corrosion for many types of service, and since the corrosion products that may form are white, other materials are not stained by them. Wrought zinc has chemical characteristics particularly adapted to certain uses, as in dry batteries and photoengraver's plate, and offers combinations of desirable physical and mechanical properties at relatively low cost. However, the wrought zincs have the characteristic of flowing under constant loads that are substantially less than the ultimate strengths; that is, wrought zincs do not have clearly defined elastic moduli, and hence creep data developed from service tests must be used in designing for strength and rigidity under conditions of continuous stress.

Virtually all commercial wrought zinc contains small amounts of natural impurities—mainly lead, iron and cadmium (*see* "The Zinc Industry", page 1077); commercial alloys may also contain additions of copper or aluminum, and sometimes smaller amounts of other elements.

Melting. When zinc is to be prepared in large quantities, it is usually melted in refractory-lined reverberatory furnaces heated with coal, gas or oil. Small quantities may be melted to advantage in low-frequency induction furnaces or in refractory crucibles. Melts should be held generally at 930 F or less to prevent loss by oxidation. No protective cover is required. Sal ammoniac is used frequently to reduce skimmings when scrap is being remelted.

Zinc alloys containing 0.5% Al or more may be melted in iron pots, since the aluminum content prevents rapid attack of the iron by molten zinc.

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Casting. Zinc is cast from bath temperatures that range between 840 and 930 F, depending on whether the metal is transferred directly from the melting pot to the mold or is transferred by means of an intermediate ladle. Zinc is usually cast into flat slabs, 1 to 4 in. thick and of convenient widths and lengths for rolling, or it is cast into billets of the size required for extrusion. Slab molds are generally of the open, book or tilting types made of cast iron. The molds should be kept smooth and clean to avoid cracking from hot shortness as a result of restricting the shrinkage. No dressing is needed for the mold. The temperature of the mold should be about 200 F when the metal is cast. Molten zinc must be poured smoothly to prevent inclusions of oxide film and, in open molds, the surface should be skimmed immediately after casting.

Rolling. Rolling-mill slabs should be preheated to about 400 F. Roughing should be started with a leveling pass of about 10%; after that, reductions may be increased according to the capacity of the mill. Slabs intended for strip are reduced by rolling longitudinally to a gage convenient for coiling—generally less than 1/10 in. In the production of sheet, slabs are rolled laterally until the desired width is obtained. Then the sheets are turned 90 deg and rolling is continued until a thickness is obtained that is two to four times the final gage. The temperature of the roughing rolls may vary from 150 F to about 300 F, depending on the continuity of rolling and whether or not a water stream is used to control the contour of the roll. A lubricant, such as machine oil or tallow, is applied during roughing.

Finish rolling of zinc strip varies widely, depending on the ultimate product desired. Strip is produced in widths as great as 20 in. and in thicknesses as small as 0.004 in. in regular mills. Foil 0.001 in. thick or less is produced in

special mills. For a bright surface combined with high ductility, finish rolling is performed hot; this requires that the rolls be held at temperatures ranging from approximately 250 to 300 F. Finish rolling may be started with either hot or cold coils, and finishing pass reductions will vary from 10 to 40%, depending on the structure desired and the particular flatness and gage required in the finished product.

Zinc sheet is produced by the pack-rolling method, in which as many as 30 rough rolled sheets are stacked together and rolled simultaneously. Packs must be "split" frequently, interchanging inner and outer sheets to equalize temperatures and reductions. In this type of rolling, reductions are light on each individual sheet and the temperature is low, so a cold worked product is obtained.

In finish rolling, a thin lubricant is used—ordinarily an oil that will not corrode zinc and will not oxidize readily itself. Machine oil and various types of vegetable oils are satisfactory.

Extrusion. Although it lacks a well-defined elastic modulus at low rates of deformation, zinc has a high apparent modulus under rapid deformation; consequently, extrusion pressures are higher than in most nonferrous materials. Ease of extrusion increases with temperature; hence billets for extrusion are usually heated to the maximum that will not cause hot shortness. This temperature will vary from 480 F to more than 570 F, depending on the composition. Speeds for extrusion of zinc are low compared with those for the brasses, because as the speed of extrusion increases, the temperature in the product rapidly increases to the point of hot shortness and cracking and crumbling may result. Because of the high temperature of extrusion, the ordinary zincs yield coarse, columnar structures and must be worked at lower temperatures to refine the grain size and to yield an ultimate product of good ductility. In the alloys containing about 4% Al and 0.04% Mg with or without copper, this grain-refining treatment is not necessary, since high temperatures do not result in the coarse structures described.

Drawing Rod and Wire. Rolled or extruded rod may be drawn to wire in operations quite similar to those used for other nonferrous metals. In the pure commercial grades of zinc or in the alloys similar in composition to the die-casting alloys, drawing operations can be carried out without intermediate annealing, but in the less pure commercial grades of zinc or in the alloys containing copper, intermediate anneals are desirable.

Fabrication. All severe fabricating operations on wrought zinc should be carried out at temperatures above 70 F. Warm, soapy water (made with a neutral soap to avoid staining) is the cheapest lubricant available and is as satisfactory as any.

The rolled zincs of the proper grade are readily drawn into a great variety of articles such as battery cups, eyelets, meter cases, novelties, flashlight reflectors and fruit-jar caps. Suitable grades of zinc are just as readily rolled or press-formed, stamped or spun, into items such as plates for addressing machines, buckles, ferrules, ornaments, nameplates, gaskets, weatherstripping or parts for lamps.

The 4% Al, 0.04% Mg alloy that contains as much as 3.5% Cu has been used widely in the aircraft industry, in the form of heavy rolled plate for dies employed in blanking aluminum alloy sheet and thin steel. Similar compositions are available as extruded rod, tubing and moldings.

The softer grades of wrought zinc are self-annealing at temperatures developed during fabricating; hence no annealing is required between operations. The harder grades work-harden somewhat and may require intermediate annealing. Temperatures slightly above 212 F are ordinarily sufficient for the usual commercial grades, and care must be taken not to raise the temperature much above the minimum required or to leave the article exposed to the annealing temperature for more than a few minutes; otherwise, coarse brittle structures will develop. In the 1% Cu alloys, annealing should be conducted between 350 and 400 F.

Classification. The classifications of wrought zinc used in Table I are arbitrary. The compositions shown are typical ones covering the range and do not necessarily include every variation found among the grades produced by the various companies. To accommodate special applications many producers supply special grades that are intermediate or perhaps quite different from those listed.

Mechanical Properties. It will be noted that among the specific uses listed for rolled zinc, few would ever require high strength under constant load. When zinc is employed for structural purposes, creep data developed from service tests must be applied in the design, and properties such as tensile strength and tensile elongation, ordinarily used in connection with structural materials, have little significance. The control tests—dynamic ductility, hardness, temper, and dynamic bend—permit comparison with other shipments of similar material and identify in a general way the type and the rolling treatment of samples of unknown history.

Table I. Classification of Wrought Zinc Alloys

Composition, percentage							Characteristics	Typical Uses
Pb	Fe	Cd	Cu	Mg	Al	Sn		
0.05 to 0.10	0.012 max	0.005 max	0.001 max	....	....	....	High ductility with low hardness and stiffness. Very little work-hardening possible.	Drawn battery cans, eyelets, fuse links, and a variety of articles drawn, formed and spun. Address plates, anodes for protection of underground pipe lines.
0.05 to 0.10	0.012 max	0.06	0.005 max	....	....	....	High ductility with low hardness. Can be work-hardened slightly.	Drawn battery cans, eyelets and grommets. Extruded battery cans. Address plates, laundry tags.
0.15 to 0.35	0.017 max	0.15 to 0.30	0.005 max	....	....	....	High hardness and stiffness. Uniform etching quality. Can be work-hardened.	Soldered battery cans, photoengraver's plate, lithographer's sheet, boiler and ship plates, weatherstrips.
0.05 to 0.10	0.012 max	0.005 max	0.85 to 1.25	....	....	....	High hardness and stiffness. Good ductility. Good creep resistance. Work-hardens easily.	Weatherstrips and drawn and formed articles requiring stiffness.
0.05 to 0.10	0.015 max	0.005 max	0.85 to 1.25	0.007 to 0.02	....	....	Maximum hardness, stiffness and creep resistance. Can be severely work-hardened.	Corrugated roofing. Flat or formed articles requiring maximum stiffness and strength.
0.15 to 0.35	0.014 to 0.025	0.15 to 0.30	0.005 max	0.005 to 0.025	....	....	High hardness. Can be baked without serious softening. Good etching characteristics.	Photoengraver's sheet
....	....	....	....	□ to 0.025	0.25 to 0.60	....	High hardness. Can be baked without serious softening. Good etching characteristics.	Photoengraver's sheet
0.007 max	0.10 max	0.007 max	0 to 3.5	0.02 to 0.10	3.5 to 4.5	0.005 max	High strength and hardness.	Shearing and forming dies. Extruded rod, tubing and molding.

Soldering and Welding. The ordinary grades of wrought zinc can be soldered easily by conventional methods. The usual precautions should be observed, regarding proper cleaning and fluxing, and care must be taken not to overheat the zinc to a point where it will melt. For information about the soldering of zinc alloys that contain aluminum, see "Casting and Production of Zinc Alloys", page 1078.

Pulsation welding technique may be used for joining zinc. Flame welding of zinc is an art and therefore is not used in production.

Machining. Wrought zinc is easily machined by standard methods and tools. However, if it should be necessary to machine zinc containing exceedingly coarse grains, the metal would require heating to the range between 160 and 210 F, in order to avoid cleavage of crystals.

Finishing. In general, the same methods are used for finishing wrought zinc and zinc alloys as are used for finishing zinc-base die castings. See "Casting and Production of Zinc Alloys", on page 1078. However, in bake-enameling, greater caution should be employed not to reach temperatures high enough to impair the mechanical properties. For this reason air-dried finishes are preferable.

The Use of Zinc for Cathodic Protection

By H. W. Wahlquist* and E. A. Anderson*

UNDER certain conditions zinc plates (anodes) are used for the cathodic protection of steel from corrosion in water or soil. The structures most frequently protected in this manner are underground pipe lines, hulls of ships, and boilers.

Underground Structures

Buried zinc anodes are being used increasingly for the cathodic protection of underground pipe lines from corrosion. The open-circuit or solution potential of zinc in ordinary soil is about minus 1.1 v measured to a copper sulfate half-cell electrode, which compares with a potential in the order of minus 0.6 v for the average unpolarized steel pipe line. The difference, or 0.5 v, is the driving voltage initially available to cause a flow of current when the two structures are tied together by a wire; this difference decreases to between 0.1 and 0.3 v when the pipe is polarized. The current discharges from the zinc anode to the soil, collects on the pipe line and returns to the anode through the connecting wire. The current discharged by the zinc into the soil corrodes the zinc, and the current collected by the pipe line prevents corrosion of the pipe. The action is similar to that which occurs in a short-circuited primary cell or battery where the current flows from the zinc anode through the electrolyte to the carbon cathode. In the circuit of cathodic protection the zinc is the anode, the pipe is the cathode, and the soil with dissolved salts is the electrolyte. The magnitude of the current from a given anode is governed chiefly by the resistivity of the soil and the polarizing characteristics of the pipe line, although factors such as the spacing and size of the anodes also influence the current.

Size of Anodes. Zinc anodes are used in various forms, such as bars, plates, rods and hollow cylinders. A commonly used plate is made of rolled zinc ½ in. thick, 3 in. wide, 3 to 5 ft long, and weighing 14 to 23 lb. Cast zinc rods 1⅜ in. in diam and 4 ft long, weighing 18 lb and equipped with a ¼-in. steel core, have been used extensively.

Backfill. In most soils it is necessary to provide a special backfill for the zinc anodes to prevent them from becoming passive. The condition of passivity may result from voltage polarization of the anode or from the formation of a corrosion product that has high resistance, frequently in the form of an impervious carbonate film. The tendency toward voltage polarization is increased by the presence of impurities in the zinc. Surrounding the anodes with a slurry of powdered gypsum and clay has been found effective in preventing anodes of high purity from becoming passive.

Output. The theoretical output of a zinc anode is 370 amp-hr per lb of metal consumed. The current efficiency of 99.9% pure Zn in a gypsum-clay backfill is about 90%, so an output of about 330 amp-hr per lb is realized in practice with that grade of zinc. This corresponds to a life of about 17 years for a 14-lb anode delivering a current of 30 milliamperes (Fig. 1).

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The section on Underground Structures was prepared by H. W. Wahlquist; the sections on Hull Plates and Boiler Plates, by E. A. Anderson.

Methods of Installation. *Uncoated or Bare Lines.* The methods of installation vary with the conditions and type of structure to be protected. In a long, electrically continuous pipe line without coating, usually referred to as a "bare line", anodes are distributed along the line in such a way that the potential of the soil surrounding the line will be raised and will result in fairly uniform collection of current. This method may be used in soils of either high or low resistance. Spacings of 10 ft between anodes and 5 ft between the anodes and the pipe are commonly used. For large pipes (more than 12 in. in diam) it is necessary in some soils to reduce the anode spacing to 5 ft in order to provide protection. The anodes are usually installed vertically in hand-augered holes 3 to 4 in. in diam and 6 to 8 ft deep. They are connected by a rubber-covered copper wire located in a trench about 18 in. deep; at intervals of 100 ft, connections are made from this wire to the pipe.

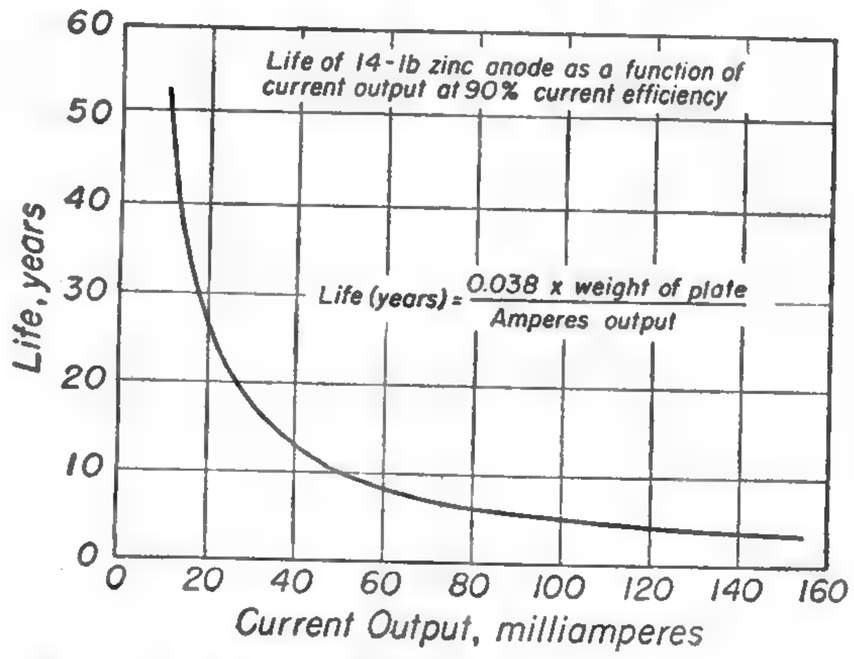

Fig. 1 Life of a 14-lb zinc anode as a function of current output at 90% current efficiency

Occasionally, where soil resistance is low, sufficient output of current is obtained to permit the installation of groups of anodes 10 ft or more from the line at intervals of 200 to 300 ft.

In other instances, corrosion may be confined chiefly to a few so-called "hot spots" or limited areas where corrosive soil exists, and the zinc requirements may be reduced by installing anodes in the corrosive areas only.

Coated Lines. For lines provided with a protective covering (coated lines), the current requirements are greatly reduced in comparison with those for bare lines, and the problem of cathodic protection is simplified. To realize the full advantages of the coating, however, it is essential to insulate the line to be protected from other underground structures that are metallically connected with the protected line. This is accomplished by using flanges, couplings or bushings of the insulating type. In this kind of installation, the zinc is usually installed in groups of 10 to 20 anodes. Where soil conditions are favorable, the holes may be drilled to a depth of 20 ft, with a stack of several anodes in each hole. The spacing between the groups may range

from a few hundred feet to several thousand feet, depending chiefly on the type and condition of the coating. The spacing to the pipe line is not significant for coated lines. It is usually advantageous to locate the groups at points where the soil is low in resistivity. Cathodic protection is obtained on these coated lines when the potential of the structure is increased to minus 0.85 v to a copper sulfate electrode.

Hull Plates

For many years zinc plates have been used to a considerable extent for the cathodic protection of the steel hulls of ships. The problem here is complicated by the presence of the bronze propeller, which is electropositive to the hull. In the absence of zinc hull plates, the steel acts as an anode to provide cathodic protection to the propeller, with the result that the normal corrosion of the steel is stimulated.

Zinc anodes, properly placed along the stern of the ship, provide the necessary cathodic protection. Depending on the current density which the potential differences can maintain against the resistances of the water and of the film produced by the corrosion of zinc, the propeller will be polarized to the potential of the hull or both the propeller and the hull will be polarized to the potential of the zinc.

If the propeller is polarized to the potential of the hull, the acceleration of the corrosion of the hull is eliminated and the steel corrodes at its normal rate. If both the propeller and the hull are polarized to the potential of the zinc, neither the propeller nor the hull will corrode. In spite of the widespread use of zinc hull plates, no data from actual installations have been published concerning measurements of polarization or performance in service.

Size of Anodes. Rolled zinc hull plates are usually supplied in thicknesses from ½ to 1 in., in widths of 12, 24, 36 or 48 in. and in lengths of 24, 36 or 48 in. Suitable holes are provided for fastening purposes. Rolled zinc weighs 0.258 lb per cu in.

Methods of Installation. In practice, plates are fastened to the rudder, to the rudder post, to the struts bearing the propeller and to the hull itself in the region around the propeller. The plates are normally insulated from direct metallic contact with the hull; the electrical circuit is completed through the fastening bolts, set in countersunk holes in the plates. These holes are later filled with insulating material to prevent local attack.

Boiler Plates

Zinc plates have been used for many years in the protection of steel boilers. The results have been satisfactory, but there is some doubt as to whether the mechanism of protection is that of cathodic polarization or something else. It has been suggested by some that the zinc acts primarily to remove the oxygen from the water, thus preventing the corrosion of the steel. Since it is known that the normal flow of current between zinc and iron reverses direction in hot water under certain conditions of experiment or service, there is some basis for the doubts as to whether the protection is really that of cathodic polarization.

Size of Anodes. Zinc boiler plates are furnished in many sizes. The most common are ½ by 6 by 12 in., 1 by 6 by 12 in., and 1 by 6 by 6 in. They are usually made from rolled metal.

Methods of Installation. Three general methods are followed for placing the plates in the boiler: (1) the plates may be placed loosely in a metal basket connected electrically with the boiler, (2) they may be hung in the boiler on hooks which make electrical contact with the steel, or (3) they may be bolted directly to the boiler.

The Metallography of Zinc and Zinc Alloys

By S. Robert Dunbar*

As with other metals, proper selection of a metallographic specimen and due care in the polishing and etching of it are necessary prerequisites to a correct interpretation of the microstructure of zinc and zinc alloys.

Polishing. Experiment has shown that while cast zinc is being polished, distortion may occur to a depth 20 to 100 times as great as the deepest scratch. Accordingly, each step of polishing should remove considerably more metal than that required for eliminating the scratches from the previous operation. Fine-grained and alloyed zincs are easier to prepare in a condition free from distortion than coarse-grained, soft zinc.

A belt sanding machine is suitable for the grinding stage, using four grades of belts—"No-lap" No. 30, 60, 120 and 240. Unavoidable local heating that results from grinding must be restricted as nearly as possible to the surface by frequent cooling of the specimen in water; otherwise heat may cause changes in the structure to a depth greater than that removed in subsequent stages of polishing.

The specimen may be hand polished on a series of three polishing papers backed by a flat surface, such as a glass plate. "Speed-wet" No. 280, 320 and 400 are satisfactory.

Methods have been described[1] for preparing specially graded wet-polishing abrasives. Commercial abrasive (alumina) dispersed in water with a peptizing agent* in a ball mill is transferred to a beaker. Portions of the supernatant suspension are drawn off at stated intervals so that particles in suspension for the respective wheels have the following maximum settling rates: No. 1 wheel, 1 in. in 20 sec; No. 2 wheel, 1 in. in 3 min; No. 3 wheel, 1 in. in 30 min; and No. 4 wheel, 1 in. in 4 hr.

The first two polishing wheels may be covered with white duck. The third wheel may be covered with a soft white felt known as "glass-polishing felt". "Gamal" polishing cloth is excellent for the fourth wheel.

The operator's hands and nails, as well as the specimen, should be washed with soap and water between wheels to avoid carry-over of the coarser grit.

Time can be saved during wet polishing by etching away some of the distorted metal between mechanical operations. The following procedure produces a surface relatively free from distortion:

Etch for 3½ min after final hand polishing
Etch for 1½ min after No. 1 wheel
Etch for 30 sec after No. 2 wheel
Etch for 10 sec after No. 3 wheel

Etching solution No. 1, in the list below, should be used. Repeated etching and polishing on the first wheel is advisable. More complete freedom from distorted structures will result. This intermediate etching procedure frequently fails to give satisfactory results where particles of another phase are present, having etching characteristics different from those of the zinc matrix.

After the polishing on the fourth wheel, the specimen may be etched for microscopic examination.

Mounting Specimens. Rolled metal is usually polished on an edge parallel to the rolling direction. A number of specimens may be mounted together conveniently in a screw clamp with thin spacers of soft zinc between the specimens and heavy strips of zinc outside the assembly. The assembly is tightly clamped to prevent seepage of etching reagents between adjacent specimens. The zinc spacers, of known structure, serve as a convenient standard of comparison for determining whether or not the specimens have been properly prepared. Most specimens other than rolled metal can be mounted in molded plastic.

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* An agent called "Darvan" used in the rubber trade.

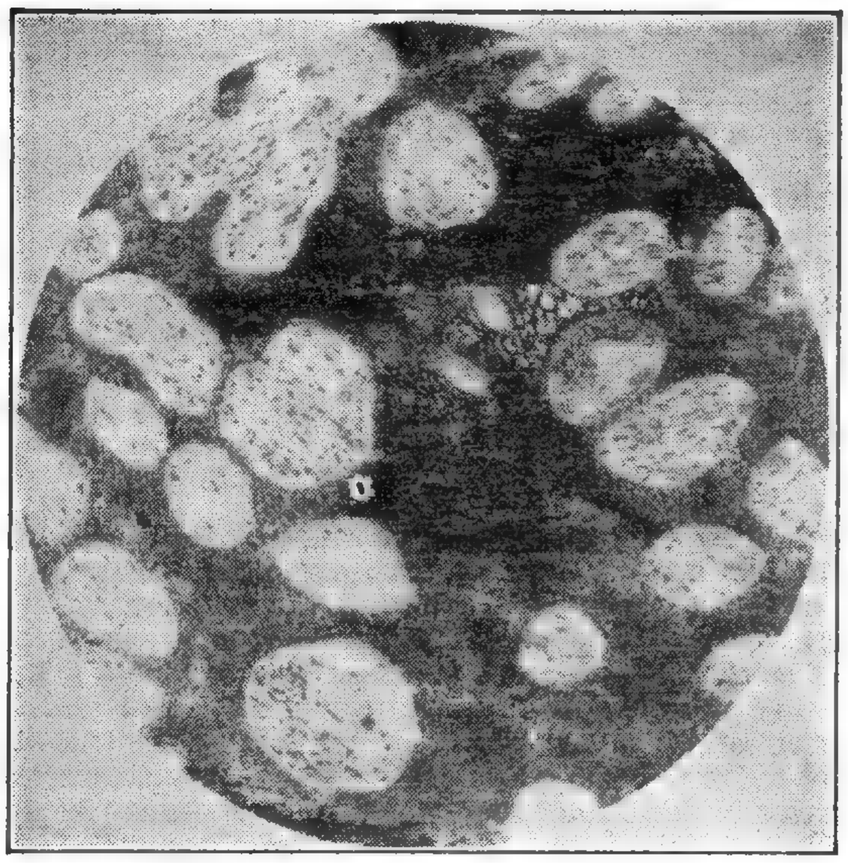

Fig. 1 ASTM alloy XXIII etched with solution No. 2 (× 1000)

Etching. The most useful etching reagent for zinc materials is pure chromic anhydride, CrO_3, to which pure sodium sulfate has been added. The grades of chromic acid used for chromium plating have been found satisfactory. The following solutions are commonly used:

Solution No. 1
200 g pure CrO_3
15 g Na_2SO_4
or 34 g $Na_2SO_4.10H_2O$
1000 ml water

*Solution No. 2**
50 g pure CrO_3
4 g Na_2SO_4
1000 ml water

Solution No. 3
200 g pure CrO_3
7.5 g Na_2SO_4
1000 ml water

Solution No. 4
200 g pure CrO_3
1000 ml water

Etching should follow soon after final polishing. The tip of the finger dipped in alcohol and rubbed over the surface of the specimen will remove any loose abrasive. The specimen should be cleaned by dipping successively in alcohol, ether, alcohol again and then in a strong stream of water. Any excess of water should be shaken off and the wet specimen should be etched. To avoid staining, the use of solution No. 1, 2 or 3 should be followed immediately by a rinse in solution No. 4. This rinse is followed by thorough washing in a strong stream of water, dipping in alcohol, then ether, and drying with a warm blast of clean air.

* Can be made by using 1 part solution No. 1 and 3 parts water.

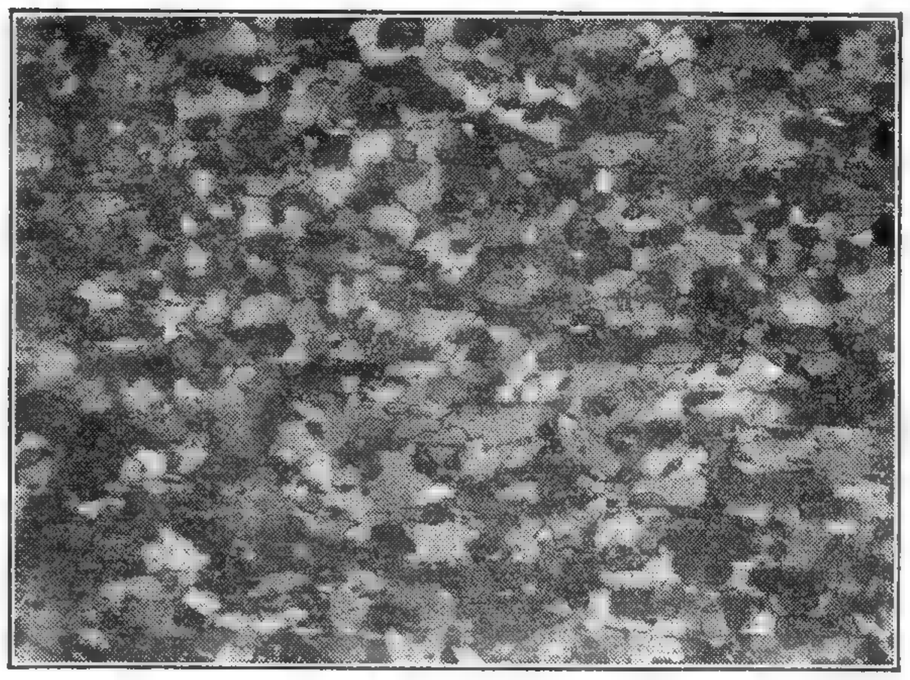

Fig. 2 Hot rolled zinc (0.1% Pb) etched with solution No. 1. Polarized light. Avg grain diam, 0.00044 in. (× 200)

Macro-etching. Concentrated hydrochloric acid produces good grain contrast on zinc.

Electrolytic Etching. Rodda[2] has described the use of electrolytic etching in studying other copper-zinc phases, particularly gamma and epsilon.

Zinc materials should be etched as follows:

Metal	Solution Number	Time, seconds: 100 Diameters	Time, seconds: 1000 Diameters
Unalloyed zinc	1	15	1
Rolled zinc-copper alloys	3	15	1
ASTM XXIII die-casting alloy	2	5	1
ASTM XXV die-casting alloy	2	5	1

Deviation from indicated etching time may be necessary.

Grain-Size Studies. It is necessary to use polarized light in making determinations of grain size in zinc. Grain boundaries are poorly defined in white light.

Typical structures of a zinc die-casting alloy and a hot rolled zinc are shown in Fig. 1 and 2 respectively.

References

1 J. L. Rodda, Preparation of Graded Abrasives for Metallographic Polishing, Trans AIME, 99, 149 (1932)

2 J. L. Rodda, Notes on Etching and Microscopical Identification of the Phases in the Copper-Zinc System, Trans AIME, 124, 189 (1937)

PROPERTIES OF ZINC AND ZINC ALLOYS

Pure Zinc*

COMPILED BY E. A. ANDERSON, E. J. BOYLE AND D. C. JILLSON*

A 1 *Common name.* **Chemically pure and spectroscopically pure zinc.**

C 1 *Density*[1] at 25 C (77 F). 7.133 g per cu cm (0.258 lb per cu in.)
2 *Density versus temperature.*[2] See Fig. 1.
3 *Density versus pressure (compressibility).*[1] See Fig. 2.
5 *Solidification shrinkage.*[2] 7.28% (volume change between 469 C and room temperature)

D 1 *Melting point*[1,3,4] 410.46 C (787.03 F)
4 *Boiling point*[5,6,7] at 760 mm Hg. 906 C (1663 F)
6 *Thermal expansion*[1] (polycrystalline) 20 to 250 C (68 to 482 F). 0.0000397 per °C
$L_t = L_0 (1 + 35.4 \times 10^{-4}t + 1 \times 10^{-8}t^2)$. (Ref 8)
7 *Thermal expansion*[3] along *a* axis 0 to 100 C (32 to 212 F). 0.000015 per °C
9 *Thermal expansion*[3] along *c* axis 0 to 100 C (32 to 212 F). 0.0000615 per °C
10 *Thermal expansion (liquid)*[2] 500 to 600 C (932 to 1112 F). 0.00006 per °C
11 *Specific heat*[5,9] at 20 C (68 F). 0.0915 cal per g
12 *Specific heat versus temperature.*[5,9] See Fig. 3.

* The properties listed here are regarded as the best available for the purest zinc. The values are not necessarily the same as those for zinc of commercial form and composition.

* Research Division, Technical Department, The New Jersey Zinc Company (of Pa.), Palmerton, Pa.

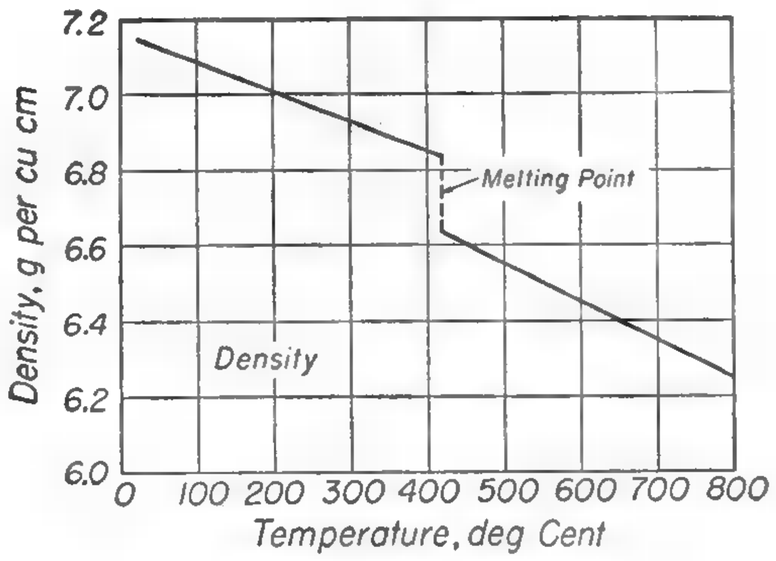

Fig. 1 Density of zinc vs temperature

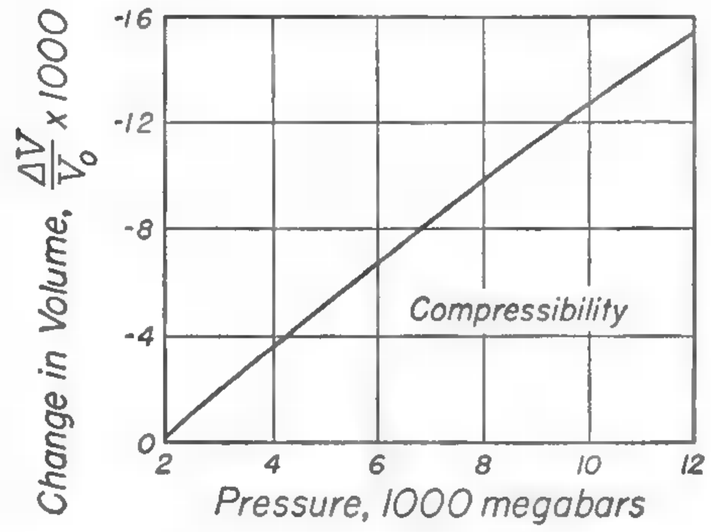

Fig. 2 Compressibility of cast zinc

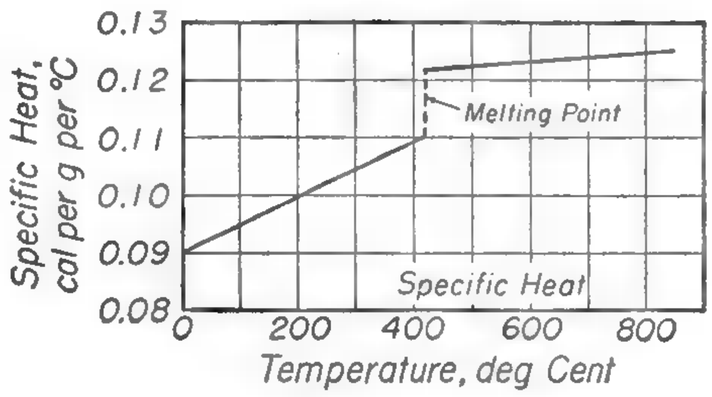

Fig. 3 Specific heat of zinc vs temperature

13 Latent heat of fusion.[5] 24.09 cal per g
15 Latent heat of vaporization.[5] 425.6 cal per g
16 Thermal conductivity[1] *(polycrystalline)* at 25 C (77 F). 0.27 cal/sq cm/cm/°C/sec
17 Thermal conductivity (polycrystalline) versus temperature.[1,18,19] See Fig. 4.
18 Heat of combustion.[5] minus 83,156 cal per g

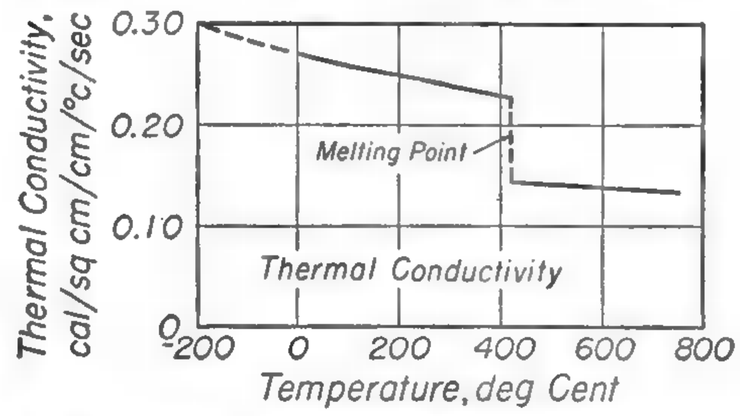

Fig. 4 Thermal conductivity of zinc vs temperature

E *1 Volume conductivity* referred to std copper.[19] 28.27%.
2 Electrical resistivity[1] (polycrystalline) at 20 C (68 F). 5.916 microhm-cm
3 Electrical resistivity along ■ axis[11] at 20 C (68 F). 5.89 microhm-cm; along *c* axis[11] 6.16 microhm-cm
4 Electrical resistivity (liquid)[1] at 419.46 C (787.03 F). 35.3 microhm-cm

5 Temperature coefficient of electrical resistivity[1] 0 to 100 C (32 to 212 F). 0.00419 per °C
Electrical resistivity versus temperature.[20] See Fig. 5.

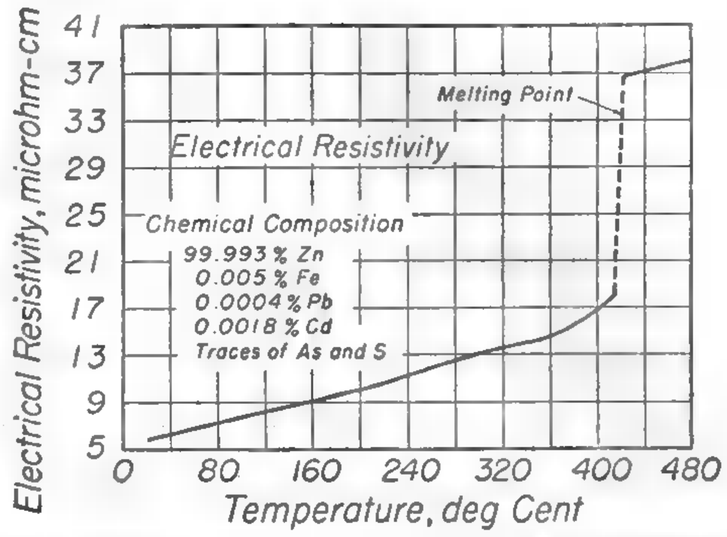

Fig. 5 Electrical resistivity of zinc vs temperature

7 Pressure coefficient of electrical resistivity.
Minus 0.25 × 10^{-6} at room temperature (calculated from Fig. 6) 1 to 3000 kg per sq cm
Electrical resistivity versus pressure.[21] See Fig. 6.

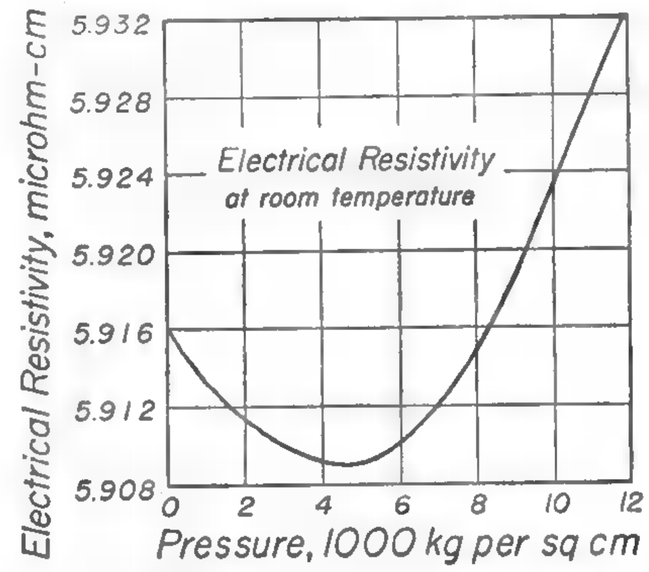

Fig. 6 Electrical resistivity of zinc vs pressure (room temperature)

10 Electrochemical equivalent.[12] 0.3388 mg per coulomb
11 Electrolytic solution potential versus hydrogen electrode.[1] minus 0.7618 volt
14 Hydrogen overvoltage.[13] 0.75 at 10 amp per sq ft, for metal rubbed with fine emery
16 Supraconductive[14] at 0.84 ± 0.05 K
F *1 Reflectivity*[15]
74.7%, at $\lambda = 0.5000\mu$ 53.3%, at $\lambda = 1.0100\mu$
66.9%, at $\lambda = 0.8000\mu$ 70.0%, at $\lambda = 1.1300\mu$
Reflectivity versus wave length.[15,22] See Fig. 7.

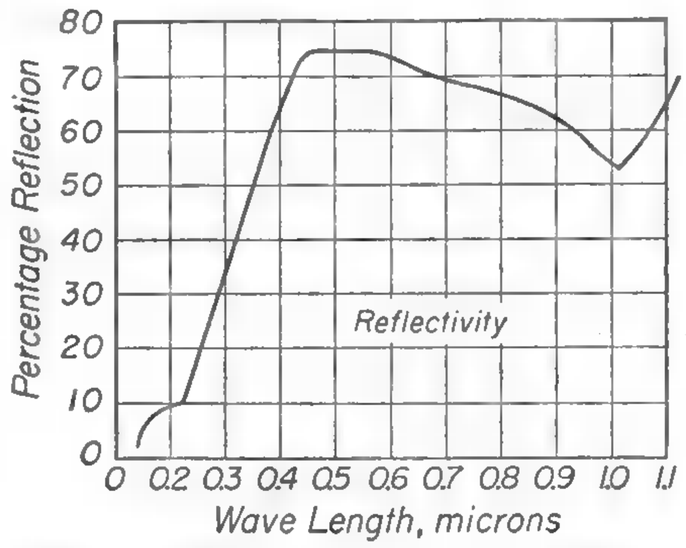

Fig. 7 Reflectivity of zinc vs wave length

2 Refractive index.[15] 1.19 in white light ($\lambda = 0.5500\mu$) $\phi = 70°$; $2\psi = 74°\ 39'$
3 Absorptive index.[15] 3.71 in white light ($\lambda = 0.5500\mu$) $\phi = 70°$; $2\psi = 74°\ 39'$
4 Color. Blue white
G *2 Magnetic susceptibility.*[1] minus 0.15 × 10^{-6} cgs

H *1 Velocity of sound*[16] at room temperature. 12,041 ft per sec (shape and size of specimen wire unknown)
J *1 Crystal structure.*[3,17] Close-packed hexagonal, $a = 2.6594$, $c = 4.9370$, (in kX units; multiply by 1.00202 to obtain value in Angstroms). $c/a = 1.8564$. Tests made with spectroscopically pure zinc.
2 Slip plane. primary (00.1) 25 C to ? C
3 Twinning plane. (10.2)
4 Cleavage plane. (00.1)
5 Minimum interatomic distance.[3,17] 2.6594 kX
7 Fracture type. Basal cleavage
K *5 Coefficient of friction.*[3] 0.21, rolled zinc vs rolled zinc
8 Surface tension (liquid)[1] at 450 C (842 F). 755 dynes per cm
L *2 Radiography.*[3] Eastman Ultra speed film with lead intensifying screen

Section, in.	Kilovolts	Milliamperes	Time, sec
¼	60	8	25
½	60	8	88
1	200	10	100
2(a)	200	10	42

(a) Calcium tungstate screen

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22 G. B. Sabine, Phys Rev, Ser II, 55, 1064 (1939)

Zn*–4 Al–0.04 Mg

COMPILED BY G. L. WERLEY*

A *2 Trade name.* Zamak-3 (die casting)
3 ASTM number. XXIII
4 Government number. QQ-Z-363, dated 2/7/46
5 Other designations. SAE 903
6 Foreign equivalents. Mazak-3, Gomak-3
B *1 Typical uses.* For all zinc alloy die castings, such as automotive parts, household utensils, office equipment, building hardware, padlocks, toys, and novelties.
2 Precautions in use. Strict maintenance of specifications regarding chemical composition and intelligent use of die design to insure sound castings having uniformly high strength.
C *1 Density* at 21 C (70 F). 6.6 g per cu cm (0.24 lb per cu in.)
5 Solidification shrinkage. 1.17% (Use 0.3 to 0.6% in die design.)
D *1 Liquidus temperature.* 386.6 C (727.9 F)
2 Solidus temperature. 380.6 C (717.1 F)
6 Thermal expansion 20 to 100 C (68 to 212 F). 0.0000274 per °C
11 Specific heat 20 to 100 C (68 to 212 F). 0.10 cal per g
16 Thermal conductivity 70 to 140 C (158 to 284 F). 0.27 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 27%
2 Electrical resistivity at 20 C (68 F). 6.3694 microhm-cm
5 Temperature coefficient of electrical resistivity 0 to 100 C (32 to 212 F). 0.003774 per °C
I *1 Corrosion resistance.* This alloy can be used safely wherever zinc or zinc-coated iron or zinc-coated steel has been used successfully in the past. Corrosion penetration outdoors in inches per year is 0.000078 in Palmerton, Pa., and 0.00022 in New York City.
K *Mechanical properties. Die cast* (¼-in. section): tensile strength 41,000 psi; elongation 10%; Bhn 82; impact value, Charpy 43 ft-lb; shear strength 31,000 psi; endurance limit (10^8 cycles) 6875 psi; compressive strength 60,000 psi.
L *4 Preferred tension-test specimen.* ¼-in. diam
Preferred impact-test specimen. ¼ by ¼ by 3 in., unnotched
Preferred hardness test. Brinell, 500 kg/10-mm ball/30 sec
M *1 Composition limits* (ASTM B 86). *components,* 3.5 to 4.3% Al; 0.03 to 0.08% Mg; *impurities,* 0.1% max Cu; 0.007% max Pb; 0.005% max Cd; 0.005% max Sn; 0.100% max Fe.
2 Consequences of exceeding impurity limits. Alloy becomes subject to intergranular attack and fails prematurely by warping and cracking.
N *1 Melting temperature range.* 386.6 to 500 C (727.9 to 932 F)
2 Die-casting temperature range. 393 to 427 C (740 to 800 F)
3 Alloying. Add aluminum as unalloyed metal as soon as zinc is molten. Add magnesium as unalloyed metal when aluminum is dissolved.
4 Deoxidizers. None required.
5 Type of flux. None desired. Fluxes volatilize the magnesium.
6 Precautions in melting. Allow a 15-min resting period after the aluminum has dissolved, during which time fine particles of aluminum and silicon (believed to be oxides) will rise to the surface of the melt and must be removed by skimming. Skimming will also remove all excess iron in the form of iron-aluminum compounds.
16 Standard finishes. Mechanical, electrodeposited, chemical, organic and plastic.
17 Joining. Soft solder with Pb-Sn solder over nickel-plated surface; acidulated zinc chloride flux.
Oxyacetylene weld with Zamak-3, no flux, soft flame.
Resistance welding. Pulsation technique is usable.

References

"Die Casting for Engineers", The New Jersey Zinc Company.
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"Practice in Machining Zinc Alloy Die Castings", The New Jersey Zinc Company.
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"The Finishing of Zinc Alloy Die Castings", The New Jersey Zinc Company.
Die Casting Magazine.
A complete bibliography appeared in the September and October 1945 issues of Light Metal Age.

*Special High Grade Zinc must be used as the basic material in making this alloy.

*The New Jersey Zinc Company (of Pa.), Palmerton, Pa.

Zn* – 4 Al – 1 Cu – 0.04 Mg

COMPILED BY G. L. WERLEY*

A *2 Trade name.* Zamak-5 **(die casting and sand casting)**
3 ASTM number. XXV
4 Government number. QQ-Z-363, dated 2/7/46
5 Other designations. SAE 925
6 Foreign equivalents. Mazak–5, Gomak–5
B *1 Typical uses.* For all zinc alloy die castings, such as automotive parts, household utensils, office equipment, building hardware, padlocks, toys, and novelties. In sand castings this alloy is being used for drop-hammer dies.
2 Precautions in use. Same as for Zn – 4 Al – 0.04 Mg
C *1 Density* at 21 C (70 F). 6.7 ■ per cu cm (0.24 lb per cu in.)
5 Solidification shrinkage. 1.17% (Use 0.3 to 0.6% in die design.)
D *1 Liquidus temperature.* 386.1 C (727.0 F)
2 Solidus temperature. 380.4 C (716.7 F)
6 Thermal expansion 20 to 100 C (68 to 212 F). 0.0000274 per °C
11 Specific heat 20 to 100 C (68 to 212 F). 0.10 cal per g
16 Thermal conductivity 70 to 140 C (158 to 284 F). 0.26 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 26%
2 Electrical resistivity at 20 C (68 F). 6.5359 microhm-cm
5 Temperature coefficient of electrical resistivity. 0 to 100 C (32 to 212 F). 0.003527 per °C
I *1 Corrosion resistance.* This alloy can be used safely wherever zinc or zinc-coated iron or zinc-coated steel has been used successfully in the past. Corrosion penetration outdoors in inches per year is 0.000063 in Palmerton, Pa., and 0.00028 in New York City.
K *Mechanical properties. Die cast* (¼-in. section): tensile strength 47,600 psi; elongation 7%; Bhn 91; impact value, Charpy 48 ft-lb; shear strength 38,000 psi; endurance limit (10^8 cycles) 8175 psi; compressive strength 87,000 psi.
L *Test specimens.* See Zn – 4 Al – 0.04 Mg.
M *1 Composition limits* (ASTM B 86). *components,* 3.5 to 4.3% Al; 0.75 to 1.25% Cu; 0.03 to 0.08% Mg; *impurities,* 0.007% max Pb; 0.005% max Cd; 0.005% max Sn; 0.100% max Fe.
2 Consequences of exceeding impurity limits. Alloy becomes subject to intergranular attack and fails prematurely by warping and cracking.
N *1 Melting temperature range.* 386.1 to 500 C (727.0 to 932 F)
2 Die-casting temperature range. 393 to 427 C (740 to 800 F)
3 Alloying. Add Al-Cu-Mg as an 80–20–0.8 hardener as soon as the zinc is molten.
4 Deoxidizers. None required.
5 Type of flux. None desired. Fluxes volatilize the magnesium.
6 Precautions in melting. See Zn – 4 Al – 0.04 Mg.
16 Standard finishes. Mechanical, electrodeposited, chemical, organic and plastic.
17 Joining. See Zn – 4 Al – 0.04 Mg.

*Special High Grade Zinc must be used as the basic material in making this alloy.

*The New Jersey Zinc Company (of Pa.), Palmerton, Pa.

References

See Zn – 4 Al – 0.04 Mg

Zn* – 4 Al – 3 Cu – 0.03 Mg

COMPILED BY G. L. WERLEY*

A *2 Trade name.* Zamak-2 **(die casting and sand casting)**
3 ASTM number. XXI
5 Other designations. SAE 921
6 Foreign equivalents. Mazak–2, Gomak–2
B *1 Typical uses.* For all zinc alloy die castings, such as automotive parts, household utensils, office equipment, building hardware, padlocks, toys, and novelties. This alloy is becoming obsolete for die casting; it is being replaced by either Zamak–3 or Zamak–5. In sand castings this alloy is widely used for drop-hammer dies.
2 Precautions in use. Strict maintenance of specifications regarding chemical composition and intelligent use of die design to insure sound and uniformly high-strength castings. This alloy is subject to embrittlement and growth on aging.
C *1 Density* at 21 C (70 F). 6.7 g per cu cm (0.24 lb per cu in.)
5 Solidification shrinkage. 1.17% (Use 0.3 to 0.6% in die design.)
D *1 Liquidus temperature.* 389.8 C (733.6 F)
2 Solidus temperature. 379.3 C (714.7 F)
6 Thermal expansion 20 to 100 C (68 to 212 F). 0.0000277 per °C
11 Specific heat 20 to 100 C (68 to 212 F). 0.10 cal per g
16 Thermal conductivity 70 to 140 C (158 to 284 F). 0.25 cal/sq cm/cm/°C/sec
E *1 Volume conductivity* referred to standard copper. 25%
2 Electrical resistivity at 20 C (68 F). 6.8493 microhm-cm
I *1 Corrosion resistance.* This alloy can be used safely wherever zinc or zinc-coated iron or zinc-coated steel has been used successfully in the past. Corrosion penetration outdoors in inches per year is 0.000073 in Palmerton, Pa., and 0.00027 in New York City.
K *Mechanical properties. Die cast* (¼-in. section): tensile strength 52,100 psi; elongation 8%; Bhn 100; impact value, Charpy 35 ft-lb; shear strength 46,000 psi; endurance limit (10^8 cycles) 8500 psi; compressive strength 93,000 psi.
L *Test specimens.* See Zn – 4 Al – 0.04 Mg.
M *1 Composition limits* (ASTM B 86). *components,* 3.5 to 4.5% Al; 2.5 to 3.5% Cu; 0.02 to 0.10% Mg; *impurities,* 0.007% max Pb; 0.005% max Cd; 0.005% max Sn; 0.100% max Fe.
2 Consequences of exceeding impurity limits. Alloy becomes subject to intergranular attack and fails prematurely by warping and cracking.
N *1 Melting temperature.* 389.8 to 500 C (733.6 to 932 F)
2 Die-casting temperature range. 393 to 427 C (740 to 800 F)
3 Alloying. Add Al–Cu–Mg as a 57–43–0.4 hardener as soon as the zinc is molten.
4 Deoxidizers. None required.
5 Type of flux. None desired. Fluxes volatilize the magnesium.
6 Precautions in melting. See Zn – 4 Al – 0.04 Mg.
16 Standard finishes. Mechanical, electrodeposited, chemical, organic and plastic.
17 Joining. Soft solder with Pb-Sn solder over nickel-plated surface; acidulated zinc chloride flux.
Oxyacetylene weld with Zamak–2, no flux, soft flame.
Resistance welding. Pulsation technique is usable.

*Special High Grade Zinc must be used as the basic material in making this alloy.

*The New Jersey Zinc Company (of Pa.), Palmerton, Pa.

References

See Zn – 4 Al – 0.04 Mg.

Zn*–4.75 Al–0.25 Cu

COMPILED BY G. L. WERLEY*

A *1 Common name.* **Zinc-base slush-casting alloy**
B *1 Typical uses.* For all slush and permanent mold castings, principally in the manufacture of lighting fixtures.
2 Precautions in use. Avoid contamination with lead, tin, or cadmium.
D *1 Liquidus temperature.* 390 C (734 F) approx
2 Solidus temperature. 380 C (716 F)
K *Mechanical properties. Chill cast* (½-in. section): tensile strength 28,000 psi; impact value, Charpy 3 ft-lb.
L *4 Preferred tension-test specimen.* ½-in. diam
Preferred impact-test specimen. ¼ by ¼ by 3 in., unnotched.
M *1 Composition limits* (customary). *components,* 4.50 to 5.00% Al; 0.2 to 0.3% Cu; *impurities,* 0.007% max Pb; 0.005% max Cd; 0.005% max Sn; 0.100% max Fe.
2 Consequences of exceeding impurity limits. Alloy becomes subject to intergranular attack and fails prematurely by warping and cracking.
N *3 Alloying.* Add aluminum and copper as a 95-5 hardener as soon as the zinc is molten.
4 Deoxidizers. None required.
5 Type of flux. Ammonium chloride or zinc chloride.
16 Standard finishes.
Castings: mechanical, electrodeposited, chemical, organic, and plastic.

*Special High Grade Zinc must be used as the basic material in making this alloy.
*The New Jersey Zinc Company (of Pa.), Palmerton, Pa.

Zn*–5.5 Al

COMPILED BY G. L. WERLEY*

A *1 Common name.* **Zinc-base slush-casting alloy**
5 Other designation. Unbreakable metal
B *1 Typical uses.* For all slush and permanent mold castings, chiefly in the manufacture of lighting fixtures.
2 Precautions. Avoid contamination with Pb, Sn, or Cd.
D *1 Liquidus temperature.* 395 C (743 F) approx
2 Solidus temperature. 380 C (716 F)
K *Mechanical properties. Chill cast* (½-in. section); tensile strength 25,000 psi; elongation 1%; impact value, Charpy 1 ft-lb.
L *Test specimens.* See Zn – 4.75 Al – 0.25 Cu
M *1 Composition limits* (customary). *components,* 5.25 to 5.75% Al; *impurities,* 0.1% max Cu; 0.007% max Pb; 0.005% max Cd; 0.005% max Sn; 0.100% max Fe.
2 Consequences of exceeding impurity limits. Alloy becomes subject to intergranular attack and fails prematurely by warping and cracking.
N *3 Alloying.* Add aluminum as unalloyed metal as soon as the zinc is molten.
4 Deoxidizers. None required.
5 Type of flux. Ammonium chloride or zinc chloride.
16 Standard finishes. Mechanical, electrodeposited, chemical, organic and plastic.

*Special High Grade Zinc must be used as the basic material in making this alloy.
*The New Jersey Zinc Company (of Pa.), Palmerton, Pa.

Zn–0.08 Pb

COMPILED BY E. H. KELTON*

A *1 Common name.* **Commercial rolled zinc**
2 Trade name. Deep drawing zinc
B *1 Typical uses.* Drawn battery cans, eyelets, grommets, laundry tags, address plates, flashing; generally any drawn, formed or spun article not requiring stiffness.
2 Precautions in use. Deforms under light, continuous load, particularly at 100 F or higher.
C *1 Density* at 21 C (70 F). 7.14 g per cu cm (0.258 lb per cu in.)
D *1 Melting point.* 419 C (786 F)
4 Boiling point at 760 mm Hg. 907 C (1665 F)
6 Thermal expansion 20 to 40 C (68 to 104 F). 0.0000325 per °C with grain, and 0.000023 per °C across grain.
11 Specific heat 20 to 100 C (68 to 212 F). 0.094 cal per g
16 Thermal conductivity at 18 C (64 F). 0.257 cal/sq cm/cm/°C/sec with grain
E *1 Volume conductivity* referred to standard copper. 28.44% (hot rolled); 28.27 (cold rolled)
2 Electrical resistivity at 20 C (68 F). 6.06 microhm-cm (hot rolled); 6.10 microhm-cm (cold rolled)
I *1 Corrosion resistance.* Excellent resistance to atmospheric corrosion. Penetration same as for next alloy.
K *Mechanical properties. Hot rolled strip:* Bhn 38; endurance limit (10^8 cycles) 2500 psi.
2 Directional properties. Finish rolled to 0.024 in. by hot rolling or cold rolling.

Condition	Tensile Strength, parallel rolling direction, psi	Tensile Strength, perpendicular rolling direction, psi	Elongation, parallel rolling direction, percentage	Elongation, perpendicular rolling direction, percentage
Hot rolled strip.....	19,500	23,000	65	50
Cold rolled strip....	21,000	27,000	50	40

L *4 Preferred tension-test specimen.* ½ in. wide by 2-in. gage length
Preferred hardness tests. Scleroscope and Rockwell Superficial
Dynamic ductility test. 3½ in. long by coil width, ASTM B 69
Temper test. 1½ by 4 3/32 in., ASTM B 69
Dynamic bend test. 1 by 4 in.
M *1 Composition limits* (strip). *components,* 0.10% max Pb; *impurities,* 0.012% max Fe; 0.005% max Cd; 0.001% max Cu; 0.001% max Sn; 0.001% max Al
2 Consequences of exceeding impurity limits. Iron or cadmium causes increased hardness and reduced ductility; copper alters the chemical characteristics; tin causes hot shortness; aluminum promotes intergranular-type corrosion.
N *1 Melting temperature.* 475 to 525 C (887 to 977 F)
2 Casting temperature. (ingot) 435 to 485 C (815 to 905 F)
5 Type of flux. Sal ammoniac
6 Precautions in melting. Use refractory crucibles and melting-pot linings. Do not raise the temperature of the metal above 525 C, preferably not above 500 C.
7 Hot working temperature. 120 to 275 C (248 to 527 F)
8 Shortness range. 300 to 419 C (572 to 786 F)
11 Suited to forming by drawing, bending, roll forming, spinning, swaging, impact extrusion.
12 Precautions in forming. Keep temperature above 21 C (70 F). Use pure soapy water or noncorrosive mineral oil as lubricant.
16 Standard finishes. See pages 1078 and 1082.
17 Joining. Soft solder with Pb-Sn, acidulated zinc chloride flux.

*The New Jersey Zinc Company (of Pa.), Palmerton, Pa.

Reference

C. H. Mathewson and A. J. Phillips, Plastic Deformation of Coarse-Grained Zinc, Proc Inst Metals Div, AIME, 143–194 (1927)

Zn – 0.06 Pb – 0.06 Cd

COMPILED BY E. H. KELTON*

A *1 Common name.* **Commercial rolled zinc**
B *1 Typical uses.* Drawn battery cans, eyelets, grommets; generally drawn, formed, or spun articles requiring some rigidity.
2 Precautions in use. Deforms under light, continuous load, particularly at temperatures slightly above room temperature (100 F and higher).
C *1 Density* at 21 C (70 F). 7.14 g per cu cm (0.258 lb per cu in.)
D *1 Melting point.* 419 C (786 F)
4 Boiling point at 760 mm Hg. 907 C (1665 F)
6 Thermal expansion. 20 to 40 C (68 to 104 F). 0.0000325 per °C with grain and 0.000023 per °C across grain.
11 Specific heat 20 to 100 C (68 to 212 F). 0.094 cal per g, approx.
16 Thermal conductivity at 18 C (64 F). 0.257 cal/sq cm/cm/°C/sec with grain, approx
I *1 Corrosion resistance.* Excellent resistance to atmospheric corrosion. Corrosion penetration in inches per year outdoors is 0.000064 in Palmerton, Pa., and 0.00028 in New York City.
K *Mechanical properties. Hot rolled strip*: Bhn 43; endurance limit (10^8 cycles) 3800 psi.
2 Directional properties. See Table I.
L *Test specimens.* See Zn – 0.08 Pb.
M *1 Composition limits (strip). components,* 0.05 to 0.10% Pb; 0.05 to 0.08% Cd; *impurities,* 0.012% max Fe; 0.005% max Cu; 0.001% max Sn; 0.001% max Al.
2 Consequences of exceeding impurity limits. Iron causes increased hardness and reduced ductility; copper alters chemical characteristics; tin causes hot shortness; aluminum promotes intergranular-type corrosion.

* The New Jersey Zinc Company (of Pa.), Palmerton, Pa.

Table I. Directional Properties of Zn – 0.06 Pb – 0.06 Cd
(Finish rolled to 0.024 in. by hot rolling or cold rolling)

Condition	Tensile strength, parallel rolling direction, psi	Tensile strength, perpendicular rolling direction, psi	Elongation, parallel rolling direction, percentage	Elongation, perpendicular rolling direction, percentage
Hot rolled strip.....	21,000	25,000	52	30
Cold rolled strip....	22,000	29,000	40	30

N *1 Melting temperature.* 475 to 525 C (887 to 977 F)
2 Casting temperature. 435 to 485 C (815 to 905 F)
5 Type of flux. Sal ammoniac
6 Precautions in melting. See Zn – 0.08 Pb.
7 Hot working temperature range. 120 to 275 C (248 to 527 F)
8 Shortness range. 300 to 419 C (572 to 786 F)
11 Suited to forming by drawing, bending, roll forming, spinning, swaging and impact extrusion.
12 Precautions in forming. See Zn – 0.08 Pb.
16 Standard finishes. See "Working of Zinc and Zinc Alloys", page 1082, and "Casting and Production of Zinc Alloys", page 1078.
17 Joining. Soft solder with Pb-Sn, acidulated zinc chloride flux.

Reference

C. H. Mathewson and A. J. Phillips, Plastic Deformation of Coarse-Grained Zinc, Proc Inst Metals Div, AIME, 143-194 (1927)

Zn – 0.3 Pb – 0.3 Cd

COMPILED BY E. H. KELTON*

A *1 Common name.* **Commercial rolled zinc**
B *1 Typical uses.* Plates and strip for soldered battery cans, photoengraver's and lithographer's sheet.
2 Precautions in use. Deforms under continuous load, particularly at elevated temperatures (125 F and higher).
C *1 Density* at 21 C (70 F). 7.14 g per cu cm (0.258 lb per cu in.)
D *1 Melting point.* 419 C (786 F)
4 Boiling point at 760 mm Hg. 907 C (1665 F)
6 Thermal expansion 20 to 98 C (68 to 208 F). 0.0000339 per °C with grain and 0.0000234 per °C across grain
11 Specific heat 20 to 100 C (68 to 212 F). 0.094 cal per g approx.
I *1 Corrosion resistance.* Excellent resistance to atmospheric corrosion. Corrosion penetration in inches per year outdoors is 0.000064 in Palmerton, Pa., and 0.00028 in New York City
K *Mechanical properties. Hot rolled strip:* Bhn 47; endurance limit (10^8 cycles) 4100 psi.
2 Directional properties. See Table I.
L *Test specimens.* See Zn – 0.08 Pb.
M *1 Composition limits (strip). components,* 0.25 to 0.50% Pb; 0.25 to 0.45% Cd; *impurities,* 0.02% max Fe; 0.005% max Cu; 0.001% max Sn; 0.001% max Al.
2 Consequences of exceeding impurity limits. Iron increases hardness and decreases ductility; copper changes the chemical characteristics; tin causes hot shortness; aluminum promotes intergranular-type corrosion.

*The New Jersey Zinc Company (of Pa.), Palmerton, Pa.

Table I. Directional Properties of Zn – 0.3 Pb – 0.3 Cd
(Finish rolled to 0.024 in. by hot rolling or cold rolling)

Condition	Tensile strength, parallel rolling direction, psi	Tensile strength, perpendicular rolling direction, psi	Elongation, parallel rolling direction, percentage	Elongation, perpendicular rolling direction, percentage
Hot rolled strip.....	23,000	29,000	50	32
Cold rolled strip....	25,000	31,000	45	28

N *1 Melting temperature.* 475 to 525 C (887 to 977 F)
2 Casting temperature range. (ingot) 435 to 485 C (815 to 905 F)
5 Type of flux. Sal ammoniac
6 Precautions in melting. See Zn – 0.08 Pb
7 Hot working temperature range. 120 to 225 C (248 to 437 F)
8 Shortness range. 275 to 419 C (527 to 786 F)
9 Annealing temperature. 105 C (221 F)
11 Suited to forming by drawing, bending, roll forming, swaging, impact extrusion.
12 Precautions in forming. See Zn – 0.08 Pb.
16 Standard finishes. See "Working of Zinc and Zinc Alloys", page 1082, and "Casting and Production of Zinc Alloys", page 1078.
17 Joining. Soft solder with Pb-Sn, acidulated zinc chloride flux.

Reference

C. H. Mathewson and A. J. Phillips, Plastic Deformation of Coarse-Grained Zinc, Proc Inst Metals Div, AIME, 143-194 (1927)

Zn – 1 Cu

COMPILED BY E. H. KELTON*

A *1 Common name.* **Copper-hardened rolled zinc alloy**
2 Trade name. Zilloy-40

B *1 Typical uses.* Weatherstrip, name plates, ferrules, and drawn, formed, or spun articles requiring stiffness.
2 Precautions in use. Deforms under heavy, continuous load, particularly at 125 F or higher.

C *1 Density* at 21 C (70 F). 7.18 g per cu cm (0.259 lb per cu in.)

D *1 Liquidus temperature.* 422 C (792 F)
2 Solidus temperature. 419 C (786 F)
4 Boiling point at 760 mm Hg. 907 C (1665 F)
11 Specific heat 20 to 100 C (68 to 212 F). 0.0957 cal per g, approx

E *1 Volume conductivity* referred to standard copper. 28% approx
2 Electrical resistivity at 20 C (68 F). 6.22 microhm-cm, hot rolled

I *1 Corrosion resistance.* Excellent resistance to atmospheric corrosion. Corrosion penetration in inches per year outdoors is 0.000064 in Palmerton, Pa., and 0.00028 in New York City.

K *Mechanical properties. Hot rolled strip*: Bhn 52; endurance limit (10^8 cycles) 6100 psi. *Cold rolled strip*: Bhn 60. *Directional properties.* See Table I.

L *Test specimens.* See Zn – 0.08 Pb.

M *1 Composition limits (strip). Components,* 0.85 to 1.25% Cu; *impurities,* 0.10% max Pb; 0.012% max Fe; 0.005% max Cd; 0.001% max Sn; 0.001% max Al.

2 Consequences of exceeding impurity limits. Iron or cadmium causes increased hardness and reduced ductility; tin causes hot shortness; aluminum promotes intergranular-type corrosion.

Table I. Directional Properties of Zn – 1 Cu
(Finish rolled to 0.024 in. by hot rolling or cold rolling)

Condition	Tensile Strength, parallel rolling direction, psi	Tensile Strength, perpendicular rolling direction, psi	Elongation, parallel rolling direction, percentage	Elongation, perpendicular rolling direction, percentage
Hot rolled strip.....	24,000	32,000	20	15
Cold rolled strip....	32,000	40,000	5	3

N *1 Melting temperature.* 475 to 525 C (887 to 977 F)
2 Casting temperature. 435 to 485 C (815 to 905 F)
3 Alloying. Add copper as pure brass in melting pot.
5 Type of flux. Sal ammoniac
6 Precautions in melting. See Zn – 0.08 Pb.
7 Hot working temperature. 175 to 300 C (447 to 572 F)
8 Shortness range. 300 to 419 C (572 to 786 F)
9 Annealing temperature. 175 C (347 F)
11 Suited to forming by drawing, bending, roll forming, spinning and swaging.
12 Precautions in forming. See Zn – 0.08 Pb.
16 Standard finishes. See pages 1078 and 1082.
17 Joining. Soft solder with Pb–Sn, acidulated zinc chloride flux.

* The New Jersey Zinc Company (of Pa.), Palmerton, Pa.

Zn – 1 Cu – 0.010 Mg

COMPILED BY E. H. KELTON*

A *2 Trade name.* Zilloy–15 **(rolled zinc alloy)**

B *1 Typical uses.* Corrugated roofing and flat, drawn or mildly formed articles requiring maximum stiffness.
2 Precautions in use. Deforms under heavy, continuous load, particularly at elevated temperatures (125 F and higher).

C *1 Density* at 21 C (70 F). 7.18 g per cu cm (0.259 lb per cu in.)

D *1 Liquidus temperature.* 422 C (792 F)
2 Solidus temperature. 419 C (786 F)
4 Boiling point at 760 mm Hg. 907 C (1665 F)
6 Thermal expansion. 20 to 100 C (68 to 212 F) 0.0000348 per °C with grain and 0.0000211 per °C across grain.
11 Specific heat. 20 to 100 C (68 to 212 F) 0.0957 cal per g
16 Thermal conductivity at 18 C (64 F). 0.25 cal/sq cm/cm/°C/sec with grain

E *1 Volume conductivity* referred to standard copper. 27% approx.
2 Electrical resistivity at 20 C (68 F). 6.31 microhm-cm, hot rolled

I *1 Corrosion resistance.* Excellent resistance to atmospheric corrosion. Corrosion penetration in inches per year outdoors is 0.000064 in Palmerton, Pa., and 0.00028 in New York City

K *Mechanical properties. Hot rolled strip*: Bhn 61; endurance limit (10^8 cycles) 6800 psi. *Cold rolled strip*: Bhn 80.
2 Directional properties. See Table I.

L *Test specimens.* See Zn – 0.08 Pb.

M *1 Composition limits (strip). Components,* 0.85 to 1.25% Cu; 0.006 to 0.016% Mg; *impurities,* 0.15% max Pb; 0.015% max Fe; 0.001% max Sn; 0.001% max Al; 0.04% max Cd.

2 Consequences of exceeding impurity limits. Iron or cadmium causes increased hardness and reduced ductility; tin causes hot shortness; aluminum promotes intergranular-type corrosion.

Table I. Directional Properties of Zn – 1 Cu – 0.010 Mg
(Finish rolled to 0.024 in. by hot rolling or cold rolling)

Condition	Tensile strength, parallel rolling direction, psi	Tensile strength, perpendicular rolling direction, psi	Elongation, parallel rolling direction, percentage	Elongation, perpendicular rolling direction, percentage
Hot rolled strip.....	28,000	36,000	20	10
Cold rolled strip....	37,000	48,000	20	2

N *1 Melting temperature range.* 475 to 525 C (887 to 977 F)
2 Casting temperature range. 435 to 485 C (815 to 905 F)
3 Alloying. Add magnesium as element in pouring ladle, and copper as pure brass in melting pot.
5 Type of flux. Sal ammoniac.
6 Precautions in melting. See Zn – 0.08 Pb.
7 Hot working temperature range. 175 to 300 C (447 to 572 F)
8 Shortness range. 300 to 419 C (572 to 786 F)
9 Annealing temperature. 175 C (347 F)
11 Suited to forming by drawing, bending, and roll forming.
12 Precautions in forming. See Zn – 0.08 Pb.
16 Standard finishes. See "Working of Zinc and Zinc Alloys", page 1082, and "Casting and Production of Zinc Alloys", page 1078.
17 Joining. Soft solder with Pb-Sn, acidulated zinc chloride flux.

*The New Jersey Zinc Company (of Pa.), Palmerton, Pa.

PRECIOUS METALS

Prepared under the chairmanship of

E. M. WISE

The International Nickel Company, Inc.

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The Precious Metals Industry

By E. M. Wise*

ON THE BASIS of dollar value of world production, the precious metals, comprising gold, silver and the six platinum metals, are surpassed only by iron. Gold has the highest commercial value of the precious metals, but its industrial uses are comparatively minor. The mining of precious metals is a world-wide industry. There are hundreds of mines, ranging from small operations where one man is panning gold, to large properties employing ten thousand workers; and varying in type from surface placers to the deepest mines in operation. The concentration of precious metals contained in the ore, as well as the smelting operation, is sometimes carried out by the mining company itself, but in many instances custom smelters are employed. The alloying, final fabrication, and marketing of these precious metals in solid, clad and electroplated form is also a sizable industry.

Mining and Refining. Large amounts of gold, silver and the platinum group metals have been derived from mining operations directed primarily toward these metals; but appreciable quantities of the precious metals are sometimes found associated with base metals, and are recovered incidentally during the refining of the base metal. For example, in recent years a large amount of silver has been recovered from silver-lead-zinc ores, and even more important has been the recovery of platinum, palladium, rhodium, ruthenium and iridium from the copper-nickel ores. Indeed, this recovery has become the source of the major proportion of the platinum metals in recent years. Silver, gold, and small amounts of some of the platinum

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metals are often associated with copper minerals and are recovered in the course of electrolytic refining of copper.

It is the usual practice to refine the precious metals to the high purity suitable for general use in the arts; sometimes almost spectrographic purity is required. For gold, however, refining is frequently carried only to the point of yielding a product containing 99.5% Au.* The U. S. Mint accepts gold of this purity without refining penalty, and such gold is good delivery in international exchange. Thus it is often advantageous to sell metal of this purity, unless it contains appreciable quantities of the platinum metals. It is possible, for example, to treat gold recovered from the cyanide process, by melting it and bubbling chlorine through it to convert the silver and other metals to recoverable chlorides, leaving gold pure enough for the Mint.

Gold for use in the arts is refined electrolytically and is generally 99.95% pure; silver likewise is generally refined electrolytically. The final refining of platinum metals is done by chemical rather than electrolytic methods.

Reuse. In addition to the refining of primary material, a large quantity of gold and substantial amounts of silver and the platinum metals are recovered from manufacturing scrap, as well as from old jewelry, chemical equipment, discarded dental restorations and other products scrapped for one reason or another. An appreciable quantity of the precious metals is also recovered from relatively low-grade industrial waste, resulting from polishing operations and the like and known as "sweeps". Substantial quantities of silver are recovered from photographic fixing solutions and from old film. Considerable quantities of platinum and palladium catalysts are ultimately saved by careful refining. Where it is necessary to remove organic material from a catalyst by burning, special care is required to prevent loss by dusting. Some of these materials cannot be handled economically by themselves, but the large smelters can work them into appropriate stages of their processes so that the recovery is economic.

Solid manufacturing scrap is generally remelted by the user as a portion of a new charge. Ordinarily this is satisfactory, if the scrap is kept scrupulously clean and segregated from other types of material, but turnings are always troublesome, and clad material requires refining.

Purity. All the precious metals are commercially available in purities suitable for their ultimate use. A substantial portion of these metals is partially fabricated before being sold. In large proportion, the metals are sold alloyed with one another or with auxiliary hardeners to yield the properties required by the user in the final product. The wrought pure metals are generally too soft.

Except for solders, most of the commercially important silver alloys, or alloys based on the platinum metals, contain at least 90% of the precious metal forming the basis of the alloy, and gold coins contain 90% gold, so the nobility of these alloys does not differ greatly from that of the major component. For most other applications, gold is usually alloyed with considerable quantities (25 to 60%) of other elements. As a result of this dilution of gold, the departure from the characteristics of the pure metal with regard to color and other properties, including resistance to tarnish and corrosion, is greater in the commercial gold alloys than in other precious metals. Where resistance to corrosion is an important factor in the carat golds—for example, for pen nibs—the alloy should be not lower than 14-carat, while gold leaf for outdoor exposure should be at least 22-carat.

Regulations. In the production of these various alloys, technical and legal requirements are the determining factors, as well as custom, modified by style trends. For coinage, where obviously something harder than pure gold or pure silver is required, copper has been accepted as the desirable hardener for both these metals. In the United States, at least, the 10% Cu, 90% Ag alloy has been used for all the regular silver coins.

The State stamping laws and fair-trade practices in the United States have defined various precious metal alloys and clad products. For example, sterling silver must contain not less than 92.5% Ag; the remaining 7.5% is unrestricted, but is normally copper, because copper is an effective hardener and is tolerable in other respects.

The gold alloys used for jewelry are described by carat and color. The carat is the fractional gold content of the articles expressed in twenty-fourths. In other words, an 18-carat gold alloy would contain 18/24 Au, or 75% by weight, while a 10-carat gold alloy would contain 10/24 or 41.65% Au. In gold-clad stock, the ratio of the weight of the gold alloy cladding to the total weight of the material is indicated, together with the carat of the cladding. For example, one-tenth 12-carat "gold filled" stock is surfaced with a layer or layers of 12-carat gold alloy that weighs 10% of the weight of the composite article. Such an article, if assayed in toto, would contain 5% Au.

The designation "gold filled" is limited by stamping regulations to articles in which the weight of the coating is at least one-twentieth of the total. Lower ratios may be stamped "rolled gold plate". The quality mark cannot be applied to articles surfaced with an alloy less than 10-carat. Watchcases require rather substantial cladding to resist wear. They can be called "gold filled" if surfaced with 0.003 in. of gold on the outside and 0.001 in. on the inside, of 10-carat gold or higher. Cases with half this thickness on the outside and none on the inside can be described as made of "rolled gold plate".

For the platinum metals, regulations were initially drawn up featuring platinum with iridium as a hardener. The uses of the other platinum metals were given less consideration at the time, an unfortunate circumstance, for they are not adequately covered. Some excellent palladium alloys suitable for uses like those of the carat golds, for instance, are not specifically provided for.

Stamping laws require that soldered platinum articles must contain at least 95% platinum metals, while articles made without solder are required to contain at least 98.5% platinum metals. When these requirements are met, an article may be stamped "platinum", providing it contains not more than 5% of the platinum metals other than platinum. An article containing more than 5% of the other platinum metals may be marked "platinum", provided the name of the predominating other platinum metal precedes the word platinum, as in "iridium platinum", and provided the article contains at least 75% Pt. An article may be stamped "palladium" if it contains at least 98.5% platinum metals, if solderless, or 95% platinum metals, if soldered, provided that the total content of platinum metals other than palladium does not exceed 5%.

Alloys used for dental purposes are rather complex in composition, and metallurgical considerations are dominant in their design. Various specifications have been established by the American Dental Association and by the Federal government, and many of the alloys have been designed to conform to these specifications, particularly to the Federal specifications, since the Army and Navy have been large purchasers of dental alloys. However, many excellent alloys in wide use have compositions or properties that differ from those covered by the specifications.

Many other important alloys have been designed for specific technical purposes—for precious metal solders, contact alloys, catalysts, crucibles, electrical resistors, frangible disks and fuses. Some of those alloys are sold according to a chemical or performance specification; others are patented or trade-marked materials with properties recognized and desired by the user. Certain existing ASTM specifications concern silver solders, which offer a basis for classification; but different manufacturers, producing alloys for specific applications, will not necessarily use identical compositions.

History and Basis for Use. Gold and silver were discovered and used in pre-Biblical times, because they occurred native in small quantities in the regions that were early civilized. The search for gold stimulated exploration, particularly in the New World, and also led to the conquest of natives who were so unfortunate as to have gold or silver mines in their territory.

Gold and silver were rare but could be worked readily by the use of very crude equipment and could be melted without much difficulty. Since these metals remained bright, they became articles of adornment, and gold in

* It is general practice to express the quality of bullion in parts per thousand, which is termed the "fineness"; thus an alloy containing 99.5% Au would be termed "995 fine".

the form of beaten leaf was used for architectural ornament. Before the use of coal, very little sulfur was in the air, so it is likely that silver remained bright and untarnished for long periods of time. Silver was therefore somewhat overrated from the standpoint of atmospheric corrosion and was considered very noble, because gold was the only other metal of lasting brilliance then known.

Platinum was discovered by the natives in South America and was used for making small articles of jewelry before it was known in Europe. The grains of platinum were cemented together by fusing with particles of gold that occurred in the same alluvial deposit as the platinum. It was not until 1741 that platinum became known in Europe, but it then aroused the attention of leading scientists, and in little more than 100 years, the other metals of the platinum group were discovered, separated and utilized. The difficulty of fusing platinum led to the development of pressing and sintering techniques, which became the standard method of producing massive platinum until about 1856. At that time the use of a lime refractory in conjunction with the oxyhydrogen torch, made it possible to melt and cast platinum. Cast ingots could be rolled and fabricated in about the same manner as gold and silver. Palladium could be handled in the same way, but the other metals of the platinum group offered special working difficulties, so no real production in wrought form has been possible until recently. During the past 15 years considerable quantities of wrought rhodium have been produced for scientific purposes. Iridium also can be hot worked with much difficulty, but ruthenium and osmium are virtually unworkable.

The use of gold and silver for coinage was a natural result of the limited production and general desire for these metals, principally for personal adornment. Later the fact that a bracelet could either be worn or be sold became important, for with the constant wars and migrations, it became necessary to have some rather compact means of carrying one's savings, and these metals were admirably suited to the need. Uses for coinage and for ornamentation have continued, but in addition, large industrial applications for the precious metals have developed, depending entirely on the unique properties of one or another of the metals.

Silver. The use of silver in photography is based on the photosensitivity and ease of reduction of certain silver salts. In silver solders the controlling factor is the rather low melting temperature and excellent properties of the silver-copper eutectic and the silver-copper-zinc alloys. In electrical contacts, the resistance of silver to oxidation, coupled with thermal and electrical conductivities of the order of those of copper, justifies the use of silver-base materials. The susceptibility of silver to sulfur, however, limits the use of silver contacts at low currents and voltages. In aircraft engine bearings, moderate hardness, good thermal conductivity, and low solubility in iron, all contribute to the worth of silver. The quick formation, the good mechanical properties, and the small dimensional changes that occur during the setting of certain silver-tin-mercury alloys, are the basis for the use of silver in dental amalgams.

Sterling silver retains its long-established position in uses where an elegant appearance is of paramount importance. For jewelry and tableware high reflectivity makes silver particularly attractive. Much work has been done to develop a nontarnishing sterling silver, but no such alloy appears to exist. Various thin, protective coatings have been used on objects not likely to be scratched. Among these coatings rhodium has been best.

Silver-clad copper, known as Sheffield plate, was once widely used for food-serving dishes and the like, as a substitute for solid sterling silver. These products have now been supplanted by electroplated ware. Silver-clad copper was also the basis of most daguerreotypes. Silver-clad copper, brass, nickel and iron are produced for a variety of modern uses, ranging from electrical conductors and contacts to chemical equipment. Silver is employed also in various chemical processes, including certain catalytic applications. Silver coatings are being applied to glass, ceramics and mica by spreading on a special silver-content paste and then warming to red heat. These coatings are widely used in electronic devices and also as a conducting base for subsequent electroplating. Other methods of applying conducting coatings to plastics and glass are also used as the base for electroplates. Finely divided silver, in the form of a paste applied to high-temperature bolting, is effective in preventing galling at temperatures as high as 1200 F.

The electrodeposition of silver from a double alkali metal cyanide, a process discovered a little more than 100 years ago, was the first commercially important electroplating process and halted the production of Sheffield plate. This process continues to be important; silver-plated ware, generally on a nickel silver base, is widely used for table service. Electrodeposited silver is also used for surfacing ultra-high-frequency conductors for radar. Heavy electrodeposits from this or other baths can be used for surfacing chemical equipment and for bearings. The high reflectivity in the visible range and the facility with which silver can be reduced chemically from certain unstable (and sometimes explosive) compounds, are the reasons for using silver for surfacing mirrors for use in the visible range.

Gold. Among the gold alloys, the Au-Ag-Cu-Pt-Pd alloys are used in dentistry because of their good mechanical properties, response to age hardening treatments, nobility and moderate melting point. Custom, the colors available, the relatively good resistance to tarnishing and corrosion, and adequate mechanical properties of the Au-Ag-Cu (yellow) golds and Au-Ni-Cu-Zn (white and sun-tan) golds, account for their use for jewelry, optical eyeglass frames and rings, as well as for certain rubbing contacts in small electrical devices. Gold-silver alloys containing about 70% Au, generally with a few per cent of platinum, are resistant to both oxidation and sulfidation, and have other properties that make them useful for low-current electrical contacts. In this field, however, they have generally been replaced by palladium.

Pure gold can be electrodeposited readily, and this metal, as well as rhodium and palladium, has been used for surfacing certain high-frequency conductors in environments where siver, which is often used for this purpose, corrodes. A considerable range of gold alloys also are electrodeposited on jewelry and other items where appearance is important. In some instances several layers of gold and other metals are deposited successively, and the article is subsequently heated to produce an alloy by diffusion. Pure gold has high reflectivity in the red and infrared spectral ranges, and therefore is sometimes used for surfacing infrared reflectors.

Although pure gold is resistant to nitric, sulfuric and hydrochloric acids and to many other corrosives, the use of pure gold in the chemical field is limited because of its susceptibility to attack by halogens (particularly when it is used as an anode), its softness and relatively low melting point and, to some extent, its cost. However, gold is sometimes used as a lining for small calorimeter bombs and as a corrosion-resistant solder. The 70% Au, 30% Pt alloy is quite hard and has been used widely for rayon spinnerets, but is being replaced by the platinum-rhodium alloy.

Platinum Metals. The jewelry uses of platinum and palladium hardened with one of the other platinum metals, are inspired by the pleasing color, good mechanical properties, resistance to tarnish, and known rarity (about 100 times that of gold). Rhodium is used in jewelry because of its high reflectivity and immunity to tarnish, plus the fact that it can be electrodeposited readily in thin coatings over silver or other metals. These same properties are responsible for its use in surfacing 60-in. anti-aircraft searchlight reflectors, and also reflectors for moving-picture and television equipment. Palladium can be electrodeposited readily in both thick and thin coatings, while platinum and rhodium baths are best suited to the production of thin deposits.

Platinum (generally hardened with ruthenium or iridium), pure palladium, and small amounts of rhodium-osmium alloy are used for electrical contacts where thoroughly reliable operation is desired at currents up to about one ampere. The resistance of these metals to sulfidation and to other types of corrosion renders them particularly valuable where the voltage, current or actuating force

is low, since other metals are unsuited for such applications.

In chemical work, palladium, platinum and occasionally ruthenium are useful for hydrogenation or dehydrogenation. Platinum is the outstanding catalyst for high-temperature oxidation and is in universal use for the production of nitric acid from ammonia (using 10% Rh-Pt). Platinum is widely employed also in the production of sulfuric acid from SO_2. The platinum versus 10% Rh-Pt thermocouple, and the platinum resistance thermometer are standard for precise measurement and control of temperature. Platinum equipment is the basis of the fiber-glass industry, and for the production of various single-crystal salts and glasses for the optical industry. Insoluble anodes of platinum or platinum-clad base metal are used for the production of persulfuric acid, yielding hydrogen peroxide, and also for producing perchlorates, and are used also for certain large-scale commercial electroplating processes. Platinum alloys, either 30% Pt, 70% Au or 10% Rh, 90% Pt, are used for spinnerets in the production of (xanthate) rayon. The use of 4% W-Pt and Pd-Ru-Pt alloy for aircraft spark plug electrodes, became extensive during World War II and continues because these alloys permit smooth operation with a leaner fuel mixture and consequent increase in efficiency. This type of plug is being used increasingly in busses and other vehicles.

The precious metal alloys, developed to meet these diverse requirements, are described in the following articles. The physical properties that can be attained differ greatly. The Brinell hardness number, for example, ranges from 25 for pure gold, to more than 600 for the hard, pen-tipping alloys; and the melting point, from less than 650 C for some of the silver solders to about 2700 C for osmium.

Melting Precious Metals

IN THE MELTING of precious metals various techniques have been employed, ranging from the use of a 200-ton furnace in melting silver for rolling into bus bars, to the torch melting of small buttons of platinum or palladium or dental gold alloys. Besides these differences in the size of the charge, the differences in the melting points and optimum melting atmospheres and refractories for the precious metals influence the practices employed.

Melting Silver and Silver Alloys for Rolling

By John L. Christie*

SILVER and silver alloys are regularly melted in gas-heated, oil-heated, and electrically heated crucible furnaces. The crucibles are made of conventional clay-graphite or other refractory material. The size of the melting unit depends on the magnitude of the operation. Melts of 1000 and 2000 oz are common. Large producers regularly use furnaces holding 10,000 to 15,000 oz, and the cakes cast for conversion into silver bus bars were melted in a 200-ton furnace normally used for melting copper.

In the melting of fine silver, the charge may consist entirely of silver bars, or it may contain large amounts of clean scrap. The charge is melted down as rapidly as possible under a charcoal cover, is heated to about 1100 C, and is poured into cast-iron molds that have been dressed with a mold oil. Molten silver may absorb considerable oxygen and, if allowed to do so, will give it off during solidification, with resulting unsoundness.

In the melting of silver-copper alloys, such as sterling silver and coin silver, relatively large amounts of scrap are likely to be utilized, resulting from the manufacture of tableware, coins and the like. Heavy scrap and finely divided light scrap are introduced directly into the crucible. Light, bulky scrap is frequently "cabbaged". In the use of scrap, care must be taken to prevent contamination. In some instances where meticulous care supplants knowledge and control, no scrap is remelted, but generally this involves unnecessary expense.

Silver-copper alloys are melted under a charcoal cover. A deoxidizer is added, and the stream of metal to the mold is protected from oxidation by the burning mold dressing, aided sometimes by a gas flame around the stream at the top of the mold. Various deoxidizers are used—phosphor-copper, sodium-zinc, calcium boride, and cadmium. Phosphorus forms a ternary Ag-Cu-P eutectic that has a low melting point (640 C); therefore the residual phosphorus should be held considerably below 0.05% to prevent hot shortness. With all deoxidizers, allowance must be made for the effect of their presence on the fineness of the alloy.

The size and shape of the casting depend obviously on the subsequent operations involved in producing sheet and strip, rod and wire, and tubing. In coinage, the metal is cast into bars—small to minimize the segregation effect.

Pouring temperatures, which depend on the alloy and on the pouring technique, should be as low as will permit the last of the charge to be poured. Ordinarily, 170 C superheat above the liquidus is sufficient.

Other alloys present various problems. The temperature of silver-cadmium alloys should be kept low and should be controlled carefully to prevent a variable loss of cadmium through volatilization. Alloys containing the small percentage of nickel that can be introduced into silver alloys, should be kept free from phosphorus to prevent the formation of a hard nickel phosphide.

In general, the relatively high value of silver calls for good housekeeping, careful handling to prevent spilling, and control to keep the composition close to the nominal.

Crucible Melting of Gold and Silver Alloys

By J. Ogden*

THE RANGE of gold and silver alloys includes the alloys employed in jewelry, dental and industrial needs, as well as the solders for use with these alloys, and encompasses alloys that have a liquidus temperature ranging from 650 to 1100 C. The dental alloys generally have the highest melting points and contain the most gold, plus palladium, platinum, silver, copper and usually about 0.5 to 1.5% Zn. The jewelry alloys melt at lower temperatures and contain less gold; normally the alloying elements for the colored golds are silver, copper and zinc, often with a small percentage of nickel, while the white golds contain nickel, copper and zinc as the alloying elements. Sterling silver contains copper as a hardener and requires about the same procedure as copper to secure ingots that are free from oxygen. Besides the above alloying elements, the solders may contain a little tin, which causes no special melting trouble, and sometimes cadmium, which is volatile and somewhat toxic.

For ensuring homogeneous alloys, the addition elements, sometimes minus part or all of the silver, may be melted, cast and rolled, as a preliminary step, or may be melted and shotted, taking care to secure sound shot that will not explode during remelting. This addition then is remelted with gold to produce the final alloy, or at times the complete gold alloys may be melted, cast and remelted to produce a uniform alloy. Under all circumstances, metal of high purity is required, low in lead, bismuth, antimony and sulfur, and the metal is melted in such a manner that undesirable elements are not introduced.

About 50% of *clean* manufacturing scrap is often introduced in the melt. Sheet scrap is satisfactory, but turnings are always a source of trouble, even when considerable care has been taken to minimize mixing with other alloys or base metals. The base metals can be removed more or less completely by pickling.

Clay-graphite crucibles are suitable for most of the

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gold and silver alloys, but under some conditions use of such crucibles may lead to a pickup of silicon, which will render most of these alloys extremely hot short. The high-palladium gold alloys should be melted in lined crucibles to avoid this difficulty.

The furnaces generally employed are fed with gas and air under pressure, and the melting atmosphere is kept slightly reducing to prevent the oxidation of the base-metal alloying elements, and for other reasons. Induction melting is employed increasingly and some use is made of electrical resistance furnaces, which are generally equipped with carbide resistors or, for small units, with platinum resistors.

Boric acid, a good melting flux for most of the alloys, should be skimmed off and replaced with fresh flux just before the metal is poured. In the melting of alloys that are free from zinc and other deoxidizers, a charcoal cover is employed, and sterling silver may be melted under a cover of old bone buttons. Some of the high-copper alloys and the silver-copper alloys may require deoxidation with about 0.05% P, just before being poured. Calcium boride is occasionally useful in some of the higher-melting gold alloys, particularly the dental alloys, but generally reliance is placed on the presence of 1% Zn or more, to maintain a low final content of oxygen. Occasionally indium is used for this purpose instead of zinc. In alloys that are subject to difficulties caused by gas, preliminary solidification in the crucible, before remelting and pouring, is often very helpful. The use of a protected noble metal thermocouple of the immersion type is desirable for controlling the final pouring temperature, which should be about 50 C above the liquidus.

The alloys are poured directly into warmed, greased cast-iron split molds, which have long life. During pouring, particularly where boric acid is not used as a flux, it is often desirable to use a reducing flame for covering the metal stream as it enters the mold. The rate of pouring is low, just equal to the rate of solidification, so that no appreciable shrinkage pipe develops. To pour slowly, without producing laps and cold shuts on the ingot surface, is a skill that requires some years to perfect.

Torch Melting of Platinum Metals

By E. M. Wise*

IN MELTING finely divided platinum metals, it is desirable to press them first into masses of convenient size. This reduces the mechanical loss during torch melting, and generally makes the metals good enough electrical conductors for satisfactory induction melting.

Torch Melting for Poured Ingots. In torch melting for casting, a furnace made from two blocks of compressed lime is generally used despite the limited life of such a refractory and its rapid deterioration if left exposed to the atmosphere. The lower block is scooped out to form the hearth, and the upper block has a central hole through which the flame of the oxyhydrogen or oxy-city-gas enters. Oxyhydrogen is required for melting platinum of the highest purity. A horizontal channel is cut in the lower block to provide an exit for the burned gas and a channel through which to pour the metal.

A torch is required that has been designed specifically for this type of melting and is preferably equipped with a nozzle of high melting point. (Platinum is best for the purpose.) This torch should ensure as complete and uniform a mixture of combustible gas and oxygen as possible. Flow meters for both gases are required, and the mixture should be quite strongly oxidizing for platinum, and slightly oxidizing for palladium during all but the final period. At least 30 to 45% more oxygen than required for complete combustion, is recommended for pure platinum. If a neutral or reducing flame is used, appreciable amounts of calcium may be reduced, damaging the platinum and causing unsoundness; if this does happen, remelting under oxidizing conditions, with the addition of a trace of silica, will slag off the calcium. It may be necessary to melt platinum alloys under less oxidizing conditions, in order to avoid loss of some of the more oxidizable components of the alloy.

After the material has been completely melted, the flame is cut down until the metal just solidifies, giving off considerable gas meanwhile. The flame is then increased to remelt the metal and bring it to pouring temperature. A slightly oxidizing flame is satisfactory for remelting platinum, but palladium requires a strongly reducing flame at the end of the melting cycle; three volumes of hydrogen to one of oxygen is about right. Palladium sometimes requires supplementary solid deoxidizers, such as calcium boride, added in minute amounts just before pouring. The pouring temperature should always be as low as possible.

Warmed graphite molds are generally employed, but nickel molds also are used when previously oxidized by heating and then coated with a little zirconia. Sometimes pure copper molds are used but care is required in order to avoid cold shuts with this type of mold. In any event, the mold should be placed and the pouring should be done in such a way that the stream of metal does not impinge on the side of the mold more than momentarily.

Torch Melting for Producing Buttons. A special high-silica crucible, cut off at an angle, is employed for melting and solidifying small quantities of platinum to produce a button. The platinum, generally in the form of small pieces of previously worked material, is cleaned and stacked against the higher wall of the crucible, and an oxygen-city-gas torch, designed to produce a large uniform flame and adjusted to be oxidizing, is played against the cavity in the crucible and the back wall. The nozzle of the torch must be heavy and of high thermal conductivity, so that it will not overheat. The torch is played on the charge until the metal is completely molten, forming a pool in the bottom of the crucible. The flame is cut down slightly, or is lifted away from time to time, to permit the metal to solidify. The torch flame should be directed in such a way that solidification of the platinum will progress upward. If gas is evolved during cooling, the top of the button may be remelted to give a good surface. After solidification is complete, the button is lifted out and most of the clinging refractory is removed. The button is then placed, bottom side up, on a silica refractory and is rapidly heated just to the point of fusing the surface, smoothing it up, and melting any residual refractory.

Palladium should not be melted in this way, since there is danger of contaminating it with silicon reduced from the silica crucibles during the later part of the melting operation. For this reason magnesia- or alumina-lined crucibles are recommended. A strongly reducing flame—three volumes of hydrogen to one of oxygen—is desirable, and at the end of the melting period, the oxygen can be cut still lower to cool the flame and permit progressive solidification. Even more satisfactory is an oxyacetylene flame, which may be operated nearly neutral, except at the end of the melt. Remelting may be required in order to secure solidity. In some instances the presence of a little charcoal during melting, or the final addition of about 0.03% calcium boride or aluminum may be required. These additions must be weighed, not estimated.

The buttons of platinum or palladium generally require preliminary forging at bright red heat, after which they can be rolled and annealed in the usual way. Cast ingots of platinum or palladium also are generally forged and hot rolled; but with highest quality metal, forging is not really necessary, except for the harder alloys.

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Induction-Furnace Melting of Precious Metals

By E. M. Wise*

HIGH-FREQUENCY induction furnaces are being used increasingly for melting precious metals.

High-Frequency Melting of Gold and Silver Alloys. The conductivity of these alloys is quite high and most of the units are fairly small, so that relatively high frequencies are desirable if nonconducting crucibles are used. Excessively high frequencies, however, cause too great heating of the metal where it is in contact with the crucible wall.

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Magnesia-lined or alumina-lined clay-graphite or even solid graphite crucibles can be used for the lower-melting alloys, but zircon is better for the higher-melting alloys. A graphite cover may be employed to maintain a reducing atmosphere; or a jet of reducing gas, such as hydrogen, may play on the surface of the melt, and pouring may be done under a cover of gas. Melting followed by solidification in the crucible, and the use of low final pouring temperatures, minimize difficulties from gas. Because of convenience in control, ease of observation of the metal, and comfort to the operator, this method of melting is being used increasingly.

High-Frequency Melting of Platinum Metals. This method of melting is particularly desirable for platinum and the higher-melting metals, such as rhodium and iridium. Zircon and zirconia crucibles are suitable for platinum; thoria crucibles have been used for iridium and rhodium, although zirconia can be used for rhodium. These crucibles do not behave like lime, in aiding in the slagging of traces of impurities. Nevertheless, an oxidizing atmosphere is desirable throughout the initial melting period—at least for platinum—but cannot be used with alloys that contain oxidizable elements. A preliminary solidification followed by remelting is also desirable. Slight reduction with CO is sometimes advisable just before pouring, and minute amounts of deoxidizers, such as calcium boride, may also be required at the time of pouring. However, if the metal is poured at minimum temperature above the liquidus, gas difficulties are minimized. Molds similar to those used with lime-block torch melting are generally suitable.

During small-scale melting in vacuo, thoria will be serviceable without much reduction at the melting point of iridium.

Arrangements for casting in a moderate vacuum have also been utilized. This type of melting is particularly suitable for alloys that contain oxidizable metals, or alloys subject to gas absorption and evolution It must be emphasized that some crucible materials, entirely suitable for melting in air, may be reduced, damaging the platinum metals, when used in vacuo. Melting in vacuo probably has slight advantages over melting in a controlled atmosphere or in an inert atmosphere, but thus far the use of this method has been very limited.

Electrical Resistance Melting

By R. C. Brumfield*

VARIOUS TYPES of electrical heating resistors have been employed for melting precious metals for centrifugal casting. Platinum-wound muffles have been found satisfactory up to about 1250 C. In this arrangement, a horizontal tubular carbon crucible is placed within the muffle, with the hot junction of a protected thermocouple close to the end of the crucible. The small difference between the temperature of the metal and that of the thermocouple is determined by experiment. With this arrangement the metal is normally in direct contact with the carbon crucible, which provides a strong reducing condition. For most alloys melting between 500 C and 1250 C, particularly for gold alloys and silver alloys, these conditions are satisfactory, but a refractory lining could be employed in special instances.

This arrangement, with about 600-watts input, is used for melting from five pennyweight to a pound of metal. In a hot furnace the melting times for a casting temperature of 1100 C are 8 to 15 min. A superheat of 50 to 100 C above the liquidus is generally suitable.

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Jewelry Casting

By Sam Tour*

THE ART of casting jewelry is centuries old. Some of the fine jewelry displayed in museums was made from castings. Cellini's work represents the high state of the art in the sixteenth century. The starting point was often a casting made with dimensions corresponding as nearly as possible to the size and shape of the finished piece.

The basic processes have changed little since then and include the lost-wax process, perfected by dentists during the last 40 to 50 years and employed for the last 15 years for producing rings and other items of jewelry. This process is the most important, although precious metals are cast also in molds made by pressing a pattern into cuttlefish bone or by packing fine sand or plaster of Paris mixtures around a permanent pattern. Since the lost-wax process permits the reproduction of fine detail and minimizes the amount of hand finishing, it is preferred, particularly where a moderate number of pieces is required.

Lost-Wax Process. The lost-wax process may be divided into seven steps as follows:

Initial Model. A model of the finished piece is required. It is generally metallic and may be the original artist's sample. When multipart molds are to be made of soft metal, the model must be made of material that will not be deformed by casting the soft metal around it nor by pressing the mold subsequently against the model to reshape it. When rubber molds are to be made, it is sometimes desirable to tin plate the model to prevent excessive adherence of the rubber.

Mold for Wax. The mold is a split form containing a cavity, conforming to the model, into which the molten wax is forced to produce replicas of the model. For very simple pieces or where very large production is involved, the metal molds may be machined, but generally metal molds are made by casting a soft metal alloy around the model. A suitable plane of parting of the mold halves must be selected, and mold frames are employed to ensure registry of the two halves. The alloys used for molds range from bismuth alloys, melting at 71 C, to alloys of the type metal class, melting at 230 C. These soft molds require reconditioning, from time to time, by placing the model in the cavity and pressing. Where undercuts are involved, as in rings set with gems, two or three loose pieces are required, in addition to the external mold halves, to reproduce the model and permit removing the replica.

Rubber molds are also employed where the model is complicated and has undercuts, and where only moderate accuracy is required. They can be used with wax cast at temperatures up to about 90 C, and with pressures of a few pounds per square inch. Rubber molds may be made in a frame, the two halves of the mold being made and vulcanized successively; or the mold may be made by coating the whole model and its sprue with a rubber paste, which is dried and cured. The model with its rubber jacket is then mounted in a frame where it is supported

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by plaster, and the rubber is cut at the desired parting line to permit the removal of the model and subsequently the wax replicas.

In jewelry castings, minor departures from the dimensions of the model are unimportant, so that shrinkage of the wax, changes in the investment, and shrinkage of the final cast metal need not be considered; but in dental and industrial castings, these factors must be considered and compensated for.

Wax Replicas or Patterns. The wax employed is required to solidify rapidly but not to adhere to the mold; to be strong but to break before bending; to run out readily at a moderate temperature; and finally to burn out completely. Generally the mold is very lightly lubricated, and the wax, 20 to 55 C above its melting point, is injected by a syringe, centrifugally, or by air pressure. Pressures of a few ounces per square inch are provided by the syringe, while from 5 to 20 psi is used with the air-pressure method. Higher pressures cause swelling and blistering in the wax castings. In a fourth mode of injection, the wax, only 10 to 15 C above its melting point, is forced into the mold by a plunger, under a pressure of several hundred pounds per square inch. This method can be used, however, only with metal molds, well clamped together to avoid fins and similar imperfections.

Changes in injection pressure, wax or mold temperature alter results, and the time of removal of the wax from the mold is quite critical because of possible warpage and change of dimensions. Where it is necessary to store wax replicas, constant temperature is desirable.

The replicas are attached with wax to the gate in a treelike or other array; the type of investment employed and the nature of the casting determine the spacing. The gate may be of an inexpensive wax made for the purpose or of wax recovered in the run-out. It is important to employ material that does not react with the investment to cause flaking.

Investing. For casting gold and silver alloy jewelry, a simple mixture of 50% plaster of Paris and 50% graded quartz is used, but this breaks down at the high temperatures required for platinum and palladium, so that investments similar to those developed for the high-melting base metals are employed. These include mixtures containing 80 to 95% of graded quartz bonded with silica, silicates, aluminates, and phosphates. Some of these latter investments are air-setting, but others become fully hard only during the firing cycle.

It is important that the investment be free from bubbles, particularly where it is in contact with the wax, for bubbles cause rough castings. Various vacuum and mechanical treatments are employed to prevent this trouble while mixing investments, and at times the wax pattern is coated by brushing on a thin layer of investment before surrounding it with the major investment. Some of the investments are rather expensive and a 5-in. diam flask requiring about 3 lb of solids costs a considerable amount.

Generally the flasks are of stainless steel, with a ring-grooved rubber base that can be removed after setting has taken place. The wax or metal runner to which the replicas are fastened, is secured to this rubber base. It is customary to allow for a ½-in. clearance between the wax replicas and the inside wall of the flask.

Firing the Mold. After standing long enough to be thoroughly set, the flasks are ready for drying, baking and firing. This is usually done in electrically heated or gas-heated ovens. The flasks are inserted at some elevated temperature (95 to 150 C) and held until the wax and free moisture are largely eliminated. Usually the wax is not recovered, but from 50 to 65% may be recovered in a properly controlled system, which must be operated below about 100 C to avoid degradation of the wax. The recovery may or may not be economical.

After moisture and wax have been eliminated, the mold is fired as rapidly as is possible without producing cracks in the investment.

Firing is continued to temperatures of 760 to 870 C for plaster of Paris investments and to 1100 C for the more refractory types. During firing, which may require 4 to 14 hours, the atmosphere should be kept oxidizing and circulating to burn out any residual wax completely.

After firing, the molds are allowed to cool to the temperature desired for casting, usually 370 to 650 C.

Casting. Several varieties of centrifugal casting arrangements and two air-pressure devices are in use. The centrifugal types include those in which the metal is melted by torch or electric furnace in a crucible adjacent to the mold. The metal is then forced into the mold as the assembly rotates in a horizontal or vertical plane. In another centrifugal type, the metal is melted in a crucible in a separate furnace and is either poured into a preheated reservoir adjacent to the mold, or is left in the crucible, which itself may be clamped to the mold; and the assembly is rotated in a horizontal or vertical plane. There is also a machine carrying a number of radially dispersed molds connected with a common central pouring chamber into which metal is poured after the device is up to speed.

Pressure casting is employed in one arrangement, in which the flask is securely fastened to the pouring spout of the melting unit in a vertical upward position; the assembly is rotated so that the metal can run into the flask; and air pressure is applied to force the metal into the flask. In another arrangement, used to some extent in the dental field, the required amount of metal is melted in place, by torch, in the sprue depression in the top of the flask. A cup is then brought down over the molten metal and air pressure is applied to force the metal downward into the mold cavities.

In the past, emphasis has been placed on the speed of introducing the metal into the mold, but too great speed results in general solidification with consequent shrinkage porosity, rather than in progressive solidification toward the sprue, a mode that can result in good, solid castings. The right pouring temperature and mold temperature, and degasification of the metal also are required to produce sound castings, and attention to these essentials will greatly reduce the percentage of rejects.

In general, with gold, silver, platinum and palladium, the same alloys are employed for cast and wrought jewelry, although it is quite certain that improvement would result if alloys were developed specifically for casting. However, trade practices and stamping regulations impose some restrictions in this direction.

Finishing. In many types of work, the castings may be removed and partially cleaned simply by quenching in water. Where this is not feasible, some variety of knocking-out process may be used, ranging from simple hand tapping of the flask until the investment disintegrates, to pneumatically operated vibrating rams. Remaining fragments of the investment that adhere to the castings are removed by hand picking, air blast, live-steam blast, or sandblast, tumbling or pickling, and this may serve as the finishing operation also. Where the cleaning and final finishing are one operation, the gates and sprues are removed before treatment. Usually final finishing operations —buffing, filing, hand-tooling, for example—are necessary, as in fabrication of other types of jewelry.

Casting by the Cuttlefish Process. The casting of metals into molds made of the porous, internal calcified shell of the cuttlefish (Sepiidae, a relative of the octopus) is an old jewelry practice, suitable for making men's heavy rings. Pieces of cuttle 1 by 2 by 3½ in. are suitable and cost about 20 cents each. One end is sawed off so that the shell can stand. The shell is carefully sectioned through the middle, and the halves are smoothed by rubbing them on the fine sandpaper supported on a flat surface.

The object to be reproduced is then pressed gently into one plane surface just far enough to seat it firmly, whereupon the other plane surface is pressed against the other half of the object. A gentle, slightly rocking pressure is exerted by hand until the halves meet. The cut end is then made smooth with a file or by rubbing on emery, and index marks are scribed across the parting line.

The mold is then opened gently, and the gate routed in with any convenient hand tool. The model is then carefully removed, a little more gating is done, and the mold is closed to match the scribe marks. It is then held closed, gently but firmly, by soft iron wire. Fine detail is not attained nor are undercuts possible by this method. For simple coring, a frequent practice is to cut additional

pieces of cuttlebone to size and place them in position between the two mold halves.

The usual casting is made of carat gold, but platinum has sometimes been cast. The average casting is far from a precision object. Filing and tooling are required to bring the casting to the size of the model, because of the rapid but uniform washing action of the molten alloy on the mold. This is always accompanied by some charring. However, for casting one or two objects of one type or size, the cuttlefish process is a most economical procedure, especially when there are no facilities for sand casting or lost-wax casting.

After cooling, which is usually speeded by quenching the mold in water, the casting is removed and the remains of the mold discarded.

Jewelry Casting by the Pattern-Molding Process. Where undercuts are not involved, where exceedingly fine detail is not required in the casting, and where models or patterns of the article desired are available, the pattern-molding process is sometimes used.

The patterns or models are best when cut in half so that they may be mounted on pattern plates as in ordinary foundry practice. When split patterns or models are not available, match plates are made of hydrocal or dental stone, in which the pattern or model is half-embedded up to the desired parting line. By using cope and drag flasks, the two halves of the mold are made in the customary way, depending on the molding material used.

If the molding material is sand, a fine grade of parting powder is used, and then a fine grade of French sand is used as a facing. This fine sand, suitably tempered with water, is backed with a somewhat coarser sand, and the flask is hand-rammed quite hard. Gates, sprues, runners and such are usually cut by hand into the cope half of the mold. Gravity casting is employed.

If the molding material is of the plaster of Paris type, sometimes strengthened with asbestos fiber, the process is somewhat similar except that gates, sprues and runners are molded in place. After the plaster of Paris has taken its initial set, usually in about 30 min, the plate and patterns are withdrawn and the mold is put aside to dry in air and to set harder for a few hours. The mold halves so set are placed in an oven to dry out the free water, and then are heated for an hour or so at higher temperatures for skin drying. When the hot, skin-dried mold halves have been assembled, the metal is cast in place while the molds are still above room temperature.

These procedures have been used for years for sterling silver castings. They are particularly suitable for objects such as pins, brooches, and pendants, where one side is relatively flat. The flat side is usually in the drag or bottom half of the mold as cast.

Dental Casting

By W. A. Crawford*

In 1907 William Taggart introduced the method of producing dental castings by the disappearing wax pattern procedure. Few procedures, if any, have so revolutionized dentistry as the casting process. Previously only two types of metallic fillings had been available—amalgam and welded or malleted pure gold foil. Both materials are still used extensively; however, in regard to strength and convenience, amalgam and gold foil both have serious disadvantages, which were overcome by the casting procedure.

Fundamentally the procedure for making a dental casting is the same as for other applications, except for the fact that the dimensions of the casting must be identical with those of the original pattern (that is, the cavity) and only one casting will be made, but it must be a good one. Inlays are usually made to replace tooth structure lost as a result of decay. The steps in making an inlay begin with the preparation of the cavity—the pattern; the decay is removed and the cavity is slightly tapered so that a wax pattern may be removed. No undercuts can exist, yet walls must be so nearly parallel that the inlay will be retained by friction when inserted. The cavity is also extended to protect the delicate enamel rods, of which the outside of the tooth crown is composed, and to bring margins where metal is to join the tooth, to positions on the surfaces of the tooth normally rubbed by the tongue and cheeks, or in other words, to self-cleansing areas. This operation requires meticulous care to avoid damaging the pulp (nerve) and is one of the most difficult operations performed on living tissue, since nature will neither correct any errors nor heal the tooth structure.

Much of the work in preparation of the inlay cavity must be done in a part of the mouth that is difficult to illuminate and difficult to see even if illuminated. The dentist must guide most of his cutting by means of indirect vision, watching the results of his cutting instruments through a mirror. His work is done in an awkward position, yet he knows that if his margins are not perfect, his work will fail.

The Pattern. The pattern for the dental casting is the exact counterpart of the cavity and no "patternmaker's shrinkage" can be provided for. Hence the cavity must be reproduced exactly as to size and shape. This is in contrast with industrial castings, now being made by the dental process, where the pattern can be made oversize to compensate for casting contraction, or with jewelry, where slight variation in dimension is of no significance.

The contraction of gold in the dental mold is about 1.25%. By 1932, investments containing SiO_2 as cristobalite, had been developed that would provide an expansion as great as 1.4% (at 700 C), which is more than is actually needed to compensate for the contraction of the gold alloy during casting.

The wax pattern may be secured by modeling it directly on the tooth, or on a model in the hand. Regardless of how the pattern is made, it is impossible to produce one without strain, because the softened wax will contract during cooling. Furthermore, if the wax has been forced into the cavity in a semisolid condition, it will contain residual stresses. These stresses and those resulting from contraction of wax during cooling, will cause distortion of a wax pattern after it has been removed from the cavity. The amount that the pattern will change will depend on three factors: (1) the amount of stress in the pattern, (2) the length of time between the removal of the pattern from the cavity and the investing, and (3) the temperature at which the pattern is stored.

Stress. The amount of stress in a wax pattern depends on the stiffness of the wax when it was forced into the cavity, and will be least when the wax is melted and poured into the cavity and held under pressure as it is cooled. By this method, only the contraction of wax during cooling is involved. Any amount of stress may be present, from this minimum to a large amount if the wax was relatively stiff when forced into the cavity.

Stress in a wax pattern will change the shape of a pattern in less than an hour in a normally heated room. Dentists have learned that they cannot store patterns overnight, or even a few hours, before investing, if they expect the castings to fit. Patterns must be invested as soon as they have been removed from the cavity, or stored in a refrigerator after they have cooled to room temperature. In a room hotter than 90 F, a pattern will change its shape in a few minutes.

Sprues. One or more wire sprues must be attached carefully to a wax pattern in the right locations to introduce the metal during casting and must be of adequate size to ensure good feeding. A long thin sprue, in bulky inlays or crowns, will freeze before the inlay and thus prevent flow during the solidification of metal in the mold. In all probability this would not impair the strength

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sufficiently to cause failure, but porous areas on the surface of restorations will discolor very quickly in the mouth.

For bulky inlays a 14-gage wire should be used for the sprue. This wire should be inserted into the bulkiest part of the wax pattern because that is where freezing will occur last and therefore is the place where new molten metal will be needed last. Larger sprues can be used in the centrifugal type of casting machine but, where the metal is melted over the sprue hole, the sprue should be no larger than 14-gage; otherwise some metal may run in prematurely.

The sprue should also be short, not more than $\frac{3}{16}$ in. from the crucible former or sprue base to the inlay. Long sprues are unnecessary since it has been shown that dense castings can be secured with 15-lb casting pressure, regardless of the thickness of investment beyond the mold.

The Investment. The selection of the investment will depend on the amount of expansion desired. Most dentists are of the opinion that different inlays should be slightly different in size in order to seat completely in different shaped cavities and still have frictional retention. Investments have therefore been made available that provide thermal expansion levels from 0.7 to 1.4% at 700 C. More than any other factor, the length and parallelism of the cavity walls indicate the investment expansion required to produce a casting that will seat easily in the cavity but still have frictional retention.

All investments for small dental castings are plaster of Paris and silica mixed with water, which must be added to the investment according to manufacturer's directions. The proportions must be strictly adhered to, because variations produce changes in the amount of expansion, hence in the size of the casting. Where dimensional errors of a few hundredths of one per cent mean the difference between success and failure of a casting, all details must be observed carefully.

Mixing. Hand-spatulated and, to a lesser extent, mechanically mixed investments, usually contain some trapped air, which frequently accumulates on the surface of the wax model and will produce a protrusion on the casting. These imperfections are annoying and, if unobserved, may cause serious injury to the tooth. The most satisfactory procedure is to remove air by vacuum after the investment has been mixed, then to fill the ring and again evacuate the air. This can be done in one step, but requires a rather high extension on the ring to hold the investment during the violent boiling while air is being eliminated.

Vacuum equipment is not essential, and satisfactory results can be obtained when thorough mechanical spatulation is followed by painting the investment on the pattern with a fine sable-hair brush. If an oily separating medium has been used when making the pattern, a very thin coating of a wetting agent applied to the surface of the wax pattern will be found helpful in applying the investment. If the coating of wetting agent is allowed to dry, its usefulness will be lost.

Heating the Investment. The casting ring or flask must be lined with a layer of asbestos at least $\frac{1}{16}$ in. thick to permit the investment to expand since, during heating, the metal ring will expand only about half as much as the investment. Unless the investment can expand, the mold will be distorted and the casting will not fit properly.

Quartz silica investments, of which many are available, show a gradual expansion from room temperature to 600 C; thereafter, no significant dimensional change results from further heating. These quartz investments are much alike in their behavior and provide a maximum expansion of approximately 1.0 to 1.1%. They should be heated to about 700 C in order to get somewhat above the critical temperature of 600 C. When the ring is removed from the heating chamber, some heat is lost before the cast is made, and if the temperature were just above 600 C, contraction might occur before the cast was made.

A cristobalite investment expands very rapidly over the range from 200 to 300 C and should be heated more slowly than a quartz investment through this temperature range in order to avoid danger from cracking and checking. Thermal expansion of cristobalite investment is about 1.2% from room temperature to 400 C and 1.4% to 700 C.

With the availability of investments to provide almost any desired expansion, with great accuracy and reliability, it remains only for the dentist to study his wax pattern, to decide what expansion will be required, and to use an investment with that expansion.

Melting. For small castings the alloy can ordinarily be melted with little difficulty by means of the usual dental equipment, consisting of a gas-and-air blowpipe. Careless manipulation of the blowpipe may result in selective oxidation of components of the alloy or may produce subsequent general porosity in the casting. During melting, the metal should be covered at all times with the reducing part of the flame, and as soon as the metal begins to melt, it should be covered with a reducing flux. After the metal has been melted and has formed into a ball, heating should be continued, carrying the temperature well above the upper limit of the melting range to ensure rapid and complete filling of the mold or casting.

Finishing. After the inlay has been cast, the sprue is removed and the outer surface is polished, except at margins, with fine garnet, cuttlefish disks, pumice in water and whiting or rouge. Then the inlay is tried in the cavity. Contacts with adjacent and occluding teeth are tested and adjusted. All margins are tested with a sharp explorer point, are finished on the tooth with fine stones and disks, and are finally polished with pumice and whiting.

Finally the cavity is dried and the restoration is cemented in place with a mixture composed chiefly of zinc oxide and orthophosphoric acid. The purpose of the cement is to seal out oral fluids and bacteria and is not to hold the inlay in the tooth.

Properties. For information concerning the compositions and mechanical properties of cast dental alloys, see page 1120.

The Working of Platinum Metals

By C. S. Sivil*

PLATINUM, PALLADIUM, and platinum and palladium alloys are usually given their first reduction by hot forging or rolling. Although it is not essential with high-quality metal, except for some of the harder alloys, hot working reduces the time of working. Hot working temperatures vary from 800 to 1300 C; the harder alloys require the higher temperatures. Although platinum and palladium will weld at high temperatures, hot working will not weld internal cavities, which must be avoided by proper melting and casting procedures.

Further working is done cold with reductions of 5 to 10% per pass. Reductions between anneals range from 50% for the harder alloys to 95% for soft alloys in strip form, and to as high as 99% for fine wire made of pure platinum. Wire may be reduced by rolling or swaging. Odd shapes are produced by special rolls, either driven or passive; the passive rolls, generally called Turk's-head rolls, are actuated by pulling the wire through. Further reductions are carried out by drawing the wire through dies made of sintered carbide or diamond. For drawing fine wire, diamond dies are essential.

Palm oil, soap powder, or one of the softer wire-drawing soaps may be used as a lubricant for drawing on the block, while emulsions of oil, soap, and water are employed on the continuous multiple-die machines used for the finer sizes. For extremely fine sizes, some of the natural fish oils are effective. In presswork, a fluid green soap is satisfactory. The fact that the platinum metals

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do not react with the usual lubricants makes effective lubrication somewhat difficult, and lubricants that contain metal may be employed, or supplementary coatings of silver or copper can be used. The usual objection is that such lubricants are hard to remove before annealing.

It is essential to pickle high-purity platinum in hot 10 to 20% HCl before annealing, in order to remove traces of iron or other base metals that would otherwise diffuse into the platinum during the anneal. Platinum and most platinum alloys are annealed in a moderately oxidizing atmosphere. Palladium and palladium alloys are often annealed in a similar atmosphere and cooled by quenching, but nitrogen or steam should be used in the early anneals and is preferable for all anneals.

Rhodium and iridium are best worked from small ingots not more than ½ to ¾ in. thick. Iridium must be worked hot (1200 to 1400 C at the start is a satisfactory range) and high-purity metal must be used. Even then it is difficult to work iridium into thin sections.

Rhodium requires an initial hot reduction at about 1100 C, but after the metal has been worked down to a thickness of approximately 0.1 in., it can be cold rolled. Annealing is required after each 30 to 40% reduction. Too high anneals should be avoided since thoroughly recrystallized metal of the usual purity is brittle.

At the start, wire is drawn at 1100 C, but the temperature is allowed to decrease during processing, so that it is about 700 C for 0.020-in. wire. Further reduction is done cold, with anneals after each 50 to 75% reduction in area. As in rolling, the anneals must be at comparatively low temperature; 750 to 800 C is suitable. In general, the working behavior of rhodium and iridium considerably resembles that of tungsten or molybdenum, but the temperature level is somewhat lower.

The Forming and Cutting of Gold Alloys

By H. R. Stegeman*

THIS ARTICLE is a brief discussion of the forming and cutting of carat gold alloys, including gold-filled parts.

Forming. Hard rolled strip may be blanked, and the blanks may be bright annealed for approximately an hour at about 650 C, or the strip can be annealed before blanking. Blanking dies are usually made of a "nondeforming" oil-hardening tool steel. Use of the high-carbon high-chromium type of steel may be justified if extremely long runs are anticipated. Cupping and drawing dies of SAE 3140 steel are preferred and are used with a lubricant consisting of paraffin oil plus 22 oz of vaseline per gallon. Drawn parts are bright annealed in a furnace with a controlled atmosphere for 20 to 25 min at 650 C.

Forming dies of carbon steel containing 0.90 to 0.95% C are used for both preliminary forming and final forming. The parts are bright annealed between these operations, are scratch-brushed, using water and soapbark, and are then dried before the final forming or coining, which is done dry.

* Wadsworth Watch Case Co., Dayton, Ky.

Cutting. When possible, gold alloys are machined after moderate cold reduction; 20 to 30% is suitable. Castor oil is the preferred lubricant. Sulfurized lubricants would bring in many complications and therefore are avoided. Facing cuts on the lathe are made at a speed of 350 ft per min with carbide-tipped tools. Grooving is done at 115 ft per min with a high speed steel tool. For drilling, carbon steel drills are used, and a speed of 5000 rpm is typical for a drill 0.040 in. in diam.

Mill facing is carried out at 470 ft per min with a spiral high speed steel milling cutter. Spot facing is done at speeds of 200 to 400 ft per min with carbide-tipped cutters. Chromium-plated cutters have somewhat longer life than uncoated high speed steel cutters. Small high speed steel saws are operated at 400 ft per min.

In machining gold-filled parts, most of the cutting may be in the core metal, and the choice of cutters thus depends partly on the nature of the base metal. With nickel silver cores, carbide tools are satisfactory for light cuts, as in lathe and spot facing, while high speed steel is better for pure nickel cores.

Joining and Cladding Precious Metals

IN THIS article the joining of precious metals is discussed under the following headings: resistance welding of precious metals, joining of platinum and palladium, brazing of sterling silver articles, resistance brazing of gold alloys, dental gold solders, cladding with gold and silver and their alloys, cladding with platinum and palladium and their alloys, and induction heating for cladding.

Resistance Welding of Precious Metals

By E. F. Holt*

In industries that produce jewelry, dental mountings, electrical contacts, optical aids and such, many of the precious metals and alloys are successfully joined by resistance welding. Binary alloys of gold and copper, ranging from 14 to 24 carats, and many of the ternary alloys of gold with copper, silver and nickel, are resistance welded for assemblies of watchcase and strap, nose bridges for eyeglasses, costume jewelry and dental mountings.

In general, welding is done by means of small, bench-type resistance-welding machines, ranging from ½ to 5 kva, depending on the size and shape of the work parts. Welding pressures range from 2 oz to 6 lb. Small synchronous timers for controlling the duration of the welding current are recommended for this type of work. The recommended weld time is usually from ½ to 2 cycles.

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Gold-filled materials are rarely resistance welded because of difficulty in avoiding exposure of the base metal. Instead, soldering and brazing are usually employed for joining gold-filled materials.

Hard Alloys. Extremely hard alloys of osmium and ruthenium, generally plus other platinum metals, are frequently used for tipping fountain pen nibs. Small pieces of the alloys are resistance welded to 14-carat gold pen nibs to provide the wearing surface. The resistance-welding equipment for welding pen nibs is generally automatic, but the welding conditions are similar to those described for welding gold alloys.

Silver Alloys. Fine silver and silver-base alloys are used extensively for electrical make-and-break contacts and are resistance welded to many types of base-metal switch and relay parts. Solid fine silver and silver alloys are difficult to join together by resistance welding because of their relatively low resistivity. However, the materials are readily welded to many base metals that have higher resistivity and that alloy readily with silver. For example, fine silver contacts, coined or headed with a welding projection on one side, may be readily welded to contact arms made of such materials as nickel silver, phosphor bronze, copper-nickel, beryllium copper, yellow brass and similar metals. A typical electrode arrangement for such applications is shown in Fig. 1.

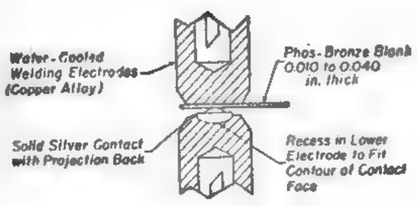

Fig. 1

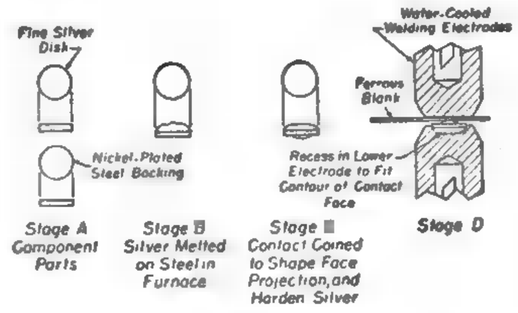

Fig. 2

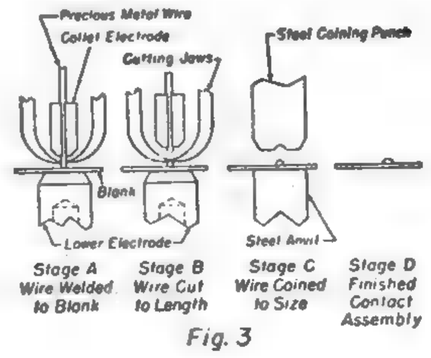

Fig. 3

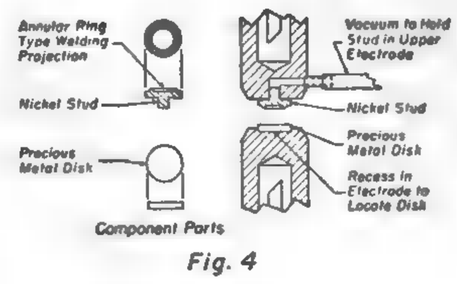

Fig. 4

Fig. 1 Resistance welding solid silver contacts to bronze blanks. Fig. 2 Fabricating and resistance welding silver-faced steel-backed contacts. Fig. 3 Resistance welding precious-metal contact assemblies. Fig. 4 Resistance welding precious-metal contact disks to nickel studs.

The welding conditions required for a silver contact ¼ in. in diam with a projection back are: duration of welding, 10 cycles; electrode force, 150 lb; and welding current, about 6000 amp.

Electrode arrangements similar to that shown in Fig. 1 may be used to weld any of the precious metals and alloys that are capable of being coined or headed to raise the required welding projection. Pure platinum and palladium are examples of other precious metals capable of being worked to provide a welding projection.

In welding silver contacts to ferrous metals, it is desirable first to attach the fine silver contact to a steel backing, which may be made with a welding projection. The precious-metal facing may be attached to the steel backing (generally nickel-plated) by furnace brazing with silver solder, or by melting the precious metal on the steel. A patented process used for producing bimetal contacts for resistance-welding applications is shown in Fig. 2. The backing may also be made of such metals as monel, nickel and the like, where greater resistance to corrosion is desired.

Many contact assemblies are resistance welded; for this purpose silver, platinum, palladium and their alloys are used in wire form. First the end of the wire is welded to the blank; then the wire is cut off close to the blank, and the welded wire is coined to the proper contact dimensions.

In Fig. 3 is shown the sequence of operations that an automatic welding machine performs in one cycle. The welding conditions are usually: duration of welding, 1 to 6 cycles; force, 1 to 2 lb; welding current, 1000 to 2500 amp.

Platinum and Palladium. Platinum, palladium and their alloys containing iridium or ruthenium are frequently resistance welded to nickel and nickel alloys by the projection method. The nickel blank is generally headed from wire; a welding projection is thrown up during the heading operation. A typical assembly is shown in Fig. 4, which also presents a welding electrode arrangement. Welding conditions for such an assembly, using a precious-metal contact disk about ¼ in. in diam and 0.040 in. thick, would be: duration of welding, 6 to 12 cycles; electrode force, 250 lb; and welding current, 6000 to 8000 amp. Platinum wire is resistance welded to platinum-rhodium alloy for thermocouples using small condenser-discharge welding controls. Platinum wire mesh is fabricated by cross-wire welding with similar equipment. Peak welding currents of 1000 to 3000 amp are required for welding platinum wires of small diameter; the duration of the discharge is from 2 to 10 milliseconds. A force of a few ounces is frequently used.

References. C. L. Pfeifer, Some Applications of the Resistance Welding Process, Welding J (Jan 1940)

W. Spraragen and G. E. Claussen, Welding of Gold, Silver and Platinum (A Review of the Literature to Jan 1, 1940), Welding J (March 1941)

Joining Platinum and Palladium

By R. H. Atkinson*

Platinum and palladium can be joined by hammer welding at about 1200 C; by welding just short of fusion, with or without a small amount of solder that melts at about 1600 C; by complete fusion, as in joining thermocouples; by electrical resistance welding; or by soldering. In soldering, pure gold is used for uniting platinum-clad chemical equipment; while for platinum jewelry, solders are used that contain approximately 60 to 70% Au, with the remainder largely platinum metals in order to make the solders white and to provide a sufficiently high melting point. Solders that melt within the range from 1300 to 1500 C are most popular for platinum jewelry. Parts are first assembled by welding or by soldering with solder that melts at 1500 C, while subsequent soldering is done with a solder that melts about 100 C lower than that used previously. Solders melting at 1400 C or lower are used with palladium. For repair work, solders are available that melt as low as 1000 C.

Strict cleanliness and freedom from grease are required in all welding or soldering operations that involve the noble metals. The parts to be united may be filed lightly with a clean file and then fixed in proper relation to each other. Very small pieces of the appropriate solder are placed at the joint with the aid of a small camel's-hair brush moistened in a solution of borax. The joint is then heated, slowly at first, by a small flame of city gas mixed with oxygen or by an oxyacetylene flame, until proper fusion occurs; overheating must be avoided. For palladium, the oxyacetylene flame is decidedly advantageous* and should be oxidizing. Under this condition, palladium maintains a good surface that is easily polished. Reducing flames are undesirable for palladium, since a reducing flame of city gas mixed with oxygen will embrittle the surface. The temperature of the acetylene flame is high, and for soldering jewelry it is desirable to use a tip with a diameter of 0.4 mm across the orifice. This small hot flame has the added advantage of localizing the heat at the joint to be soldered, without disturbing joints previously made.

Difficulties in soldering may be caused by the following factors: dirt, excessively wide joints, excessive heating, insufficient flux (particularly with the lower-melting solders), or the stressing of the solder while it is near the melting point.

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Brazing of Sterling Silver Articles

By Henry B. Smith*

Preparation and Cleaning. The removal of oil, grease, dirt and scale is essential. This can be accomplished by using hot alkaline cleaners or by degreasing with suitable oil solvents and pickling in acid if oxides are present. Cyanide solution is also useful in removing tarnish films.

The surface is prepared ordinarily by mechanical means, such as shaving, turning, filing and scraping. As with other metals, a closely fitted mechanical joint is superior to one with larger seams and openings.

Flux. Solutions of borax or boric acid, sometimes plus sodium fluoride, are used with or without a wetting agent. After application of wet flux, the article should be dried before soldering. A reducing gas, used advantageously in furnace brazing, permits a minimum use or, with some kinds of work material, a total absence of flux, and maintains a clean bright surface on the brazed article, so that no subsequent cleaning operation is required. The gas does not need to be strongly reducing; a content of 2 or 3% hydrogen is enough to prevent the occurrence of "fire" in the silver article. (Fire is oxidation of the copper in the sterling

* R. H. Atkinson and G. P. Gladis, A Study of the Behavior of Rutheniopalladium in Torch Flames, with the Object of Improving Soldering Techniques, Trans AIME, 166, 426, (1946)

* R. Wallace & Sons Mfg. Co., Wallingford, Conn.

silver.) Boric acid is useful also for coating the work piece away from the joint to protect it from oxidation during torch soldering.

Methyl borate is sometimes used as a flux and is introduced in the gas line to the torch. It will protect the surface on which the flame impinges, imparting a green color to the flame.

Solder. ASTM solders 3, 4, 5 and 6 (*see* page 80) are used, as well as a lower-melting solder in which some of the zinc has been replaced by cadmium.

Form of Solder. Solder is often used in granular or wire form, but in furnace brazing, strips or stampings in the form of washers or gaskets may be employed. A gasket fitted to a closely machined joint will give the best results, and incidentally use less solder.

Supporting the Work. Jigs or fixtures are sometimes used to support the article while it travels through the furnace. These should be as light as possible to keep the dead load at a minimum. Supports of this kind can be made from heat-resisting alloys, stainless steel, or nickel alloys.

In torch soldering, turntables are used to hold the articles so that flame can be played over all parts with more or less uniformity.

Component parts of an assembly can be held or stitched together satisfactorily by a putter welder, which holds the parts in alignment for the actual brazing operation.

Torch. Torches using city gas and air provide a suitable means of heating. The flame should be slightly reducing for the best results and large enough to cover the articles satisfactorily.

Bottled gas, such as propane or butane, can be used if provided with suitable torches. If oxidation occurs in the sterling silver, it is ordinarily necessary to remove a film of metal containing copper oxide. This is done by immersing the oxidized area for a definite period, usually less than one minute, in a warm solution of one part nitric acid and two parts water, at approximately 54 C.

Furnaces. Gas-heated or electrically heated furnaces are the types ordinarily used. They are of either the batch type or the conveyer type, according to the amount of production that is needed. The batch type is more economical as far as atmosphere gas is concerned, but has a smaller capacity for a given size of hearth than the conveyer type.

The conveyer type of furnace usually gives a very uniform product, since the temperature is controlled automatically. If the capacity of the furnace is not exceeded, a markedly uniform product can be secured. The duration of cooling should be long enough for the sterling piece to reach a point between 70 and 150 C before exposure to the air; otherwise a slight discoloration is likely to occur.

Resistance Brazing of Gold Alloys

By Carl Samans*

In joining small parts, as in the manufacture of spectacle frames and some types of jewelry, resistance heating by direct passage of a low-voltage current through the joint is used and the parts are held in suitable clamps. Through proper design and location of the clamps and the surfaces of contact, the process can be closely controlled to liberate the heat exactly where it is needed. Copper (both OFHC and free-cutting), silver, tungsten and Elkonite have all been used for the contact surfaces. For this work on a small scale, 500 to 600 watts is required; and 200 to 300 amp at 1 to 3 volts is normal for soldering a section about 0.07 in. in diam.

The brazing alloy in wire form is fed through an insulated pencil to the articles, which are preassembled and held in place by the contacting jaws. The heating continues as long as desired, and is subject to constant control by the brazing wire, which can be used as a make-and-break contact switch. By this method, such widely different parts as gold-filled iron or stainless steel, solid 10-carat gold, and gold-filled nickel or 10% nickel silver have been brazed together successfully. Staining can be kept at a minimum by use of the proper fluxes—ordinarily borates or phosphates, often containing a small amount of a fluoride.

* American Optical Company, Southbridge, Mass.

Dental Gold Solders

By Walter S. Crowell*

Dental gold solders are alloys of gold, silver, copper, tin and zinc. Small quantities of active deoxidizers, such as phosphorus, may be added to improve resistance to oxidation. Copper is replaced by nickel to produce solders approximately matching white or platinum-colored plate and wire. Copper and silver are varied to control color and working characteristics.

The precious-metal alloys on which gold solders are used have a high precious metal content and are confined to a relatively limited range of composition. Dental alloys are almost always soldered in an open flame. The solders are formulated for desirable properties under these conditions.

Applications. In dentistry there are two broad classes of applications for gold solder—orthodontia and crown and bridge work. In orthodontia the high-strength wires of precious metal described on page 1120 of this Handbook are joined. In crown and bridge work, parts made of 22-carat gold plate and the high-strength wires are assembled. In many instances the solder not only serves to join the parts but is also used in bulk as part of the structure itself. Complicated appliances may require assembly in steps by successive soldering operations, making it necessary to use a series of solders with graded melting points.

Composition. The gold content of dental solders varies between 40% and 85%. Most of the solder used contains between 58% and 65% Au. When solders contain less than 58% Au (about 14 carats), resistance to corrosion and tarnish decreases rapidly; consequently, appliances joined by such solders are unfit to remain continuously in the mouth. For repairing soldered structures, it is usual to employ lower-carat solders because of their lower melting temperatures. Lower-carat solders are often preferred for orthodontic soldering, since high temperatures tend to affect adversely the physical properties of the wires used in constructing appliances. Tarnish and corrosion are not serious factors, because these orthodontic appliances are not worn for extended periods. High-melting, usually high-carat, solders are required where stepwise assembly is practiced. High-carat solders are useful also where close matching of the color of high-carat plate is considered necessary.

Typical compositions and characteristics of solders are given in the table below. Hardness data represent averages of the class. Melting ranges are extreme limits.

Class	Composition, percentage[a] Gold	Silver	Copper	Bhn (as cast)	Melting Range, deg Cent
Low-carat	45	30–35	15–20	140	816–691
General-purpose	60	12–22	12–22	110	835–724
High-carat	80	3–8	8–12	80	871–746

(a) All three solders contain from 2 to 3% Sn and from 2 to 4% Zn.

When gold, tin and zinc contents are constant and copper and silver are varied, significant differences in working characteristics are obtained with only a small change in melting point (liquidus); also changes in color are produced. High-copper alloys have a rich goldlike color, while high-silver alloys are lighter and less goldlike.

Melting Range. The melting range of high-silver alloys is relatively shorter than that of high-copper alloys. When flowed on high-carat gold plate, the sharp-melting solders spread freely with a minimum of attack on the plate itself. The high-copper alloys, which have a longer melting range, attach themselves to the plate before they are entirely melted. On continued heating, they do not spread over the plate, but alloy with it and finally "burn through".

Flowing and Burning Through. These phenomena of flowing and burning through occur when the usual dental wrought plate and wire alloys are soldered. Variations in melting range are not the only cause of the observed behavior. An important consideration is the melting point of the alloy that is formed when the solder diffuses into the part being soldered. When the high-carat wrought gold dental alloys are used, the resulting alloy melts at a higher

* Supervising Chemical Engineer, S. S. White Dental Mfg. Co., Philadelphia

temperature than the high-silver solders, and at a lower temperature than the high-copper solders. This is probably the factor that determines whether the solder flows out over the parts or "burns through".

The free spread or flow of the high-silver solders and their slow rate of attack on the pieces that are being joined, are characteristics that recommend them for use when parts are well fitted, and when it is important to retain as far as possible the original properties of the pieces.

The high-copper solders are useful when it is necessary to add material to a part that is deficient in size because of wear, accident or design. A skillful operator can build up this type of solder, layer by layer, until a considerable bulk of metal is obtained. Such a practice is followed in the construction of soldered bridgework, where fitting surfaces are made of wrought plate and the remainder of the piece is built up of solder.

In the general-purpose solders, the composition is chosen so that neither "build-up" nor "flow" is overemphasized, and a material is obtained that incorporates a useful compromise in these properties.

Process. A discussion of the process of soldering with gold solder would be a repetition of what has been said in the article in this Handbook on silver brazing (page 78). The same principles apply to both procedures. Surfaces must be clean and well fluxed. (Borax glass is an excellent flux.) Parts must fit together closely and reducing flame must be applied.

Gold solders are used principally in the jewelry industry and in dentistry, and to a small extent in electronics.

Cladding With Gold and Silver

By Ermand H. Davignon*

The bonding of gold and silver and their alloys to base metals is a process that is being developed increasingly. Many physical and mechanical properties of base metals, highly desirable for certain applications, cannot be duplicated in the gold or silver alloys alone; but when these base metals are combined permanently with gold or silver alloys by cladding, new applications can be developed.

It is sometimes difficult to obtain the desired color and composition in a gold alloy and at the same time have the physical and mechanical properties that are optimum for the intended use. In many instances the cladding of a desirable base metal with a gold alloy of a definite carat and color, in the correct proportions, will give necessary mechanical properties unobtainable in the gold alloy alone.

The composite of fine silver (or suitable silver alloy) clad on the proper base metal has desirable spring qualities, greater hardness, and the ability to be spot welded. In addition, the silver can be clad with a predetermined thickness of solder for subsequent joining in subassemblies.

Methods. On flat sheet stock, the gold alloy to be bonded is proportioned in thickness to the base metal, in order to provide the specified ratio by weight for a composite article. For example, 1/10 12-carat "gold filled" would require a sheet of 12-carat gold (50.0% Au) approximately 0.056 in. thick, to be bonded onto a base-metal bar approximately 0.750 in. thick. The exact thickness of the 12-carat gold is determined by careful weighing so that the gold alloy will equal 10% of the composite assembly.

Some methods by which gold, silver and their alloys have been clad are described here:

Dry Bonding. By this method two or more surfaces can be bonded together without solder, by the application of heat and pressure. The temperature should never be allowed to exceed the solidus point of either metal. Dry bonding is sometimes referred to as "sweating".

Moist Bonding. This method makes use of a solder that has a wide plastic range before its melting point is reached. The liquid present in the solder is utilized while other phases are still solid.

Wet Bonding. This method joins metals with a solder that is completely liquid at the time of bonding.

Welded Bonding. Two metal surfaces are joined together without solder, in this method, while the temperature remains in the plastic range of one or both of the metals to be joined, never reaching the liquidus temperature before completion of the bond. The liquid of the joined metals is used to form the bond.

Puddled Bonding. This is the melting of one metal onto the surface of another that has a higher melting point.

Conditions of Operation. In cladding gold, silver and their alloys on base metals, four major requisites are necessary in order to insure results that will meet high standards.

1 The surfaces of the metals to be joined must be thoroughly cleaned.

2 The cleaned surfaces must be kept free from oxidation during the heating cycle, either by a flux or by suitable control of atmosphere.

3 The mode of heating and its control should be such that the temperature of the entire bar is uniform at the end of the heating cycle, and has the correct value for proper bonding.

4 Pressure should be applied during the heating cycle or at the termination of the cycle and should be held constant until a strong bond has been developed over the entire surface. Pressure is secondary to temperature in the bonding of metals, provided *complete* contact is effected at the proper time. The pressure necessary to produce a bond of high quality depends on several factors, such as the composition of the metals, the area of the surface, the thickness of the base metal, the temperature employed to effect the bond, and the method used for bonding. For example, if a base metal of 90% Cu, 10% Zn is to be clad with a gold or silver alloy, pressures would be as follows, on a bar one inch thick:

Dry bond	3000 to 4000 psi
Moist bond	1000 to 2000 psi
Wet bond	500 to 1000 psi
Welded bond	2000 to 3000 psi
Puddled bond	None

These pressures should be lower for metals that are less malleable at the temperature of bonding, such as tin bronzes, 70–30 brass, and gilding metal; and should be higher for metals such as Inconel, steel and pure nickel.

Solders used in cladding precious metals to base metals should be free from cadmium and low in zinc content. These two metals, having comparatively low boiling points, are undesirable in a solder to be used for cladding, since they frequently cause trouble by distillation, which may result in future blisters under certain conditions. Solders should be ductile enough to allow the clad metal to be rolled without danger of the bond becoming brittle. The melting point of the solder used must be high enough to allow for subsequent annealing and soldering of the finished composite metal without damage to the original bond. Metals to be clad are wired, clamped, or wrapped with sheet metal, steel plates and sheet asbestos before bonding. Furnaces that bond clad metals successfully are of the open-box gas-heated, salt bath, closed-box (electric-resistance or gas-heated) and bell types. Also, as a recent trend, high-frequency electric heating is being used for cladding precious metals.

* Metals & Controls Corp., Attleboro, Mass.

Cladding With Platinum and Palladium

By F. E. Carter *

Platinum, palladium and their ductile alloys can be welded or brazed to silver or to base metals by the same general procedures employed in cladding with gold or silver. However, welding is ordinarily preferred for the platinum metals, since it permits the use of higher annealing temperatures with minimum damage by diffusion, and permits the use of pure gold or related high-melting solders for final assembly. In any event, the possible melting of the alloys that are developed at interfaces must be avoided. The minimum melting point in the palladium-nickel system is 1240 C; in the platinum-nickel system, 1400 C. Cladding is most easily done on nickel cores, and less easily on silver, copper, and molybdenum. Molybdenum is very difficult to clad.

* Baker & Co., Newark, N. J.

The plates of platinum and base metal may have a ratio of thickness between 1 to 1 and 1 to 100. After bonding, the composite block is cold rolled to the thickness required for utilization as sheet, or blanks may be cut from the stock, to be pressed and drawn into seamless tubing. The cladding may be applied to one or both surfaces of the base metal; consequently, seamless tubing is available clad on the inside, on the outside or on both surfaces. Similarly, rod and wire with outside cladding are fabricated from platinum tubing welded to silver and base-metal cores. From these elemental forms, a large variety of chemical and electronic equipment may be constructed. Strip that is clad with palladium or platinum is used for electrical contacts, and platinum-clad molybdenum and molybdenum-nickel wire are used for grids in VHF (very high frequency) electronic tubes.

Applications. The development of clad equipment for heat exchangers has been most successful. Heating and cooling coils, bayonet and candle heaters, and evaporators have been built with the tubes and tube sheets. Platinum-clad anodes are being used increasingly as insoluble anodes in electroplating processes, and often as supplementary anodes in the electrodeposition of nickel on intricate shapes, to secure uniform deposition despite the irregularities. Long experience has indicated that the platinum thickness should not be less than 0.004 in. where plant equipment is concerned. Usually a thickness of 0.005 in. is recommended as the minimum; 0.010 in. is desirable. Before installation, all clad materials can be thoroughly tested with acids for continuity of the platinum surface, and methods are available for repairing minute punctures in the cladding.

If clad material is to be used at temperatures higher than about 700 C, the rate of diffusion of the base metal into the platinum and of platinum into the base metal must be considered, and if the composite is to be used in atmospheres that would oxidize the core material, the rate of diffusion of oxygen through the platinum is important, because oxygen, reacting at the metal-to-metal interface, will oxidize the base metal and ultimately damage the cladding. The duration of usefulness increases rapidly in length with an increase in the thickness of cladding. Fortunately, the diffusion rate of nickel and copper into platinum is rather low; at 800 C, for instance, the diffusion rate for low concentrations of nickel into platinum is 1/600 of the rate of diffusion of nickel into gold at the same temperature.*

Platinum-clad silver has been used at temperatures as high as 750 C; this is considered a maximum for silver core material. Platinum-clad copper has been used at temperatures as high as 800 C, and platinum-clad nickel or steel at slightly higher temperatures. In any event, equipment operating at high temperatures requires individual consideration. Under some circumstances, a thin platinum tube may be inserted into a preoxidized nickel-chromium or stainless steel tube, or ceramic supports can be used.

Induction Heating for Cladding

By Carl Samans*

In the cladding process for the manufacture of 12-carat gold-filled wire, a core, generally of nickel or bronze, 1.3 in. in diam and 12 in. long, is slipped into a shell of gold alloy that weighs one-tenth of the total. A sheet of silver solder, 0.002 in. or 0.003 in. thick, and a trace of flux are interposed between the core and the shell; then the shell is drawn down to a snug fit. The assembly is placed within a cooled solenoid, fed by a 6-kva, 35,000-cycle tube converter, and is rotated slowly until the solder melts and effects a good bond.

In the manufacture of flat stock, arrangements have been developed so that external pressure can be applied simultaneously with the heating, which may be accomplished with a low-frequency (60-cycle) supply; about 75 kva is required.

A number of features involved in the above process were developed by W. J. Wrighton and T. C. Jarrett (U. S. Patents 2,273,609; 2,284,504; and 2,360,185).

* Kubaschewski and Ebert, Z Elektrochem, 50, 138 (1944)
* American Optical Company, Southbridge, Mass.

Electroplating With Precious Metals

GOLD, silver, platinum, palladium and rhodium are electrodeposited on various base metals in order to obtain a surface that is pleasing in appearance, resistant to corrosion or oxidation, or high in reflectivity. Often one precious metal is plated on another precious metal as a finish. The more important plating solutions and conditions of operation are described here, and brief remarks are included concerning the usefulness of the electrodeposited coatings.

Gold and Gold Alloy Plating

By Louis Weisberg*

GOLD and gold alloy electrodeposits are generally produced in cyanide solutions, except in gold refining, where the chloride solution is used. A distinction is sometimes made between flashing or coloring (which involves very thin deposits, seldom much more than 0.00001 in.) and heavy gold plating. The only important difference lies in the degree of control and the amount of care required. Coloring is subject to precise control but, in practice, is usually judged by eye.

Color is a dominant consideration in many applications. A pure gold deposit normally has an orange cast. The color may be influenced to some extent by choice of temperature, current density and other variables, but most colors are obtained by plating gold alloys. Addition of copper makes pink or red gold; silver or cadmium makes green; nickel or zinc, white. So-called "white gold" deposits, at best, are hardly white enough to pass as such and are usually covered with a rhodium flash. A wide range of gold colors can be obtained; one color that cannot be matched by any of these alloy deposits, however, is the rich orange yellow of 24-carat gold.

* Louis Weisberg, Inc., New York

Table I. Composition of Gold Plating Solutions

Material	Grams per liter				
	24-carat	Red	Green	Yellow	White
Gold	1.5	1.5	1.5	1.5	1.5
Copper	...	1	...	0.8	...
Silver	...	...	0.1	0.15	...
Nickel	...	...	...	...	5
Zinc	...	...	...	...	0.5
Free potassium cyanide	8	8	8	0.2	3
Potassium carbonate	15	15	15	15	15

Combinations of three or even four metals may be employed to obtain the properties desired in the deposit. Some typical gold plating solutions are shown in Table I.

The compositions of some typical gold deposits are shown in Table II.

It is clear from comparison of Tables I and II that the proportions in which various metals are present are by no means the same in the deposit and in the solution.

Current density, temperature, and the content of free cyanide are just as important as the metal composition in the operation of gold plating solutions. In most gold

Table II. Composition of Gold Deposits

Material	Composition, percentage				
	24-carat	Red	Green	Yellow	White
Gold	100	94	97	75	85
Copper	...	6	...	8	...
Silver	...	...	3	17	...
Nickel	...	...	...	...	■
Zinc	...	...	...	...	10

plating, the temperature of the solution ranges from about 110 to 150 F. The middle of the range is preferable. High current efficiency is favored by high metal content, low current density, high temperature and moderate amounts of free cyanide. High content of carbonate decreases current efficiency. Increased free cyanide content raises the conductivity and improves the throwing power of the solution.

Cathode current density for ordinary gold plating should not exceed 5 or 10 amp per sq ft. If the solution is agitated vigorously or if there is rapid motion of the work material relative to the solution, the current density can be increased far beyond these values without much, if any, drop in current efficiency.

Anodes of gold or of a suitable gold alloy may be employed. Since these do not always dissolve at the same rate as that at which metal is deposited at the cathode, supplementary insoluble anodes are used occasionally. Some platers prefer to use only insoluble anodes and to replenish the solution by adding salts. Either method is satisfactory if adequate control is provided.

An ampere-hour meter facilitates control, especially if it is adjusted to signal when additions should be made. For this purpose, it is important to know the weight of metal deposited per ampere-hour as well as the composition of the deposit. With 24-carat deposits, the weight laid down per ampere-hour may approach 7.3 g; with alloy deposits, the weight per ampere-hour is likely to be about 2.5 to 3.5 g.

Thick deposits of alloy are sometimes brittle and require heat treatment to produce satisfactory physical properties. Heat treatment of such deposits often causes a change of color, on account of diffusion between the gold layer and the underlying metal. Where the underlying metal may be softened too much by the heat treatment, use can be made of an age hardening base metal chosen so that the same heat treatment is applicable to the base metal and to the gold coating.

Success in depositing gold alloys requires the maintenance of uniform operating conditions. Replenishment of the solution depends on the principle that what goes in must equal what comes out. Allowance must be made for loss of solution by drag-out as well as for the composition of the deposit. Uniform distribution of deposit, and deposition of the proper amount of gold on each piece are factors that rank in importance with the maintenance of color and physical properties.

Silver Plating

BY N. E. PROMISEL*

SILVER can be plated from a variety of baths, but except in special instances, the cyanide type of bath is the one used commercially. The basic constituents of this bath are silver, sodium or potassium cyanide to dissolve the silver as a complex salt, plus an excess quantity of cyanide (called "free cyanide") and either sodium or potassium carbonate. Generally the potassium salts are preferred, though they are somewhat more expensive. Potassium nitrate is sometimes used to replace the carbonate. To obtain semibright rather than matte white deposits, very small amounts of carbon disulfide, or in certain instances other brighteners, are added.

Most silver plating is done by using two baths in succession. (When steel is to be silver plated, it is given a copper "flash" or treated as indicated under Strike Solution, below.) The first bath, called the "strike" solution, has a low concentration of silver and a high cyanide content. This solution serves several functions, primarily promoting good adhesion and improving covering power and throwing power. The strike solution is used to produce only the initial flash coating and is rarely used longer than a minute or two. This "flashing" is then followed by silver plating in the second or "plating" solution, in order to build up the deposit to the desired thickness. In all instances the work pieces must have been cleaned well previously, pickled, and immersed in a cyanide dip.

* Bureau of Aeronautics, Navy Dept., Washington

The anodes used for silver plating should be the purest obtainable, in general not less than 999.5 fine. This is important because very small traces of certain impurities may cause "black anodes", that is, the covering of the anode by a blackish scum that interferes with corrosion of the anode and the composition of the bath, and may cause rough deposits. A high content of free cyanide minimizes this danger, especially at the higher current densities. The content of free cyanide should always be ample to ensure good corrosion of the anode. The ratio of anode to cathode areas should not be less than one to one.

For general purposes, the formulas of Tables III and IV have been used successfully; many modifications are possible.

Table III. Strike Solution for Silver Plating

Material	Range	Recommended
Silver cyanide[a]	0.25 to 0.87 troy oz/gal	0.62 troy oz/gal
(Metallic silver equivalent to above)	0.2 to 0.7 troy oz/gal	0.5 troy oz/gal
Sodium cyanide (free)	8 to 14 avdp oz/gal	10 avdp oz/gal
Temperature	.....	22 to 30 C, preferably 26 C
Current density	.....	15 to 25 amp/sq ft
Voltage	.....	Usually about 6 volts

(a) In plating directly on steel, a preliminary strike is used, containing about one-third as much silver. Fractions of 1 oz of copper cyanide per gallon may also be added, if necessary, to improve adhesion.

For the potassium cyanide and carbonate in the above plating solution, the cheaper sodium cyanide and carbonate may be substituted, in quantities of 2.5 to 5.0 oz avdp per gal and 3 to 10 oz avdp per gal, respectively. In instances when, for reasons of economy, 15 to 20 oz avdp of potassium nitrate per gallon is added to the "sodium" solution, the quantities of the other constituents are held to the lower part of the range. Agitation of the work material is nearly always desirable.

For contact with the solution, iron is a convenient and satisfactory material for tanks, anode racks and cathode racks, especially if its original tight black scale has not been removed. However, care should be taken not to contaminate the solution with chlorides. Ceramic material and glass may also be used where practicable, and several

Table IV. Solutions for Silver Plating

Material	Range	Recommended
Silver cyanide	2.5 to 4.3 troy oz/gal	3.7 troy oz/gal
(Metallic silver equivalent to above)	2.0 to 3.5 troy oz/gal	3.0 troy oz/gal
Potassium cyanide (free)	4 to 7 avdp oz/gal	5.5 avdp oz gal
Potassium carbonate	5 to 15 avdp oz/ gal	6.0 avdp oz/gal
Brightener (carbon disulfide dissolved in a cyanide solution)	.....	As needed (avoid excess)
Temperature	22 to 26 C	preferably 26 C
Current density	8 to 20 amp/sq ft	
Voltage	Generally not more than 1 volt, depending on the plating conditions and geometry of the setup	

synthetic plastics have been successful, such as phenol-formaldehyde and some polyvinyl types.

If proper attention is paid to minimizing drag-out and if enough anodes are used, the silver content of the bath will be maintained automatically at the desired value. If silver is needed, the best addition is a silver cyanide. While the bath is standing, as well as while it is in use, the free cyanide content will gradually decrease and must be replenished. The brightener disappears also, even when the bath is not in operation. It is better to add small quantities of brightener often than to add large quantities at one time. Impurities and dirt should be kept out of the solution, but few of the common impurities (except sometimes iron) give trouble. The carbonate content of the bath increases gradually. When more than 12 oz of carbonate per gallon is present in a "sodium" solution, and more than 15 oz per gal in a "potassium" solution, the excess should be removed either by adding gypsum and filtering or by lowering the temperature to very low values to precipitate the sodium carbonate.

For special applications, it may be advantageous to modify the plating conditions. For example, in plating bearings, higher temperatures, greater agitation, special racking, more concentrated solutions, and additions of potassium hydroxide, permit much higher current densities and give good, heavy deposits expeditiously.

Platinum and Rhodium Plating

By K. Schumpelt*

PLATINUM and palladium have long been electrodeposited, and the commercial deposition of rhodium, although more recent, has advanced rapidly. These metals can be deposited directly on precious metals as well as on copper and nickel and on copper and nickel alloys. When base metals and their alloys are to be electroplated, a nickel underplate is desirable, and is essential for plating on tin, zinc, and tin or zinc alloys.

Electrodeposits of platinum and rhodium are used for ornamental or decorative finishes and also for finishes that are to perform a definite function; for instance, as a permanent reflector, as protection against oxidation and finger stains, or as an oxide-free, hard, gall-resisting surface on sliding electrical contacts. Many essential parts in radar and other electronic equipment have been rhodium-plated.

Complex phosphate baths have long been used for depositing platinum; two such compositions are given below:

	A	B
Ammonium phosphate $(NH_4)_2HPO_4$	20 g	43 g
Sodium phosphate $Na_2HPO_4 . 12H_2O$	100 g	120 g
Pt as $H_2PtCl_6 . 6H_2O$	4 g	6.6 g
Water	1000 ml	1000 ml

Operating temperature, 90 C; current density, about 1 amp per sq dm; 3 to 4 v, with insoluble platinum anodes.

The above formulas give bright flash deposits at a pH of about 7. For building up heavier deposits, the bath should be made strongly ammoniacal. The rate of deposition is rather slow, about 8 mg Pt per amp-min.

The solution, which originally has an orange color, should be boiled until it becomes pale yellow. During this boiling, the platinic chloride is transformed into a complex ammino phosphate. Since the bath is operated with insoluble platinum anodes, the metal content must be replenished by additions of platinic chloride; after each such addition, the boiling should be repeated. Chlorides gradually accumulate in the bath to a point where good deposits can no longer be obtained.

To permit replenishment without accumulating chlorides, an ammino nitrite of platinum, called platinum "P" salt, containing 61% Pt, was devised. One bath based on the use of this salt has the following composition:*

Ammonium nitrate	100 g
Sodium nitrite	10 g
Platinum as diammino nitrite	10 g
Ammonia	50 ml
Water	1000 ml

Operating temperature, 95 C; current density, 6 to 13 amp per sq dm; 4 to 5 v.

This solution covers quickly and has rather good throwing power. For the building up of heavy deposits, a voltage of 2.5 and a current density of 6 amp per sq dm are recommended. The bath is replenished with platinum "P" salt, dissolved in ammonia.

Rhodium† is generally employed for producing rather thin, very white, highly reflective plates, that can be secured from either the sulfate or complex phosphate baths. In either instance the rhodium is generally supplied in the form of a concentrated solution.

Baths for rhodium plating are:*

	A	B
Sulfuric acid	20 ml	.....
Phosphoric acid	.....	10 to 40 ml
Rhodium (in prepared solution)	2 g	2 to 4 g
Water	1000 ml	1000 ml

Optimum operating temperature, 40 to 45 C; current density 1 to 8 amp per sq dm; 2.5 to 5 v.

Insoluble platinum anodes are used, and the bath is replenished with the concentrated solution of rhodium supplied by the manufacturer. The rate of deposition varies from 2 to [illegible] mg per amp-min for different types of solutions.

Where rhodium or one of the other platinum metals is to be applied to Invar, Kovar or stainless or ordinary steel, special treatment of the base metal is required to secure an adherent nickel plate. For outdoor exposure or at high humidity, the nickel plate should be 0.002 or 0.003 in. thick, since the surface is very noble, and if pores are present, rapid attack on the underlying metal can occur. For many purposes, rhodium deposits 0.000006 to 0.00001 in. thick are sufficient, but where heavier plates up to 0.001 in. are required, special sulfate solutions are employed.

* Baker & Co., Newark, N. J.

* Keitel and Zschiegner, U. S. Patent 1,779,436

† Editor's Note. For further discussion of the engineering properties and uses of rhodium electrodeposits, the reader may refer to an article by L. B. Hunt in Met Ind (London), 71, 339 (1947).

Palladium Plating

By R. H. Atkinson*

PALLADIUM in its use for thin decorative platings has been overshadowed by rhodium, which is harder and has higher reflectivity (80%, compared with 60%), but palladium is superior for thick deposits (0.0001 in. and thicker). The following bath[1] is suitable for thin decorative and protective plates:

Palladium (as dinitro-diammino palladium)	10 g per liter
Ammonium nitrate	100 g per liter
Sodium nitrite	10 g per liter
Ammonia (sp gr 0.880)	50 ml
Temperature	40 C
Anode (insoluble)	Pd or Pt
Current density	0.1 amp per sq dm

Another bath[2] has been developed for heavy deposits required in electroforming:

Palladium (as chloride)	50 g per liter
Hydrochloric acid	18 g per liter
Ammonium chloride	20 g per liter
pH	0.4
Temperature	70 C
Anode (soluble)	Very pure palladium
Current density	1 amp per sq dm

The ammonium chloride refines the grain size of the deposit, but since it makes deposits likely to blister when heated, it should be omitted or replaced by sodium chloride if the plated articles are to be heated subsequently. The palladium chloride and the palladium anodes must be extremely pure to yield ductile, heavy plates. Base metals that are attacked by hydrochloric acid should be plated first in the dinitro-diammino bath, or with gold.

In addition to the foregoing, other baths[3] have been found suitable for both thin and thick deposits.

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1 W. Keitel and H. E. Zschiegner, Trans Electrochem Soc, 59, 273 (1931)

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* Baker & Co., U. S. Patents 1,949,131, 1,981,820, and others.
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* The International Nickel Company, Inc., Bayonne, N. J.

Polishing Precious Metals

By H. K. Stegeman*

THROUGH all rolling and forming operations on articles made of precious metals, great care is used in maintaining the high quality of the surface; however, several additional finishing operations are necessary for producing the excellent quality of surface generally required. These operations include the removal of sufficient metal to develop an essentially smooth surface, and then buffing to develop the maximum specular reflectivity; or controlled, fairly coarse abrasion, to produce the "butler" finish. Scratch brushing also is sometimes used for producing a final finish, and is ordinarily employed as a cleaning operation before the last press operation, when the work is coined in highly polished dies.

Where the objects have sharp corners that must be preserved, or where they have rather large, essentially flat areas, lapping is the best surfacing method. In this operation the work piece may be brought into contact with either the end, side or circumference of the hard felt lap.

Lapping

1 Felt wheels, from ¼ to 10 in. in diam
2 Spindle speed, from 2000 to 3450 rpm
3 Compound, tripoli or a mixture of 600-grit aloxite and stearic acid

Lapping may be followed by a cutting buffing, or the buffing may be used instead of lapping on objects that have rounded contours.

Buffing

1 Cotton buffs, 64 by 68-weave and from 6 to 8 in. in diam
2 Spindle speed, from 2000 to 3450 rpm
3 Compound, tripoli

Brushing is used where the objects are very irregular or where decorations have appreciable depth.

Brushing

1 China hog-bristle brushes, 3½ in. in diam
2 Spindle speed, 3450 rpm
3 Compound, red rouge (greasy type)

* Wadsworth Watch Case Co., Dayton, Ky.

Following the lapping or cutting buffing, buffing with greasy rouge and color buffing with dry rouge are suitable for the usual gold alloys and silver, and provide the final specular finish desired.

Rouge and Color Buffing

1 Cotton buffs, 64 by 68-weave and from 4 to 8 in. in diam
2 Spindle speed, 3450 rpm
3 Compound, red rouge (grease or dry type as required)

For platinum and palladium, separate wheels are required in order to avoid transferring particles of gold to these metals, and thus causing a slight yellow cast. A cutting buff charged with tripoli is used and should be followed by cleaning in hot water that contains ammonia and soap. After this cleaning, white rouge is applied with the type of cotton buff described above, and the metal is cleaned with hot water, ammonia and soap as before. Red rouge is not desirable on the platinum metals.

Alternatively, a "butler" finish may be used as the final finish. It can be produced by the wheel method or by abrasion with a sharp cutting material such as 240 or 320-grit emery cloth.

Butler Finishing

Wheel Method.
1 Cotton buffs, 64 by 68-weave and from 6 to 8 in. in diam
2 Spindle speed, 1750 rpm
3 Compound, No. 240 grit greaseless

Hand Method.
1 Either 240 or 320-grit emery cloth
2 Abrading performed by hand

Scratch Brushing Carat Gold Alloys and Sterling Silver

1 Brushes
(*a*) German silver, 2½ in. in diam by ⅜ in. wide with wires ¾ in. long
(*b*) Brass, 1½ in. in diam by ⅛ in. wide with wires ¼ in. long
(*c*) Brass, 2½ in. in diam by ⅛ in. wide with wires $\frac{5}{16}$ in. long
2 Spindle speed, 1800 rpm
3 Lubricant, warm water or soapbark solution for press cleaning

The Metallography of Precious Metals

By E. M. Wise*

MOST SAMPLES of precious metals are small and require mounting before they can be examined microscopically. Because it is transparent, methyl methacrylate is generally preferred to bakelite as a mounting material. Where electrolytic etching is to be employed, small samples should be wrapped with a connecting wire before being mounted. This is unnecessary for large samples, since contact can be made with the face of the specimen in a region not to be examined.

Polishing. In polishing the precious metals it is extremely important to avoid surface flow, because shallow etches will be employed, and some of these metals have a marked tendency to pit during continued etching.

Grinding successively on 180, 240, 320 and graphited 400-grit silicon carbide papers is generally satisfactory. After the sample has been washed carefully, it may be polished on two 6-in. diam disks covered with unweighted flat silk crepe. The first disk runs at 300 to 500 rpm and is wet with a suspension of A. O. M303 or Fisher 12–300–3 abrasive, diluted 1 to 5. Four or five minutes on this wheel may be required for developing a good surface on the specimen. After the sample and the hands of the operator have been washed, further polishing is done on a disk wet with Rite Tonerde No. 3, diluted 1 to 2. This step may require two minutes, at 600 rpm.

* The International Nickel Company, Inc., New York

Etching. The most widely used nonelectrolytic etch is a mixture of equal volumes of 10% ammonium persulfate in water with 10% KCN in water.* Although the separate solutions are stable in air, the mixture must be used within a few minutes after being made. Since this solution and the fumes from it are poisonous, it should be used under a hood. The fumes also make tobacco smoke taste very unpleasant, but aside from these disadvantages, the mixture is excellent. When swabbed on specimens of the usual gold alloys and palladium alloys, the mixture acts rapidly and smoothly. It may be used also on silver and certain nickel alloys. For the more resistant alloys, 20% solutions may be employed.

These same metals can be etched when made the anode in a 5% KCN solution, but this is not effective for platinum and the usual platinum alloys, which are best etched with alternating current in a 5% NaCN solution at a current density of 0.5 to 1.5 amp per sq cm. Only one or two minutes is required for etching pure platinum at this current density. The cathode in this etching solution is platinum, and the voltage is from 1 to 5, preferably delivered from a low-voltage transformer fed from a small Variac. This etchant can be used also with palladium and gold alloys.

Another etchant widely used with the a-c etching pro-

* Adapted to metallography by E. M. Wise, from the work of M. C. Jewett, who developed this reagent for a somewhat different purpose.

cess, is a 20% solution of hydrochloric acid in water saturated with sodium chloride.[1] This can be used with most of the platinum metals, but rhodium is best etched with 20% H_2SO_4 in water, using alternating current.

Sterling silver and fine silver are usually etched by swabbing with a modified chromic-sulfuric mixture.* A concentrated stock solution is made, containing 100 ml saturated solution of potassium dichromate in water, ▮ ml saturated solution of sodium chloride in water, and 10 ml concentrated sulfuric acid, added slowly. One volume of this solution is added to 9 volumes of water before use.

Various etches are available for special purposes; for instance, pure palladium may be etched with concentrated cp nitric acid to which a trace of chloride has been added in the form of a drop of tap water per 20 ml of nitric acid.* For darkening certain precipitates in 14-carat Au-Cu-Ag alloys without attacking the matrix, a 25% solution of ferric chloride in water has been employed after adding it to an equal volume of a water solution that contains 3% H_2O_2.[2] Dilute aqua regia and various molten chloride mixtures containing oxidizing agents have been employed for etching platinum alloys, but the use of a-c etching has virtually eliminated interest in these.

* As modified by C. H. Chatfield

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PROPERTIES OF PRECIOUS METALS

SILVER AND SILVER ALLOYS

Silver

COMPILED BY E. M. WISE*

B *1 Important uses.* The photosensitivity of silver halide salts, particularly in sulfidized areas, and the ease with which silver can be reduced, are the basis of photography. Silver offers advantage over copper for electrical purposes, principally because of resistance to oxidation; it is used both solid and as an electroplate for contacts in electrical devices, and performs best where sufficient arcing and wear occur to keep the contact clean, and where the contact pressure, current and voltage are not too low. Other industrial uses are based on corrosion resistance, catalytic activity, ease of electrodeposition and, particularly in brazing alloys, on the moderately low melting point and good mechanical properties of many of the silver alloys. Uses in bearings also are important (*see* page 754). The high and uniform reflectivity in the visible region and the ease of deposition are responsible for use in reflectors and in silverware and jewelry. Resistance to corrosion by foods and organic acids is a factor in these latter uses. The first use of silver alloys for coinage probably resulted from appearance and moderate scarcity.

C *1 Density* at 20 C (68 F). 10.49 ▮ per cu cm (0.379 lb per cu in.).[2] 10.50 ▮ per cu cm computed from lattice parameter and atomic weight.[3] Density is lowered by cold work and probably by oxygen.

Solid, at 960 C (1760 F). 9.85 ▮ per cu cm (calculated from linear expansion data)

Liquid, at 960 C (1760 F). 9.3 g per cu cm
at 1100 C (2012 F). 9.18 g per cu cm
at 1200 C (2192 F). 9.1 ▮ per cu cm[14,15]

D *1 Melting point.* 960.5 C (1760.9 F) for *oxygen-free* silver. Freezing point in approximate equilibrium with the oxygen in the atmosphere (partial pressure of oxygen 149 mm Hg) is about 950 C (1740 F).[4,5] Freezing point is not lowered by carbon.

4 Vapor pressure of liquid silver.[7,8,9]

Temperature, deg Cent....	1190	1360	1580	1870	2212
Vapor pressure, mm Hg....	0.1	1	10	100	760

The rate of volatilization is quite high at high temperatures and is greater under oxidizing gases than under reducing gases.[6]

* The International Nickel Company, Inc., New York

6 Thermal expansion from minus 190 to 0 C (–310 to 32 F).[10,11,12] 0.0000170 per °C
0 to 900 C (32 to 1652 F).[13]

$L_t = L_o (1 + 19.494 \times 10^{-6}t + 1.0379 \times 10^{-9}t^2 + 2.375 \times 10^{-12}t^3)$

0 to 100 C (32 to 212 F).[2] 0.00001968 per °C
0 to 500 C (32 to 932 F). 0.00002061 per °C

11 Specific heat at 0 C (32 F).[16] 0.0559 cal per g
at 100 C (212 F).[16] 0.0568 cal per ▮
0 to 800 C (32 to 1472 F).[16]

$C_p = 0.055401 + 0.14414 \times 10^{-4}t - 0.16216 \times 10^{-8}t^2$

At 39.8 K, 0.00187 cal per g. Between 3 and 4 K, the value drops to 0.1% of that at 39.8 K

13 Latent heat of fusion.[3] 25 cal per g approx

15 Latent heat of vaporization.[2] 556 cal per ▮ approx

16 Thermal conductivity at 0 C (32 F). 1.0 cgs. This is about 8% higher than for copper, and shows only a small temperature dependence. Values of 1.018 cgs at minus 183 C (minus 297 F) and 0.85 cgs at 450 C (840 F) have been reported.[2]

19 Recrystallization temperature. Probably about room temperature, under extreme conditions.

E *1 Volume conductivity* referred to standard copper. 108.4% for extremely pure silver (105% referred to very pure copper)

2 Electrical resistivity at 20 C (68 F). 1.59 microhm-cm for extremely pure silver, melted and annealed in vacuo. This is 94.5% of that of equally pure copper.[19] 1.47 microhm-cm has been calculated for 0 C (32 F) from the temperature coefficient and the resistivity at 20 C.[20]

5 Temperature coefficient of electrical resistivity 0 to 100 C (32 to 212 F).[20] 0.0041 per °C. The temperature coefficient for minus 192 to 500 C[20] and from 500 C to above the melting point[21] is shown in Fig. 1.

At 20.4 K, R_t/R_o is about 0.01 and at 1.3 K, 0.0068.[22] Cold working silver increases its resistivity considerably, an increase of 5% for 90% reduction has been observed.[23] Annealing silver of commercial purity, successively in air and hydrogen, disrupts the grain boundaries and also increases the resistance.

Hydrostatic pressure reduces the resistivity slightly; 12,000 kg per sq cm causes a 4% reduction.[24] Tension also reduces the resistance slightly.

9 *Thermal emf versus platinum* (cold junction 0 C, hot junction at 100 C)[2] is plus 0.74 mv

F 1 *Reflectivity.* This value for clean silver is high in the visible and infrared, but shows a sharp valley in the near ultraviolet. The curve of Fig. 2 is from the work of several investigators,[27,28] whose data are in fair agreement in overlapping areas. As a result of the high and fairly uniform reflectivity in the visible range, silver is considered white, but if human eyes were sensitive to a slightly shorter wave length region, silver would be colored.

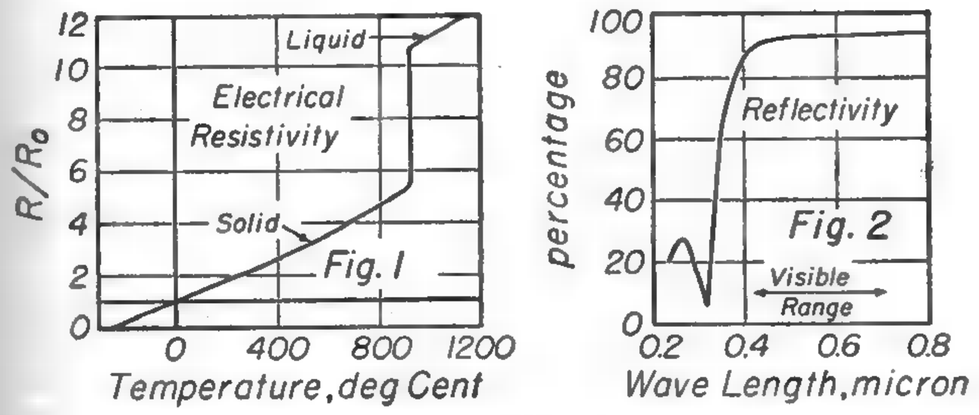

Fig. 1 and 2 Resistivity and reflectivity of silver

5 *Emissivity.* The emissivity of silver at 0.65 microns is extremely low and not known accurately, but values of 0.044 at 940 C (1724 F) and 0.072 at 980 C (1796 F) have been observed for liquid silver.[25] Other experiments on the relative emissivity of silver and a black body show no discontinuity at the melting point of silver, the emissivity being about 0.055 at about 700 C (1292 F) and increasing only slightly at 1800 C (3272 F).[26]

G 2 *Mass magnetic susceptibility.*[33] Minus 0.020 × 10^{-6} cgs

I 2 *Resistance to specific agents.*

Silver is resistant to acetic acid and has been used for condensers handling this acid. It is also resistant to various other organic acids and foods that are free from sulfur. It shows good resistance to phenol and to hydrofluoric and phosphoric acids. It is resistant to sodium and potassium hydroxides, is used in the laboratory for caustic fusions, and has also been considered for large equipment. It is attacked by moist bromine, iodine and chlorine and vigorously by HCl, HI and HBr. Alkaline cyanides, in the presence of air or other oxidizing agents, dissolve silver rapidly. Nitric acid that contains traces of nitrous acid attacks silver vigorously as does hot concentrated sulfuric acid. Hot dilute sulfuric acid also attacks silver. A more complete discussion is presented in the "Corrosion Handbook".[34]

Silver does not appear to oxidize at room temperature in air and thus differs from copper, but is attacked and blackened by ozone. Silver oxide however does exist and has extremely high resistivity. Sulfur attacks silver rapidly as it does copper, and the rate of tarnishing of silver in indoor atmospheres is determined by the supply of sulfur atoms, since the coating is nonprotective. This sulfide decreases the reflectivity of silver and also increases the electrical contact resistance, particularly at low currents, since it is nonohmic in character. The rate of sulfidation of silver indoors in a large city is of the order of 70 micrograms per sq dm per day.* Much work has been done searching for a tarnish-resistant high-silver alloy, but it appears that substantial additions of noble metals are required to achieve this goal, about 50% palladium[34]* or 70% gold being needed for complete resistance. Various protective plates have been used to protect silver from tarnishing. Of these, rhodium plate applied over a very thin nickel plate is the most successful and maintains a very pleasing appearance.

J 1 *Crystal structure.* Face-centered cubic; lattice parameter 4.0778 kX at 18 C (64 F).

K *Mechanical properties.*

Tensile strength and hardness. Considerable spread exists in values reported for both tensile strength and hardness of quite pure silver. An average of 18,200 psi for tensile strength has been reported[31] for 5-mm wire annealed at 600 C. Commercially pure silver (about 999 fine) annealed at 650 C had a tensile strength of 22,900 psi.[2] Work on the effect of oxygen on the hardness of annealed silver of various purities[32] indicates that oxidation of impurities during oxidizing anneals generally causes a substantial increase in surface hardness and restrains grain growth, effects that are absent in spectroscopically pure silver. Very pure silver had a Vickers hardness of 25 after a hydrogen anneal at 650 C, and 27 VPN after annealing in air at 650 C. 100 VPN was obtained on electrodeposited silver that had a higher electrical resistivity than wrought silver.*

Yield strength. 7900 psi (divider method) was reported for commercially pure silver.[2] The proportional limit for pure silver strained 5% and annealed 1 hr at 700 C is 670 psi. The 0.01% proof stress is 1100 psi.[29]

Elongation (over 20 mm) for 5-mm wire is 48%.[31] For commercially pure silver, 54% elongation.

Reduction of area for 5-mm wire.[31] 91%

Modulus of elasticity for silver strained 5%, then heated 0.5 hr at 350 C is 10,300,000 psi.[29] Another value from the same investigator is 11,300,000 psi.

Poisson's ratio for annealed silver is 0.37, and for hard drawn material is 0.39.[30]

N *Working data.* Because molten silver dissolves oxygen and evolves some of it on solidification, the oxygen content should be brought to a low level before the metal is poured. Where high electrical conductivity is required, purity must be maintained as with copper, but iron need not be guarded against. Sulfur is undesirable, as are many base metals. The solid solubility of oxygen in silver and the rate of diffusion of oxygen through hot silver are high; consequently silver of normal purity will be damaged if it is heated first under oxidizing conditions and then in hydrogen.[32,35]† Academically pure silver may not be damaged by this treatment.[32] The effect of heating first in hydrogen and then in air is probably negligible.[32]†

9 *Annealing temperature.* 300 C (572 F) is suitable for commercially pure silver, cold worked at least 50%.

11 *Suited to forming* by hot or cold methods, with high reductions, since the metal is extremely ductile.

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† E. M. Wise and R. F. Vines, unpublished research

Silver-Copper Alloys

By E. M. Wise*

THE SILVER-COPPER alloys have been used for thousands of years. These elements are reduced together in most refining operations. Traces of copper are likely to be present in commercial silver, and copper containing up to 30 oz Ag per ton is produced to provide a higher recrystallization temperature without impairing the conductivity of copper. Copper is effective in hardening silver, but lowers the melting point considerably and lowers the electrical and thermal conductivities appreciably.

Sterling silver must contain at least 92.5% Ag. The remainder is unrestricted but is normally copper since, in general, other metals have proved less desirable and are less effective hardeners. The 10% Cu, 90% Ag alloy is called "coin silver". The eutectic alloy contains 28.1% Cu.

Although sterling silver can be age hardened without difficulty, and part of the merit of this composition in providing acceptable properties after miscellaneous treatments, results from some hardening on cooling in air, the fact that this alloy can be age hardened escaped notice by metallurgists for more than 1000 years. Substantial hardening can be obtained by simple treatments, as was discovered in 1922 from tension tests on sterling silver quenched from 650 C, and also after annealing at 650 C and aging at 325 C for 30 min.[2] The quenched material had a tensile strength of 37,400 psi, and a yield strength of 19,700 psi, with 42% elongation, while the quenched and aged material showed a tensile strength of 43,400 psi, and a yield strength of 30,000 psi with 25% elongation. This was discovered independently by Fraenkel in 1926,[3] and in 1927 by Norbury,[4] who performed tension and hardness tests on sterling silver quenched and aged for ½ hr at a series of temperatures. Numerous investigations have since been made concerning the hardening process[5-8] and the correction of the equilibrium diagram.

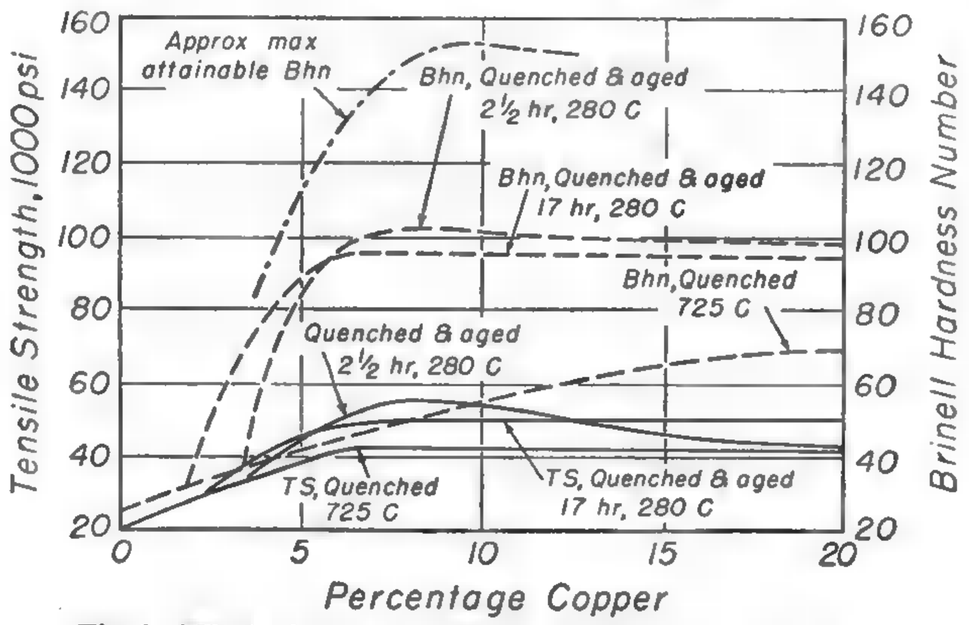

Fig. 1 Effect of copper content on the tensile strength and Brinell hardness number of silver-copper alloys

Leach and Chatfield[14] conducted tension and ductility tests on sterling silver variously annealed and air-cooled or quenched. These investigators demonstrated that material annealed above 650 C was harder when air-cooled than when quenched, and they showed particularly that for general use, where neither quenching nor age hardening is contemplated, annealing at 650 C is most suitable. Fraenkel and Schaller[5] determined the tensile strength, hardness and resistivity for alloys containing from 2 to 20% Cu quenched from 725 C and variously aged. Figures 1 and 2 are based principally on the work of these two men. Higher values for resistivity and for hardness after aging, can be secured in most of the alloys by the use of slightly higher quenching temperatures or somewhat different aging cycles. Approximate maximum values for hardness are shown in Fig. 1.

The solubility of copper in silver at 650 C is about 4%, and at 725 C about 6%, so sterling silver processed at these temperatures is duplex with small amounts of the copper-rich phase scattered through the silver-rich matrix. Aging treatments cause precipitation of the copper-rich phase and, if prolonged, increase the electrical conductivity considerably. Annealing for some time at 770 C produces a coarse-grained single-phase alloy that is somewhat harder, has lower conductivity, and perhaps is less ductile than material annealed at lower temperature, but is more responsive to age hardening.

Coin silver will remain duplex after any annealing treatment, and ages in much the same manner as the 7.5% Cu alloy. Both alloys respond to an aging treatment of 2 hr at about 280 C or 1 hr at 300 C. The mechanical properties of coin silver are virtually the same as those of copper sterling after the usual annealing treatments at about 650 C, since the composition of the silver-rich phase will be the same. Alloys containing 20 to 30% Cu have much more of the copper-rich phase, which does not age harden at the temperature suitable for the silver-rich alloy, and therefore the hardness of the higher-copper alloys is usually lower after aging.

Many articles made of sterling or coin silver are left in the cold worked condition and may be hard enough in that condition, but where hard soldering has been done and the cooling was rapid, a final aging treatment will greatly improve the article, increase its yield strength, and minimize denting. It is probable that the low-temperature aging treatment could be applied to advantage to many old articles.

Resistance to Corrosion and Oxidation. At ordinary temperatures, the presence of copper in solid solution in silver will have little effect on the resistance of the metal to corrosion. The presence of small areas of the slightly less noble copper-rich phase might be expected to cause difficulty because of electrolytic effects, but apparently the difference between the potentials is small enough for the duplex alloys to behave satisfactorily in their usual applications. In sea water, however, and in similar electrolytes, some selective attack may be anticipated.

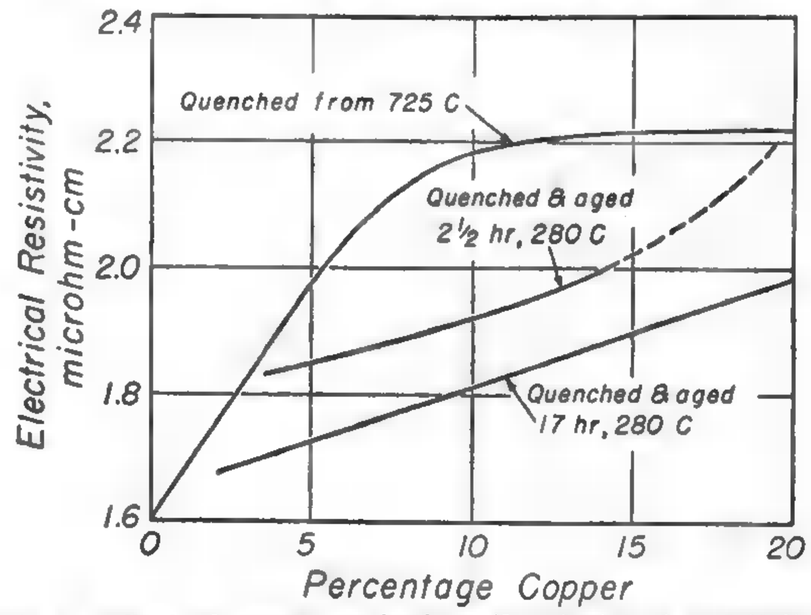

Fig. 2 Effect of copper content on the electrical resistivity of silver-copper alloys

At slightly elevated temperatures, copper oxidizes selectively. This behavior is of some consequence in electrical contacts, since it necessitates higher contact pressure. At approximately 600 C, oxidizing atmospheres will cause rapid oxidation of the copper and oxygen will diffuse to a considerable depth, forming a substance called "fire".[13,14] One hour of exposure to air at this temperature will oxidize the 7.5% Cu alloy to a depth of 0.003 in.[13] This was formerly very troublesome but with the production of well-deoxidized alloys and the use of nonoxidizing atmospheres, effects from the oxidation of copper have been minimized.

Because sulfur tarnishes the silver-copper alloys in about the same way as it tarnishes silver, sulfur must be excluded or the silver must be protected by appropriate

* The International Nickel Company, Inc., New York

coatings, such as rhodium over nickel. if appearance is to be maintained without polishing.

Processing. In the melting of the alloys, the oxygen content should be brought to a low level before pouring at 1050 to 1100 C.[13] Where the electrical conductivity is not important, final deoxidation with 0.05% P is convenient. Cadmium has been used as a partial deoxidizer; 0.5% or more is required. Melting the material under a cover of bone buttons and pouring the alloy through a reducing flame during casting, also gives good results. The alloy may be reduced approximately 60% in rolling, and short anneals are suitable at 650 to 740 C in a steam atmosphere or a salt bath. Where the higher temperature is used, quenching is required for producing full softness. Alternation of oxidizing and reducing atmospheres is very damaging. Where oxidation has occurred in annealing, pickling in a hot sulfuric acid solution (5 to 10%) is suitable. After soldering, dipping for *less than one minute* in a solution of one part HNO_3 and one part water is effective.

Uses. Sterling silver is used for flat and hollow tableware and various items of jewelry. Coin silver with 10% Cu and 90% Ag is used for U. S. silver coins and for electrical contacts operating under service conditions where pure silver is considered too soft and is more likely to pit. The 20% Cu alloy has no special properties, but the 28% Cu eutectic alloy finds some use as a brazing solder where an alloy is required that is free from zinc, cadmium and tin and will melt at 779 C (in the absence of oxygen).[15] Various modifications of the silver-copper alloys are made, and small amounts of nickel are added to some of the contact alloys. Sometimes 0.5% Cd or more is added for various reasons. Palladium has been added to the eutectic to provide a higher-melting, strong solder and age hardenable contact alloy. Zinc, cadmium, and sometimes tin or phosphorus, are added to the eutectic or lower-silver alloys to provide useful brazing alloys.

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Silver-Copper-Zinc(-Cadmium-Tin) Brazing Alloys

By Robert H. Leach*

SILVER ALLOYS in this group, used principally for joining metals, have been known for many years as "silver solders". Recently the name "silver brazing alloys" has come into use, a term more accurately suggestive of their characteristics, particularly of the temperatures at which they are used and the strength of joint made with them.

The article on brazing methods (page 78) lists 15 alloys representing a range of composition of specific alloys in common use for joining both ferrous and nonferrous metals and alloys. Since the term "brazing" implies that there is no melting of the material being joined, the important thermal property of these alloys is the temperature at which they are molten and flow freely into a joint.

The silver-copper eutectic, which contains 72% Ag, 28% Cu, melts at 779 C (1434 F). Quaternary alloys having varying percentages of cadmium or tin, as well as silver, copper and zinc, have lower liquidus temperatures; the liquidus range of these alloys extends from approximately 620 C (1150 F) to 845 C (1550 F) or higher. The solidus temperatures range from about 0 to 65 C (150 F) below the liquidus temperatures.

The strongest joints are made with these alloys when the maximum joint clearance is only a few thousandths of an inch. When the alloys are in the form of thin castings of relatively small cross-sectional area, their physical properties are of interest in connection with their ultimate use. However, since the diffusion into the joint members varies with the type of metal or alloy being joined, and the time and temperature of heating, the factors of greatest importance are the strength, malleability and ductility of the finished joint. As a general guide, tests show that the alloys in common use have tensile strengths from approximately 40,000 to 60,000 psi in cast form. These alloys are malleable and ductile and can be fabricated into sheet and wire with 50% or greater reductions between anneals.

The mechanical properties of the joint vary with the type of joint and composition of the material being joined. Lap joints are preferred if the design permits. The length of the lap affects the shear strength of the joint with any given alloy, but a reasonable lap of a maximum of about two or three times the thickness of the metal to be joined, will produce a joint as strong or stronger than the metal. With many nonferrous metals and alloys, the strength of butt joints will equal or exceed the strength of the joint members. Tests have shown also that butt joints properly made on steel or iron exceed the yield strength and often show values that approximate the tensile strength of the material. Joint strength greater than that of the silver brazing alloy can be obtained with butt joints on materials that have strengths higher than the alloy. The malleability and ductility of butt joints with many materials, allow severe cold work to be done on the joint without causing failure.

Experimental data and service records show that joints made with silver brazing alloys offer high resistance to fatigue when subjected to repeated shock and vibration.

The strength of silver brazing alloys declines rapidly at elevated temperatures. Short-time tests indicate that the loss in strength at 400 to 450 F will approximate 20 to 30% of the strength at room temperature and 50% at 600 F. Service tests of longer duration indicate that 400 F (205 C) is about the limit for the use of silver brazing alloys, unless the type of joint allows for an unusually large factor of safety.

The electrical conductivity of silver brazing alloys varies from 15 to 80% of the conductivity of copper. Alloys with higher silver content and lower zinc content have the highest conductivity. The silver-copper eutectic (72% Ag, 28% Cu) has approximately 77% the conductivity of copper. The thickness of the silver brazing alloy in joints on electrical equipment is so small in comparison with the joint area that the conductivity is usually satisfactory for all requirements.

The corrosion resistance of silver brazing alloys compares favorably with that of most of the nonferrous alloys with which they are used. Alloys containing 50% Ag or more are suitable for joining corrosion-resistant base metals such as nickel, Monel, stainless steel and allied materials used in chemical equipment, where enough nobility in the brazing alloy is desirable to avoid the selective attack on it. The melting range of the silver brazing alloys is neither low enough nor high enough to prevent carbide precipitation in unstabilized stainless steels.

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Silver Materials for Electrical Contacts

UNALLOYED SILVER can be used successfully for electrical contacts where some slight arcing and wear occur to keep them clean, and where the contact pressure, current and voltage are not too low. Under higher-current conditions certain silver alloys, or various aggregates of silver with metals or nonmetals, may be employed for greater serviceability, even though the addition of these other materials to silver increases the electrical resistivity considerably.

The following substances discussed here are added to silver in order to provide useful material for contacts: tungsten, molybdenum, nickel, graphite, cadmium oxide, and lead oxide. The methods of powder metallurgy—rather than melting—are used for compounding the alloy or aggregate of silver with each of these substances.

Silver-Tungsten and Silver-Molybdenum

By E. F. Swazy* and Lee S. Busch*

BECAUSE of lack of mutual solubility of the component metals, alloys of silver with tungsten or molybdenum cannot be made by the usual metallurgical methods; powder metallurgy is necessary. These materials are useful as arcing tips, current-carrying contacts, and in aircraft, where they are used in the voltage-regulator system. A silver-molybdenum material is particularly useful in household circuit breakers, which are now widely used to replace fuses. To function satisfactorily, the aggregates must be free from porosity.

The desirable properties of these materials are the result of the combination of the high electrical conductivity and corrosion resistance of silver with the hardness and resistance to arcing and abrasion of tungsten or molybdenum. Both tungsten and molybdenum form oxides, but these oxides are not adherent and are easily separated from the parent metal by the wiping action of the contact mechanism.

Figures 1 to 4 show relationships between silver content and tensile strength, density, electrical resistivity and hardness. The figures include data theoretically obtainable in the ranges of very high and very low silver contents, as well as from the commercial materials.

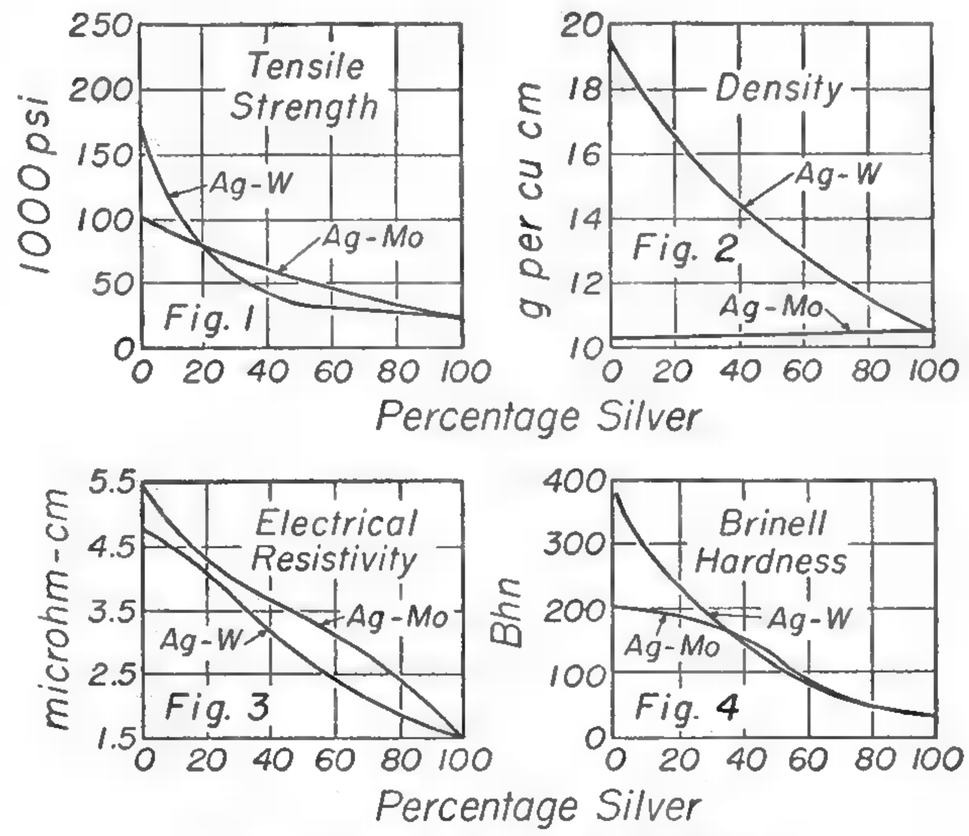

Fig. 1 to 4 Some properties of silver-tungsten and silver-molybdenum materials

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Silver-Nickel

By Gregory J. Comstock* and Fred Farnham†

NICKEL has a much higher melting point than copper or silver; also nickel is harder and much more resistant to tarnishing. A mixture of silver and nickel has characteristics desirable for electrical contacts. The mutual solubility of silver and nickel is so low that most compositions must be made by the powder method. The product is unusual in that both components are ductile at atmospheric temperature if sufficiently pure; consequently it is possible to cold work all the mixtures. These mixtures are not to be confused with nickel silvers, which are copper-base alloys containing nickel and zinc, but no silver.

The data shown in Fig. 5 relate to products made by the powder method. Tensile properties are shown for the annealed condition and after reducing the cross section 4 B&S numbers by rolling. These mixtures are sufficiently ductile to be cold headed, and annealed material may have an elongation of 10% or more. Contacts are made also by sintering to shape without appreciable subsequent working, but the properties of such articles differ from those in Fig. 5.

The addition of nickel to silver increases the hardness and decreases the mechanical and electrical wear without greatly reducing the electrical or thermal conductivities. For example, the 5% Ni mixture has an electrical conductivity approximately equal to that of copper. The electrical contact resistance of the higher-silver alloys is very low; that of the 15% Ni alloy is of the same order as the electrical contact resistance of fine silver. The low contact resistance of these mixtures makes them useful as contact surfaces. Mixtures containing approximately 15%

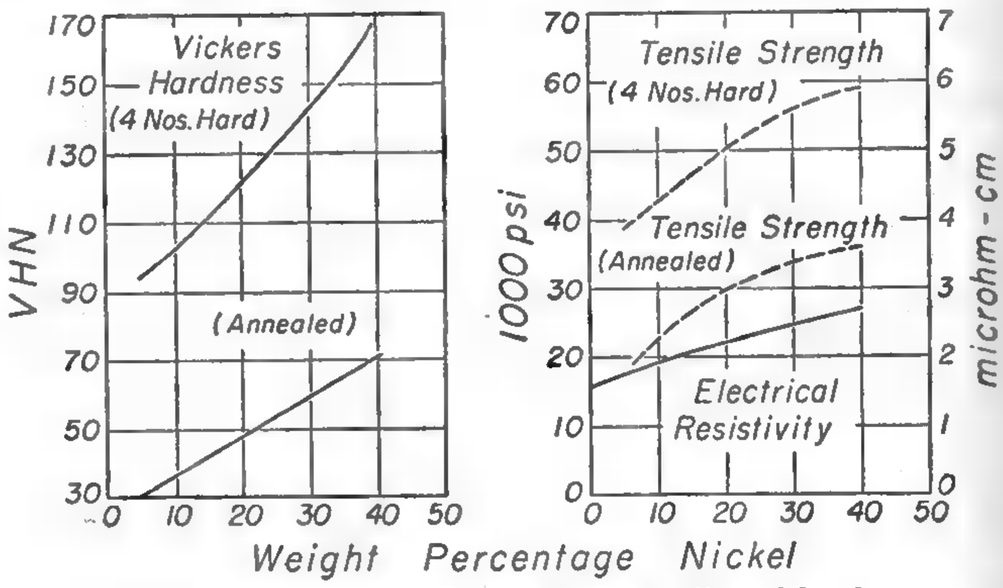

Fig. 5 Electrical resistivity, tensile strength and hardness of wrought silver-nickel alloys

Ni are useful for high-conductivity applications, while the mixture with higher nickel content is used where resistance to arcing is essential, as in medium-size circuit breakers.

Where maximum resistance to sticking is required, one contact of silver-nickel is used in conjunction with one of silver-graphite. In high-capacity circuit breakers, where arcing contacts are utilized to protect the main contacts, frequently the main current-carrying contacts are silver-nickel. Silver-molybdenum and silver-tungsten are used for the arcing contacts where ability to break high currents is required, and silver-tungsten is employed where maximum resistance to erosion by the electric arc is demanded.

Contacts of silver-nickel mixtures can be bonded to massive copper conductors. In large apparatus, this construction is commonly used and, for heavy service, offers an advantage over silver. Such applications include disconnect switches, transformer tap changers, and main contacts of large circuit breakers.

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Silver-Graphite

By E. I. Shobert, II*

THE TECHNIQUES of powder metallurgy are used for making these materials when the volume of silver is greater than 50%, which corresponds to 15% graphite by weight. Less metallic mixtures, containing less than 50% metal by volume, employ carbonized binders or are made by impregnating a porous carbon with molten silver. The properties of the high-silver silver-graphite alloys are shown in Fig. 6.

Originally these materials were produced to minimize the welding of electrical contacts. The resistance to welding improves with the graphite content; however, the contact resistance also increases with the graphite content and is approximately doubled at 5% graphite. Consequently

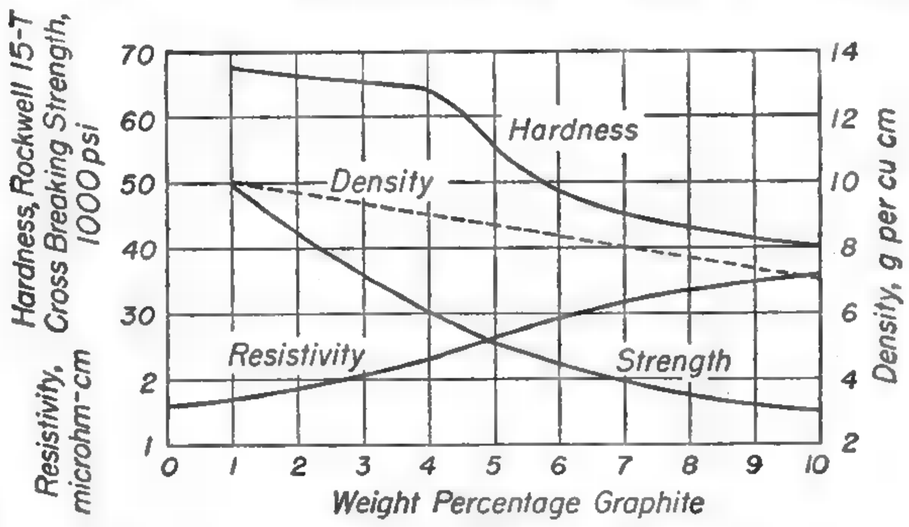

Fig. 6 Some properties of silver-graphite mixtures

some compromise is necessary in selecting the proportions of silver and graphite. These materials have found substantial use in contacts for circuit breakers, switches and the like where the frequency of operation is moderate, and also for various sliding contacts on instruments, variable resistors and low-voltage motors and generators. For these latter applications, materials with substantial amounts of graphite are employed, and it has been observed that during use, copper slip rings acquire a coating of silver that further reduces the contact drop.

Silver–Cadmium Oxide

By E. F. Swazy* and Lee S. Busch*

SILVER ALLOYS that contain small percentages of cadmium have good qualities as electrical contacts, although these contacts can be used only in circuits where the current is low. The presence of cadmium lowers the transfer of material to a minimum and permits longer use of the contact. However, larger amounts of cadmium lower the electrical properties to a point where the operating characteristics are inferior to those of fine silver.

If cadmium oxide and silver powders† are properly mixed, pressed and sintered, the properties of the resultant material are excellent for heavy-duty contacts. The amount of cadmium oxide determines the current rating at which the material has optimum performance within the limits of the design of the electrical circuit.

The fabrication is typical of powder metallurgy processes; that is, mix, press, sinter and re-press. By this method, finished electrical contacts are made that require no further finishing after they have been attached to their carrying member. The material may also be fabricated by hot pressing, but this method is not well suited to economical, high-speed production, except in special instances.

The cadmium oxide used is considered an additive and is ordinarily present in amounts less than 15% by weight.

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* Research Department, P. R. Mallory & Co., Inc., Indianapolis
† U. S. Patent 2,145,690

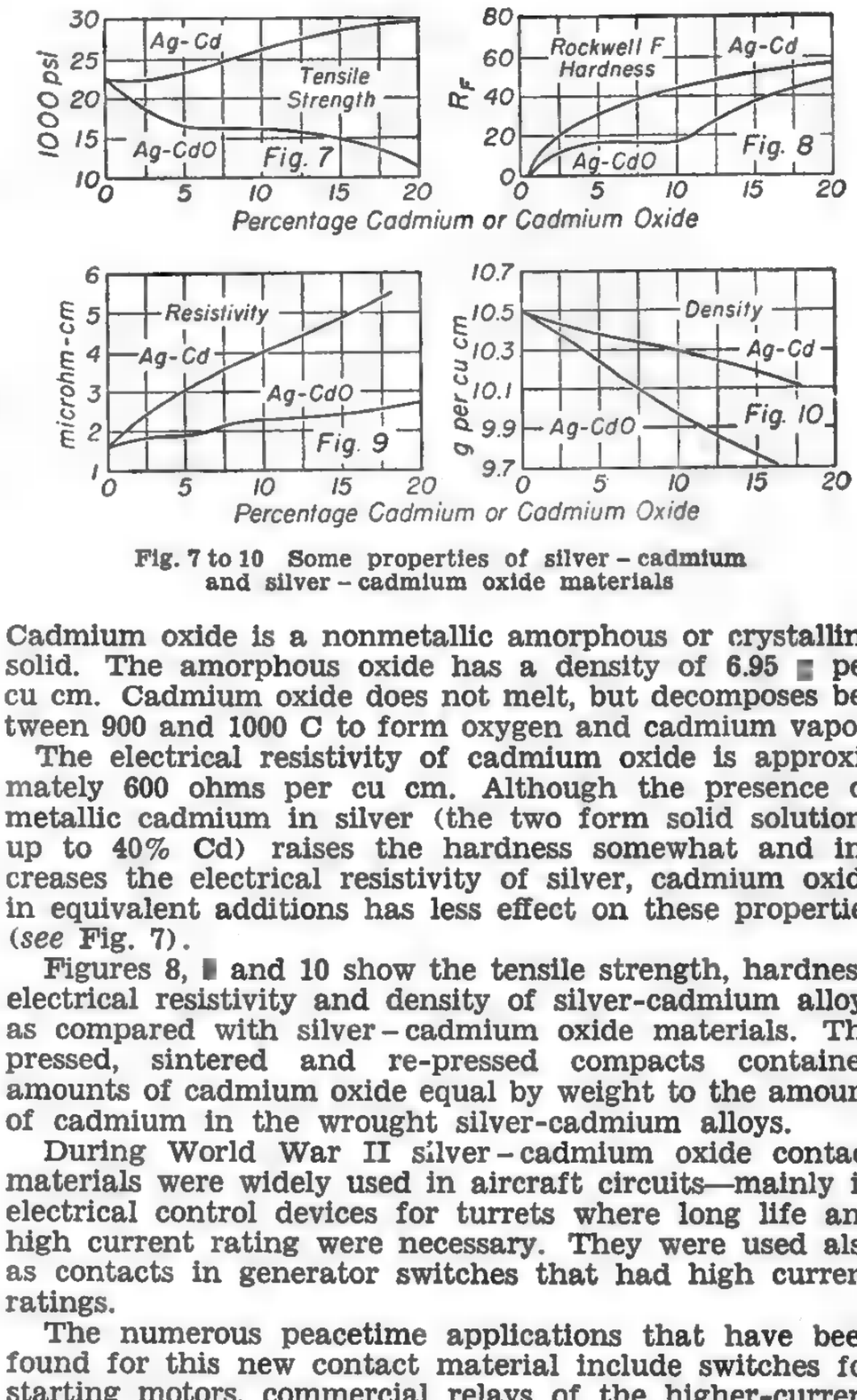

Fig. 7 to 10 Some properties of silver – cadmium and silver – cadmium oxide materials

Cadmium oxide is a nonmetallic amorphous or crystalline solid. The amorphous oxide has a density of 6.95 ■ per cu cm. Cadmium oxide does not melt, but decomposes between 900 and 1000 C to form oxygen and cadmium vapor.

The electrical resistivity of cadmium oxide is approximately 600 ohms per cu cm. Although the presence of metallic cadmium in silver (the two form solid solutions up to 40% Cd) raises the hardness somewhat and increases the electrical resistivity of silver, cadmium oxide in equivalent additions has less effect on these properties (*see* Fig. 7).

Figures 8, ■ and 10 show the tensile strength, hardness, electrical resistivity and density of silver-cadmium alloys as compared with silver – cadmium oxide materials. The pressed, sintered and re-pressed compacts contained amounts of cadmium oxide equal by weight to the amount of cadmium in the wrought silver-cadmium alloys.

During World War II silver – cadmium oxide contact materials were widely used in aircraft circuits—mainly in electrical control devices for turrets where long life and high current rating were necessary. They were used also as contacts in generator switches that had high current ratings.

The numerous peacetime applications that have been found for this new contact material include switches for starting motors, commercial relays of the higher-current class, and various alternating-current applications where fine silver is not a suitable electrical contact material.

Silver–Lead Oxide

By E. I. Shobert, II*

THIS MATERIAL is used principally for contacts in low-voltage electrical circuits where fairly heavy currents are to be controlled. It has been used also in vibrating contacts for direct current, including inductive loads where it may be used as the positive contact in combination with another material for the negative contact to minimize transfer. Although the resistivity of the material is increased considerably by the lead oxide, the contact resistance is increased only about 15%. Some pertinent properties are listed in Table I.

Table I. Some Properties of Silver – Lead Oxide

Composition, % Silver	Lead Oxide	Cross Breaking Strength, psi	Rockwell Superficial Hardness	Density, g per cu cm	Electrical Resistivity, microhm-cm
97.5	2.5	37,000	30-T 39	9.8	2.3
97.5	2.5	45,000	15-T 67	9.0	2.5
95	■	42,000	15-T 67	9.7	3.2
95	5	27,000	30-T 25	9.4	3.5

* Research Dept., Stackpole Carbon Co., St. Mary's, Pa.

Silver-Palladium-Platinum, Silver-Palladium-Copper and Silver-Palladium-Gold Alloys

See Palladium and Palladium Alloys, pages 1128 and 1129.

33 Ag – 52 Hg – 12.5 Sn – 2 Cu – 0.5 Zn

COMPILED BY WILMER SOUDER*

A *1 Common name.* **Dental Amalgam,** "Silver" Filling
4 Government number. U-A-451a

B *1 Typical uses.* Restoring lost tooth structure
2 Precautions in use. Small amounts of moisture (from the hand or mixing equipment) added during amalgamation cause excessive expansion of the hardened alloy. Excess mercury, remaining in the alloy after packing, causes the alloy to expand and flow excessively. Excessive working of the alloy during amalgamation or packing reduces or eliminates the setting expansion. Incomplete amalgamation produces an alloy that corrodes readily. Improper condensation (packing) increases the rate of corrosion and decreases physical properties.

C *1 Density* at −3 C (+26 F). 11 g per cu cm (0.397 lb per cu in.)
5 Solidification shrinkage. Expands 8 ± 5 microns per cm during solidification

D *1 Liquidus temperature.* Begins to sweat mercury and to break down at about 75 C (167 F)
6 Thermal expansion at or near body temperature. 0.000022 to 0.000028 per °C

E *11 Electrolytic solution potential* versus gold in normal sodium chloride solution. minus 0.5 volt

F *4 Color.* Silvery white

I *1 General resistance to corrosion.* Tarnishes readily unless well polished. Electrolytic corrosion and pitting may result from contact with other metals, incomplete amalgamation or nonuniform mixing. The amalgam is attacked readily by inorganic acids.

K *Mechanical properties.* Compressive strength 40,000 to 50,000 psi after ▮ days; tensile strength ⅛ to $\frac{1}{10}$ of the compressive strength; rigidity, all amalgams flow when subjected to loading; loads of $\frac{1}{10}$ of the compressive strength may cause a flow amounting to 1% per 24 hr; flow 2 to 4% at 20 to 25 C in the first 24 hr for loads of $\frac{1}{10}$ the crushing strength applied 3 hr after amalgamation; modulus of elasticity 1,500,000 psi (very uncertain); indentation hardness (Knoop method) 90 after 5 days

M *Composition limits* (U-A-451a). For silver alloy used in the preparation of amalgam: 65% Ag min; 25% Sn min; 6% Cu max; 2% Zn max.

N *3 Alloying.* Usual composition is 5 parts silver alloy of above type to 8 parts of mercury mixed in a mortar. Approximately 3 parts of mercury is expressed during packing.
11 Suited to forming by packing from its plastic form.
12 Precautions in forming. Avoid over-trituration, excess mercury in finished material, and contamination with moisture during amalgamation and packing.
13 Compacting pressure. 1 to 3 kg per sq mm

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Wilmer Souder and George C. Paffenbarger, "Physical Properties of Dental Materials", Circular of Nat Bur Standards C433, 1942. Many references are cited in this circular.

* Chief, Division of Metrology, National Bureau of Standards, Washington, D. C.

GOLD AND GOLD ALLOYS

Gold (99.99+ Au)

COMPILED BY WM. F. ROESER*

B *1 Typical uses.* Gold of the highest purity, called "Proof Gold", contains more than 99.99% Au, and is a premium product used for standardizing purposes. The usual grade of refined gold contains from 99.95 to 99.98% Au and is suitable for most purposes, including dental and jewelry alloys. Metal that contains 99.5% Au is acceptable for international exchange and by the U. S. Mint without a refining penalty. Coin gold containing only copper as a hardener with 89.9 to 91.7% Au may also be acceptable.

Besides monetary uses, nearly pure gold is employed as beaten foil for decorative and dental uses, for electroplating and surfacing china and glass, for thermal limit fuses to protect electric furnaces, as a freezing-point standard, and occasionally as a high-melting noble solder and lining material for chemical equipment. Gold alloys are used for jewelry, dental, electrical and some chemical purposes.

2 Precautions in use. Unless you have a license, do not buy or sell gold without consulting the U. S. Bureau of the Mint. In melting avoid contamination with base metals, particularly lead, bismuth and the like. Keep atmosphere oxidizing during melting.

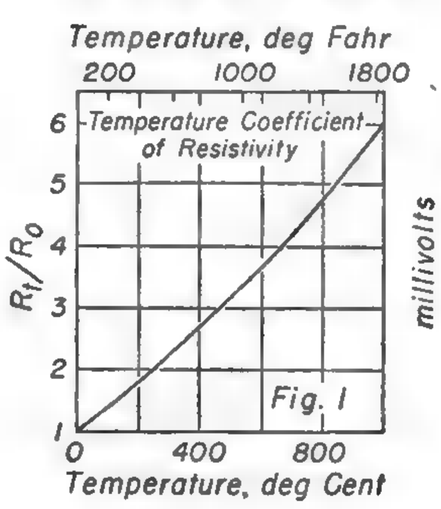
C *1 Density* at 20 C (68 F). 19.32 g per cu cm (0.698 lb per cu in.)

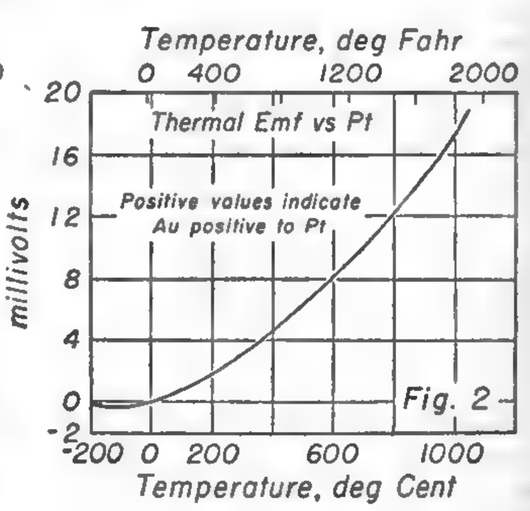
D *1 Melting point.* 1063.0 C (1945.4 F)
4 Boiling point. 2970 C (5380 F)
6 Thermal expansion at 20 C (68 F). 0.0000142 per °C ▮ to 950 C (32 to 1742 F)

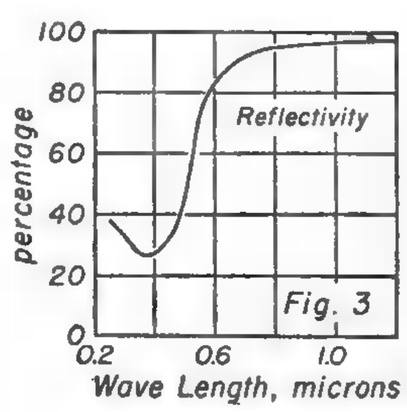
$$L_t = L_o\,[1 + (14.103t + 0.001628t^2 + 0.000001145t^4) \times 10^{-6}]$$

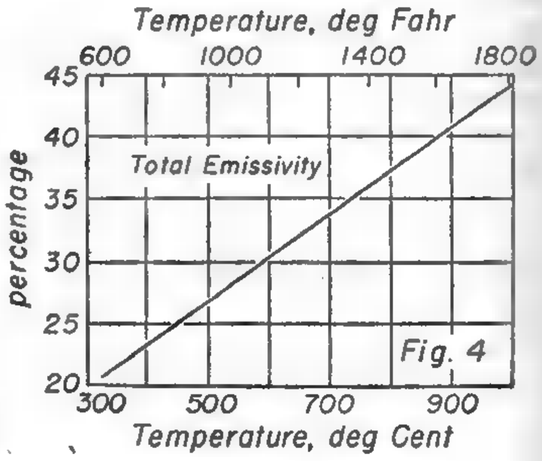
11 Specific heat at 18 C (64 F). 0.0312 cal per ▮
13 Latent heat of fusion. 16.1 cal per g
15 Latent heat of vaporization. 446 cal per ▮
16 Thermal conductivity at 0 C (32 F). 0.71 cgs

E *1 Volume conductivity* referred to standard copper. 73.4% at 20 C (68 F)









* National Bureau of Standards, Washington, D. C.

2 *Electrical resistivity* at 0 C (32 F). 2.19 microhm-cm at 20 C (68 F). 2.35 microhm-cm
5 *Temperature coefficient of electrical resistivity* 0 to 100 C (32 to 212 F). 0.004 per °C
See Fig. 1 for resistivity versus temperature.
9 *Thermal emf versus platinum. See* Fig. 2.
10 *Electrochemical equivalent.* Variable in chloride solutions

F 1 *Reflectivity* at room temperature. *See* Fig. 3.
Reflectivity versus wave length. *See* Fig. 3.
5 *Emissivity. See* Fig. 4.

G 2 *Magnetic specific susceptibility.* minus 0.15×10^{-6} cgs

J 1 *Crystal structure.* Face-centered cubic, $a = 4.070$ kX
5 *Minimum interatomic distance.* 2.878 kX

K *Mechanical properties. See* Table I.
Endurance limit. (wrought, annealed) 4600 psi for 10^7 cycles
Poisson's ratio 0.42 (form not known)

N 2 *Casting temperature.* 1100 to 1300 C (2000 to 2370 F)
4 *Preferred deoxidizer.* None required.

Table I. Mechanical Properties of Gold (99.99+ Au)

Condition	Tensile Strength, psi	Yield Strength (0.2% offset), psi	Elongation in 2 in., percentage	Bhn	Modulus of Elasticity, psi
Cast	18,000	.....	30	33	10,800,000
Wrought, annealed	19,000	nil	45	25	11,600,000
60% reduction ...	32,000	30,000	4	58	11,500,000

7 *Hot working temperature range.* Gold can be worked at any temperature below the melting point.
9 *Annealing temperature.* Apparently no annealing is required.
11 *Suited to forming* by all methods so far as is known.
17 *Joining.*
Braze with silver solder; no flux; any flame.
Oxyacetylene welding with gold; no flux; any flame.
Resistance welding. Any method

Gold-Copper-Silver Alloys (Green, Yellow and Red Golds)

By E. M. Wise*

THE Au-Cu-Ag system is the base for the high-carat green, yellow and red gold alloys used in jewelry. Frequently the properties of these alloys are modified somewhat by additions of other elements, such as zinc and nickel. The pink golds contain sufficient nickel and zinc to yield appreciably different properties and colors. The white golds are Au-Cu-Ni-Zn alloys.

Ten-carat alloys, particularly the greenish types, generally contain considerable zinc and a little nickel, so they also must be considered apart from the ternary group. Many of the dental casting alloys are closely related to the high-carat Au-Cu-Ag alloys, but the higher-strength compositions contain sufficient palladium and platinum to alter their properties substantially. Although the Cu-Ag-Pd system is closely analogous, structurally, to the Cu-Ag-Au system, the melting points of Cu-Ag-Pd alloys are higher, with the result that a continuous series of useful alloys exists in which palladium replaces gold, atom for atom.

The liquidus and solidus and the hardness of alloys in the annealed condition are shown in Fig. 1, based essentially on the work of Sterner-Rainer.[1] Alloys containing a few per cent of zinc are slightly softer in the annealed condition than the basic ternary alloys. Copper hardens these alloys, not only by the usual solid-solution effect, but also by inducing in some of the alloys, the type of low-temperature atomic rearrangement termed "ordering", which causes substantial age hardening.

Copper lowers the melting temperature of the high-gold alloys to a minimum of 884 C in the liquidus of the binary copper-gold alloys, while a eutectic, melting at 779 C, forms between copper and silver. The solid solubility of copper in silver and silver in copper is limited and decreases with temperature, and the domain of heterogeneous alloys increases as the temperature decreases.[11] As a result of these phenomena, alloys containing about 25% Cu have nearly the minimum melting temperature, and alloys containing less than 50% Au (12-carat) may contain some eutectic.

The 10-carat alloys are generally limited to the high-copper side of the eutectic. Even alloys that contain more gold than this, also may precipitate phases of rather low nobility during slow cooling. Photomicrographs of these structures, as well as of structures associated with ordering, have been published.[2,3,4,5]

Age hardening can be induced in certain Au-Cu-Ag alloys by heating for ½ to 2 hr at 200 to 350 C[2,4,6] or by slow cooling,[7,8] depending on the alloy. The more complex alloys used in dentistry may require higher temperatures.[9] Maximum values for the hardness of aged ternary alloys are shown in Fig. 1 for 18- and 14-carat alloys, based principally on the work of Nowack.[6] If considerable ductility is required, less drastic hardening may be necessary. Low-carat alloys that contain considerable zinc plus a small amount of nickel, age harden very effectively,[2] as do various other commercial alloys.[2,5,7,9] A review of the age hardening of precious metal alloys is accessible.[10]

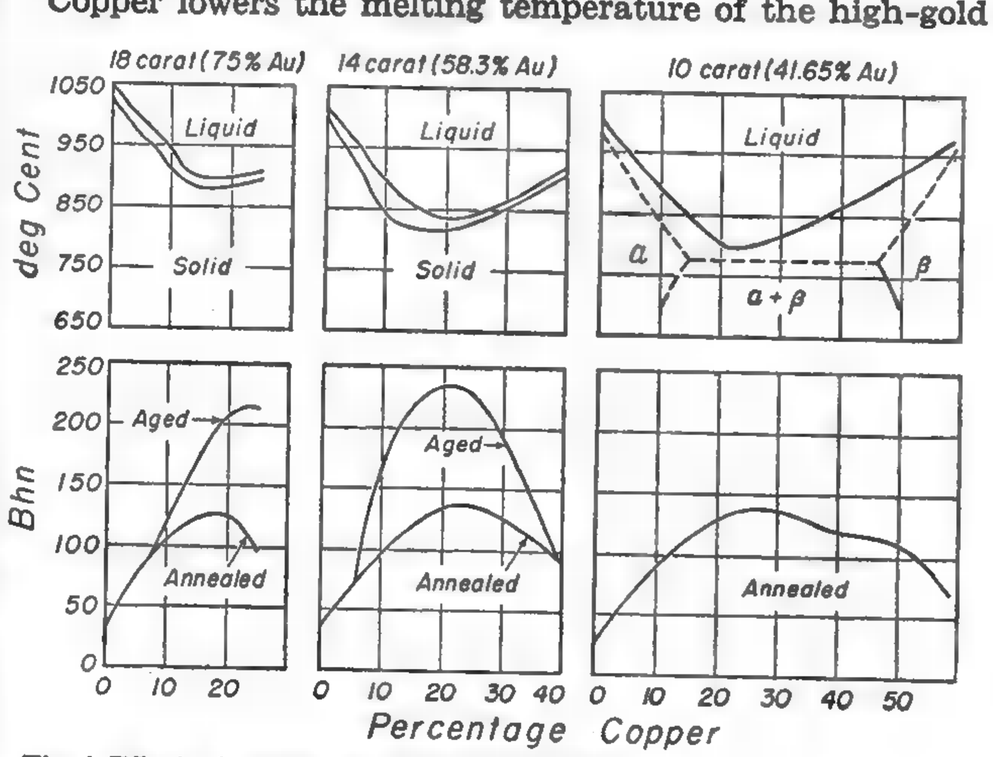


Fig. 1 Effect of copper on melting and hardness of Au-Cu-Ag alloys

Color. The addition of silver to gold apparently reduces the reflectivity in the extreme red, with the result that a 75% Au – 25% Ag (18-carat) alloy has quite a good green color. Replacing about half the silver with copper produces a yellow gold and a further increase produces a red gold. The 58.35% Au – 41.65% Ag (14-carat) alloy has an unattractive greenish white color, and also is too soft to be useful, but if 6 to 12% of the silver is replaced by copper, a fair green results (which is somewhat improved by the replacement of a certain amount of silver by zinc). If 20 to 30% Cu is present, yellow alloys are formed. A further increase in copper yields reddish alloys. The presence of a little nickel lightens the color and hardens the alloy; zinc lightens the color, adds a slight greenish cast and may soften the alloy. At 41.65% Au (10-carat) useful compositions are confined largely to the high-copper alloys with considerable zinc and often appreciable nickel added to yield greenish, yellow, red and pink golds. (Pink golds are described on page 1119.)

Working. The melting and casting of these alloys is described on page 1096. All of them are cold worked; reductions of 50% or more are usual. Annealing for 15 to 30 min at 650 to 700 C is normal, and reducing atmospheres are desirable in order to avoid the oxidation of copper and any other base metals present. Such oxidation, which can

* The International Nickel Company, Inc., New York

extend to an appreciable depth, is called "fire", and to remove it is more difficult than to prevent it. When reducing atmospheres cannot be used, coatings of boric acid, ochre and the like are applied, and when flame heating is employed, methyl borate introduced into the combustible gas has a protective effect.* The age hardenable alloys should be cooled rapidly, but water quenching is not always possible because some of the alloys may crack.

Resistance to Corrosion. The 18-carat alloys contain 75% Au by weight, corresponding to about 50 to 60 atomic % Au, and are very resistant to tarnishing in indoor atmospheres, although probably not to outdoor urban exposures. They resist nitric, sulfuric, and hydrochloric acids and ferric chloride, but are attacked rapidly by mixtures of nitric and hydrochloric acids (aqua regia) and slowly by solutions of alkali cyanides plus air or other oxidizing agent. They are attacked when made anode in hydrochloric acid or cyanide solutions. Fourteen-carat alloys contain 58.33% Au by weight, or about 30 to 40 atomic % Au, and thus approach the region where the nobility decreases rapidly. They tarnish slowly in air but because of the color this is not very obvious. If free from stress, they are quite resistant to nitric acid or ferric chloride, but if highly stressed, these alloys may be cracked by various corrosives or may crack even in the apparent absence of a corrosive. Mercury is also likely to crack 14-carat alloys when they are under stress. Decreasing the gold content still further to 12 and 10 carats (about 20 atomic % Au) results in a rather sharp decrease in resistance to acids and an increase in the susceptibility to tarnish and sensitivity to stress-corrosion cracking. The resistance to corrosion of some of the alloys may be lowered or occasionally raised by aging.[5,10] Some aspects of this problem as it concerns a 10-carat light yellow gold have been considered.[5]

Uses. These alloys are used mostly in jewelry, pen nibs and the like, where they are employed in the form of castings, or in products made from rolled or drawn stock, or from clad material comprising a layer of gold on one or both sides of a core made of nickel silver, pure nickel, brass or bronze. Certain of these alloys can be electrodeposited, and sometimes coatings are produced by electrodeposition followed by heating to cause diffusion with the underlying metal. The closely related dental alloys are described on page 1120 in this Handbook.

* Devised by E. M. Wise, 1925

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Gold-Nickel-Copper-Zinc Alloys (White Gold)

By E. M. Wise*

When first offered as substitutes for platinum in jewelry these alloys contained about 80% Au. Later 18-, 14-, and 10-carat alloys were developed for use in solid and clad forms in the same manner as yellow and green golds, although the hardness and tendency to fire crack make white golds more troublesome to work. Faintly greenish whites are normally considered the whitest, but are the most difficult to handle. The optical industry makes considerable use of 12-carat alloys, white and pink, or "suntan", as described on page 1119. In recent years palladium has often been used instead of white gold, particularly in rings and gem mountings where maximum reliability is required. The white precious metal alloys used in dentistry are very different; they contain gold, platinum, palladium, silver and copper, as described in the articles on cast dental alloys and wrought dental alloys.

Composition and Constitution. The gold-nickel system just escapes being eutectiferous, since nickel and gold have limited mutual solubility at low temperatures,[1,2,3] although they form a continuous solid solution just below the solidus. As a result, an 18-carat (75%) gold-nickel alloy, oil-quenched from 850 C, is homogeneous and hard, though somewhat ductile, and is white in color and resistant to nitric acid. After very slow cooling, the same alloy becomes heterogeneous, is yellowish white in color, and is readily attacked by nitric acid. Various transformations occur in the gold-copper system, and only portions of the several binary systems involving zinc are face-centered cubic, so the constitution and transformations in the commercial alloys are complex—particularly in the high-carat alloys. However, the usual alloys are face-centered cubic solid solutions at high temperatures. Unfortunately the low-temperature transformations in these materials have been studied little in recent years.

The compositions employed for a given carat are the result of a compromise between color and working properties, and are quite critical—especially in the higher-carat alloys. For instance, the introduction of 1 or 2% Cu in the 19.2-carat alloy improved the elongation and largely eliminated edge cracking during rolling, without changing the color much. Further study and the use of very pure metals led to development of a whole series of lower-carat white alloys.[4] Compositions of the base metals to be alloyed with appropriate amounts of gold for providing alloys of good color, are shown in Fig. 1. The annealing curve for 14- and 18-carat alloys is shown in Fig. 2.[2] Alloys outside this band are made, but generally the appearance is somewhat inferior. The tensile properties for fully annealed and air-cooled alloys in this band, ranging from 10 to 19 carats, will be of the order of 95,000 to 105,000 psi, 30 to 50% elongation in 2 in. Published values scatter considerably, in part from the use of partial anneals, so fine details in the hardness-composition relation cannot be indicated. When the high-carat alloys are cooled slowly, extreme brittleness and some hardening result; for example, a decrease in elongation from 47 to 2% is noted in an 18-carat white

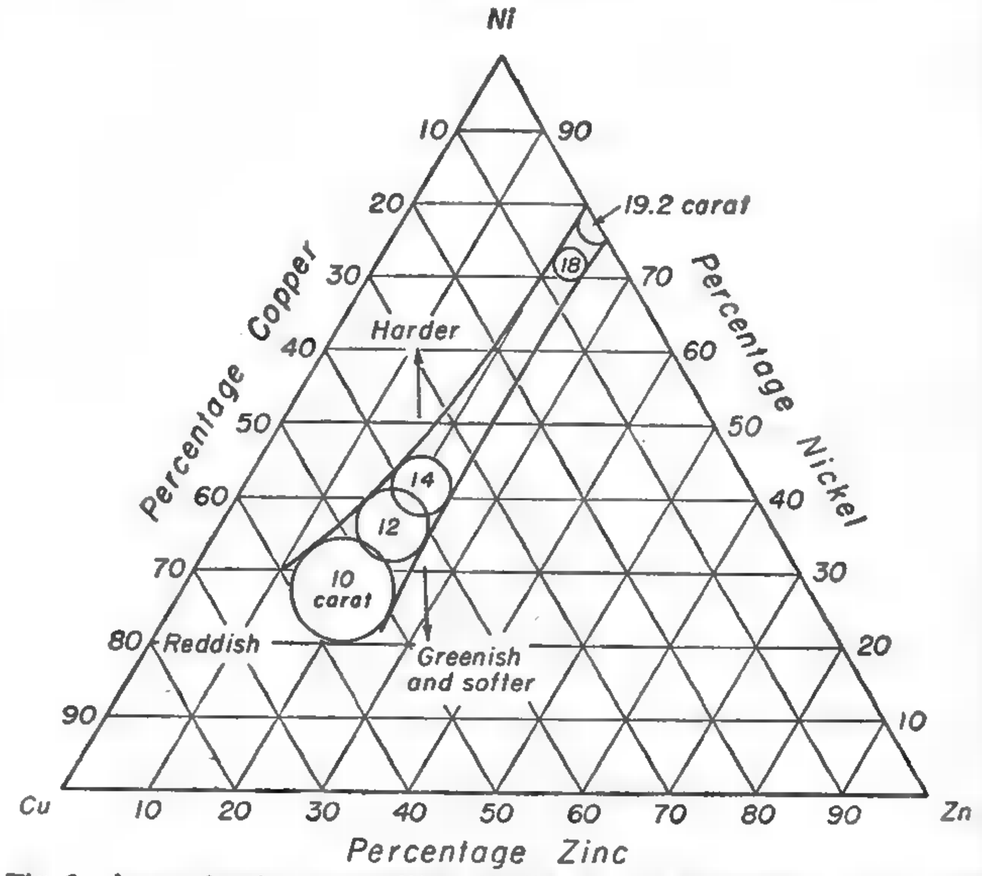

Fig. 1 Approximate composition limits of the base-metal alloy that is added to gold to make relatively white alloys of various carats

* The International Nickel Company, Inc., New York

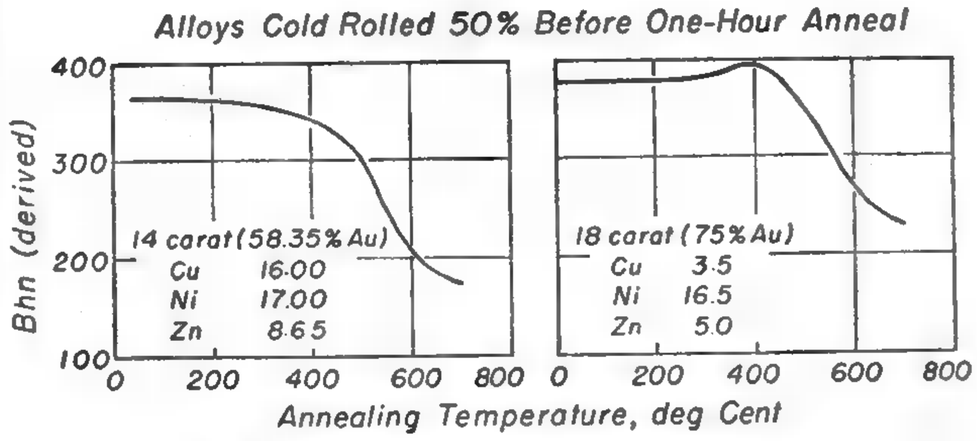

Fig. 2 Hardness of two white golds after annealing

gold. Though some of the lower-carat alloys also age harden on heating at 400 to 500 C, the alloys are usually harder than desired without such treatment, and aging may lower the corrosion resistance in certain of them.

Limitations and Precautions in Use. Cracking is the most serious limitation to the production and use of the whiter alloys and may have any of several different causes. "Fire cracking" (the most troublesome type in 14-carat and higher-carat alloys) develops during the heating of stressed material. Slow heating is not a remedy, since some alloys become extremely brittle at 200 to 300 C and crack before the release of stress by creep. Therefore it is necessary to adjust the working operations to minimize the stress in the parts before annealing. Good pinches are essential, as well as fairly high reductions (50% or more) between anneals in rolling; and side walls should be reduced adequately in shell drawing, sometimes followed by turning to remove rough edges before annealing. These precautions minimize fire cracking. Corrosion cracking is sometimes a problem with the lower-carat alloys, and even a small amount of cold work, before pickling or exposure to other corrosives, may result in cracking. Annealing prior to such exposures is desirable where possible. In general, white golds resist tarnish somewhat better than colored golds of the same carat, but the resistance of white golds to general corrosion is probably less, largely because the atomic percentage of gold in the white golds is lower for a given carat.

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Gold-Silver-Copper-Nickel-Zinc Alloys (Pink or Suntan Golds)

By Carl Samans*

SOME physical and mechanical properties of several gold alloys of the pink or suntan types are listed in Table I. These alloys contain either 58.35% Au (14 carat), 50.0% Au (12 carat) or 41.65% Au (10 carat).

Tensile strengths range from 60,000 to 90,000 psi in annealed alloys, depending on the composition, with yield strengths 50 to 60% of the tensile strength, which is high for nonferrous alloys. After 50% cold work, the tensile strength will be 110,000 to 120,000 psi, with yield strength 90% or more of the tensile strength.

Thermal expansivities cover a considerable range, but are approximately 14×10^{-6} per °C at room temperature. Some of the alloys show abnormally high coefficients of the order of 25×10^{-6} at 300 C, but values of about 22×10^{-6} per °C at 700 C are fairly typical.

The mechanical properties and age hardening of a 10-carat alloy of this type were studied by Wise,[1] and recently the effects of a variety of mechanical and thermal treatments on essentially the same alloy were reported by Patterson and Iannone.[2] Not all the commercial alloys age harden, and this treatment is not always applied to those that are responsive. Jarrett[3,4,5] studied the effect of varying the individual components of 10-, 12- and 14-carat alloys, and a number of his alloys fall in the category of pink or suntan golds. The two latter investigators have included data on the rate of attack by nitric acid; this rate is considerable in the lower-carat alloys. These investigators also indicate the behavior of the alloys toward mixtures presumed to simulate perspiration.

Resistance to Corrosion. Many of the 10- and 12-carat gold alloys are known to be susceptible to stress-corrosion cracking[6] under certain conditions. This might be anticipated from the relatively high yield strength of the alloys even in the annealed condition. Immersion in 10% ferric chloride solution is effective in testing this tendency, although it is a severe test. Drying under stress in an artificial perspiration solution, is probably a closer approximation to actual conditions, and is known to cause cracking, although failures in actual service are not common. In general, alloys free from zinc seem to be somewhat less susceptible to stress-corrosion cracking than alloys that contain zinc.

The pink golds are by no means stainless and they may darken appreciably when exposed to sulfidizing and oxidizing conditions, such as some types of urban atmospheres, or to perspiration. Two artificial approximations of perspiration are commonly used for testing—a solution containing 1% acetic acid and 1% salt, and a solution containing 5% acetic acid and 5% salt. The two concentrations differ appreciably in their action, depending on the test conditions and the composition of the material tested. Lactic acid, rather than acetic acid, is present in perspiration, and the pH of perspiration changes with time so that care must be taken in conducting such tests and in correlating them with service behavior.

Uses. Certain of these alloys have been used for jewelry,

* American Optical Company, Southbridge, Mass.

Table I. Compositions and Some Physical and Mechanical Properties of Commercial Pink Gold Alloys

Composition, %					Density, g per cu cm	Solidus, °C	Yield Strength, psi	Tensile Strength, psi	Elongation, %	Red. Area, %	Rockwell B Hard	Approx VHN
Au	Ag	Cu	Ni	Zn								
						14-carat						
58.3	4.9	31.6	5.2	...	13.08	949	48,000(b)	82,600	41.0	36.0	87	170
58.3	3.3	31.0	3.5	3.9	12.37	938	43,800(b)	71,300	58.0	42.5	72	130
						12-carat						
50.0	4.0	37.1	4.3	4.6	12.17	954	.....	75,600	47.5	37.5	73	132
50.0	....	42.0	6.0	2.0	12.19	999	.....	83,300	37.5	35.0	78	146
						10-carat						
(a)41.6	9.2	41.0	1.9	6.3	.....	...	.....	65,000(d)	41.0	....	60	107
41.6	4.6	43.4	5.0	5.4	11.60	952	38,700(b)	67,900	41.5	36.0	68	122
41.6	6.8	44.3	7.3	...	11.55	980	54,100(b)	86,800	32.0	28.0	89	178
41.5	11.7	46.8	...	...	11.2	...	41,500(c)	73,200	37.5	....	70	126
41.5	....	51.5	3.7	3.3	.....	...	.....	.....	....	....	..	...

(a) This alloy quenched in water; all others cooled in still air. (b) Yield strength for 0.1% offset. (c) Yield strength for 0.2% offset. (d) After 50% reduction by cold rolling, the following properties are obtained: tensile strength 116,000 psi, Rockwell B 104, VHN 240.

but in recent years they have been used principally for eyeglass frames and they are particularly well suited for this purpose. The alloys are employed in solid form or are clad upon a core of nickel, nickel silver or bronze. The methods of melting, casting and processing are similar to those employed with other golds, as described elsewhere in this section of the Handbook.

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2 V. H. Patterson and B. N. Iannone, Trans ASM, 37, 278 (1946)
3 T. C. Jarrett, Trans AIME, 137, 447 (1940)
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Gold Alloys in Dentistry

THREE principal types of gold alloy products are used in dentistry: castings, wires, and solders. The cast gold dental alloys and high-strength precious metal wires are described in this article. Information concerning the composition and use of dental gold solder is included in the article entitled "Joining Precious Metals" (*see* page 1104). The process of casting dental alloys is discussed in the article on page 1100.

High-Strength Precious Metal Wires

By N. O. Taylor*

THE PRECIOUS METAL wires used in dentistry are considerably stronger than might be anticipated from a superficial consideration of the properties of the constituent metals, which are all relatively soft.

Dental applications require high strength and elasticity in wires, as well as adequate resistance to corrosion by mouth fluids. The precious metal alloys that meet dental requirements are age hardenable and, when properly heat treated, wires of these alloys have high strength and, at the same time, relatively low moduli of elasticity (14,000,000 to 17,000,000 psi). The nature of these alloys and their response to heat treatment have been considered by R. L. Coleman,[1] Wise, Crowell and Eash,[2,3] and others.

Table I. Composition Limits of High-Strength Precious Metal Wires Used in Dentistry

Alloy	Composition, percentage[a] Au	Pt	Pd	Ag	Cu	Ni	Zn	Color
1	25–30	40–50	25–30	....	.....	...	...	Platinum
2	54–60	14–18	1– 8	7–11	11–14	0–1	0–2	Platinum
3	45–50	8–12	20–25	5– 8	7–12	...	0–1	Platinum
4	62–64	7–13	0– 6	9–16	7–14	0–2	0–1	Light Gold
5	64–70	2– 7	0– 5	9–15	12–18	0–2	0–1	Gold
6	56–63	0– 5	0– 5	14–25	11–18	0–3	0–1	Gold
7	10–28	0–25	20–37	6–30	14–21	0–2	0–2	Platinum
8	.....	0– 1	42–44	38–41	16–17	0–1	...	Platinum

(a) Fractional percentages of iridium, indium and rhodium are omitted here.

The high intrinsic value of the alloys, coupled with the fact that manufacturing lots are small, makes it impractical to test samples comparable in size with those used for most metals. Manufacturers of dental alloys publish data obtained from their alloys by test methods adopted by the Gold Division of the American Dental Trade Association.[4]

These methods are somewhat different from methods outlined in the American Dental Association Specification 7 for Wrought Gold Wires, yet differences in data from the two types of tests are minor except for values of percentage elongation. The manufacturers' methods are based on 8-in. gage lengths and the American Dental Association's methods on 2-in. gage lengths.

The high-strength wires used in dentistry may be classified into eight fairly well-defined groups. The data in Tables I and II were supplied by the members of the Dental Gold Institute as representing current products.

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Cast Gold Dental Alloys

By E. M. Wise*

DENTAL ALLOYS must have good casting properties. Such alloys are generally melted with a gas-air torch, yet they must have a solidus temperature high enough to permit the use of gold solders. Also the metal must have adequate nobility and a desirable yellow or white color, coupled with the mechanical properties required for the inlay, bridge or partial denture involved. The necessary mechanical properties can be found in three or possibly four alloys, ranging from those having a Brinell hardness number as low as 40, suitable only for inlays not subject to stress, to progressively harder alloys from 100 to 130 Bhn, required for inlays subject to considerable stress and for bridge abutments and crowns. Alloys harder than 200 Bhn and having a high elastic limit are required for partial dentures.

The harder alloys are also responsive to age hardening, and when maximum elastic properties are required, the alloys should be suitably heat treated. If extensive shaping or leveling is necessary, castings should be softened by quenching from between 700 and 750 C. Some alloys are hardened by remaining in the investment while cooling from the casting temperature to about 350 C, before being quenched. Castings made of other alloys must first be quenched from between 700 and 750 C, and then hardened by heating to between 250 and 450 C and cooling slowly, or by aging for a suitable time at a temperature appropriate to the specific alloy. Most dental castings are irregular in shape and close dimensional accuracy is re-

* The International Nickel Company, Inc., New York

Table II. Some Physical and Mechanical Properties of High-Strength Precious Metal Wires Used in Dentistry

Alloy[a]	Tensile Strength,[b] 1000 psi Soft[c]	Hardened[d]	Prop. Limit, 1000 psi Soft	Hardened	% Elongation (8-in. gage) Soft	Hardened	Bhn[e] Soft	Hardened	Fusion Temp (Wire Method), deg Fahr	Specific Gravity, g/cu cm	Electrical Resistivity[g] microhm-cm
1	125–180	(f)	80–150	(f)	14–15	(f)	200–245	(f)	2730–2790	16.9–17.6	42–43
2	110–130	160–186	72–102	130–151	12–22	5–10	150–190	240–285	1840–2010	15.0–18.5	28–33
3	140–150	160–170	110–120	130–140	8–10	7–9	210–230	250–270	1950–2050	15.5–15.8	.....
4	90–115	120–165	55–80	85–140	14–26	2–8	166–195	240–295	1730–1860	14.5–15.6	.....
5	82–120	130–165	53–73	103–139	14–20	1–3	135–200	230–290	1650–1710	14.1–15.2	20–22
6	84–100	96–157	52–58	70–124	20–28	1–2	138–170	220–280	1610–1650	13.7–14.0	.....
7	96–148	150–192	60–115	110–160	9–20	1–8	150–225	180–270	1725–1975	11.5–15.6	.....
8	100–110	130–170	63–87	107–127	16–24	8–15	150–200	235–270	1910–1970	10.7–11.2	.....

(a) *See* Table I for chemical compositions of alloys. (b) Tension tests on wires 0.040 in. in diam. Most elongation data on 8-in. gage lengths. (c) Quenched from 1300 to 1600 F, depending on type of alloy. (d) Cooled slowly and uniformly from 840 to 480 F in 30 min. This is a severe hardening treatment used for test purposes in determining the behavior of wire under adverse conditions. Manufacturers recommend hardening treatments for specific uses. (e) Brinell hardness numbers obtained with the "Baby Brinell" testing machine. (f) Not appreciably affected by heat treatment. (g) Very few data are available on the electrical resistivity of dental alloys, since resistance is not an important factor in their use.

Table III. Composition Limits of Cast Gold Dental Alloys

No.	Type	Composition, percentage: Au	Ag	Cu	Pd	Pt	Zn
		Yellow Golds					
1	Soft	79–92.5	3–12	2–4.5	0–0.5	0–0.5	0–0.5
2	Medium	75–78	12–14.5	7–10	1–4	0–1	0.5
3	Hard	62–78	8–26	8–11	2–4	0–3	1
4	Partial denture	60–71.5	4.5–20	11–16	0–5	0–8.5	1–2
		White Golds					
5	Hard	65–70	7–12	6–10	10–12	0–4	1–2
6	Partial denture[a]	60–65	10–15	9–12	6–10	4–8	1–2
7	Partial denture[b]	28–30	25–30	20–25	15–20	3–7	0.5–1.5

(a) Yellowish white (b) Very white

quired; therefore warping caused by quenching from high temperatures is likely to be serious, especially in the larger castings. Pickling in a hot solution of 50% sulfuric acid, 50% water, is generally desirable for cleaning the surface of the cast alloy.

The American Dental Association has provided specifications for several types of cast dental golds and parallel Federal specifications have been established for several classes. Many of the commercial dental alloys fit into these classifications, but many other alloys have been designed to meet special requirements.

The alloys in use are the results of much research and the specific compositions adopted by individual manufacturers differ considerably in some instances. The general compositions of the widely useful alloys are shown in Table III. Table IV presents typical mechanical properties as determined on cast bars about 0.090 in. in diam and several inches long—a shape that is obviously difficult to cast at normal casting temperatures.

Table IV. Mechanical Properties of Cast Gold Dental Alloys

No.[a]	Treatment[b]	Bhn	Tensile Strength, 1000 psi	Proportional Limit, 1000 psi	Elongation, %	Liquidus, deg Cent
			Yellow Golds			
1	Q	45– 70	30– 45	8– 15	20–35	950–1050
2	Q	80– 90	45– 55	20– 25	20–35	930–970
3	Q	95–115	48– 57	23– 30	20–25	.....
3	A	115–165	60– 82	29– 58	6–20	950–1000
4	Q	130–160	60– 75	35– 47	4–25	.....
4	A	210–235	100–120	60– 92	1–6	870–985
			White Golds			
5	Q	105–115	50– 57	24– 30	9–18	.....
5	A	120–170	60– 75	28– 45	2–12	1030–1070
6	Q	130–180	65– 75	40– 45	9–15	1025–1050
6	A	225–260	110–120	75– 83	1–3	.....
7	Q	160–180	82– 87	50– 55	9–12	.....
7	A	220–280	115–130	65–100	2–3	930–1000

(a) *See* Table I for compositions of these alloys.
(b) Q, Quenched; A, Aged.
Modulus of Elasticity. 11,000,000 to 15,000,000 psi.

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SEE ALSO:
"Dental Gold Solders", page 1104
"Dental Casting", page 1100
"Palladium-Gold-Silver Alloys", page 1129

69 Au – 25 Ag – 6 Pt

COMPILED BY H. T. REEVE*

B *1 Typical uses.* Electrical contacts handling currents in the milliampere range. This alloy withstands considerable rubbing during the make and break, but where this type of closure is not involved, it has largely been supplanted by palladium.

C *1 Density* at 20 C (68 F). 16.11 g per cu cm (0.582 lb per cu in.)

D *1 Liquidus temperature.* Approx 1110 C (2030 F)
2 Solidus temperature. Approx 1030 C (1886 F)
16 Thermal conductivity. 0.13 cal/sq cm/cm/°C/sec

E *2 Electrical resistivity* at 20 C (68 F). 14.9 microhm-cm

K *Mechanical properties.*

Condition	Tensile Strength, psi	Rockwell Hardness, 30-T scale	Vickers Hardness Number
Annealed	54,500	60	112
Hard, 50% reduction	.....	64	130

* Bell Telephone Laboratories, Murray Hill, N. J.

PLATINUM AND PLATINUM ALLOYS

Platinum

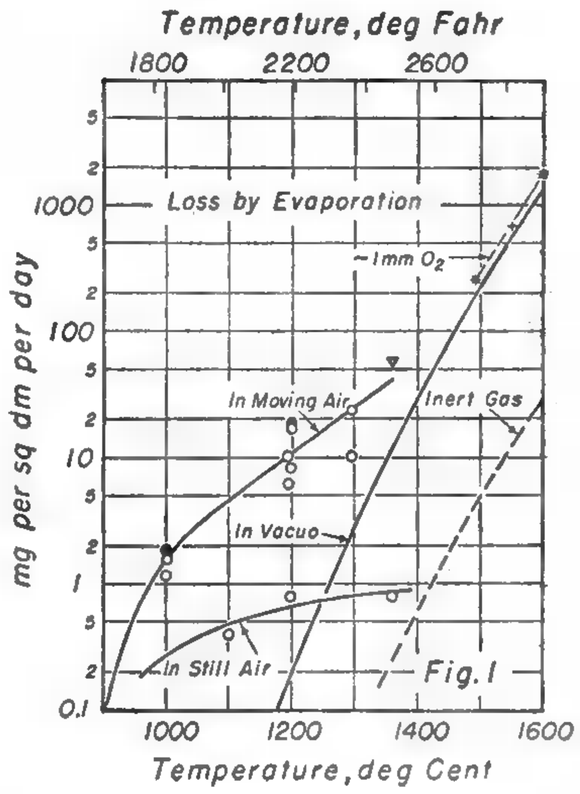
COMPILED BY E. M. WISE*

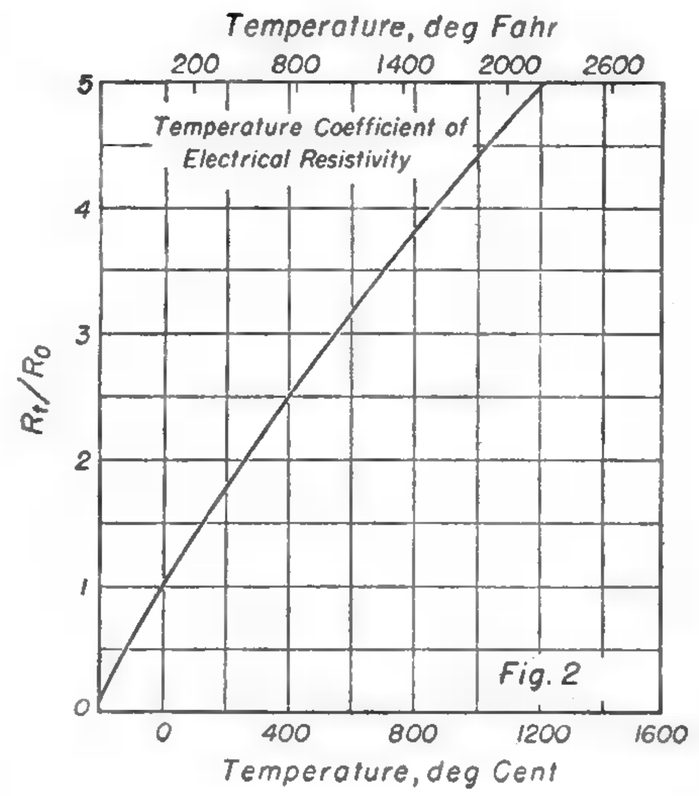
B *1 Typical uses.* Platinum is the best known and least rare of the platinum group metals, and has the widest range of uses because of its general corrosion resistance, high melting point, appearance, and ductility. Platinum of the highest purity (sometimes called "physically pure") is required for resistance thermometers and thermocouples. In addition, various alloying elements, such as ruthenium, iridium and, for special purposes, other hardeners are employed to develop higher mechanical properties or to withstand peculiar corrosive conditions better. Platinum is used for electrical contacts, chemical production, and laboratory equipment including spinnerets, anodes in both solid and clad form, for jewelry, and as leaf for decorative purposes. It is also used for producing high-purity optical glass and glass fiber. Platinum is an outstanding catalyst, both for oxidation, as in production of H_2SO_4 and HNO_3, and for hydrogenation in production of vitamins and other chemicals.

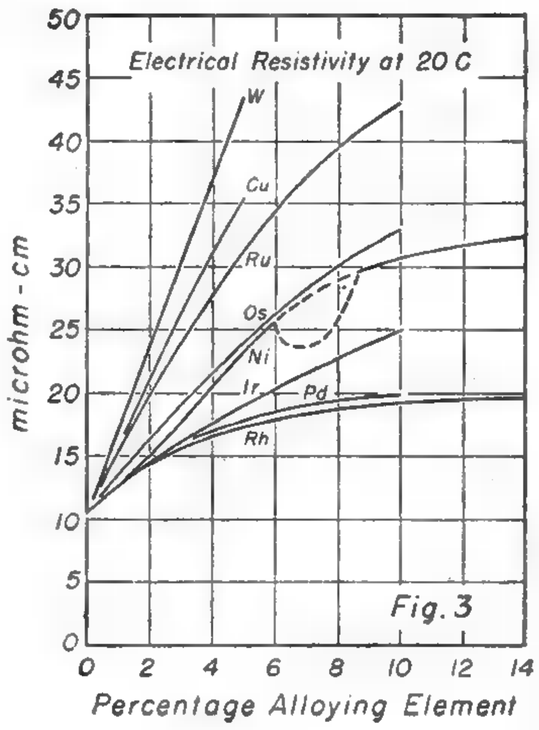
C *1 Density* at 20 C (68 F).[2] 21.45 g per cu cm (0.775 lb per cu in.)

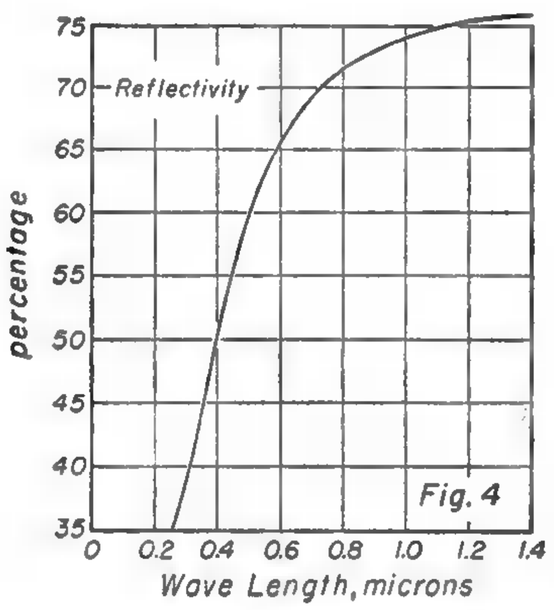
D *1 Melting point.*[4] 1773.5 C (3223.8 F)
4 Boiling point.[5] Approximately 4530 C (8185 F) calculated from thermodynamic data.[9] 4407 C (7965 F)
5 Vapor pressure
at 1000 C (1832 F). 1.1×10^{-12} mm of Hg
at 1500 C (2732 F). 1.1×10^{-6} mm of Hg
at 1773 C (3223 F). 1.3×10^{-4} mm of Hg

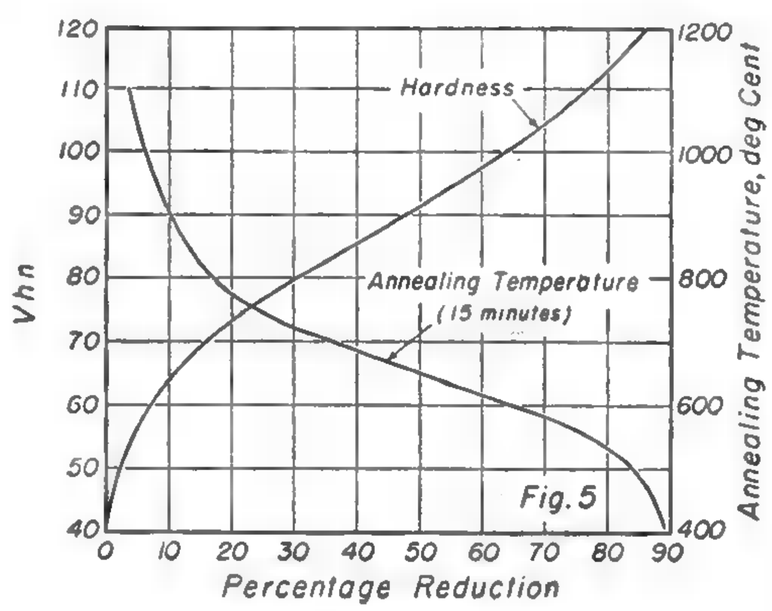
* The International Nickel Company, Inc., New York

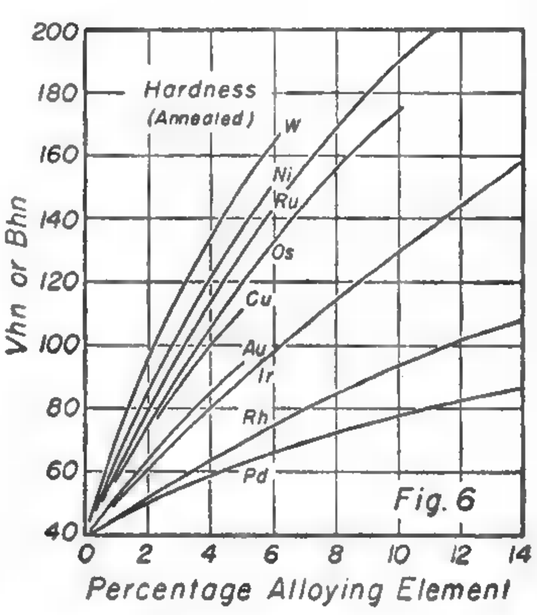












6 *Thermal expansion* at 20 C (68 F). 0.0000089 per °C
References 11 and 12 develop the equations for length versus temperature. Reference 12 is preferred for temperatures between minus 188 and plus 95 C. See reference 13 for equation for higher temperatures.

11 *Specific heat* at 0 C (32 F),[14] 0.0314 cal per g

13 *Latent heat of fusion.*[14] 26.9 cal per g

16 *Thermal conductivity*
at 17 C (63 F). 0.165 cal/sq cm/cm/°C/sec
at 100 C (212 F). 0.173 cal/sq cm/cm/°C/sec

20 *Rate of evaporation* in vacuo[5] and in low-pressure oxygen or air, based on the results of several experiments[6,7,8] and on unpublished data communicated by F. E. Carter, has been summarized in Fig. 1.[15]

E 2 *Electrical resistivity* at 0 C (32 F). 9.83 microhm-cm
at 20 C (68 F). 10.6 microhm-cm

5 *Temperature coefficient of electrical resistivity** 0.003925 per °C (0 to 100 C). The resistivity over a wide range of temperature corresponds closely to the formula:[2]

$$R_t = R_0 (1 + 3.9788 \times 10^{-3}t - 5.88 \times 10^{-7}t^2)$$

The ratio of resistivity at various temperatures to that at 0 C is shown in Fig. 2.[16] The change in resistivity with temperature is fundamental to accurate resistance thermometry and also is useful in estimating the purity of platinum, since the temperature coefficient is sensitive to traces of impurities, as is the thermal emf. For effects of alloying, see Fig. 3.[2]

9 *Thermoelectric force.* Very pure platinum is often the reference electrode in comparing the thermoelectric behavior of individual metals and alloys. Measurements of the thermal emf of samples of platinum (with the hot end at 1200 C and the cold end at 0 C) against platinum of extreme purity are useful for estimating the purity of different lots of platinum, as small amounts of impurities (except gold) in solid solution in platinum make the slightly impure platinum thermoelectrically positive to strictly pure platinum. Iron is perhaps the most troublesome element in this respect. Data on these matters, assembled from various sources, are included in reference 2.

F 1 *Reflectivity.** 67.3% in white light. *See* also Fig. 4.[18,19,20]

5 *Emissivity* with red filter.[16] Solid, 0.30 at $\lambda = 0.65$ μ (used in optical pyrometry). Liquid, 0.38

G 2 *Magnetic susceptibility* at 18 C (64 F).[17] 1.1×10^{-6} mass units

I 1 *General resistance to corrosion.* A detailed summary of the corrosion of the platinum metals is given in reference 15.

2 *Resistance to specific agents.* Platinum is resistant to reducing or oxidizing acids at room temperature, but is attacked by a mixture of nitric and hydrochloric acids, known as aqua regia, and somewhat slowly by hydrochloric acid plus other oxidizing agents. Platinum is resistant to ferric chloride at room temperature. Hydrobromic acid plus bromine attacks it at room temperature. All the free halogens attack platinum at elevated temperatures, but hydrochloric acid in the absence of oxidizing agents does not attack it, and platinum is useful against this normally active gas up to 1100 C. Sulfur dioxide does not attack platinum, even at 1000 or 1100 C.[27]

As an anode, platinum is outstanding and is used commercially in sulfuric and persulfuric acids, various sulfate-chloride plating electrolytes, and in chlorates, with very little corrosion. If electrolyzed with alternating current, chlorides may attack it and use is made of this fact in etching platinum and platinum alloys.

Platinum is quite resistant to acid potassium sulfate, sodium carbonate, potassium nitrate at moderate temperatures and to sodium carbonate at 800 to 900 C under nonoxidizing conditions, although it is attacked vigorously by molten alkali cyanides and polysulfides, but it is quite resistant to the normal sulfides plus alkali. Certain phosphates attack it at high temperatures, and care must be taken to avoid reducing conditions, particularly when compounds of arsenic, phosphorus, tin, lead, or iron, are present. Platinum is resistant to molten glasses, especially to those low in lead and arsenic.

Platinum, even in the form of thin leaf, is resistant to corrosion and tarnishing on atmospheric exposure, including urban sulfur-bearing atmospheres.

* W. F. Roeser, private communication

* F. L. Jones, private communication

J *1 Crystal structure.*[3] Face-centered cubic; lattice parameter at 20 C (68 F) 3.9158 kX

K *Mechanical Properties.*

Annealed: tensile strength 17,000 to 19,000 psi; proportional limit less than 2000 psi; elongation 25 to 40%; Vickers pyramid hardness 38 to 40; modulus of elasticity (for small cyclic strains) 21,300,000 psi* and also 24,600,000 psi[23] (which seems high); Poisson's ratio[24] 0.39.

Hard drawn: Modulus of elasticity 22,600,000 psi

Electrodeposited:[26] Vickers hardness, approx 600

The effect of cold rolling on the hardness after annealing for 15 min at various temperatures, for a sample about 99.99% pure[24] is shown in Fig. 5. The grain size after annealing this type of platinum is determined almost entirely by the prior reduction; virtually no grain growth occurs on the usual short anneals. It is probable, however, that platinum, free from oxygen in solution, will show grain growth after recrystallization and may possess a still lower annealing temperature. The effects of alloying elements on the hardness are shown in Fig. 6.

High-temperature properties. The short-time tensile strength of annealed, quite pure platinum was 20,700 psi at room temperature; at 400 C it was 13,000 psi; at 800 C, 8000 psi; and at 1000 C, 4000 psi.[27] The elongation increased with the temperature and exceeded 25% in all tests. The strengths of the alloyed platinums generally are higher than these values. The "time to fracture" of platinum and some platinum alloy wires at 1100 C has been studied.[22]

6 Creep behavior between 850 and 1000 C (1560 to 1830 F) is discussed in reference 21.

N *6 Precautions in working.* Melting procedures are described on page 1097. The maintenance of oxidizing conditions throughout processing is essential to avoid contamination in the high-purity materials. Pickling in hot hydrochloric acid, after rolling and before annealing, to remove iron, likewise is essential for high-purity wire and sheet.

15 Heat treatment. Hot reducing atmospheres, particularly where silica, iron or manganese are in the vicinity, are almost certain to result in contamination.

* R. L. Wegel, private communication

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Commercial Types of Platinum

By F. E. Carter*

THE FOUR generally recognized grades of wrought platinum that contain at least 99% Pt are known commercially as types A, B, C and D.

Type A, which is at least 99.99% pure, is used for thermocouples and resistance thermometers. This grade is sometimes called "physically pure" because estimation of purity is based on determinations of the thermal emf and the temperature coefficient of resistivity, in addition to spectroscopic and chemical analyses. The properties of this type of material have been summarized in the data sheet on pure platinum.

Type B contains 99.9% Pt and is often called "chemically pure", "special pure" or "specially refined platinum". It is used for the preparation of pure salts and for making platinum-rhodium catalysts and the like.

Type C contains 99.5% Pt or more and is very low in iron and other base metals. It is called "crucible grade" and is used for general laboratory purposes and for anodes.

Type D, containing 99.0% Pt or more, is known as "commercial platinum" and is used for jewelry, electrical contacts and the like.

The resistance to corrosion at ordinary temperatures is the same for all these types, but at very high temperatures, under oxidizing conditions, some slight differences may be found. The electrical resistivity, temperature coefficient of electrical resistivity, and thermal emf differ among these grades, and the mechanical strength and annealing temperatures increase as the purity decreases. Platinum should not be heated under reducing conditions or with elements that will diffuse into the metal.

Typical values for the properties that would be expected to differ appreciably are listed in Table I.

* Baker & Company, Newark, N. J.

Table I. Some Physical and Mechanical Properties of Commercial Platinum

Property	Types A	B	C	D
Electrical resistivity, microhm-cm				
0 C	9.83	.....	.....	.....
20 C	10.6	10.8	11.4	14.9
Temperature coefficient of electrical resistivity				
0 to 100 C	0.003923	.....	.....	.....
20 to 100 C	0.00364	0.0036	0.0035	0.0034
Thermal emf (hot end 1200 C, cold end 0 C) versus high-purity Pt such as Nat Bur Standards Pt 27, millivolts	0 to plus 0.030 mv	to approx plus 0.150 mv	to 1.0 mv	.....
Tensile strength (annealed), 1000 psi	17 to 19	20 to 23	24	26
VHN (annealed)	38 to 42	42 to 46	50	52
Tensile strength (hard drawn), 1000 psi	34	35	35.4	45.5
VHN (hard drawn)	97	100	110	130
Annealing temperature, 50% reduction	650 C	.....	.....	.....
Annealing temperature, 75% reduction	550 C	750 C	850 C	950 C
Hot working temperature	800 to 1200 C	800 to 1200 C	800 to 1200 C	800 to 1200 C

Platinum Alloys Containing from 3.5 to 20% Rhodium

BY F. E. CARTER*

SOME physical and mechanical properties of platinum-rhodium alloys are listed in Table I and Fig. 1 and 2.

Working. The alloys that contain up to about 20% Rh can be worked hot or cold; alloys richer in rhodium require considerable hot work before they can be cold worked satisfactorily. The working range is from 900 to 1200 C and the annealing temperature is from 900 to 1000 C. Reductions up to 90% between anneals are satisfactory.

Uses. Rhodium is the preferred addition to platinum for most applications at high temperatures under oxidizing conditions since, in contrast with most other hardeners, rhodium is not selectively volatilized. The 10% Rh alloy is the most important of the series and finds major use as the catalyst for the oxidation of ammonia by air, in the production of nitric acid. This same alloy, but with composition controlled precisely, is the positive element in the standard thermocouple (Pt–10% Rh versus platinum) that is widely used in laboratories and in industrial control. Some use is made of the Pt–13% Rh versus platinum thermocouple in instruments that are calibrated for it.

Table I. Some Properties of Platinum-Rhodium Alloys

Rhodium content	3.5%	5%	10%	20%
Density, ▮ per cu cm	20.9	20.65	19.97	18.74
Electrical resistivity at 20 C, microhm-cm	16.6	17.5	19.2	20.8
Temp coeff of elec resistivity, 20 to 100 C	0.0022	0.0020	0.0017	0.0014
Tensile strength (annealed), psi	25,000	30,000	45,000	70,000
Elongation (annealed), %	....	....	35	40
Bhn (annealed)	60	70	90	120
Tensile strength (hard), psi	60,000	70,000	90,000	130,000
Elongation (hard), %	....	....	2	2
Bhn (hard)	120	130	165	210

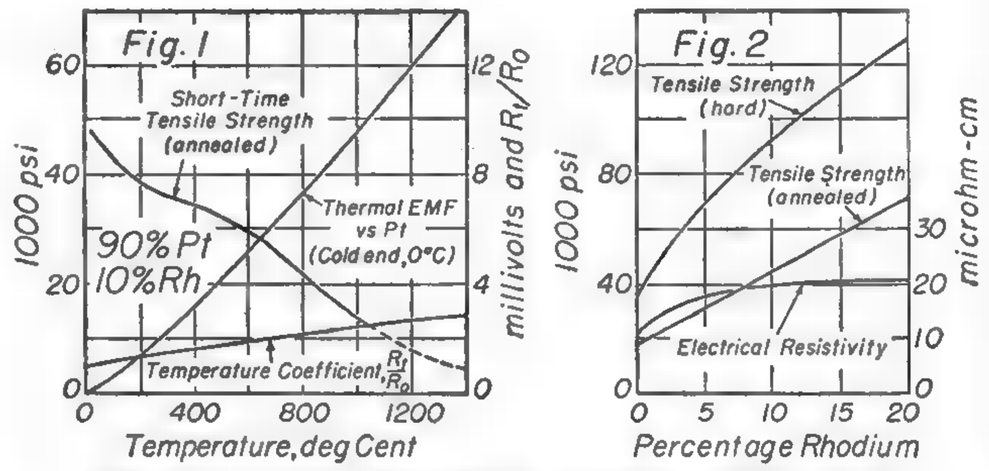


Fig. 1 and 2 Some properties of platinum-rhodium alloys

The 3.5% Rh alloy, used for crucibles, serves well and shows very little loss in weight at high temperatures. Platinum-rhodium alloys are useful in contact with molten glass; the 10% Rh alloy, in particular, is used for glass feeder dies and the like, and is especially desirable for handling the glasses of higher melting point.

The 10% Rh alloy is used for rayon spinnerets.

Both 10 and 20% Rh platinum make excellent windings for high-temperature electric furnaces that operate under oxidizing conditions. These are the preferred platinum alloys for this purpose.

Resistance to Corrosion. The resistance of the platinum-rhodium alloys to corrosion is as good as, or better than, that of pure platinum at ordinary temperatures, and at high temperatures is usually better than the resistance of pure platinum, except under sulfidizing conditions.

Platinum Alloys Containing from 5 to 30% Iridium

BY F. E. CARTER*

SOME physical and mechanical properties of four grades of platinum-iridium alloys are listed in Table I and the effect of iridium content is shown in Fig. 1.

Working. The alloys that contain from 5 to 10% Ir can be hot worked between 1000 and 1200 C. Temperatures between 1000 and 1300 C are suitable for the 25% alloy. In cold working, reductions of 75% between anneals are suitable for the 5 and 10% Ir alloys, and of 50% for the 25% Ir alloy. Annealing temperatures are about 1100 C for the lower alloys and 1200 C for alloys with 25-30% Ir.

Uses. Alloys that contain from 5 to 25% Ir are in general use. The 5 and 10% Ir alloys, also known as "medium hard" and "hard platinum", are widely used for jewelry; the 10% Ir and particularly the 25% Ir alloys are used for electrical contacts. The 25 and 30% alloys are used for tubing for pens and hypodermic needles, for spring elements and other articles in which maximum hardness and high annealing temperature plus ductility are required. The 10% Ir alloy is also used for anodes in electrolysis. Various platinum-iridium alloys are used in equipment for chemical plants and to some extent in dentistry.

Table I. Some Properties of Platinum-Iridium Alloys

Iridium content	5%	10%	25%
Trade designation	Medium Hard	Hard	....
Density, g per cu cm	21.49	21.53	21.66
Electrical resistivity at 20 C, microhm-cm	19	25	33(a)
Temp coeff, 0 to 100 C	0.0020	0.0013	0.00065(a)
Thermal cond at 17 C	....	0.074 cgs	....
Tensile strength (annealed), psi	40,000	55,000	125,000
Bhn (annealed)	90 (33R_B)	130 (62 R_B)	240 (18.5 R_c)
Tensile strength (hard), psi	70,000	90,000	170,000
Bhn (hard)	140 (79 R_B)	185 (91 R_B)	310 (31.5 R_c)

NOTE. For the 10% Ir alloy the thermal expansivity at 20 C is 8.89 × 10^{-6} per °C. The effect of temperature on the length of this alloy between 0 and 1000 C is

$$L = L_0 10^{-6} (1 + 8.841\ t + 0.0013\ t^2)$$

(a) With an iridium content of 30%, the resistivity is 35 microhm-cm and the temperature coefficient is 0.0006 between 0 and 100 C.

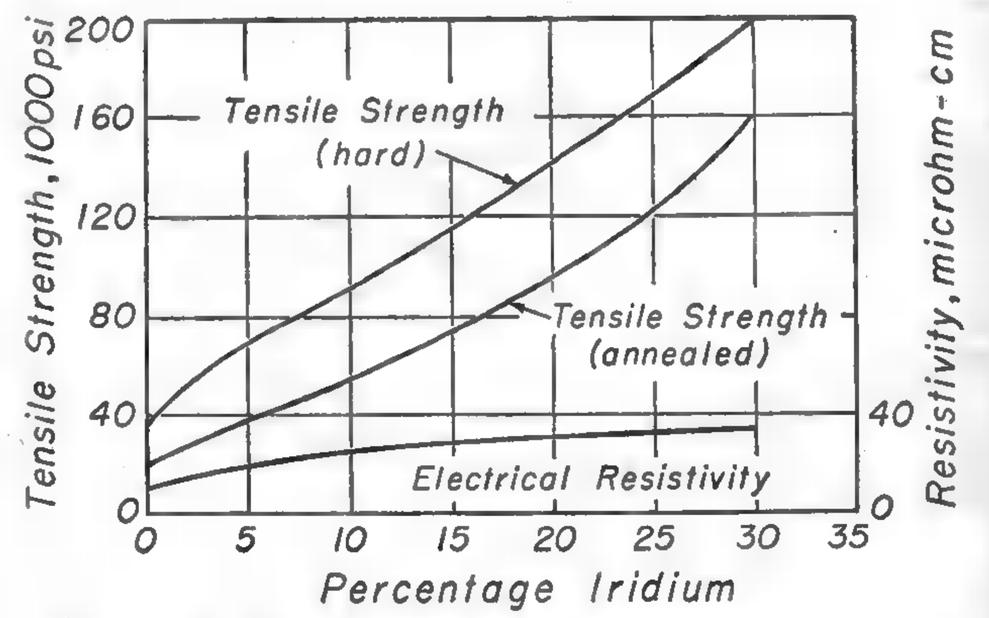


Fig. 1 Effect of iridium content in platinum-iridium alloys

Resistance to Corrosion. In general, the resistance to aqueous solutions of halogens is increased by the presence of iridium, particularly when 20 to 25% Ir is present, but for high-temperature service in air, alloys that contain more than about 1% Ir are seldom used, since iridium is lost through oxidation and volatilization.

* Baker & Company, Newark, N. J.

Platinum Alloys Containing 5 and 10% Ruthenium

By F. E. Carter*

PERTINENT physical and mechanical properties of two grades of platinum-ruthenium alloy are listed in Table I and the effect of ruthenium content is shown in Fig. 1.

Working. The 5% Ru alloy is hot worked between 900 and 1200 C and the 10% Ru alloy, between 1000 and 1300 C. Annealing temperature for the 5% alloy is about 1000 C and for the 10% alloy, 1100 C. Maximum reduction between anneals should not exceed 90% for the 5% alloy, or 75% for the 10% alloy. The atmosphere for high-temperature anneals should be only slightly oxidizing, since excessively oxidizing atmospheres cause loss of ruthenium in the same general manner as with iridium alloys.

Uses. The alloy that contains 5% Ru is used in jewelry, since it has properties essentially the same as the 10% Ir alloy—the so-called "hard platinum" of the jewelry trade. The same alloy is also used for laboratory electrode stems and for certain other chemical equipment, but it is not completely suitable for service at high temperatures under strongly oxidizing conditions. Platinum-ruthenium alloys are frequently employed as electrical contacts—the 5% Ru alloy in the medium-duty field and the 10% alloy in aircraft magnetos. Complex platinum-base alloys that contain 4 to 5% Ru are being used to some extent for spark plug electrodes in aircraft.

Table I. Some Physical and Mechanical Properties of 95 Pt–5 Ru and 90 Pt–10 Ru Alloys

Property	Hard Jewelry Grade	Contact Grade
Ruthenium content, %	5	10
Density, g per cu cm	20.67	19.94
Electrical resistivity, microhm-cm	31.5	43.0
Temperature coefficient, 0 to 1000 C	0.0009	0.0008
Tensile strength (annealed), psi	60,000	85,000
Elongation (annealed), %	34	31
Hardness (annealed), Bhn	130 (70 R_B)	190 (86 R_B)
Tensile strength (hard), psi	115,000	150,000
Elongation (hard), %	2	2
Hardness (hard), Bhn	210 (94 R_B)	280

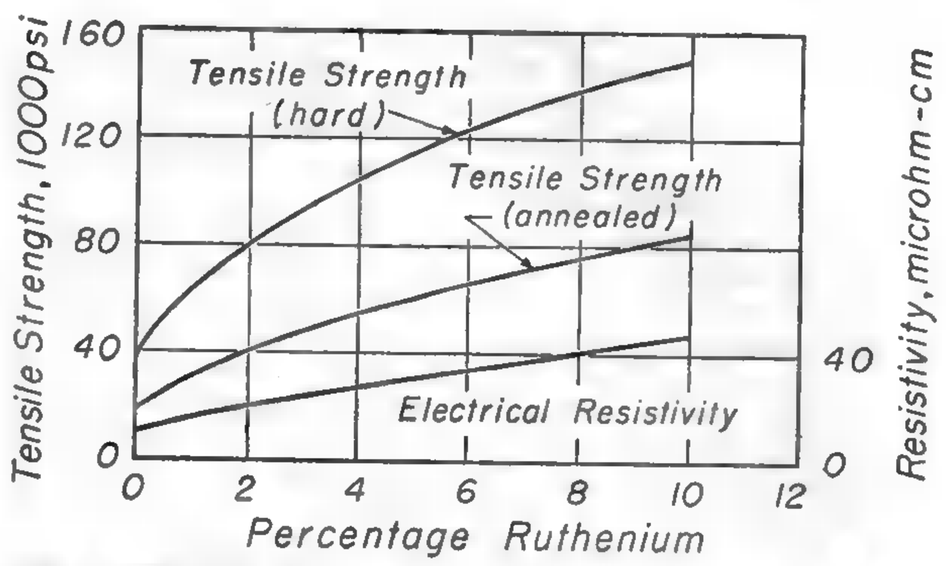


Fig. 1 Effect of ruthenium content on the tensile strength and electrical resistivity of platinum-ruthenium alloys

* Baker & Company, Newark, N. J.

Platinum Alloys Containing from 1 to 5% Nickel

By E. M. Wise*

SOME physical and mechanical properties of platinum alloys that contain 1, 2 and 5% Ni are listed in Table I and Fig. 1 and 2.

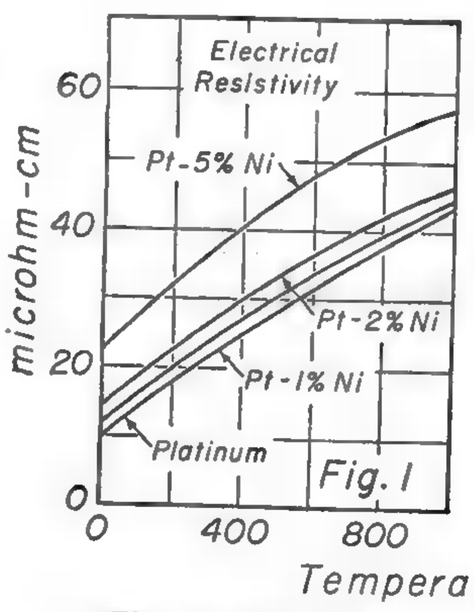
Uses. This type of alloy has long been used because of good strength at high temperature. The 5% Ni alloy has been used in a vacuum as the base for long-life oxide-coated thermionic cathodes.[1] Alloys that contain up to 2% Ni are used for spinnerets and associated equipment in producing fiber glass.[2]

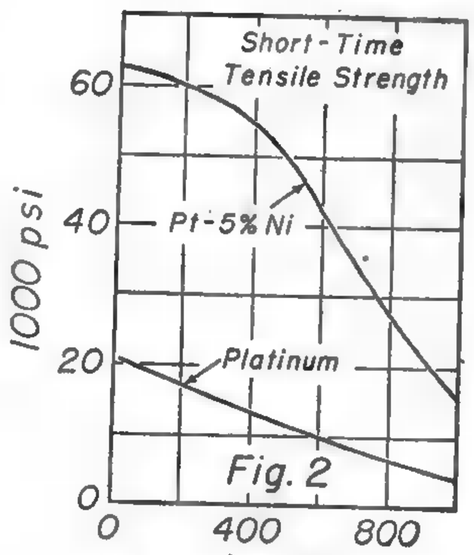
Resistance to Corrosion. Selective oxidation of nickel will occur when these alloys are heated to high temperatures under strongly oxidizing conditions. For this reason an alloy containing 5% Ni will gain rather than lose in weight while heating below 1500 C in air, but in the alloys that contain less than 2% Ni, this effect is reduced and such alloys are satisfactory for handling molten glass.[2]

Table I. Some Physical and Mechanical Properties of Platinum-Nickel Alloys

Nickel content	1%	2%	5%
Density, g per cu cm	21.1	20.8	20.0
Electrical resistivity at 20 C, microhm-cm	12.7	15.0	23.3 (Ref 3)
See Fig. 1 for high-temperature resistivity			
Temperature coefficient, per °C[a]	0.0033	0.003	0.002
Vickers hardness (annealed)	60 to 65	80 to 90	130 to 140
Tensile strength (annealed), psi.	30,000	41,000	65,000 (Ref 4)
Tensile strength (50% reduction), psi	....	....	104,000 (Ref 4)
Tensile strength at high temperature (*See* Fig. 2 and Ref 5)			

(a) From 0 to 100 C





Temperature, deg Cent

Fig. 1 Electrical resistivity of platinum-nickel alloys
Fig. 2 Short-time tensile strength of platinum-nickel alloys

* The International Nickel Company, Inc., New York

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Platinum-Palladium-Silver Alloys

See Properties of Palladium Alloys, page 1129.

84 Pt – 10 Pd – 6 Ru

COMPILED BY E. M. WISE*

B *1 Typical uses.* This alloy was developed specifically for electrodes in spark plugs in high-duty aircraft engines, where maximum resistance to highly leaded fuels is required. Under combustion conditions some lead from the fuel is reduced, and in alloys in which lead is virtually insoluble it tends to penetrate along grain boundaries. Damage from this cause is reduced if the alloy is in the cold worked, unrecrystallized condition.[1] With pure platinum and the platinum-palladium alloys lead is absorbed in the surface layers and shows less tendency toward the more damaging intercrystalline attack, apparently because of some solid solubility of lead in the alloy. However, these materials are too soft to resist erosion and mechanical stresses, so a small amount of ruthenium is added to harden them.[2] For the best results this alloy should be used in the drastically cold worked condition. Although designed especially for spark plug electrodes, this alloy, as well as the 10 to 12% Pd platinum alloy, is useful for electrical contacts in magnetos and the like.

C *1 Density.* Approx 19.1 g per cu cm (0.69 lb per cu in.)

E *2 Electrical resistivity* at 20 C (68 F). 39.5 microhm-cm

K *Mechanical properties.*[3]

Condition	Tensile Strength, 1000 psi	Elongation in 1 in., percentage	Vickers Hardness Number
Annealed	80	18 to 25	150 to 170
90% cold reduction	129 to 135	6 to 2	260 to 280

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96 Pt – 4 W

COMPILED BY E. M. WISE*

B *1 Typical uses.* This alloy was developed initially for spark plug electrodes in aircraft engines, but was shortly adopted for grids in radar tubes where reduced electron emission was required. It performs outstandingly in both situations. For spark plugs it is employed in the drastically hard drawn condition because it is more resistant to lead in that state. For radar use, slightly softer wire is preferred since it is more easily handled. Because of the selective oxidation of tungsten, this alloy is not recommended for service at very high temperatures under oxidizing conditions where platinum or rhodium platinum would be suitable.

C *1 Density* at 20 C (68 F). 21.3 ■ per cu cm (0.770 lb per cu in.)

D *1 Liquidus temperature.* 1825 C (3317 F)
2 Solidus temperature. 1800 C (3272 F)

E *1 Volume conductivity* referred to standard copper. 4.7%
2 Electrical resistivity at 20 C (68 F). 36.9 microhm-cm
9 Thermal emf versus platinum 0 to 1000 C (32 to 1832 F). 21.5 mv

K *Mechanical properties.*

Condition	Tensile Strength, 1000 psi	Elongation, percentage	Vickers Hardness Number
Annealed	70 to 75	25	140 to 150
Hard drawn, 50% reduction	100 to 105	3 to 4	220 to 230
Hard drawn, 90% reduction	130	1 to 2	260

* The International Nickel Company, Inc., New York

PALLADIUM AND PALLADIUM ALLOYS

Palladium

COMPILED BY E. M. WISE*

B *1 Typical uses.* Palladium resembles platinum in many respects including appearance, high ductility, and strength, and follows it in importance and abundance. Palladium is used for contacts in electrical relays, as an alloying element in complex wrought and cast dental alloys, in jewelry, and as an industrial catalyst in the manufacture of synthetic organic products, such as vitamins and ethylene, and also in the manufacture and purification of hydrogen. Some use is also made of the rapid and selective diffusion of hydrogen through palladium to prepare chemically pure hydrogen. Sometimes this effect is used to act as a valve that will admit hydrogen to vacuum systems when the palladium is warmed.

C *1 Density* at 20 C (68 F).[2] 12.02 g per cu cm (0.4343 lb per cu in.)

D *1 Melting point.*[5, 6, 7] 1554 C (2829 F)
4 Boiling point. Probably about 3980 C (7200 F)
6 Thermal expansion at 20 C (68 F). 0.00001176 per °C

$$L_t = L_o (1 + 1.167 \times 10^{-5} t + 2.187 \times 10^{-9} t^2)$$ (Ref 9)

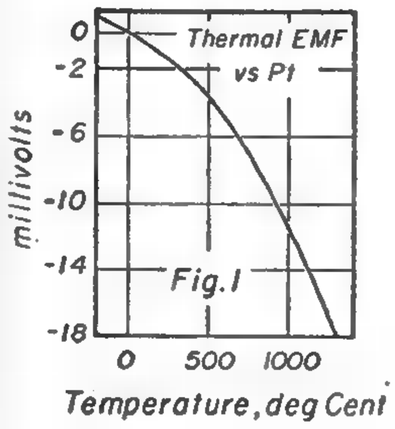
11 Specific heat[10,11]
at 0 C (32 F). 0.0584 cal per ■
at 1000 C (1832 F). 0.0707 and 0.0743 cal per g[10,11]
16 Thermal conductivity[8] at 18 C (64 F). 0.168 cal/sq cm/cm/°C/sec

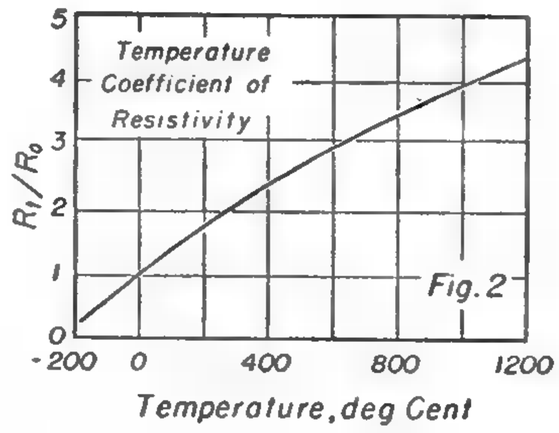
E *1 Volume conductivity* referred to standard copper. 16% at 20 C (68 F)
2 Electrical resistivity
at 20 C (68 F). 10.8 microhm-cm
at 0 C (32 F). 10.0 microhm-cm
5 Temperature coefficient of electrical resistivity.[12] 0.00377 per °C between 0 and 100 C
9 Thermal emf of a palladium-platinum couple with cold junction zero is shown in Fig. 1.[16]
17 The effect of temperature on the resistivity relative to its value at 0 C (32 F) is shown in Fig. 2.[13,14,15] Alloying with other metals increases the resistivity appreciably, as shown in Fig. 3.[12]

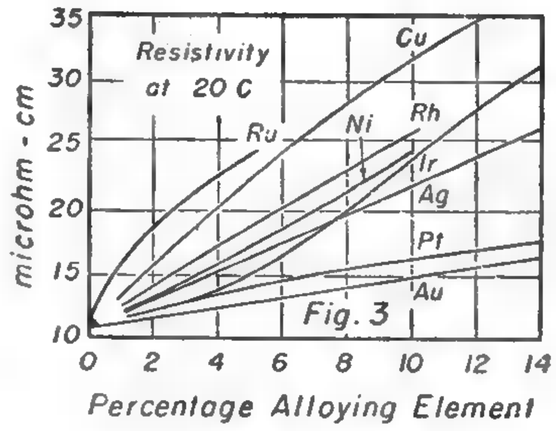
F *1 Reflectivity.* 62.8% in white light.* The reflectivity increases slightly in going from blue to red.[18] (Fig. 4)

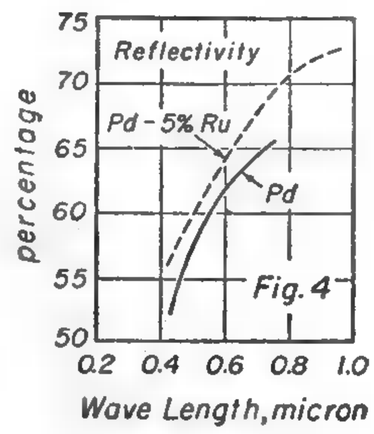
* The International Nickel Company, Inc., New York

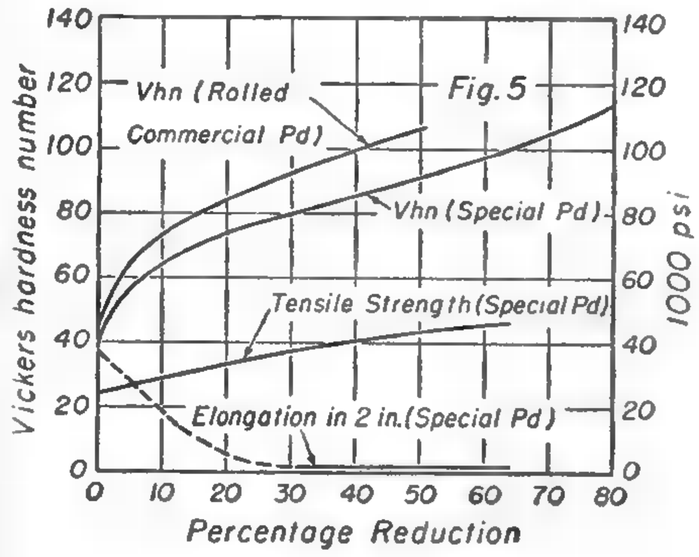
* F. L. Jones, private communication

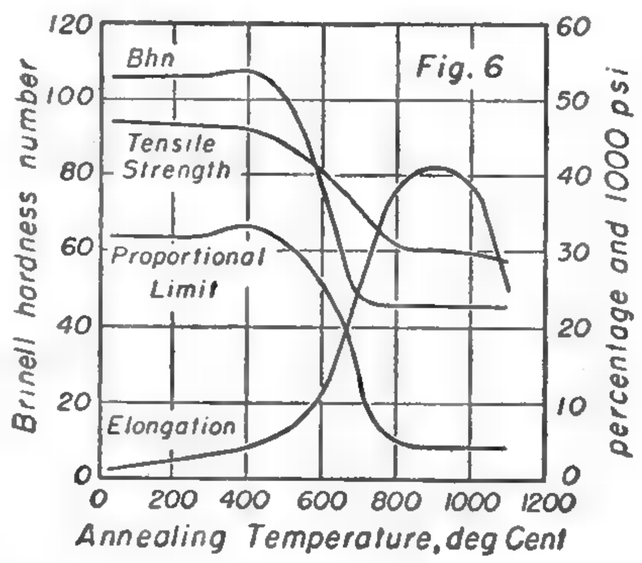


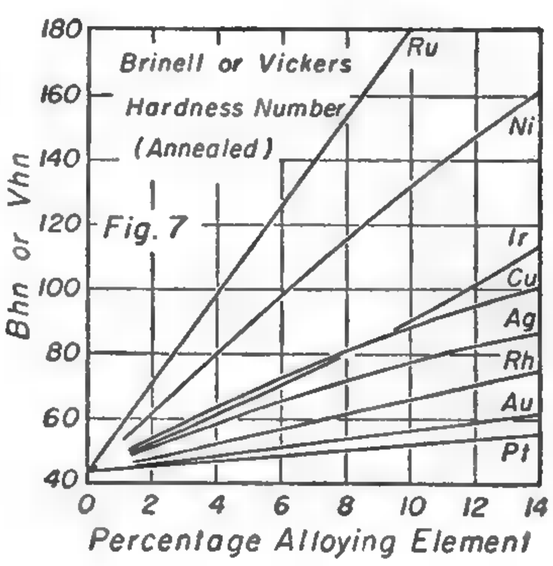












5 *Emissivity*[20] with a mean wave length of 0.65 μ: (solid) 0.33; (liquid) 0.37.

G 2 *Magnetic susceptibility*[17] at 18 C (64 F). Approx 5.8×10^{-6} mass units

I 1 *General resistance to corrosion.* At room temperature palladium is resistant to corrosion by hydrofluoric, perchloric, phosphoric and acetic acids. It is attacked slightly by sulfuric, hydrochloric and hydrobromic acids, especially in the presence of air; and it is attacked readily by slightly impure nitric acid, ferric chloride, hypochlorites, and moist chlorine, bromine and iodine. In ordinary atmospheres palladium is resistant to tarnish, but some discoloration may occur during exposure to moist industrial atmospheres that contain sulfur dioxide. Adding palladium to gold or silver alloys improves the tarnish resistance.

J 1 *Crystal structure.* Face-centered cubic; lattice parameter, 3.8825 kX at 20 C.[4]

K *Mechanical properties.*

Modulus of elasticity. 16,000,000 psi;[21,22] 17,500,000 psi.[23]

Strength and hardness. The hardness of pure, rolled and annealed palladium is about 37 to 39 Vickers, almost the same as that of platinum, and when tested as 0.050-in. wire after annealing at a high temperature, the metal may show a tensile strength as low as 21,000 psi with about 24% elongation. Similar wire annealed at 800 C will have a tensile strength of about 25,000 psi with 30% elongation. Such material work hardens slowly and will show a tensile strength of about 37,000 psi after 75% reduction by drawing. The effect of cold working upon the Vickers hardness of pure palladium, wrought from pure sponge melted in a lime block furnace, is shown in Fig. 5,* along with data on the tensile properties for cold drawn wire. Data on the hardness of commercial palladium are also shown in Fig. 5. This commercial palladium was also very pure (approx 99.9%), but differences in the method of melting and the presence of traces of deoxidizing elements increased its hardness and strength. Such material has a tensile strength from 25,000 to 30,000 psi as annealed, and about 47,000 psi after cold drawing 50%. The tensile properties of commercial palladium, initially reduced 50% by cold drawing and annealed for 5 min at various temperatures are shown in Fig. 6.[19] The optimum anneal for this material is about 800 C (1472 F). Electrodeposited palladium, much harder than the wrought materials, ranges from 190 VPN for metal from the chloride bath to about 400 VPN for deposits from complex nitrite baths. The types of palladium employed for jewelry and in some other articles generally contain ruthenium and are considerably harder than the pure metal. The relative effects of various additions on the hardness of annealed material are summarized in Fig. 7.[12]

High temperature properties. The short-time tensile strength of commercial palladium initially annealed at 1100 C was 28,000 psi at room temperature, 18,100 psi at 400 C, 8300 psi at 800 C, and 3800 psi at 1000 C.[3]

N 6 *Precautions in working.* Procedures for melting have been described on page 1097. Nitrogen is a good annealing atmosphere, and temperatures of about 800 C 1470 F) for five minutes give good combinations of properties in the commercially pure material, while 1000 to 1100 C (1832 to 2012 F) is required for some of the harder alloys.

17 *Joining.* In soldering palladium, an oxyacetylene torch is desirable, and platinum solders melting from 1100 to 1300 C (2000 to 2375 F) should be used.

* R. H. Atkinson

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60 Pd – 40 Ag

COMPILED BY R. F. VINES*

B *1 Typical uses.* For electrical contacts at low currents and as a nontarnishing electrical resistor of low temperature coefficient. This alloy contains sufficient palladium to be nontarnishing in indoor atmospheres and, where resistance to nitric acid is desired, 5 to 10% Pt can be added at the expense of palladium. The alloy, solid or as cladding, is suitable for jewelry.

C *1 Density.* 11.3 g per cu cm (0.408 lb per cu in.)

D *1 Liquidus temperature.* 1390 C (2534 F)
2 Solidus temperature. 1330 C (2426 F)

E *2 Electrical resistivity* at 20 C (68 F). 42 microhm-cm
5 Temperature coefficient of electrical resistivity 20 to 100 C (68 to 212 F). 0.00002 per °C
Coefficient of strain resistivity. $(dR/R)/(dL/L) = 0.88$

K *Mechanical properties. Annealed:* tensile strength 51,000 psi; elongation in 2 in. 47%; VHN 100.
50% reduction: tensile strength 94,000 psi; elongation in ▮ in. 4.5%

* Dentists' Supply Company, York, Pa.

60 Pd – 40 Cu

COMPILED BY H. T. REEVE*

B *1 Typical uses.* This alloy was devised for electrical contacts in the milliampere range, in circuits containing sufficient capacity so that a considerable rush of current occurs on closure. It is also used where a hard material is required for slip rings running against brushes of the same material, and is generally given a final heat treatment to convert it to the ordered, highly conducting condition. This conversion is accelerated greatly by cold work or by the presence of hydrogen in solution.

C *1 Density* at 20 C (68 F). 10.6 g per cu cm (0.383 lb per cu in.)

D *1 Liquidus temperature.* Approx 1225 C (2235 F)
2 Solidus temperature. Approx 1195 C (2185 F)

E *2 Electricial resistivity.* 35 microhm-cm, annealed and quenched; 3.5 microhm-cm, ordered, which is best produced by heating cold worked material at about 300 C.
5 Temperature coefficient of electrical resistivity 20 to 100 C (68 to 212 F). 0.00032 per °C, annealed; 0.00224 per °C, ordered.

K *Mechanical properties.* Tensile strength 75,000 psi, annealed; 193,000 psi, hard drawn

* Bell Telephone Laboratories, Murray Hill, N. J.

Palladium-Silver-Copper Alloys

BY E. M. WISE*

PALLADIUM increases the liquidus and solidus temperatures of silver-copper alloys and increases the mutual solubility of silver and copper. At high temperatures most of the ternary alloys are solid solutions, and all are workable after quenching. At lower temperatures there are ordered phases based on PdCu and $PdCu_3$. In the low-palladium alloys, copper-rich and silver-rich phases may be precipitated.

Many of the alloys are age hardenable. The maximum hardnesses are shown in Fig. 1. It will be noted that values in excess of 450 Vickers or about Rockwell C 49 are attainable in alloys that contain approximately 30% Cu, 30% Ag, 40% Pd. This hardness is unusually high for an alloy that is readily workable in the quenched condition.

Alloys that contain less than 5% Cu or more than about 65% Pd (slightly more than 50 atomic % Pd) do not age harden and have properties intermediate between the silver-palladium and copper-palladium alloys.

Melting and Working. The alloys must be melted in such a manner that oxygen, silicon and sulfur are low in the metal when it is cast. Final deoxidation with a few hundredths per cent of calcium or calcium boride often is useful. Annealing in nitrogen at about 800 C is suitable for most of the alloys, and the age hardenable ones should be cooled fairly rapidly to ensure full softness. If much zinc is present, oil quenching may be required to prevent partial hardening during cooling. Treatment for ¼ to 5 hr between 400 and 450 C hardens many alloys effectively.

Resistance to Tarnishing. The silver-palladium alloys that contain 50 to 60 weight or atomic % Pd, have good resistance to tarnishing but that of the corresponding copper-palladium alloys is not quite so good. If substantial age hardening is required, the palladium content should not exceed about 45%, but small amounts of gold or platinum can be added without impairing the hardening, and may actually increase it along with the resistance to tarnishing. As a result, a whole series of useful quaternary alloys exists between Cu-Ag-Pd and Cu-Ag-Au systems.

Uses. Alloys that contain about 45% Pd with sufficient copper to age harden to the desired level are used in dentistry, as are variants that contain a small percentage of platinum or gold. These alloys are used also for electrical contacts subjected to sliding wear or for applications that require good spring properties. About 1% Zn may be present, and this as well as platinum appears to accelerate the age hardening. The alloys containing 10 to 15% Pd have been considered for silver solders of unusually high strength.

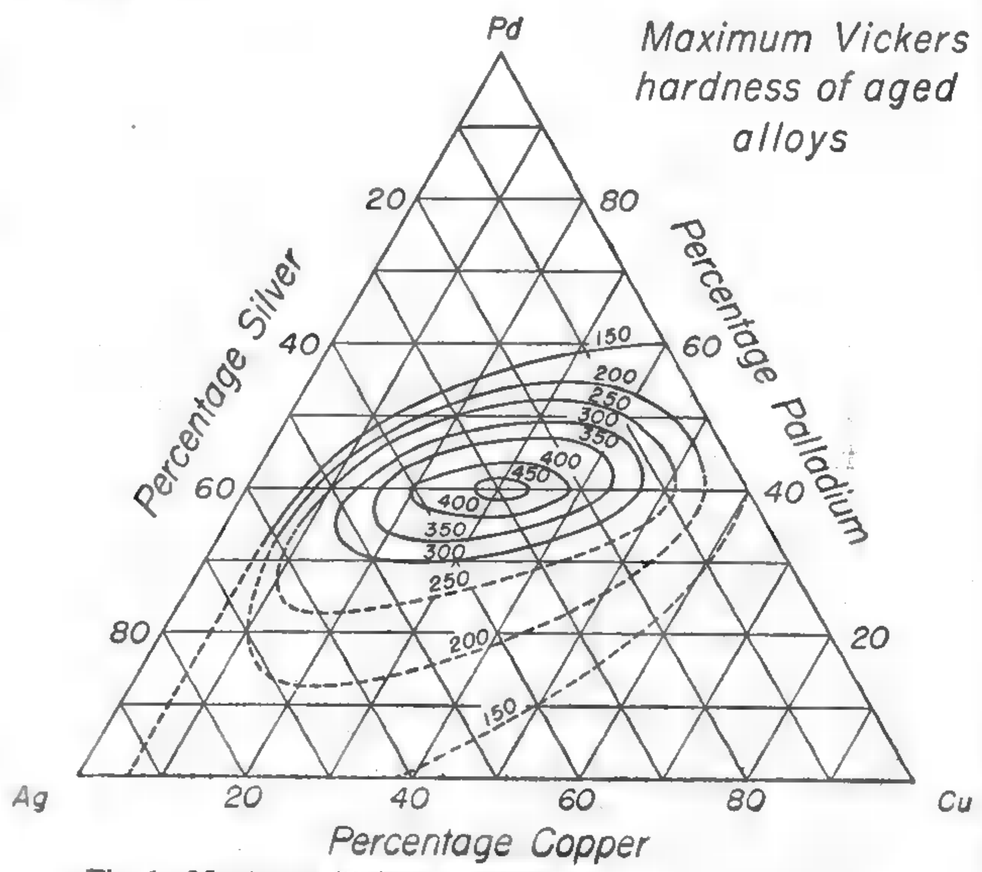

Fig. 1 Maximum Vickers hardness of aged Pd-Ag-Cu alloys

* The International Nickel Company, Inc., New York

Palladium-Gold-Silver Alloys

By E. M. Wise*

SOLID Pd-Au-Ag alloys are probably free from transformations, as are all the binary alloys of these metals. The solidus and liquidus temperatures are higher than for most gold alloys, and throughout the system, the melting range is narrow. The hardness of annealed alloys is shown in Fig. 1.

Working Properties. Precautions are required to secure low oxygen, sulfur and silicon contents in the cast alloys. The best annealing temperatures are higher than required for the usual gold alloys. Steam or nitrogen are probably the best annealing atmospheres. Alternately oxidizing and reducing atmospheres should always be avoided, since they cause damage to the surface of most of the alloys. The working properties of high-purity alloys are excellent; both solid and clad materials can be fabricated by cold working and in some instances by hot working.

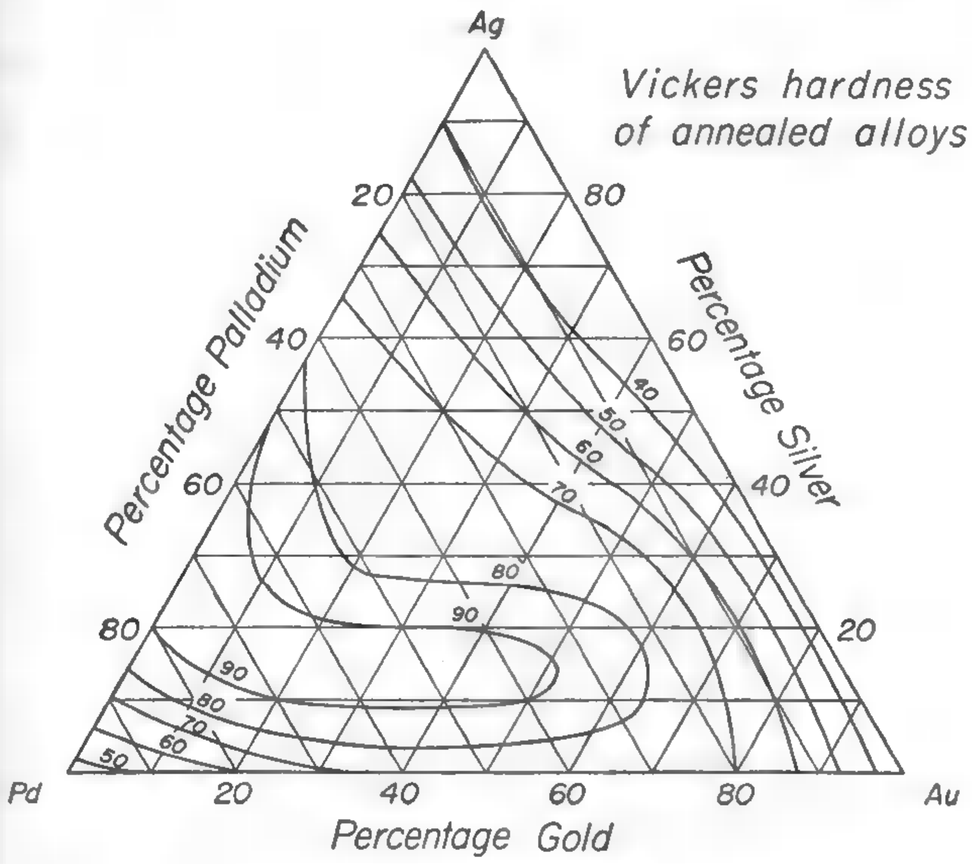

Fig. 1 Vickers hardness of annealed Pd-Au-Ag alloys

* The International Nickel Company, Inc., New York

Corrosion Properties. In general the resistance to tarnishing of the ternary alloys increases with the sum of the percentages of gold plus palladium, but palladium is somewhat more effective. The resistance to tarnishing becomes very good at 50 to 60% Pd or at about 70% Au. The addition of 20% Au to palladium or about 60% Au to silver, results in substantial resistance to nitric acid, and the ternary alloys from these points to the gold corner are very resistant to nitric acid. Although these alloys do not oxidize at high temperatures, they do dissolve some oxygen if heated in air; then if the alloys are heated later in a hydrogenous gas, hydrogen will diffuse into the metal, will react with the oxygen in solid solution, and will produce small surface blisters. This effect is greater in the silver-rich and the silver-palladium-rich alloys.

Uses. Gold-palladium alloys that contain 15 to 20% Pd are essentially white in color and are tarnishproof. The gold-silver alloys that contain about 50% Ag also are white, but will tarnish. The ternary alloys extending from these points to the palladium corner are white, and those that contain sufficient palladium plus gold are sometimes used where a somewhat subdued white color is desired, as in certain soft and ductile dental alloys and some high-melting solders. These alloys, however, should not be confused with the Au-Ni-Cu-Zn alloys, which are also white but much harder and more difficult to fabricate.

The addition of copper to Pd-Au-Ag alloys provides metals that are responsive to age hardening and are the basis for many of the cast and wrought high-strength dental materials.

Palladium-Platinum-Silver Alloys

By R. F. Vines*

THE WIDE spread between the liquidus and solidus temperatures of the silver-platinum alloys and the transformations that occur in the binary alloys generally have limited the interest to alloys containing a few per cent of platinum. The addition of palladium, which forms simple solid solutions with both platinum and silver, avoids both troubles and gives rise to a wide field of readily fabricated single-phase alloys.

The hardness of rolled and annealed alloys is approximately as shown in Fig. 1. Some of the ternary alloys can be age hardened appreciably, but the solid solution alloys are of most interest. If higher hardness is desired, supplementary hardeners may be added—for example, a few per cent of nickel.

Palladium-silver alloys that contain 50 to 60% Ag possess adequate resistance to tarnishing to be suitable for jewelry and optical uses, but sometimes resistance to nitric acid is considered necessary also, in order to conform to the customs of the industry, and experiment shows that this resistance can be secured by the addition of a small amount of platinum. Typical alloys, comparable with the usual carat gold alloys in cost, would contain 40% Pd, 10% Pt, 50% Ag or 50% Pd, 7.5% Pt, 42.5% Ag, sometimes with 2% Ni replacing silver where higher hardness is desired.

Alloys that contain about 25% Pt, 25% Ag, 50% Pd, offer a good base for high-melting, corrosion-resistant dental alloys. These alloys, like those lower in platinum and palladium, can be hardened further by small additions of certain other metals.

* The Dentists' Supply Company, York, Pa.

Considerable use has been made of a silver-rich alloy containing 3% Pt, particularly for instrument slip rings, where something harder than pure silver is desired. This amount of platinum would, of course, have little effect on the resistance to tarnishing. Aside from this

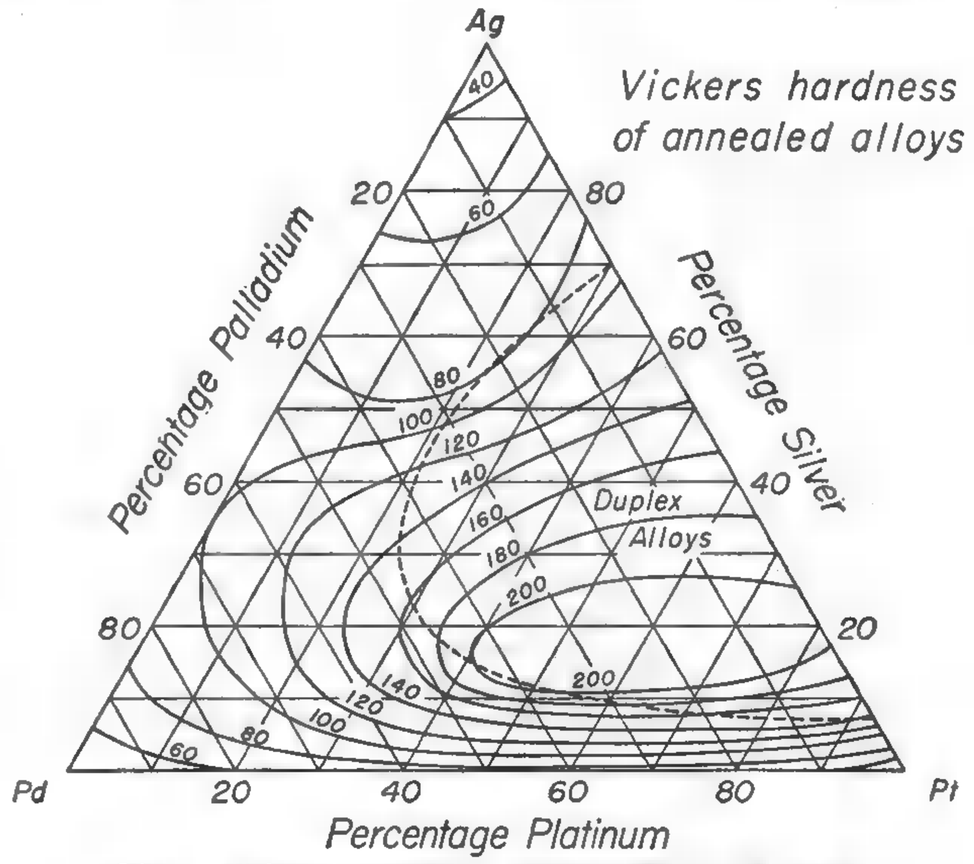

Fig. 1 Vickers hardness of annealed Pd-Pt-Ag alloys

application, the silver-rich alloys of this series have been used little; however, the 40% Ag, 60% Pd alloy, and related alloys in which a little palladium is replaced by platinum, are useful for electrical contacts, particularly where resistance to tarnishing is essential.

The alloys high in palladium or platinum can be melted best in a high-frequency furnace with final deoxidation by a trace of calcium boride. Annealing is desirable at 800 to 1000 C in a neutral atmosphere such as nitrogen. Rolling of the single-phase alloys involves no special problems. The heterogeneous alloys are troublesome to fabricate but thus far have been used very little.

95.5 Pd – 4.5 Ru and 95 Pd – 4 Ru – 1 Rh

COMPILED BY R. H. ATKINSON*

B *1 Typical uses.* Ruthenium, alone or with a small percentage of rhodium, is the principal hardener employed with palladium. The resulting alloy is designed primarily for jewelry; it can also be used for electrical contacts. The alloy is used principally in wrought form; production by casting is anticipated.

C *1 Density* at 20 C (68 F). 12.0 g per cu cm (0.434 lb per cu in.)

E *2 Electrical resistivity* at 20 C (68 F). 23.5 microhm-cm for the 4.5% Ru alloy

F *1 Reflectivity.* See Fig. 4 on page 1127.

K *Mechanical Properties. See* Table I.

N *9 Annealing. See* Fig. 1, the annealing curve for 95 Pd – 4 Ru – 1 Rh, which indicates that temperatures between 1000 and 1100 C are suitable. Annealing in nitrogen is desirable for high-quality jewelry.

17 Joining. Soldering with an oxyacetylene torch and melting with this torch or electrically without contamination with silicon, oxygen or sulfur, are highly desirable.

Table I. Mechanical Properties of Pd-Ru and Pd-Ru-Rh

Condition	Tensile Strength, 1000 psi	Elongation, percentage	Vickers Hardness Number
95.5 Pd – 4.5 Ru			
Annealed	....	....	80 to 90
Annealed and furnace cooled	....	....	100 to 130
50% reduction	....	....	150 to 160
95 Pd – 4 Ru – 1 Rh			
Annealed	55 to 60	25	100 to 110
50% reduction	70	3	180 to 190

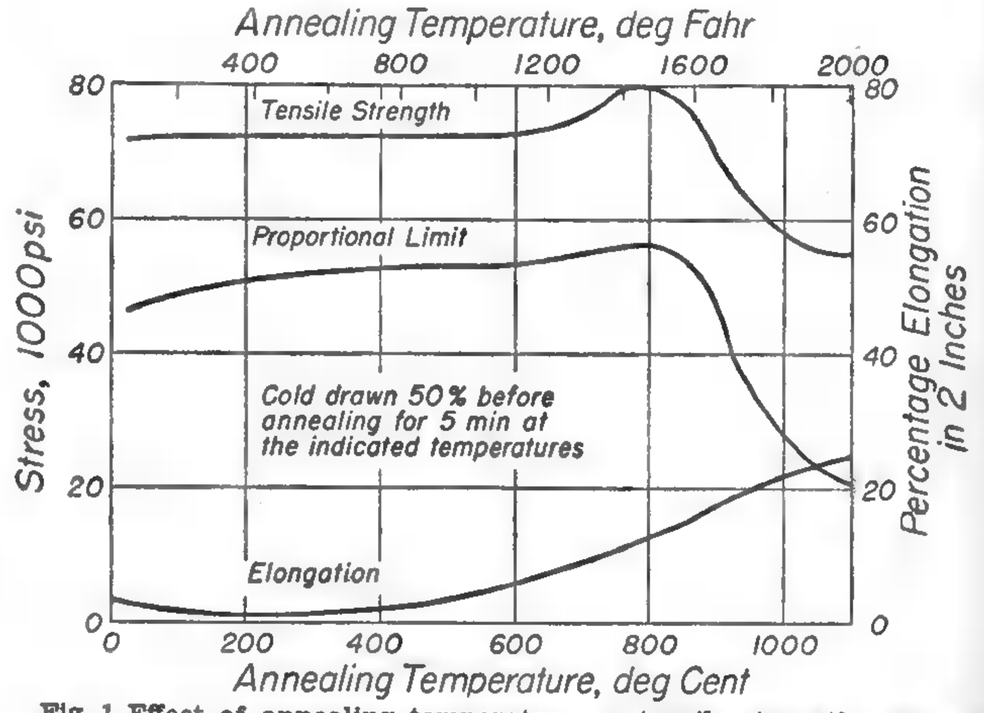

Fig. 1 Effect of annealing temperature on tensile strength, proportional limit and elongation of 95 Pd – 4 Ru – 1 Rh, initially cold drawn 50%. Duration of annealing, 5 minutes.

* The International Nickel Company, Inc., Bayonne, N. J.

IRIDIUM, OSMIUM, RHODIUM AND RUTHENIUM

Iridium

COMPILED BY R. F. VINES*

B *1 Typical uses.* Small crucibles have been made of iridium for studying high-temperature reactions. Iridium has been used for extrusion dies for very-high-melting glasses.* Iridium is not wet by mercury and this phenomenon has been used in certain electrical devices. The major use is as an alloying element in platinum; occasionally iridium is added to other metals of the platinum group. This addition increases the resistance to aqueous corrosives and reduces the rate of attack in aqua regia. More than about 1% Ir in platinum is usually not desirable if the alloy is to be used at high temperatures under oxidizing conditions, since iridium is oxidized and volatilized. Platinum-iridium alloys, which are used for jewelry, electrical contacts and elsewhere, are discussed in the article on page 1124.

C *1 Density* at 20 C (68 F). 22.5 ▮ per cu cm (0.813 lb per cu in.)

D *1 Melting point.*[3, 4] 2454 ± 3 C (4449 ± 5 F)

4 Boiling point.[5] Approximately 5300 C (9570 F)

6 Thermal expansion[6] at 20 C (68 F). 0.0000068 per °C

11 Specific heat[7] at 20 C (68 F). 0.0307 cal per g

16 Thermal conductivity.[8] 0.14 cal/sq cm/cm/°C/sec

E *2 Electrical resistivity* at 0 C (32 F). 4.9 microhm-cm at 20 C (68 F). 5.3 microhm-cm[9]

5 Temperature coefficient of electrical resistivity.[10] 0.003925 per °C (0 to 100 C)

6 Thermal emf versus platinum[11] 0 to 100 C (32 to 212 F). + 0.65 mv

F *1 Reflectivity.*[12] 64% at $\lambda = 0.45\ \mu$
70% at $\lambda = 0.55\ \mu$
78% at $\lambda = 0.75\ \mu$

Iridium is intermediate between palladium and rhodium in reflectivity and color.

5 Emissivity at 0.65μ. 0.30 for solid unoxidized metal[13]

G *2 Mass magnetic susceptibility* at 18 C (64 F).[14] 0.15×10^{-6} cgs

I *1 General resistance to corrosion.*[17] Iridium is the most corrosion-resistant element. It is not affected by

* Research Laboratory, Dentists' Supply Co., York, Pa.

* J. C. Chaston, private communication

common acids, including hot sulfuric acid. It is slightly attacked by sodium hypochlorite solutions but not by aqua regia at ordinary temperatures. However, at elevated temperatures and pressures aqua regia does attack iridium, and this method may be used for dissolving iridium and its refractory alloys for analysis. Iridium is virtually insoluble in lead even at high temperatures and use is often made of this fact in preliminary steps in chemical analysis.

K *Mechanical properties.* The Vickers hardness[15] of annealed iridium is approximately 170 and that of hard rolled material, 350.

The modulus of elasticity[16] is extremely high, perhaps as high as 76,000,000 psi.

N *Working data.* Iridium can be melted in a high-frequency furnace in a thoria crucible and can be forged with some difficulty at temperatures ranging from 1200 to 1500 C (2190 to 2730 F). Hot rolling is possible. In general, the workability of iridium is between that of ruthenium and rhodium.

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Osmium

COMPILED BY E. M. WISE*

B *1 Typical uses.* Osmium is the rarest of the platinum metals and is the hardest and has the highest melting point. It is completely unworkable. The hardness, resistance to wear and to corrosion of high-osmium and related alloys in which osmium and ruthenium are present account for their use for tips of fountain pen nibs, long-life phonograph needles and instrument pivots. The best quality alloys often contain 60% or more of osmium, plus ruthenium, the remainder platinum metals, sometimes plus a little tungsten or other metal. The hardness of these alloys is approximately 700 to 800 VPN. For instance, the 25 Pt–75 Os alloy has a VPN of 800; the 50 Pt–50 Os alloy, a hardness of 720 VPN.[10] The resistance to rubbing wear is perhaps the most important characteristic of the high-osmium alloys but is not solely the result of high hardness; other alloys as hard or harder are inferior. The low magnetic permeability, hardness and corrosion resistance of the osmium alloys makes them useful for certain instrument pivots. In certain types of vibrating electrical contacts where the movement is small, an alloy containing 66 to 70% Os, balance rhodium, made by fusion or by sintering, has been employed for the positive contact with 10% Ru platinum for the negative. This combination minimizes metal transfer and results in smooth wear.

C *1 Density* at 18 C (64 F). 22.61 g per cu cm (0.82 lb per cu in.) from X-ray data;[2] 22.48 g per cu cm (0.812 lb per cu in.) has been obtained by direct measurement. The difficulty of securing completely sound specimens renders the measurement uncertain.

D *1 Melting point.* Probably about 2700 C (4890 F)

4 Boiling point.[4] Probably about 5500 C (9950 F)

Vapor pressure. Probably lowest of platinum metals. The rate of evaporation in vacuo or in an inert gas is correspondingly low, but in the presence of appreciable oxygen, oxidation occurs, resulting in rapid volatilization through the formation of the volatile and toxic OsO_4 (boiling point, 130 C); consequently osmium and osmium alloys are not used at elevated temperatures under oxidizing conditions.

7 Thermal expansion at 50 C (122 F) parallel to *c*-axis. 0.0000058 per °C

8 Thermal expansion at 50 C (122 F) perpendicular to *c*-axis. 0.000004 per °C

11 Specific heat at 0 C (32 F).[6] 0.0309 cal per g
at 100 C (212 F). 0.0314 cal per g
at 1600 C (2912 F). 0.0385 cal per g

E *2 Electrical resistivity* at 20 C (68 F).[7] Approx 9.5 microhm-cm

5 Temperature coefficient of electrical resistivity 0 to 100 C (32 to 212 F).[8] 0.0042 per °C

G *2 Mass magnetic susceptibility.*[9] Approx 0.074×10^{-6} cgs

I *2 Resistance to specific agents.** The rapid oxidation of osmium in air at elevated temperatures must be recognized in considering uses and processing. Osmium is resistant to sulfuric, hydrofluoric, hydrobromic and hydrochloric acids at room temperature. Finely divided osmium is attacked by nitric acid, but the fused metal is quite resistant to this acid, although reasonably well sintered samples are attacked appreciably by nitric acid and by aqua regia. The alkaline hypochlorites also attack the sintered metal. The usual high-osmium alloys are, however, extremely resistant to corrosion by inks even when subject to simultaneous rubbing on paper, although this combination is quite corrosive to some alloys that will withstand ink alone.

J *1 Crystal structure.*[3] Close-packed hexagonal; $a = 2.7304$ kX; $c/a = 1.5785$ at 18 C (64 F).

K *Mechanical properties.* Vickers hardness about 400; values of 350 and 438 have been observed.† Variations in the porosity of the sample and differences in purity probably account for the spread in observed values. Modulus of elasticity has been estimated to be as high as 81,000,000 psi,[11] highest of all elements.

N *Working data.* Osmium is completely unworkable. No ductility is apparent, so that osmium and osmium alloys must be produced by melting or sintering, followed by grinding to produce the final shapes required. Care must be taken to avoid oxidation during high-temperature operations and particularly in the recovery of the metal from grindings and other scrap.

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* The International Nickel Company, Inc., New York

* "Corrosion Handbook"[5] and private communication from Atkinson, Raper and Middleton.

† O. Winkler[10] and private communication from R. H. Atkinson

Rhodium

COMPILED BY C. S. SIVIL*

B *1 Typical uses.** The pure metal is used principally where maintained high and uniform reflectivity is essential. This includes mirrors, principally those made by electrodeposition of rhodium on metal, plus some made by subliming rhodium on glass. Various types of light filters can be made by applying very thin coatings by subliming. A substantial amount of rhodium is electrodeposited as a nontarnishing finishing plate on jewelry articles, including white gold, silver, and other metals, as described in the article on Plating Precious Metals. Some use is also made of rhodium for the plating of sliding electrical contact surfaces; for this purpose rhodium is sometimes applied over a heavier plate of palladium. Some pure wrought rhodium is used but rhodium is most important as an alloying element with platinum, since these materials find much use at elevated temperatures for crucibles, furnace windings, glass working equipment, thermocouples, and particularly for catalysts.

C *1 Density* at 20 C (68 F). 12.44 g per cu cm (0.447 lb per cu in.)

D *1 Melting point.*[2] 1966 C (3571 F)
4 Boiling point.[3] Probably about 4500 C (8130 F).
6 Thermal expansion[4] 20 to 100 C. 0.0000083 per °C
11 Specific heat[5] at 0 C (32 F). 0.059 cal per g
16 Thermal conductivity[6] at 17 C (63 F). 0.21 cgs

E *2 Electrical resistivity* at 20 C (68 F). 4.51 microhm-cm
5 Temperature coefficient of electrical resistivity[2] 20 to 100 C (68 to 212 F). 0.0042 per °C

$$(R_{100} - R_0)/100R_0 = 0.00457$$

F *1 Reflectivity.*[7,8] *See* Fig. 1.
5 Emissivity[9] at $\lambda = 0.65$ μ. 0.24 (solid), 0.30 (liquid)

G *2 Magnetic susceptibility*[10,11] at 18 C. 1.14×10^{-6} cgs

I *1 General resistance to corrosion.* Rhodium remains bright and untarnished during atmospheric exposure, and its general resistance to corrosion is exceptionally high. It is resistant even to boiling aqua regia. However, rhodium is attacked somewhat by hydrobromic acid, particularly when hot; by moist iodine, and by sodium hypochlorite. Hot sulfuric acid also attacks it, and sufficient corrosion occurs on electrolysis with alternating current in sulfuric acid to make this a useful metallographic etch.

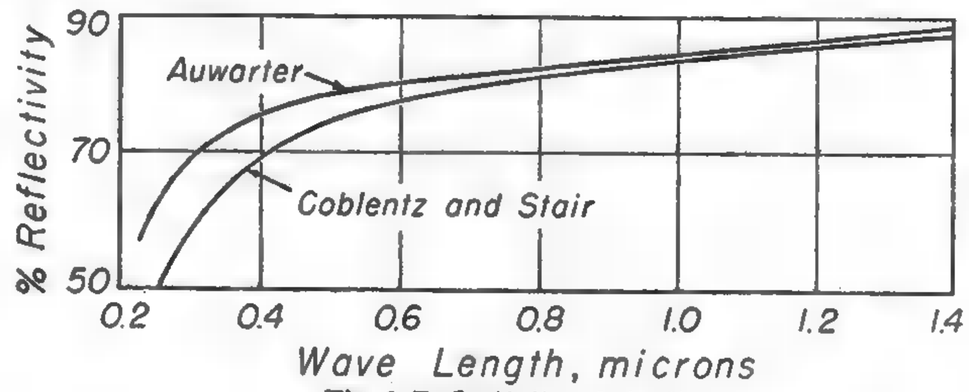

Fig. 1 Reflectivity of rhodium

J *1 Crystal structure.*[1] Face-centered cubic; lattice parameter 3.796 kX at 20 C (68 F).

K *Mechanical properties.*

Condition	Tensile Strength, psi	Brinell Hardness Number	Vickers Hardness Number[12]	Modulus of Elasticity, psi
Annealed	73,000	...	...	.....
Hard	300,000	...	...	.....
Hard wire	.....	...	...	42,500,000
Not stated	.....	135		55,000,000[13]
		101	122	

* Baker and Company, Newark, N. J.

* EDITOR'S NOTE. For a more extended discussion of the engineering properties and uses of rhodium, the reader may refer to an article by L. B. Hunt in Metal Industry (London), 71, 339 (1947)

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Ruthenium

COMPILED BY R. H. ATKINSON*

B *1 Typical uses.* As a hardener for platinum and palladium for jewelry and other applications, including 10 to 11% Ru platinum for aircraft magneto contacts and similar contacts. Hard, complex high-ruthenium alloys are also used for pen tipping and the like. Some of these alloys also contain osmium.

C *1 Density* at 20 C (68 F). 12.2 ■ per cu cm (0.441 lb per cu in.) 12.45 g per cu cm at 18 C (64 F) computed from lattice constants.

D *1 Melting point.* 2500 ± 100 C (4530 ± 180 F)
4 Boiling point. Probably about 4900 C (8850 F)
6 Thermal expansion at 20 C (68 F). 0.0000091 per °C
11 Specific heat at 0 C (32 F). 0.057 cal per g

E *2 Electrical resistivity* at 0 C (32 F). 7.6 microhm-cm
10 Electrochemical equivalent (valence 2). 0.527 mg per coulomb
16 Supraconductive at 2.04 K

F *1 Reflectivity* in the visible range. 63% avg

G *2 Magnetic susceptibility.* 0.895×10^{-6} mass units

I *1 General resistance to corrosion.* The general resistance of ruthenium to corrosion approaches that of iridium. It is unaffected by common acids, including aqua regia, at temperatures up to 100 C, or by sulfuric acid up to 300 C. It is moderately attacked by aqueous solutions of alkaline hypochlorites.

J *1 Crystal structure.* Close-packed hexagonal; $a = 2.6987$ kX; $c = 4.2728$ kX.

K *Mechanical properties.* Vickers hardness 220 as cast; 390 for metal forged above 1500 C; modulus of elasticity, approx 60,000,000 psi

L *1 Metallography.* Etching: Use a-c electrolytic.

N *6 Precautions in melting.* Use inert atmosphere for induction melting. For torch melting, compress ruthenium powder to bar and use lime hearth and neutral oxyacetylene flame; work in hood with good draft to remove ruthenium tetroxide fumes.
7 Hot working temperature. 1500 to 2400 C (2730 to 4350 F)
11 Forming. Very difficult to work, but with care it can be forged at temperatures above 1500 C (2730 F).
13 Compacting pressure. 40,000 psi

* The International Nickel Company, Inc., Bayonne, N. J.

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MISCELLANEOUS METALS

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Antimony

COMPILED BY K. C. LI*

B *1 Typical uses.* Alloyed with lead for batteries. Alloyed with tin or lead for bearings and type metal. In the form of an oxide (Sb_2O_3) in enamels, pigments, and in fire-proofing materials.
C *1 Density* at 20 C (68 F). 6.62 g per cu cm (0.239 lb per cu in.)
D *1 Melting point.* 630.5 C (1166.9 F)
4 Boiling point. 1440 C (2620 F)
6 Thermal expansion 20 to 60 C (68 to 140 F). 0.0000085 to 0.0000108 per °C, the value depending on the crystal orientation in the polycrystalline material.
11 Specific heat at 20 C (68 F). 0.049 cal per g
13 Latent heat of fusion. 38.3 cal per ■
15 Latent heat of vaporization. 320 cal per ■
16 Thermal conductivity. 0.045 cal/sq cm/cm/°C/sec
E *2 Electrical resistivity* at 0 C (32 F). 39.0 microhm-cm
F *1 Reflectivity.* 70% at $\lambda = 5890$ A
G *2 Mass magnetic susceptibility.* minus 0.87 cgs
I *2 Resistance to specific agents.* See Table I.
J *1 Crystal structure.* Rhombohedral; lattice constant at 20 C, 4.4974 kX; axial angle, 57° 6.5′.

Table I. Resistance of Antimony to Corrosion

Corrosive Agent	Resistance	Remarks
Acid hydrochloric	Resistant	.....
Acid hydrochloric	Moderate attack	In presence of air
Acid hydrofluoric	Resistant	.....
Aqua regia	Severe general attack	.....
Acid nitric	Severe general attack	.....
Acid sulfuric	Severe general attack	Warm, concentrated
Acid sulfuric	Resistant	Cold or dilute
Ammonia	Resistant	.....
Carbon dioxide	Resistant	.....
Chlorine	Severe general attack	.....
Alkalies and alkali salts	General attack	.....
Air	Resistant	When dry
Air	Moderate general attack	When moist and in presence of light

5 Minimum interatomic distance. 2.898 kX
K *Mechanical properties.*
Brinell hardness number. 30 to 58
Ultimate tensile strength. 1560 psi (1.1 kg per sq mm)
Modulus of elasticity. 11,300,00 psi
Torsion modulus. 2,800,000 psi

* Chairman, Wah Chang Trading Corporation, New York

Arsenic

COMPILED BY A. C. VAUGHAN*

A *1 Common name.* Black Crystalline Arsenic
5 Other designations. There are two other forms of arsenic—black amorphous (density 3.70) and yellow cubic arsenic (density 2.0)
B *1 Typical uses.* Alloyed with lead to facilitate forming more perfect spheres in making lead shot. Alloyed with copper to increase corrosion resistance and to raise the recrystallization temperature. Added to lead-base babbitt and solder alloys to improve properties.
C *1 Density* at 15 C (59 F). 5.73 g per cu cm (0.207 lb per cu in.)
D *1 Melting point.* 814 C (1497 F) at 36 atmospheres
4 Boiling point. Arsenic sublimes at 610 C (1130 F)
6 Thermal expansion at 20 C (68 F). 0.0000047 per °C
11 Specific heat 0 to 100 C (32 to 212 F). 0.082 cal per g
15 Latent heat of vaporization. 444 cal per g
E *1 Volume conductivity* referred to standard copper. 4.9%
2 Electrical resistivity at 0 C (32 F). 35 microhm-cm
10 Electrochemical equivalent. (valence 3) 0.15254 mg per coulomb, (valence 5) 0.25876 mg per coulomb
G *2 Magnetic susceptibility.* minus 0.31×10^{-6} cgs at 18 C
J *1 Crystal structure.* Rhombohedral; $a = 4.151$ kX; alpha 53° 49′

* American Smelting and Refining Company, Barber, N. J.

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Beryllium

COMPILED BY N. W. BASS AND BENGT KJELLGREN*

A *1 Common name.* Beryllium
6 Foreign equivalent. Glucinum

B *1 Typical uses.* As an alloying element in copper. In aluminum-base and magnesium-base alloys, beryllium decreases oxidation and combustibility of the melt and increases the fluidity (particularly of aluminum alloys). Vacuum-tight "windows" of pure beryllium are used in X-ray tubes. Also used as source of neutrons with radium, polonium or other elements.
2 Precautions in use. Beryllium oxidizes appreciably in air above 700 C. It reacts generally with dilute acids, alkalies and hot water. Liquid beryllium reacts with carbon.

C *1 Density* at 20 C (68 F). 1.816 g per cu cm (0.0658 lb per cu in.)

D *1 Melting point.* 1284 C (2343 F)
4 Boiling point. 2770 C (5030 F)
6 Thermal expansion 20 to 200 C (68 to 392 F). 0.0000124 per °C
11 Specific heat 30 to 100 C (86 to 212 F). 0.516 cal per g
13 Latent heat of fusion. 250 to 275 cal per g
15 Thermal conductivity at 20 C (68 F). 0.385 cgs

E *1 Volume conductivity* referred to standard copper. 38.9 to 43.1%
10 Electrochemical equivalent (valence 2). 0.04674 mg per coulomb

F *1 Reflectivity.* 50 to 55% in white light
4 Color. Gray

I *1 Resistance to corrosion.* Beryllium is resistant to acetic acid, concentrated nitric acid, ammonia and to air at room temperature. No actual corrosion resistance tests have been carried out on pure beryllium, so far as is known. The above observations are therefore highly qualitative. Organic substances such as sugar, formaldehyde, petroleum products and alcohols, will probably not attack beryllium appreciably.

J *1 Crystal structure.* Close-packed hexagonal; $a = 2.2680$ kX; $c = 3.5942$ kX
5 Minimum interatomic distance. 2.22 kX

K *Mechanical properties.*

Condition	Tensile Strength, psi	Yield Strength, (a) psi	Brinell Hardness (b)	Modulus of Elasticity, psi
Vacuum cast	17,000 to 21,000	.....	.....	42,000,000
Vacuum cast, forged and annealed(c)	27,000	26,400	97 to 114	36,800,000

(a) 0.2% offset
(b) 500 or 1000-kg load, 10-mm ball
(c) Elongation of this sample was zero.

N *1 Melting temperature.* 1284 to 1300 C (2343 to 2372 F)
5 Flux. Alkaline earth metal chlorides or fluorides
6 Precautions in melting. Avoid excessive contact with oxygen. Carbon easily produces Be_2C above 1300 C.
11 Suited to forming by casting (centrifugal, vacuum, air) and possibly by extrusion.

* The Brush Beryllium Company, Cleveland

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C. B. Sawyer, Beryllium, Glamour Child of Metallurgy, Yale Sci Mag, Spring, summer and fall issues, 1941
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Cadmium

COMPILED BY PAUL A. BECK AND JOHN F. COLLINS*

B *1 Typical uses.* Bearing alloys, electroplating, pigments, low-melting alloys.
2 Precautions in use. Good ventilation is necessary when melting, since poisonous fumes develop in large quantity. Maximum allowable cadmium vapor in air 1 mg per 10 cu meters.

C *1 Density.*
at 20 C (68 F). 8.65 g per cu cm
at 25 C (77 F). 8.62 g per cu cm
at 700 C (1292 F). 7.56 g per cu cm
at 720 C (1328 F). 7.54 g per cu cm
at 750 C (1382 F). 7.51 g per cu cm

D *1 Melting point.* 320.9 ± 0.1 C (609.6 ± 0.2 F)
4 Boiling point. 765 C (1409 F)
6 Thermal expansion (polycrystalline) at room temperature. 0.0000298 per °C
$L_{t+20} = L_{20}\,[1 + (95.1t + 38 \times 10^{-3}t^2 + 5 \times 10^{-6}t^3) \times 10^{-6}]$
7 Thermal expansion along *a*-axis 18 to 190 C (64 to 374 F). 0.0000185 per °C
$L_{t+20} = L_{20}\,[1 + (21.7t - 3.8 \times 10^{-3}t^2 + 13.4 \times 10^{-6}t^3) \times 10^{-6}]$
9 Thermal expansion along *c*-axis 18 to 190 C (64 to 374 F). 0.0000482 per °C
$L_{t+20} = L_{20}\,[1 + (55.8t - 15 \times 10^{-3}t^2 - 4.7 \times 10^{-6}t^3) \times 10^{-6}]$
11 Specific heat at room temperature. 0.055 cal per g
12 Specific heat versus temperature. See Fig. 1.
13 Latent heat of fusion. 13.2 cal per ■
15 Latent heat of vaporization. 286.4 cal per g
16 Thermal conductivity at room temperature. 0.22 cgs

E *1 Volume conductivity* referred to standard copper. 25.2%
2 Electrical resistivity at 0 C (32 F). 6.83 microhm-cm
5 Temperature coefficient of electrical resistivity at 0 C (32 F). 0.0042 per °C
7 Pressure coefficient of electrical resistivity at 100 C (212 F). minus 0.000011 per kg/sq cm
10 Electrochemical equivalent. 0.5824 mg per coulomb
11 Electrolytic solution potential. 0.4 volt
14 Hydrogen overvoltage. 0.4 volt
15 Hall effect. $+ 5.5 \times 10^{-13}$ volt-cm per ampere-gauss
16 Supraconductive at 0.6 K

F *1 Reflectivity.*
78% at $\lambda = 4100$ A — 72.5% at $\lambda = 5180$ A
74% at $\lambda = 4740$ A — 73% at $\lambda = 5540$ A
Reflectivity versus wave length. See Fig. 2.

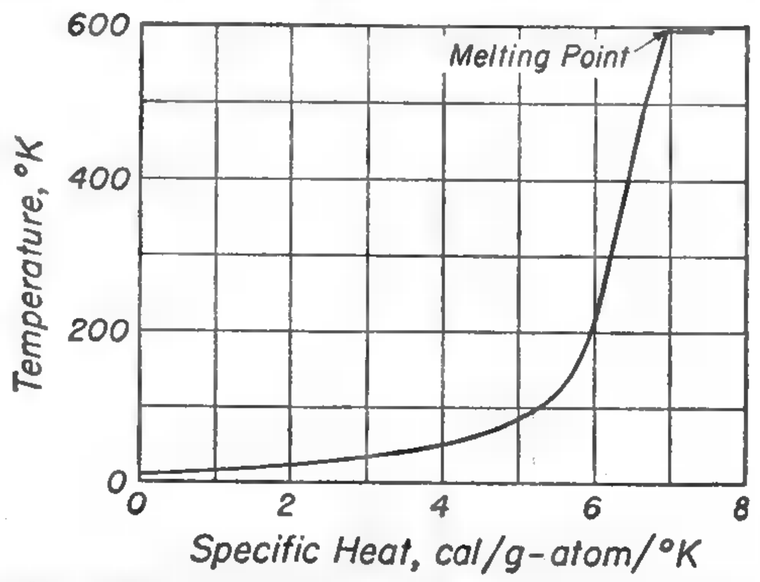

Fig. 1 Specific heat of cadmium versus temperature (Lange and Simon[1])

* University of Notre Dame, Notre Dame, Ind.

2 *Refractive index.* 1.8 at 5780 A
3 *Absorptive index.* 1.17 at 5780 A
G 2 *Magnetic susceptibility.* minus 0.18 × 10^{-6} cgs (electromagnetic)
J 1 *Crystal structure.* Close-packed hexagonal; $a = 2.9727$ kX; $c = 5.606$ kX
2 *Slip plane.* (0001). *Slip direction.* [11$\bar{2}$0]
3 *Twinning plane.* (10$\bar{1}$2)
5 *Minimum interatomic distance.* 2.972 kX
K *Mechanical Properties. Chill cast* (1-in. diam section): tensile strength 10,300 psi; elongation 50%; Brinell hardness number 21 to 23.
Sand cast: modulus of elasticity 8,000,000 psi
8 *Surface tension (liquid)* at 321 C. 630 dynes per cm
N 5 *Type of flux.* Zinc chloride

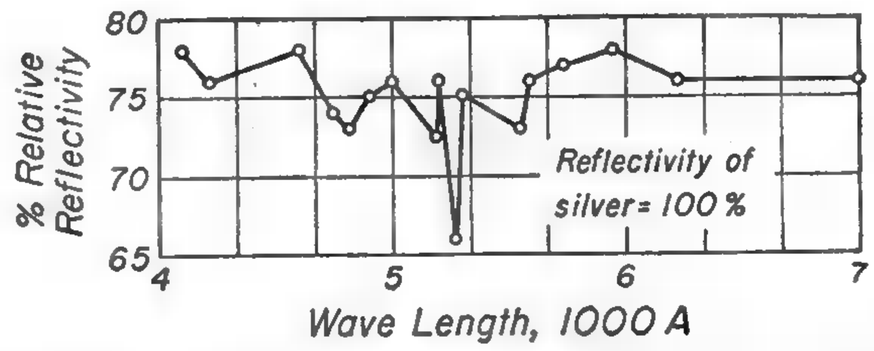

Fig. 2 Relative reflectivity of cadmium versus wave length (Cinamon[2])

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Calcium

COMPILED BY C. L. MANTELL*

B 1 *Typical uses.* Modifying agent for aluminum, beryllium and magnesium alloys. Alloying agent for aluminum, beryllium, copper, lead and magnesium. Decarburizer and desulfurizer for ferrous metals and alloys. Deoxidizer for various ferrous and nonferrous metals. Evacuating agent for the production of high vacuum. Reducing agent in the preparation of chromium, thorium, uranium, zirconium, and calcium hydride. In its commercial forms, calcium is available as the direct or remelted product of the electric furnace, or as sublimed material, in chips, slugs, rods and sticks.
2 *Precautions in use.* Calcium is a reactive metal; it decomposes water and must be handled more carefully than magnesium.
C 1 *Density* at 20 C (68 F). 1.55 g per cu cm (0.056 lb per cu in.) at 450 C (842 F) the α phase in extruded wire has a density of 1.48 g per cu cm; at 480 C (896 F) the β phase has a density of 1.52 g per cu cm
3 *Compressibility.*
at 30 C (86 F) and 0 atm pressure. 5.885 × 10^{-6}
at 30 C (86 F) and 11,600 atm pressure. 5.300 × 10^{-6}
at 20 C (68 F) and 99 to 493 atm pressure. 5.8 × 10^{-6}
at 20 C (68 F) and 100 to 500 megabars per sq cm. 5.7 × 10^{-6}

$$\text{Compressibility} = -\frac{1}{\text{Vol (cu cm)}} \times \frac{\Delta \text{ Vol (cu cm)}}{\Delta \text{ Pressure (atm)}}$$

D 1 *Melting point.* 850 C (1562 F)
4 *Boiling point.* 1440 C (2625 F)
5 *Transformation temperature* (cooling). 450 C (840 F)
6 *Thermal expansion.*
(linear) 0 to 300 C (32 to 570 F). 0.0000220 per °C
(cubic) 0 to 21 C (32 to 70 F). 0.000717 per °C
11 *Specific heat* between minus 185 and 20 C (minus 301 and 68 F). 0.157 cal per g
0 to 100 C (32 to 212 F). 0.149 cal per g
15 *Latent heat of vaporization.* 45,300 cal per g-atom
16 *Thermal conductivity.* Of the same order as that of sodium and the alkali metals.
18 *Heat of combustion.* 151.9 cal per
E 1 *Volume conductivity* referred to standard copper. 48.7%
2 *Electrical resistivity* at 0 C (32 F). 3.43 microhm-cm
5 *Temperature coefficient* of electrical resistivity at 20 C (68 F). 0.00457 per °C
10 *Electrochemical equivalent* (valence 2). 0.20762 mg per coulomb
11 *Electrolytic solution potential* vs hydrogen. —2.76 volts
F 4 *Color.* In its commercial forms, calcium on freshly cut surfaces is white, approximating the color of silver. Fractured surfaces are more brilliant than steel.
G 2 *Mass magnetic susceptibility.*[2] plus 1.10 × 10^{-6} cgs
I 1 *General resistance to corrosion.* Readily corroded by water, acids, alkalies and halogens.
J 1 *Crystal structure.* Face-centered cubic, $a = 5.56$ kX
5 *Minimum interatomic distance.* 3.93 kX
K *Mechanical properties.* Cast slab: tensile strength 8000 psi, yield strength 5500 psi, elongation 53 to 60%, Brinell hardness number (500-kg load) 17, Rockwell B 36 to 40, modulus of elasticity 3 to 4 × 10^6 psi
N *Casting.* Because of its rapid oxidation at or above the melting point, calcium cannot be cast by usual foundry methods. When melted in the absence of air, other oxidizing influences, or reactive gases, it can be cast into various shapes. Recently, melting and casting procedures employing protective fluxes have been worked out for the production of cast forms of the metal from the irregularly shaped cabbages separated from furnace electrodes.
11 *Suited to forming* by machining, turning, drilling, threading, sawing, wire drawing, pressing and hammering. The wire is extruded between 420 and 460 C.

* Consulting Chemical Engineer, New York

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Chromium

COMPILED BY C. O. BURGESS AND F. E. BACON*

A 1 *Common name.* Chromium, Chrome Metal, Electrolytic Chromium
B 1 *Typical uses.* Alloying agent in steel and cast irons (0.25 to 35%); alloying agent in nonferrous alloys of nickel, copper, aluminum and cobalt; electroplating; powder metallurgy; X-ray targets; mirrors.
2 *Precautions in use.* No special precautions necessary.
C 1 *Density* at 20 C (68 F).[1] 7.19 g per cu cm (0.260 lb per cu in.)
3 *Density versus pressure (compressibility).*[2]

At 30 C (86 F) $\frac{\Delta V}{V_0} = -5.187 \times 10^{-7}p + 2.19 \times 10^{-12}p^2$

At 75 C (167 F) $\frac{\Delta V}{V_0} = -5.310 \times 10^{-7}p + 2.19 \times 10^{-12}p^2$

6 *Transformation volume change.*[3,4,5] Hexagonal form

* Union Carbide and Carbon Research Laboratories, Niagara Falls, N. Y.

(sp gr 6.08) changes to body-centered cubic (sp gr 7.21) at 26 C or above. An α-manganese type (sp gr 7.48) has also been identified.

D *1 Melting point.* 1800 ± 50 C (3270 ± 90 F)
4 Boiling point at 760 mm Hg.[10] 2500 (4500)
5 Transformation temperature. Below 20 C (68 F) the close-packed hexagonal form is produced in electroplating, while the cubic form is produced above 20 C. The α-manganese form (58 atoms per unit cube) identified as electroplated, slowly ages to the cubic form.[3,4,5] The α-manganese form appears above 26 C.
6 Thermal expansion[6,7] at 20 C (68 F). 0.0000062 per °C

$$L_t = L_0 [1 + (5.88t + 0.00774t^2 - 0.00000388t^3) \times 10^{-6}]$$

11 Specific heat[8] at 20 C (68 F). 0.11 cal per g
12 Specific heat versus temperature[8] 273 to 1873 K (0 to 1600 C). $C_p = 4.84 + 2.95 \times 10^{-3}t$
13 Latent heat of fusion.[9] 75.6 cal per g
15 Latent heat of vaporization[10] at boiling point. 1470 cal per g
16 Thermal conductivity at 20 C (68 F). 0.16 cgs

E *1 Volume conductivity* referred to standard copper 8.8%
2 Electrical resistivity[1] at 0 C (32 F). 18.9 microhm-cm
5 Temperature coefficient of electrical resistivity[11] at 0 C (32 F). 0.00588 per °C. Some anomalies occur in the specific resistance of chromium with temperature.[12,13]
9 Contact potential versus constantan. +511 × 10^{-7} volts per degree
10 Electrochemical equivalent[14]
(valence 3). 0.08983 mg per coulomb
(valence 6). 0.17965 mg per coulomb
11 Electrolytic solution potential[15] (valence 3) versus hydrogen electrode. 0.5 volt
14 Hydrogen overvoltage.[15] 0.38
16 Chromium is not supraconductive down to 2.5 K.[11]

F *1 Reflectivity.*[16]

67% at λ = 3,000 A	63% at λ = 10,000 A
70% at λ = 5,000 A	88% at λ = 40,000 A

2 Refractive index.[17] 1.64 to 3.28 for λ from 2570 to 6080 A
3 Absorptive index.[17] 2.25 to 1.31 for λ from 2570 to 6080 A
4 Color. Steel gray
5 Emissivity.[18] Total at 100 C (212 F) in nonoxidizing atmosphere, 0.08; spectral (at 6500 A) for solid chromium, 0.34; for liquid, 0.39

G *2 Magnetic susceptibility.*[12] 3.49 × 10^{-6} cgs

I *2 Resistance to specific agents.*[19,20] (Ten per cent solutions at 55 F were used unless otherwise noted.)

Chromium is resistant to the following acids: acetic, benzoic (saturated), butyric, carbonic, citric, fatty, hydrobromic, hydroiodic, lactic, nitric, oleic, oxalic, palmitic, phosphoric, picric, salicylic, stearic and tartaric.

Chromium is not resistant to hydrochloric acid.

Chromium is resistant to the following agents: acetone, air, ethyl and methyl alcohol, higher alcohols, aluminum chloride, aluminum sulfate, ammonia, ammonium chloride, barium chloride, beer, benzyl chloride (saturated and 100%), calcium chloride, carbon dioxide, carbon disulfide, carbon tetrachloride (saturated and 100%), dry chlorine, chlorobenzene (saturated and 100%), chloroform, copper sulfate, ferric chloride, ferrous chloride, foodstuffs, formaldehyde, fruit products, glue, hydrogen sulfide (100%), magnesium chloride, milk, mineral oils, motor fuels, crude petroleum products, phenols, photographic solutions, printing ink, sodium carbonate, sodium chloride, sodium hydroxide, sodium sulfate, sugar, sulfur (100%), sulfur dioxide (100%), chlorinated, distilled, or rainwater, zinc chloride and sulfate.

J *1 Crystal structure.*[21] Body-centered cubic α, $a = 2.878$ kX; close-packed hexagonal β, $a = 2.71$ kX, $c = 4.41$ kX. Chromium with the α-manganese structure and $a = 8.717$ kX
5 Minimum interatomic distance. 2.493 kX
6 Microstructure. See Fig. 23 in reference 22.

K *Mechanical properties.*[1, 23, 24] Brinell hardness number: as cast 110 to 170, electrodeposited 500 to 1250 (depending on the amount of hydrogen in the deposit), electrodeposited and annealed 70 to 90.
5 Coefficient of friction.[23] 0.12 for sliding condition, 0.14 for static condition.

L *1 Metallography.* Polishing: same as for steel.
Etching: Vilella's reagent, used electrolytically, according to Adcock's directions.[22]

M *Composition limits.*

Material	C min	C max	Cr min	Fe max
Electrolytic chromium	...	...	99	...
Pyrometallurgical or thermit chromium	...	0.2	97	1
Pyrometallurgical or thermit chromium	...	0.5	97	1
Pyrometallurgical or thermit chromium	9.0	...	87	1.25

N *7 Hot working temperature.*[25] 1250 C (2280 F)
13 Compacting pressure.[25] 40,000 psi
14 Sintering temperature.[25] 1300 C (2370 F) in vacuo until free from gas, then further heating at 1600 to 1700 C in argon.
17 Joining.
Silver solder with low-melting-point silver brazing alloys, potassium fluoborate flux, and reducing flame.

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Cobalt

COMPILED BY W. C. ELLIS AND E. S. GREINER*

A *6 Foreign equivalents.* Kobalt (German)

B *1 Typical uses.* As an alloying element in (*a*) permanent and soft magnetic materials, (*b*) high speed tool steel, (*c*) electrical resistance alloys, (*d*) high-temperature creep-resistant alloys, (*e*) cemented carbide cutting tools, (*f*) cobalt-base tool materials.

C *1 Density* at 20 C (68 F). 8.9 g per cu cm (0.322 lb per cu in.)
6 Transformation volume change (face-centered cubic cooling to close-packed hexagonal). approx −0.3%

D *1 Melting point.* 1495 C (2723 F)
4 Boiling point. 2900 C (5250 F) approx
5 Transformation temperature. 420 C (788 F) There is conflicting evidence for transformations in the vicinity of 850 and 1050 C.
6 Thermal expansion 30 to 850 C (86 to 1560 F). *See* Fig. 1.
11 Specific heat at 20 C (68 F). 0.099 cal per g per °C
13 Latent heat of fusion. 58.4 cal per ■
15 Latent heat of vaporization. 1500 cal per ■
16 Thermal conductivity at 20 C (68 F). 0.165 cal/sq cm/cm/°C/sec

* Bell Telephone Laboratories, Murray Hill, N. J.

E *1 Volume conductivity* referred to standard copper. 27.6% at 20 C (68 F)
2 Electrical resistivity at 20 C (68 F). 6.24 microhm-cm
5 Temperature coefficient of electrical resistivity 0 to 100 C (32 to 212 F). 0.00604 per °C
Figure ▮ shows electrical resistivity over a wide range of temperature.
9 Contact potential versus platinum. See plot of temperature versus millivolts, Fig. 3.
10 Electrochemical equivalent (valence 2). 0.3054 mg per coulomb

F *1 Reflectivity.* 37% at $\lambda = 2{,}000$ A
67.5% at $\lambda = 10{,}600$ A
92.7% at $\lambda = 67{,}500$ A
96.6% at $\lambda = 120{,}300$ A

G *3 Initial permeability* 68; maximum permeability 245.
4 Coercive force. 8.9 oersteds, for $H_{max} = 1000$ gausses

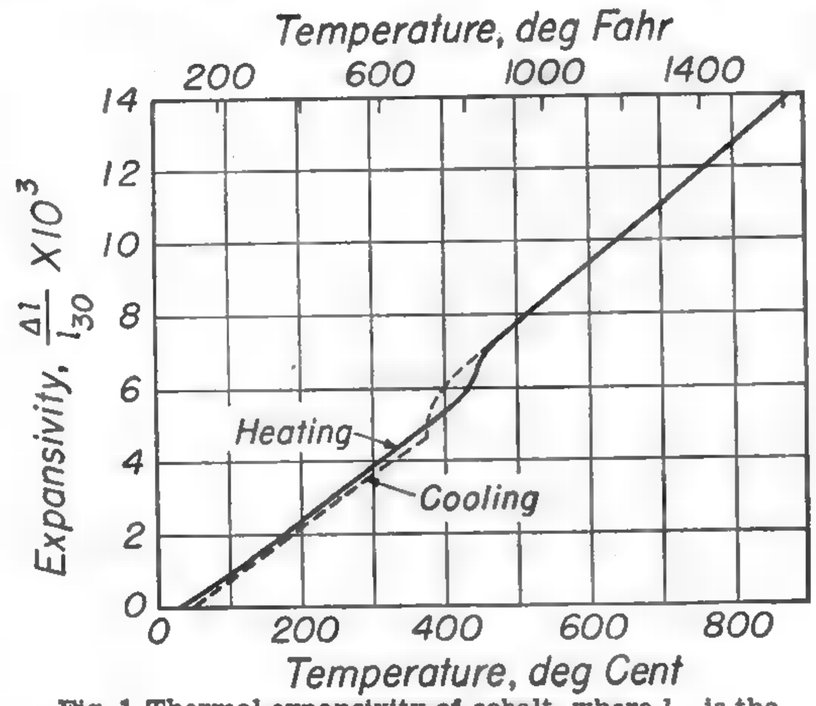

Fig. 1 Thermal expansivity of cobalt, where l_{30} is the specimen length at 30 C

5 Saturation magnetization. 18,700 gausses ($4\pi I_s$)
6 Residual induction. 4900 gausses for $H_{max} = 1000$ gausses
7 Hysteresis loss. 6900 ergs per cu cm per cycle for $B_m = 5000$ gausses
9 Magnetic transformation temperature. 1115 C (2039 F)

H *1 Velocity of sound.* 15,500 ft per sec

J *1 Crystal structure.*

Type	*a*, kX	*c*, kX
Face-centered cubic	3.5368	.....
Close-packed hexagonal	2.5020	4.0611

5 Minimum interatomic distance of face-centered cubic structure. 2.5009 kX

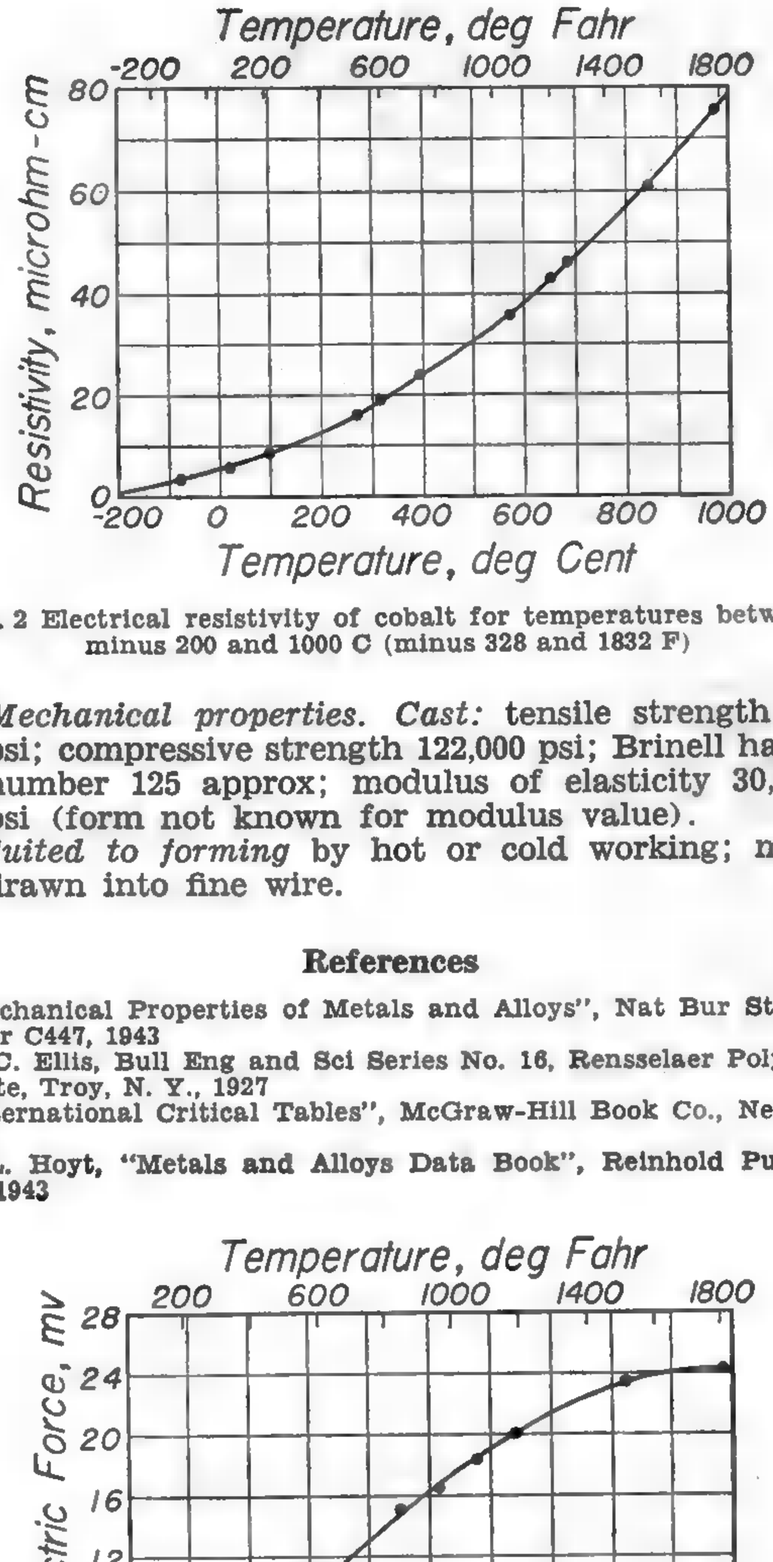

Fig. 2 Electrical resistivity of cobalt for temperatures between minus 200 and 1000 C (minus 328 and 1832 F)

K *Mechanical properties. Cast:* tensile strength 34,400 psi; compressive strength 122,000 psi; Brinell hardness number 125 approx; modulus of elasticity 30,000,000 psi (form not known for modulus value).

N *11 Suited to forming* by hot or cold working; may be drawn into fine wire.

References

"Mechanical Properties of Metals and Alloys", Nat Bur Standards Circular C447, 1943
W. C. Ellis, Bull Eng and Sci Series No. 16, Rensselaer Polytechnic Institute, Troy, N. Y., 1927
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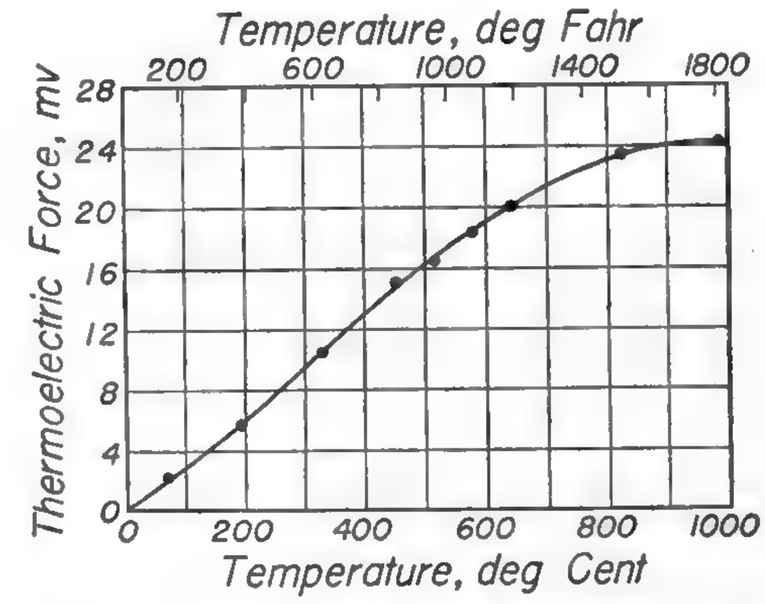


Fig. 3 Thermoelectric force of cobalt versus platinum for temperatures between 0 and 1000 C (32 and 1832 F)

Columbium

COMPILED BY L. F. YNTEMA*

A *6 Foreign equivalent.* Niobium

B *2 Precautions in use.* Columbium oxidizes in air above 250 C (482 F). Soluble in HF and in alkalies.

C *1 Density* at 20 C (68 F). 8.57 g per cu cm (0.310 lb per cu in.)

D *1 Melting point.* 2415 C (4379 F)
6 Thermal expansion. 0.0000071 per °C
11 Specific heat at 0 C (32 F). 0.0647 cal per g
15 Latent heat of vaporization. 1840 cal per g

E *1 Volume conductivity* referred to standard copper. 13.2%
2 Electrical resistivity at 18 C (64 F). 13.1 microhm-cm
5 Temperature coefficient of electrical resistivity at 20 C (68 F). 0.00395 per °C
10 Electrochemical equivalent (valence 5). 0.1926 mg per coulomb

* Director of Research, Fansteel Metallurgical Corporation, North Chicago, Ill.

G *2 Magnetic susceptibility.* plus 1.5×10^{-6} cgs

I *2 Resistance to corrosion.*

Columbium is resistant to the following: acetic, lactic, nitric, perchloric and tartaric acids, and aqua regia; ammonium hydroxide; phenol; oxygen when cold; air; distilled, rain and sea water. It is attacked moderately by: hydrochloric, phosphoric, oxalic and sulfuric acids; sodium carbonate; and hydrogen peroxide. It is attacked severely by: sodium hydroxide, potassium hydroxide, and hydrofluoric acid.

J *1 Crystal structure.* Body-centered cubic; $a = 3.294$ kX

K *Mechanical properties.*

Form and Condition	Section, in.	Tensile Strength, psi	Percentage Elongation
Sheet, annealed	0.010	50,000	30
Sheet, worked	0.010	100,000	1
Wire, worked	0.005	100,000	1

L *1 Metallography.* Polishing: emery to 000, levigated alumina to finish. Etching: $HF\text{-}NH_4F$ solution.
M *Composition limits.* For sheet, wire and compacts the allowable percentages for various impurities are: 0.20 Ta; 0.002 Ti; 0.03 Si; 0.01 Fe; and 0.02 C.
2 Consequences of exceeding impurity limits. Reduction in elongation; high yield and tensile strength; no change in resistance to corrosion.
N *7 Hot working temperature.* None; it is worked cold.
9 Annealing temperature. Above 1050 C in vacuo
10 Maximum reduction between anneals. Not limited
11 Suited to forming by all conventional methods such as rolling, drawing, pressing, bending, and swaging.
12 Precautions in forming. For drawing, a nonloading die material is used; other practices conventional.
16 Standard finishes. Dull or bright rolled finish for sheet; smooth dull finish for wire.
17 Joining.
Rivet composition. Columbium
Carbon-arc welding. Special techniques under protective liquids. *Resistance welding.* Spot and seam

References

"Mechanical Properties of Metals and Alloys", Nat Bur Standards Circular C447, 1943
A. E. van Arkel, "Reine Metalle", Julius Springer, Berlin, 1939
C. W. Balke, Ind Eng Chem, 27, 1166 (1935)
C. W. Balke, Trans Electrochem Soc, 85, 89 (1944)
L. Sanderson, Chem Age, May 30, 1936

Lithium*

B *1 Typical uses.* As a scavenging agent in liquid metals, as a component of protective furnace atmospheres, and as an alloying element in lead, copper and magnesium—especially in lead.
2 Precautions in use. Must be kept in airtight containers or under kerosene.
C *1 Density* at 20 C (68 F). 0.53 g per cu cm
D *1 Melting point.* 186 ± 5 C (367 ± 9 F)
4 Boiling point. 1370 C (2500 F)
6 Thermal expansion at 20 C (68 F). 0.000056 per °C
11 Specific heat at 20 C (68 F). 0.79 cal per g per °C
16 Thermal conductivity at 20 C (68 F). 0.17 cgs
E *2 Electrical resistivity* at 0 C (32 F). 8.55 microhm-cm
I *1 General resistance to corrosion.* Oxidizes readily and reacts with water; tarnishes quickly in moist air; unites with nitrogen at 20 C.
J *1 Crystal structure.* Body-centered cubic; $a = 3.5019$ kX
K *Mechanical properties.* Lithium is harder than the other alkali metals but softer than lead. The metal can be drawn into wire or rolled thin.

* Compiled from the sources listed and from a selection of data by members of the National Bureau of Standards.

References

"Mechanical Properties of Metals and Alloys", Nat Bur Standards Circular C447, 1943
K. K. Kelley, Bur Mines Bull 383, 1935
"Metal Industry Handbook & Directory", The Louis Cassier Co., Ltd, London, 1947
A. E. van Arkel, "Reine Metalle", J. Springer, Berlin, 1939

Manganese

COMPILED BY REGINALD S. DEAN*

C *1 Density* at 20 C (68 F).
α 7.43 g per cu cm (0.270 lb per cu in.)
β 7.29 g per cu cm (0.2631 lb per cu in.)
γ 7.18 g per cu cm (0.259 lb per cu in.)
liquid 6.54 g per cu cm (0.236 lb per cu in.)
3 Compressibility. 0.00000084
5 Solidification shrinkage. 1.7%
D *1 Melting point.* 1245 C (2273 F)
4 Boiling point. 2150 C (3900 F)
5 Transformation temperature.
678 C (1252 F) $\alpha \rightarrow \beta$
1100 C (2012 F) $\beta \rightarrow \gamma$
1138 C (2080 F) $\gamma \rightarrow \delta$
6 Thermal expansion 0 to 100 C (32 to 212 F).
α (measured) 0.000022 per °C
γ (measured) 0.000014 per °C
γ (extrapolated) 0.000012 per °C
11 Specific heat at 25.2 C (77.3 F). α, 0.115 cal per g; γ, 0.120 cal per g.
12 Specific heat versus temperature. See Fig. 1.
13 Latent heat of fusion. 3500 cal per g-atom (63.7 cal per g)
14 Latent heat of transformation (cooling).
535 cal per gram atom $\alpha \rightarrow \beta$
545 cal per gram atom $\beta \rightarrow \gamma$
430 cal per gram atom $\gamma \rightarrow \delta$
15 Latent heat of vaporization. 53,700 cal per g-atom at the boiling point
E *1 Volume conductivity* referred to standard copper. 0.9%, alpha
2 Electrical resistivity at 20 C (68 F). α, 185 microhm-cm; β, 91 microhm-cm; γ, 45.1 microhm-cm.
10 Standard electrode potential. 1.134 volts
G *1 Influence of treatments.* Manganese is ferromagnetic after certain treatments—for example, after absorption and expulsion of nitrogen which leaves the lattice expanded.
2 Magnetic susceptibility. α, 0.000014 cgs; γ, 0.000008 cgs
I *1 General resistance to corrosion.* Pure manganese is stable in dry air; it is attacked readily by dilute acids.

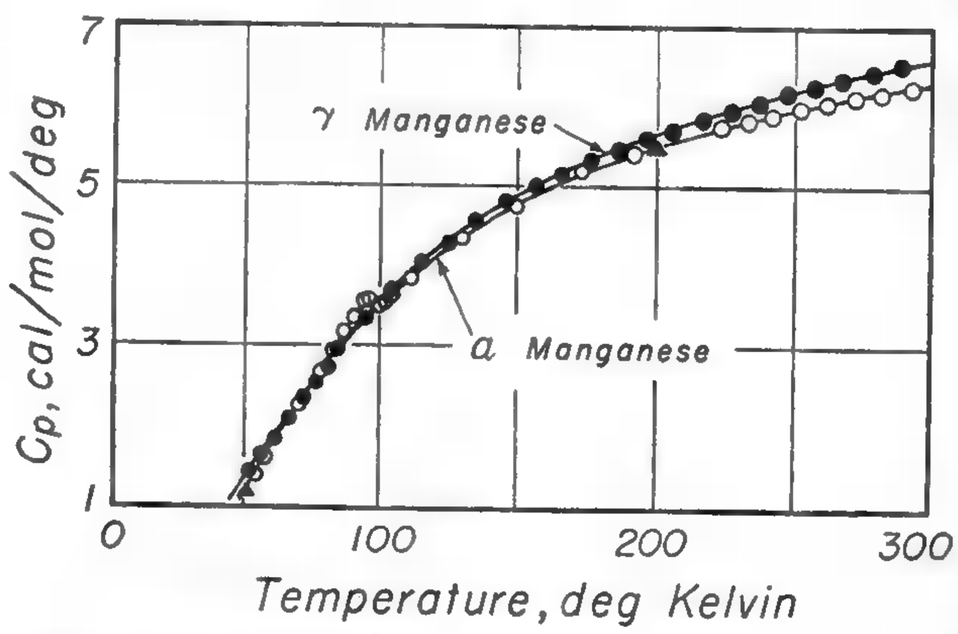


Fig. 1 Specific heats of α and γ manganese at low temperature

J *1 Crystal structure.*

Phase	Structure	a, kX	c/a	Atoms per unit cube
α	Cubic	8.894	....	58
β	Cubic	6.305	....	20
γ	Tetragonal	3.774	0.937	..

K *Mechanical properties.* The α and β forms are brittle. γ (quenched): tensile strength 72,000 psi, yield strength 35,000 psi, elongation 40%, Rockwell C 35

* Metallurgical Engineer and Consultant, Washington, D. C.

Reference

K. K. Kelley, B. F. Naylor and C. H. Shomate, Bur Mines Tech Paper 686, 1946

Molybdenum

COMPILED BY E. C. PIERCE*

B *1 Typical uses.* Alloying additions, heating elements, supporting members of incandescent lamps and vacuum tubes, contacts, switches, thermocouples, glass-metal seals, welding electrodes.

2 Precautions in use. Do not heat above 500 C in an oxidizing atmosphere.

C *1 Density* at 20 C (68 F). 10.2 g per cu cm (0.369 lb per cu in.)

4 Density versus percentage deformation. See Fig. 1.

D *1 Melting point.* 2625 C (4760 F)

4 Boiling point. 4800 C (8670 F)

6 Thermal expansion 20 to 100 C (68 to 212 F). 0.0000049 per °C (0.0000027 per °F)

$L_t = L_0 [1 + (5.01t + 0.00138t^2) \times 10^{-6}]$ *See also* Fig. 2.

11 Specific heat at 20 C (68 F). 0.061 cal per g

12 Specific heat versus temperature. See Fig. 3.

13 Latent heat of fusion. 70 cal per g

15 Latent heat of vaporization. 1340 cal per g

16 Thermal conductivity.
at 17 C (63 F). 0.346 cal/sq cm/cm/°C/sec;
at 100 C (212 F). 0.333 cal/sq cm/cm/°C/sec

17 Thermal conductivity versus temperature. See Fig. 4.

18 Heat of combustion. 1810 cal per ■

19 Recrystallization temperature. 900 C (1650 F)

■ *1 Volume conductivity* referred to standard copper. 33.3%

2 Electrical resistivity at 0 C (32 F). 5.17 microhm-cm

5 Temperature coefficient of electrical resistivity at 25 C (77 F). 0.0033 per °C. *See* Fig. 5.

9 Thermal emf against platinum 0 to 100 C. 1.45 mv

10 Electrochemical equivalent (valence 6). 0.1658 mg per coulomb

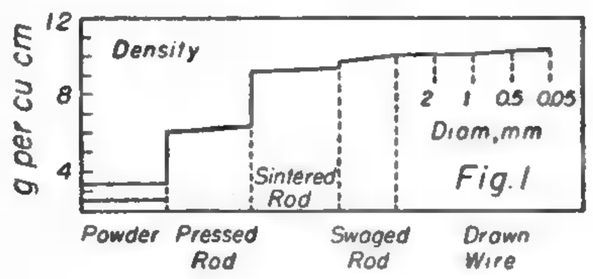
14 Hydrogen overvoltage. 0.168 ± 0.003 v

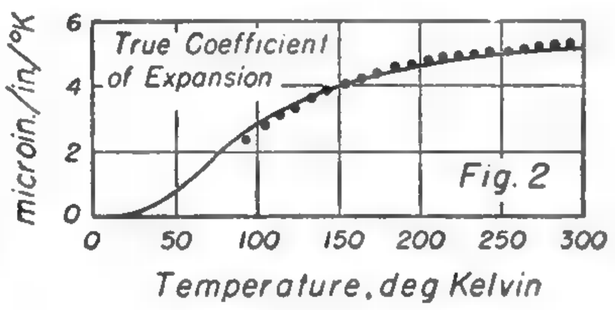
F *1 Reflectivity* at $\lambda = 5000$ A. 46% *See* Fig. 6.

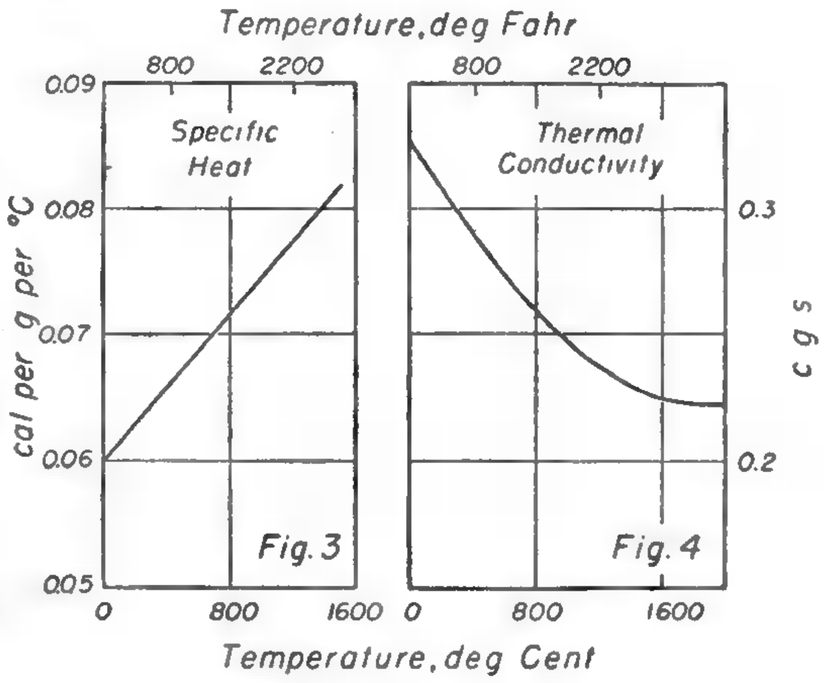
4 Color. Silvery white

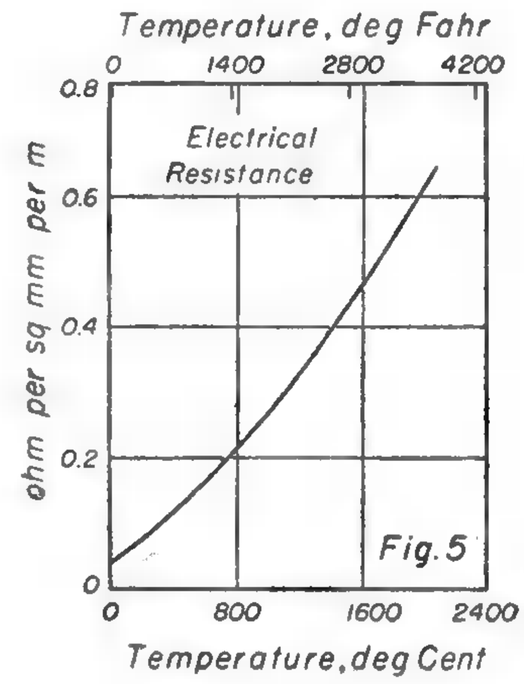
5 Emissivity
at 1000 C (1832 F). 0.13
at 1500 C (2732 F). 0.19
at 2000 C (3632 F). 0.24

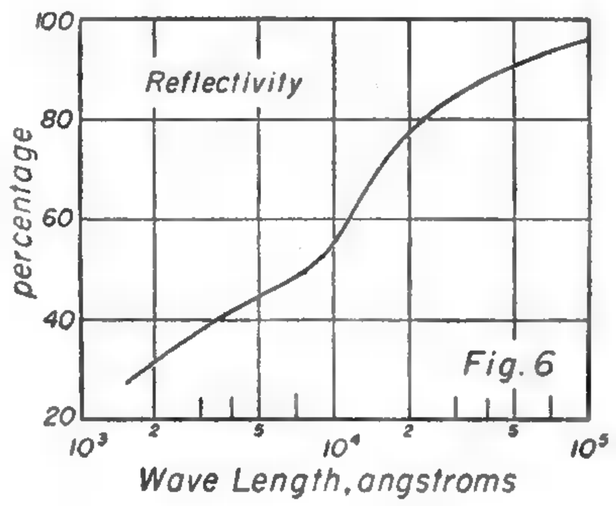
* Research Laboratory, Climax Molybdenum Company, Detroit

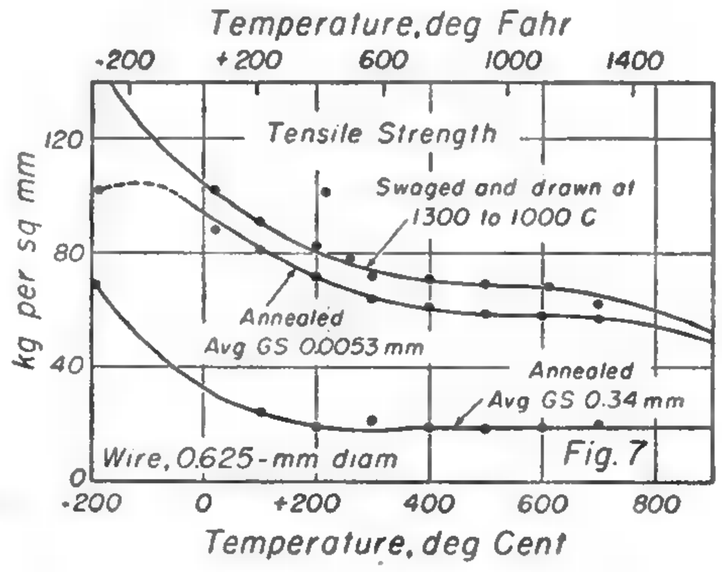


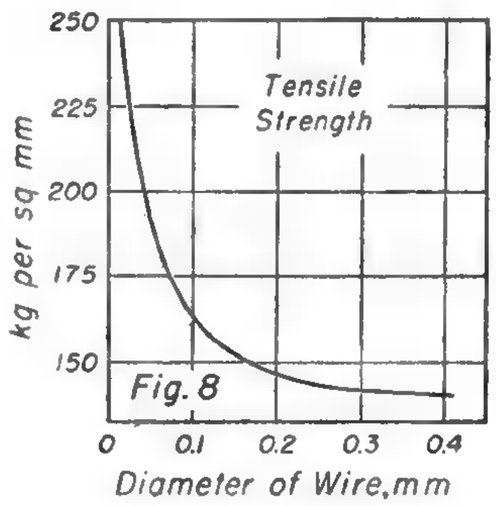


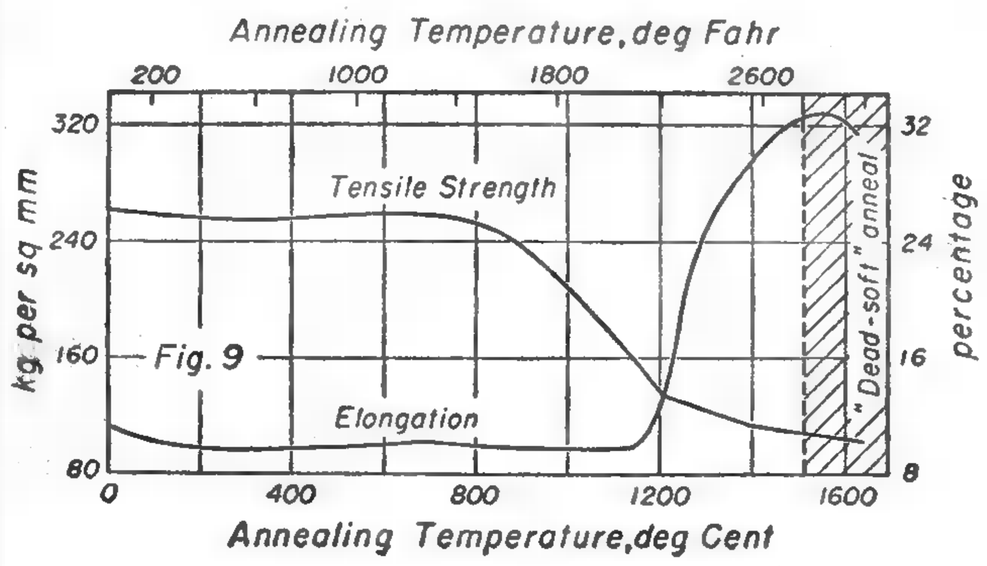


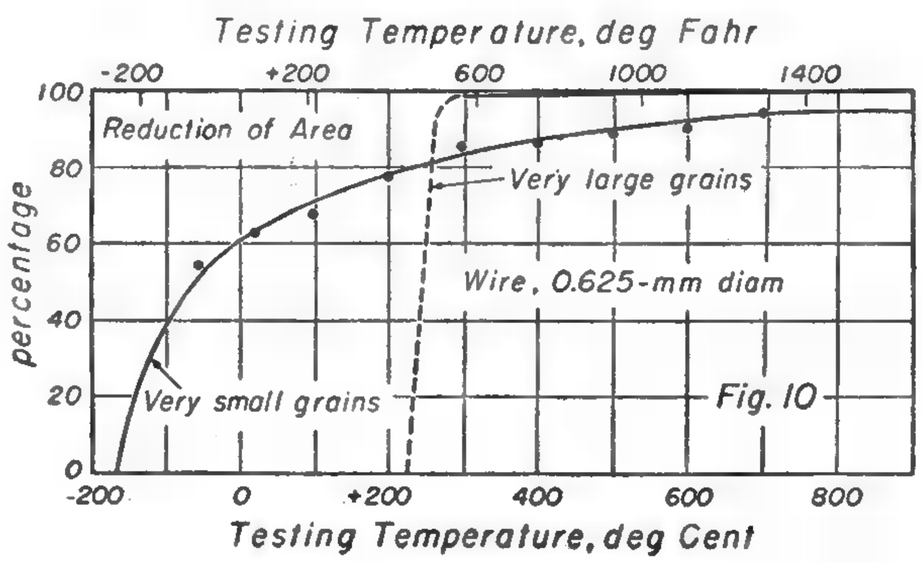












G 2 *Magnetic susceptibility.* 0.04×10^{-6} cgs
H 1 *Velocity of sound.* About 16,000 ft per sec
I 2 *Resistance to specific agents.*

Molybdenum is resistant to the following: hydrofluoric acid, air, ammonia, bismuth salts, bromine, chlorine, iodine, cadmium salts, carbon dioxide, hydrogen sulfide, lead nitrate, nitrous and nitric oxides, phosphorus, potassium hydroxide, sulfur and sulfur dioxide, and distilled, rain and sea water. It is resistant to hydrochloric acid, but subject to severe attack in hot dilute acid. It is resistant to cold sulfuric acid, but is severely attacked in the hot concentrated acid. Molybdenum is moderately resistant to ammonium hydroxide and ferric chloride. It is severely attacked by fluorine, nitric acid, and mixed acids (aqua regia).

J 1 *Crystal structure.* Body-centered cubic; $a = 3.1400$ kX at 20 C
2 *Slip planes.* (112) (110). *Slip direction.* [111]
5 *Minimum interatomic distance.* 1.2115 kX
K *Mechanical properties* of pressed and sintered molybdenum.
Tensile strength of wire.
0.125-mm diam. 200,000 to 260,000 psi
0.070-mm diam. 230,000 to 270,000 psi
0.038-mm diam. 270,000 to 310,000 psi
Tensile strength of sheet. 100,000 psi
See also Fig. 7, 8 and 9.
Elongation and reduction of area. See Fig. ■ and 10.
Yield strength,
Unannealed. 57,000 to 85,000 psi
Annealed. Up to 57,000 psi
Modulus of elasticity. 50,000,000 psi
Brinell hardness number,
Rolled, unannealed. 160 to 185
Highly sintered bar. 156

Sheet thickness, mm	8	4	2	1
Bhn	229	240	245	255

Shear modulus. 6.6×10^{11} dynes per sq cm
2 *Directional properties.* The tensile strength of rolled molybdenum sheet is about 20% greater in the direction of rolling than when the inclination of the direction of tension to that of rolling is 45 or 90°.
3 *Properties of single crystals.* Tensile strength 50,000 psi
L 1 *Metallography.* Polish with diamond paste.
Etching: (1) 1:1 10% NaOH + 30% $K_3Fe(CN)_6$
(2) 50% HNO_3, wash with conc HCl
(3) $NH_4OH + H_2O_2$
(4) $HNO_3 + HF$
N 11 *Suited to forming* by swaging, wire drawing and rolling.
13 *Compacting pressure.* 13,500 to 56,000 psi
15 *Heat treatment.* Annealing at 300 to 400 C above the recrystallization temperature produces a large-grained equiaxed structure with the grains covered by films of impurities. The mechanical properties are poor for metal in this condition.
17 *Welding.* Molybdenum can be butt-welded by resistance heating in vacuum, or it can be welded in the atomic hydrogen arc.

References

"Gmelins Handbuch der Anorganischen Chemie, System Number 53, Molybdän", 8th Ed, Verlag Chemie, Berlin, 1935
A. E. van Arkel, "Reine Metalle", J. Springer, Berlin, 1939
E. Pokorny, "Molybdän", Halle, 1927
W. Espe and M. Knoll, "Werkstoffkunde der Hochvakuumtechnik", J. Springer, Berlin, 1936

Selenium

COMPILED BY A. C. VAUGHAN*

A 1 *Common name.* Gray Selenium
5 *Other designations.* Other varieties are the alpha and beta monoclinic forms.
B 1 *Typical uses.* Coloring and decoloring glass and ceramics; making rectifiers; making photoconductive light-sensitive cells; improving machinability of stainless steels, copper-base alloys and Invar; and promoting resistance to heat and abrasion in rubber cable covers.
C 1 *Density* at 25 C (77 F). 4.81 g per cu cm (0.174 lb per cu in.)
D 1 *Melting point.* 220 ± 5 C (428 ± 9 F)
4 *Boiling point.* 680 C (1256 F)
6 *Thermal expansion* at 40 C (104 F). 0.000037 per °C
11 *Specific heat.* 0 to 41 C (32 to 106 F). 0.084 cal per g
13 *Latent heat of fusion.* 6.6 cal per g
15 *Latent heat of vaporization.* 94 cal per g
E 2 *Electrical resistivity* at 20 C (68 F). 12 microhm-cm
10 *Electrochemical equivalent* (valence 6). 0.13637 mg per coulomb
G 2 *Magnetic susceptibility* at 18 C (64 F). minus 0.32×10^{-6} cgs
J 1 *Crystal structure.* Hexagonal; $a = 4.337$ kX, $c = 4.944$ kX

* American Smelting and Refining Company, Barber, N. J.

References

"International Critical Tables", McGraw-Hill Book Company, 1926
C. S. Barrett, "Structure of Metals", McGraw-Hill Book Company, 1945
"Minerals Yearbook for 1943", U. S. Government Printing Office, 1945
C. H. Mathewson, editor, "Modern Uses of Nonferrous Metals", AIME, 1935

Silicon

COMPILED BY C. O. BURGESS AND F. E. BACON*

B 1 *Typical uses.* Alloying agent in steel, cast iron and nonferrous metals; reducing and deoxidizing agent; in photoelectric cells and in the rectification, modification, and detection of electric currents; in the production of hydrogen; siliconizing.
C 1 *Density*[1] at 25 C (77 F). 2.33 g per cu cm (0.084 lb per cu in.)
3 *Density versus pressure* (compressibility)[1] at 30 C (86 F). 0.137×10^{-6}
D 1 *Melting point.*[12] 1430 C (2605 F)
4 *Boiling point.*† 2300 C (4200 F)
6 *Thermal expansion* at 20 C (68 F).[2] 0.0000028 to 0.0000073 per °C.
See also references 1, 3, and 4. Fig. 1 of reference 4 reports 0.0000029 over range of 0 to 1400 C
11 *Specific heat*[5] at 0 C (32 F). 0.162 cal per g
12 *Specific heat versus temperature.*[5] (0 to 900 C)
$C_p = 5.74 + 0.617 \times 10^{-3}t - 1.01 \times 10^{5}t^{-2}$ ($t = {}^\circ$K)
13 *Latent heat of fusion.*[6] 337 cal per g
15 *Latent heat of vaporization.*[7] 1570 cal per g up to 1315 C
16 *Thermal conductivity*[1] at 20 C (68 F). 0.20 cgs
18 *Heat of combustion.*[7] 6800 cal per ■
E 2 *Electrical resistivity*[1] at 0 C (32 F). 10^5 microhm-cm
5 *Temperature coefficient of electrical resistivity.* It is not certain whether the temperature coefficient of electrical resistivity is positive or negative.

* Union Carbide and Carbon Research Laboratories, Inc., Niagara Falls, N. Y.

† Approximate value based on the selection of data by Kelley (U. S. Bur of Mines, Bull 383, 1935), and rounded to the nearest 100°.

7 *Electrical resistivity versus pressure.*[7] Of the order of minus 0.000012 when pressure is in kg per sq cm
9 *Thermoelectric force against copper.*[7] 478×10^{-6} volts per °C
10 *Electrochemical equivalent.*[8] 0.07269 mg per coulomb
11 *Electrolytic solution potential versus hydrogen electrode.*[9] minus 0.453 volt
14 *Hydrogen overvoltage.*[10] 0.192 ± 0.002 versus platinum electrode
15 *Hall effect*[2] at 20 C (68 F). 41.0 volt-cm per ampere-gauss

F 1 *Reflectivity.*[11] 39 to 23% from 2000 to 1300 A
Reflectivity versus wave length. See Fig. 4 in reference 7.
2 *Refractive index.*[2]
3.87 at $\lambda = 5780$ A; 4.24 at $\lambda = 5890$ A; and 4.07 at $\lambda = 10{,}000$ A
3 *Absorptive index.*[2]
0.12 at $\lambda = 5780$ A; 0.114 at $\lambda = 5890$ A; and 0.095 at $\lambda = 10{,}000$ A
4 *Color.* Dark steel gray

G 2 *Magnetic susceptibility.*[2] minus 0.13×10^{-6} cgs

I 2 *Resistance to specific agents.*

Corrosive Agent	Resistance	Remarks
Acid hydrochloric	Resistant	Dilute or conc, cold or boiling
Acid hydrofluoric	Resistant	Dilute or conc, cold or boiling
Acid nitric	Resistant	Dilute or conc, cold or boiling
Acid sulfuric	Resistant	Dilute or conc, cold or boiling
Air	Resistant	.....
Ammonia	Resistant	Reacts with vapors at bright red heat
Bromine	Resistant	Burns at 500 C
Carbon dioxide	Resistant	.....
Chlorine	Resistant	Burns at 340 C
Copper sulfate	Resistant	10% solution
Ferric chloride	Resistant	10% solution
Hydrogen sulfide	Resistant	.....
Iodine	Resistant	.....
Oxygen	Resistant	.....
Potassium hydroxide	Attacked	.....
Sodium hydroxide	Attacked	.....
Sulfur	Resistant	Reacts at elevated temperatures
Sulfur dioxide	Resistant	.....
Water, distilled	Resistant	.....
Water, rain	Resistant	.....

J 1 *Crystal structure.*[13] Cubic, diamond; $a = 5.417$ kX
5 *Minimum interatomic distance.*[13] 2.346 kX
6 *Microstructure. See* Fig. 2 in reference 14.

K *Mechanical Properties.*
Chill cast (3.55 by 0.97 by 0.97 in.):[14] modulus of elasticity 16,350,000 psi; compressive strength 13,470 psi.
Chill cast (3.0 by 0.254 by 0.254 in.):[4] modulus of elasticity 15,490,000 psi; transverse strength 35 lb; deflection on 3-in. span under 12-lb load 0.00180 in.; modulus of rupture 9046 psi.

L 1 *Metallography.*[14] Polishing: no special technique, same as for iron.
Etching: *see* reference 14.

M 1 *Composition Limits.*
Silicon Metal.[15] 96 to 98% Si; 0.3 to 1.0% Al; 0.2 to 0.5% Ca; 0.1 to 0.2% Ti; 0.03 to 0.2% C; 0.01 to 0.05% P. The remainder is chiefly Fe, plus small amounts of Cr, Mn, Ni and Cu.
Purified Silicon. 99.70 to 99.90% Si; 0.02 to 0.03% Al; 0.01% max Ca; 0.002 to 0.004% Ti plus Zr; 0.02 to 0.04% C; 0.005 to 0.010% P; 0.005 to 0.015% Fe; 0.0005 to 0.0015% Mn; 0.004% Cr max; 0.004% Co plus Ni max.

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Sodium

COMPILED BY H. N. GILBERT*

B 1 *Typical uses.* Removal of antimony from lead and solder, production of metals by reduction of their chlorides, production of alloys such as sodium-lead and sodium-zinc, descaling of metals by the sodium-hydride process, in heat-transfer systems, coolant for exhaust valves of internal-combustion engines, refining of the grain size of metals and alloys, lowering of the surface tension of molten metals, production of bearing metals, deoxidizing of metals.

2 *Precautions in use.* For many purposes it is convenient to handle sodium in liquid form. The metal may be melted and pumped through heated pipe lines. In adding solid or liquid sodium to a molten metal that has a melting point higher than the boiling point of sodium, care must be taken to add the sodium in small increments because of the violent boiling of the sodium. Sodium may be boiled in iron equipment. Sodium does not inflame in air at temperatures below 120 C but it is always desirable to conduct operations involving molten sodium under nitrogen to avoid losses of the metal by oxidation.

C 1 *Density*[1] at 20 C (68 F). 0.97 g per cu cm (0.035 lb per cu in.); at 97.6 C, 0.93 g per cu cm; at 877 C, 0.74 g per cu cm
7 *Surface tension*[1] at the melting point. 293.6 dynes per cm (in CO_2), at 250 C 211 dynes per cm (in high vacuum)
8 *Viscosity*[2] at 98 C. 0.00726 cgs

* Electrochemicals Department, E. I. du Pont de Nemours & Company, Niagara Falls, N. Y.

D 1 *Melting point.*[3] 97.7 C (207.9 F)
2 *Boiling point.*[4] 892 C (1638 F)
Vapor pressure.[4]

Temperature, °C	349	534	679	892
Vapor pressure, atm	0.0001	0.01	0.1	1.0

6 *Thermal expansion.*[1] 0.000071 per °C
11 *Specific heat.*[5] 0.295 cal per g per °C
12 *Latent heat of fusion.*[6] 27.5 cal per g
15 *Latent heat of vaporization*[6] at the melting point. 24,600 cal per g-atom
16 *Thermal conductivity*[7] at room temperature. 0.32 cal/cm²/cm/°C/sec

E 2 *Electrical resistivity*[5] at 0 C (32 F). 4.2 microhm-cm
10 *Electrochemical equivalent.*[8] 0.2384 mg per coulomb

G 2 *Mass magnetic susceptibility.*[9] plus 0.51×10^{-6} cgs

I *Chemical properties.*

Water reacts with sodium to form hydrogen and caustic soda. The reaction is violent and usually explosive. Water vapor or steam also reacts. For this reason, operations that involve the handling or storage of sodium should be conducted in a dry room away from steam or water pipes and automatic sprinkler systems.

Oxygen combines with sodium and forms sodium monoxide, and at higher temperatures sodium peroxide. Solid sodium rapidly becomes coated with a layer of white oxide when exposed to air. The coating also absorbs CO_2 and water from the air to form sodium carbonate and caustic soda. Liquid sodium can be handled in air at 110 C with only moderate oxidation on the surface. If a pure nitrogen atmosphere is employed, sodium can be handled indefinitely in closed systems.

Ammonia gas combines with molten sodium to form sodamide.

Chlorinated hydrocarbons react violently with sodium, and extinguishers that contain carbon tetrachloride should not be used on sodium fires.

Carbon monoxide and carbon dioxide react with sodium. Solid CO_2 will detonate with molten sodium and should not be used on burning sodium.

Sodium fires are best extinguished by excluding air from the reaction vessel or by adding nitrogen to the equipment. Unconfined fires are best extinguished by adding an excess of dry soda ash or dry salt. Extinguishers of the acid – soda ash type should never be used on sodium.

Dry liquid hydrocarbons such as benzene, toluene, xylene and refined mineral oils do not react with solid sodium and may be used to protect it from the air.

Sodium reacts with alcohols to form hydrogen and alcoholates. This reaction is sometimes used to dispose of residues that contain sodium. When used for this purpose the operation should always be conducted in an open vessel.

J *1 Crystal structure.* Body-centered cubic, $a = 4.2820$ kX at 20 C.

K *Brinell hardness number.*[10] 0.07, using 10-mm ball, 3.2-kg load

M *Composition limits.* Sodium is available with a purity of 99.9 + %.

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5 Gmelins Handbuch der Anorganische Chemie, Vol XXI
6 Proc Roy Soc (London), A 89, 573 (1914)
7 Phys Rev, (2) 2, 237 (1913)
8 Hering and Getman, "Standard Table of Electrochemical Equivalents", 1907, ■ 12
9 Ann Physik, (4) 37, 664 (1912)
10 J Inst Metals, 20, 86 (1918)

Tantalum

COMPILED BY L. F. YNTEMA*

B *1 Typical uses.* Corrosion-resistant metal in heat-transfer area in acidproof chemical equipment. Rectifier element in the rectification of alternating current. Surgical usage as suture wire, cranioplasty and fixation plates. Electronic usage as anode and grid element in vacuum tubes.

2 Precautions in use. Tantalum oxidizes in air above 300 C (570 F). It is soluble in hydrofluoric acid, in strong alkalies and in solutions that contain free sulfur trioxide.

C *1 Density* at 20 C (68 F). 16.6 g per cu cm (0.600 lb per cu in.)

D *1 Melting point.* 2996 C (5425 F)

6 Thermal expansion. 0.0000065 per °C (0.0000036 per °F)

11 Specific heat at 0 C (32 F). 0.036 cal per g

16 Thermal conductivity at 20 C (68 F). 0.130 cal/sq cm/cm/°C/sec

18 Heat of combustion. 1380 cal per ■

E *1 Volume conductivity* referred to standard copper. 13.9%

2 Electrical resistivity at 18 C (64 F). 12.4 microhm-cm

5 Temperature coefficient of electrical resistivity 0 to 100 C (32 to 212 F). 0.00382 per °C

10 Electrochemical equivalent (valence 5). 0.3749 mg per coulomb

F *2 Refractive index.* 2.05

G *2 Magnetic susceptibility.* plus 0.93×10^{-6} cgs

I *1 General resistance to corrosion.* Tantalum is resistant to corrosion except when subject to galvanic couple action.

2 Resistance to specific agents.

Tantalum is resistant to the following chemicals: acetone; acetic, butyric, carbonic, citric, fatty, formic, hydrochloric, hydrobromic, lactic, nitric, and tartaric acids; ethyl, methyl and higher alcohols; aluminum sulfate; ammonium chloride, hydroxide, nitrate and sulfate; calcium chloride; carbon dioxide and tetrachloride; copper sulfate; ferric chloride; foodstuffs; formaldehyde; fruit products; hydrogen peroxide; magnesium chloride and sulfate; milk; mineral oils; motor fuels; petroleum products; phenols; potassium tri-iodide, chloride and nitrate; refrigerants; sodium chloride, nitrate and sulfate; sugar; sulfur; chlorinated, distilled, rain and sea water.

Tantalum is resistant to the following chemicals when cold: oxalic, phosphoric and sulfuric acids; air; ammonia; bromine, chlorine and iodine; hydrogen sulfide; oxygen; and sulfur dioxide. It is resistant to mixed acids and acid salts if fluorides are absent. It is resistant to bleaching solutions, dyestuffs, and photographic solutions, except when alkaline. It is subject to moderate general attack by sodium carbonate. It is attacked severely by hydrofluoric acid, fuming sulfuric acid, potassium hydroxide, and sodium hydroxide.

J *1 Crystal structure.* Body-centered cubic; $a = 3.296$ kX

K *Mechanical properties.* See Table I.

2 Directional properties. The tensile strength and elongation, measured parallel and transverse to the direction of rolling, are substantially equal in both worked and annealed sheet.

4 Machinability. Tantalum is like cold rolled steel. Carbon tetrachloride and light oil should be used as a cutting fluid.

5 Coefficient of friction. Galls against itself and 18-8 steel.

Table I. Mechanical Properties of Wrought Tantalum

Form and Condition	Section, in.	Tensile Strength, psi	Elongation in 2 in., percentage	Rockwell Hardness
Sheet, annealed	0.010	50,000	40	E 60
Sheet worked	0.010	110,000	1	E 95
Wire, annealed	0.002	100,000	11	....
Wire, worked	0.002	180,000	1.5	....
Plate, hardened	0.010	145,000	18	B 103

L *1 Metallography.* Polishing: emery to 000, levigated alumina to finish; etching: HF-NH_4F solution

M *Composition limits.* Allowable percentages of impurities for sheet, wire and compacts are: 0.03% C, and 0.01% Fe.

2 Consequences of exceeding impurity limits. Reduction in elongation; high yield and tensile strengths; no change in resistance to corrosion.

N *3 Alloying.* Add tungsten as powder when high tensile strength, higher yield strength and higher annealing temperature are required. Add thorium as powder for special electronic properties.

7 Hot working temperature range. None; it is worked cold.

9 Annealing temperature. Above 1050 C (1920 F) in vacuo

10 Maximum reduction between anneals. Not limited

11 Suited to forming by all conventional methods such as rolling, drawing, pressing, bending and swaging.

12 Precautions in forming. For drawing, a nonloading die material is used; other practices conventional.

16 Standard finishes. Dull or bright rolled finish for sheet; smooth dull finish for wire.

17 Joining.

Rivet composition. Tantalum

Silver solder. Not readily soldered except by special techniques.

Braze with copper in vacuum.

Carbon-arc welding. Special techniques under protective liquids.

Resistance welding. Spot and seam

References

"Mechanical Properties of Metals and Alloys", Nat Bur Standards Circular C447, 1943
A. E. van Arkel, "Reine Metalle", Julius Springer, Berlin, 1939
C. W. Balke, Ind Eng Chem, 27, 1166 (1935); 30, 251 (1938)
C. C. Balke, Iron Age, 147, 23 (1941)

* Director of Research, Fansteel Metallurgical Corporation, North Chicago, Ill.

Tellurium

COMPILED BY A. C. VAUGHAN*

B *1 Typical uses.* In rubber to promote resistance to heat and abrasion; alloyed with lead to improve work hardening and to increase recrystallization temperature; alloyed with copper, for free-machining alloys.
C *1 Density* at 20 C (68 F). 6.24 g per cu cm (0.225 lb per cu in.)
D *1 Melting point.* 450 ± 10 C (842 ± 18 F)
4 Boiling point. 1390 C (2534 F)
6 Thermal expansion at 40 C (104 F). 0.0000168 per °C
11 Specific heat at 20 C (68 F). 0.047 cal per ■
13 Latent heat of fusion. 7.3 cal per g
15 Latent heat of vaporization. 159 cal per g

* American Smelting and Refining Company, Barber, N. J.

E *2 Electrical resistivity* at 19.6 C (67.3 F). 200,000 microhm-cm
10 Electrochemical equivalent (valence 6). 0.22040 mg per coulomb
G *2 Magnetic susceptibility* at 18 C (64 F). minus 0.31 × 10^{-6} cgs
J *1 Crystal structure.* Hexagonal; ■ = 4.445 kX; c = 5.912 kX

References

"International Critical Tables", McGraw-Hill Book Co., 1926
C. S. Barrett, "Structure of Metals", McGraw-Hill Book Co., 1943
"Minerals Yearbook for 1943", U. S. Government Printing Office, 1945
W. E. Milligan, in "Modern Uses of Nonferrous Metals", AIME, 1935

Titanium

COMPILED BY J. T. MILEK*

B *1 Typical uses.* As an addition agent in alloying with aluminum, copper, magnesium, steel, nickel, and other metals; to produce grain refinement in aluminum alloys; to enhance mechanical and physical properties (strength, ductility, hardness); and, as powder, in pyrotechnics.
2 Precautions in use. Powdered titanium is stable at room temperature, but begins to oxidize at about 120 C (250 F). It unites readily with nitrogen and hydrogen at low temperatures. The consolidated metal may be heated to at least 800 C (1470 F) in air without taking fire. Static electric charges will ignite dry powdered titanium at room temperature; consequently the powder is transported wet.
C *1 Density* at 20 C (68 F). 4.54 g per cu cm (0.164 lb per cu in.) α form
at 875 C (1607 F). 4.31 g per cu cm (0.156 lb per cu in.) β form
6 Transformation volume change (α to β on heating). 5.5%
D *1 Melting point.* 1820 ± 100 C (3300 ± 180 F)
5 Transformation temperature (cooling). 875 C (1607 F)
6 Thermal expansion at 20 C (68 F). 0.0000085 per °C
11 Specific heat at 25 C (77 F). 0.126 cal per ■
12 Specific heat versus temperature.[1] See Fig. 1.

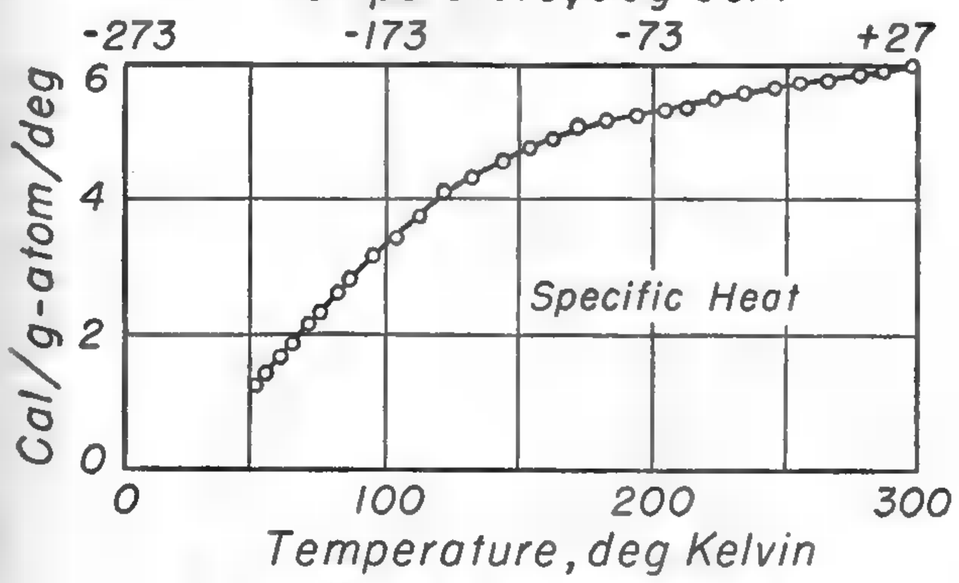

Fig. 1 Specific heat of titanium at low temperature

18 Heat of combustion. 510 cal per ■
E *1 Volume conductivity* referred to standard copper. 2.2%
2 Electrical resistivity at 0 C (32 F). 80 microhm-cm
Volume resistivity 0.000056 ohm per cu cm
F *4 Color.* The powdered form is dark gray; the fused metal, similar to polished steel.

* Research Laboratory, The Titanium Alloy Manufacturing Company, Niagara Falls, N. Y.

G *2 Magnetic susceptibility versus temperature.*

Temperature, °C	−170	−140	−110	−80	+20
Susceptibility, 10^6 cgs	1.6	1.4	1.3	1.25	1.25

I *1 General resistance to corrosion.* Titanium has resistance to corrosion similar to that of 18-8 steel. It is attacked by sulfuric and hydrochloric acids. Dilute sulfuric acid attacks the metal slowly. Concentrated and dilute nitric acid have no appreciable effect. The metal does not tarnish during exposure to laboratory atmospheres, nor during 30 days in salt spray.
J *1 Crystal structure.*

Type	a, kX	c, kX	deg Cent	deg Fahr
α ..... Close-packed hexagonal	2.95	4.73	up to 880	up to 1616
β ..... Body-centered cubic	3.32	...	above 880	above 1616

6 Microstructure. See micrographs in reference 2.
K *Mechanical properties* (all sections $\frac{1}{16}$ in. thick).

Condition	Tensile Strength, psi	Yield Strength, psi	Elongation, percentage	Rockwell Hardness, G scale
Annealed	78,700	62,800	25.2	76
¼ hard, 20% reduction	110,500	101,100	8.2	86
½ hard, 40% reduction	122,200	113,300	7.5	91
Hard, 60% reduction	111,500	.....	1.5	92

Modulus of elasticity 16,800,000 psi, annealed
L *1 Metallography.*[2] Etchant: 5% solution of HF.
M *2 Effects of impurities.* Oxygen and nitrogen cause brittleness, higher strength and hardness, and lower elongation. Small amounts of silicon cause embrittlement.
N *3 Alloying.* Titanium alloys with most metals, especially copper, tin, iron, aluminum, chromium, cobalt, molybdenum, and tungsten. Columbium, molybdenum and tungsten harden titanium considerably. Alloys with thorium are very soft. All alloys of titanium and tantalum are malleable when hot.
4 Preferred deoxidizers. None
6 Precautions in melting. Oxygen, hydrogen, nitrogen and carbon must be excluded during melting, which must be done in a vacuum or an argon atmosphere.
7 Hot working temperature range. Rolling at 500 C (930 F) permits greater reductions per pass and larger total reductions between anneals. The temperature is below the recrystallization temperature of titanium and material so rolled work hardens, but to a much slighter extent than in cold rolling.
9 Annealing temperature. 400 to 1100 C (750 to 2010 F)
10 Maximum reduction between anneals. 60%
11 Suited to forming by the usual processes of swaging, hot and cold rolling, and wire drawing
12 Precautions in forming. For wire drawing, air an-

nealing is preferred to vacuum annealing because of the formation of an oxide film that prevents the metal from sticking to the dies.

13 Compacting pressure. 100,000 psi

14 Sintering temperature. 950 to 1000 C (1740 to 1830 F); time 16 hr; atmosphere 10^{-4} mm Hg.

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2 Dean, Long, Wartman and Hayes, Trans AIME, 166, 382 (1946)
3 Dean, Long, Wartman and Anderson, Trans AIME, 166, 369 (1946)
4 W. Kroll, Trans Electrochem Soc, 78, 35 (1940)
5 "Mechanical Properties of Metals and Alloys", Nat Bur Standards Circular C 447, 1943

Tungsten*

B *1 Typical uses.* Principally as an alloying element in ferrous alloys; also in cobalt-base alloys and in tungsten carbide. As filaments in electric lamps.

C *1 Density* at 20 C (68 F). 19.3 g per cu cm (0.697 lb per cu in.)

3 Compressibility at 20 C (68 F). 0.00000028 per megabar. This value is the smallest for any metal.

D *1 Melting point.* 3410 ± 20 C (6170 ± 35 F)

2 Boiling point. 5930 C (10,700 F)

6 Thermal expansion near 20 C (68 F). 0.0000043 per °C

11 Specific heat at 20 C (68 F). 0.032 cal per g per °C

13 Heat of fusion. 44 cal per g

16 Thermal conductivity near 20 C. 0.48 cgs

20 Vapor pressure.

Deg Cent	3940	4440	5080	5650	5930
Atmospheres	0.001	0.01	0.1	0.5	1.0

E *2 Electrical resistivity* at 20 C (68 F). 5.5 microhm-cm

5 Electrical resistivity versus temperature.

Deg Cent	227	727	1727	2727	3227
Microhm-cm	10.5	24.3	55.7	90.4	108.5

F *5 Emissivity (spectral)* at 4670 A.

Deg Cent	227	727	1727	2727	3227
Emissivity	0.498	0.486	0.469	0.455	0.449

J *1 Crystal structure.* Body-centered cubic, $a = 3.1585$ kX; other forms known or probable.

K *Mechanical properties.*

Vickers hardness number. Sintered bar, 255; swaged to 5 mm, 407; reheated to 2700 C, 392; swaged to 3.5 mm, 474; swaged to 1.8 mm, 488.

Tensile strength of drawn wire.

Diameter, mils	18	7.23	5.78	3.96	1.40
1000 psi	264	340	366	483	590

Modulus of elasticity. 50,000,000 psi

Modulus of rigidity. 19,600,000 psi

* Compiled from the sources listed and from a selection of data by members of the National Bureau of Standards.

References

"Mechanical Properties of Metals and Alloys", Nat Bur Standards Circular C447, 1943
A. E. van Arkel, "Reine Metalle", J. Springer, Berlin, 1939
K. C. Li and C. Y. Wang, "Tungsten", 2nd Ed, Reinhold Publishing Co., New York, 1947
C. J. Smithells, "Tungsten", 2nd Ed, D. Van Nostrand Co., New York, 1936
K. K. Kelley, Bur Mines Bull 383, 1935

Vanadium

COMPILED BY JEROME STRAUSS*

B *1 Uses.* Alloying element in steel and nonferrous metals.

2 Precautions in use. Oxidizes in molten unkilled steel.

C *1 Density* at 22 C (71.6 F). 6.0 g per cu cm (0.217 lb per cu in.)

D *1 Melting point.* 1735 ± 50 C (3150 ± 90 F)

4 Boiling point. 3400 C (6150 F) calculated

11 Specific heat 20 to 100 C (68 to 212 F). 0.120 cal per

E *2 Electrical resistivity* at 20 C (68 F). 26 microhm-cm

5 Temperature coefficient of resistivity. 0.0028 per °C

10 Electrochemical equivalent (valence 5). 0.1056 mg per coulomb

G *2 Magnetic susceptibility.* 1.5×10^{-6} cgs

I *2 Resistance to specific agents.* Vanadium metal dissolves easily in nitric acid, both concentrated and dilute. It reacts very slowly with strong hydrochloric acid, but is not attacked by dilute hydrochloric or by concentrated or dilute sulfuric acids.

J *1 Crystal structure.* Body-centered cubic; $a = 3.033$ kX

K *Mechanical properties.* Ductile enough to be cold worked.

* Vanadium Corporation of America, New York

References

J. W. Marden and M. N. Rich, Ind Eng Chem, 19, 786 (1927)
A. W. Hull, Phys Rev, 20, 113 (1922)

Zirconium†

B *1 Typical use.* As a "getter" in vacuum tubes, because of ability to absorb gases at high temperature.

C *1 Density* at 20 C (68 F). 6.5 g per cu cm

D *1 Melting point.* 1750 ± 700 C (3200 ± 1300 F)

6 Thermal expansion near 20 C (68 F). 0.000005 per °C

11 Specific heat at 20 C (68 F). 0.066 cal per g per °C

E *2 Electrical resistivity* at 0 C (32 F). 41.0 microhm-cm

I *1 General resistance to corrosion.* Excellent. Resists all dilute acids and will withstand hydrochloric and nitric acids in hot concentrated solutions. Also resists hot concentrated caustic solutions.

J *1 Crystal structure.* Close-packed hexagonal, $a = 3.223$ kX, $c = 5.123$ kX. Other forms known or probable.

K *Mechanical properties.* See Table I.

N *Working data.* Fully annealed zirconium is soft and ductile, and can be drawn and shaped easily. The metal work hardens rapidly, but has a high capacity for work hardening. By a special method, zirconium wire has been drawn as fine as 0.0012-in. diam.

Table I. Mechanical Properties of Zirconium (Raynor)

Property	Hard Drawn	Tempered at 850 F	Annealed at 1450 F
Cold Reduced From ¼-in. Turned Bars Rolled and Swaged to ⅛-in. Diam (76.9% reduction in area)			
Tensile strength, psi	88,300	81,600	35,900
Yield strength (0.2% offset), psi	69,700	55,200	15,900
Elongation in 4 diam, percentage	18.0	20.0	31.0
Modulus of elasticity, million psi	14.5	14.0	11.35
Rockwell B hardness	87.4	87.7	30.3
Rockwell 30-T hardness	77.1	76.1	29.4
Rockwell F hardness	106.0	107.1	75.1
Commercial Wire (0.017-in. diam) Tested in Scott Machine			
Tensile strength, psi	128,800	93,500	61,000
Elongation, percentage	2	5.5	14

9 Annealing temperature. 1375 to 1475 F for 15 min, in a vacuum or in one of the noble gases.

† Compiled from the sources listed and from a selection of data by members of the National Bureau of Standards.

References

"Mechanical Properties of Metals and Alloys", Nat Bur Standards Circular C447, 1943
A. E. van Arkel, "Reine Metalle", J. Springer, Berlin, 1939
W. M. Raynor, Mining and Met, 28, 284 (1947)

CONSTITUTION OF ALLOYS

Prepared under the direction of the

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OF THE AMERICAN SOCIETY FOR METALS

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Form and Arrangement of the Section

IN ALL PREVIOUS EDITIONS OF THE METALS HANDBOOK, the articles about the constitution of binary and ternary alloys were distributed throughout the several ferrous and nonferrous sections of the book. For the present edition, the Metals Handbook Committee decided that all such articles, with the included phase diagrams, should be placed in a single section and prepared according to a uniform style. The Phase Diagram Committee was organized to plan the new section and to direct the preparation of it.

After the general outlines for the section were complete, the Phase Diagram Committee appointed sectional chairmen — listed above — to supervise the construction of the diagrams involving the principal metals. In collaboration with these chairmen and with the Committee, 82 authors have prepared the 284 diagrams and have written the discussions that go with them.

An enlargement in the size of the phase diagrams and a twofold increase in the number of them have made it necessary to reduce the amount of space given to the text accompanying each diagram. Discussions of controversial data and of physical properties of alloys have therefore been omitted, except where space was available in the column next to a particular diagram. For most of the articles, journal references have been limited to publications actually used in constructing the selected phase diagram.

The alloy systems are arranged in the alphabetic order of the chemical symbols of the components; for example, silver-cadmium is listed under "Ag", iron-carbon under "C". The component having alloys of the greater commercial importance in a binary system appears at the left side of the diagram. Intermediate phases have been designated by consecutive Greek letters from left to right, except where phases have other designations that are generally accepted.

The co-ordinates of the diagrams are in weight percentage and degrees Centigrade; atomic percentages are marked on the top, and degrees Fahrenheit on the right of each diagram. Temperatures of reaction horizontals are indicated in Centigrade with a plain degree sign; compositions at line intersections are shown by numbers without the per cent sign.

All complete binary phase diagrams are reproduced to a scale of 10 weight per cent equals one centimeter. On the partial diagrams also, one weight per cent corresponds to a simple multiple of one millimeter. The temperature scale has been drawn so that either 25, 50, 100, 200 or 400 degrees Centigrade equals one centimeter. Thus, both weight percentage and degrees Centigrade can be read directly from each binary diagram by using a centimeter scale.

Dashed lines signify doubt as to the position of the line in question. Dotted lines show the temperatures of magnetic changes. A dot-dash line indicates the existence of an ordered structure. Because of present uncertainty in the data concerning superstructures, it has been necessary in some diagrams to show constructions that are not in harmony with general laws of phase equilibrium.

Melting points of the pure components are shown according to the temperatures given in the table of Physical Properties of the Elements, on pages 20 and 21. The temperatures of polymorphic transformations in the metallic elements have also been standardized. In order to obtain consistency in these transformation and melting temperatures, adjustments in other data have sometimes been necessary.

TAYLOR LYMAN
Editor, Metals Handbook

CONSTITUTION OF BINARY ALLOYS

Ag-Al Silver-Aluminum

By W. Earl Lindlief*

Crystal structures of β, β', and γ are respectively: body-centered cubic, β-Mn cubic, and close-packed hexagonal.

References

1 M. Hansen, Z Metallkunde, 20, 217 (1928)

* National Bureau of Standards, Washington, D.C.

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4 W. Hume-Rothery, G. W. Mabbott and K. M. Channel-Evans, Phil Trans Roy Soc, A 233, 1 (1934)
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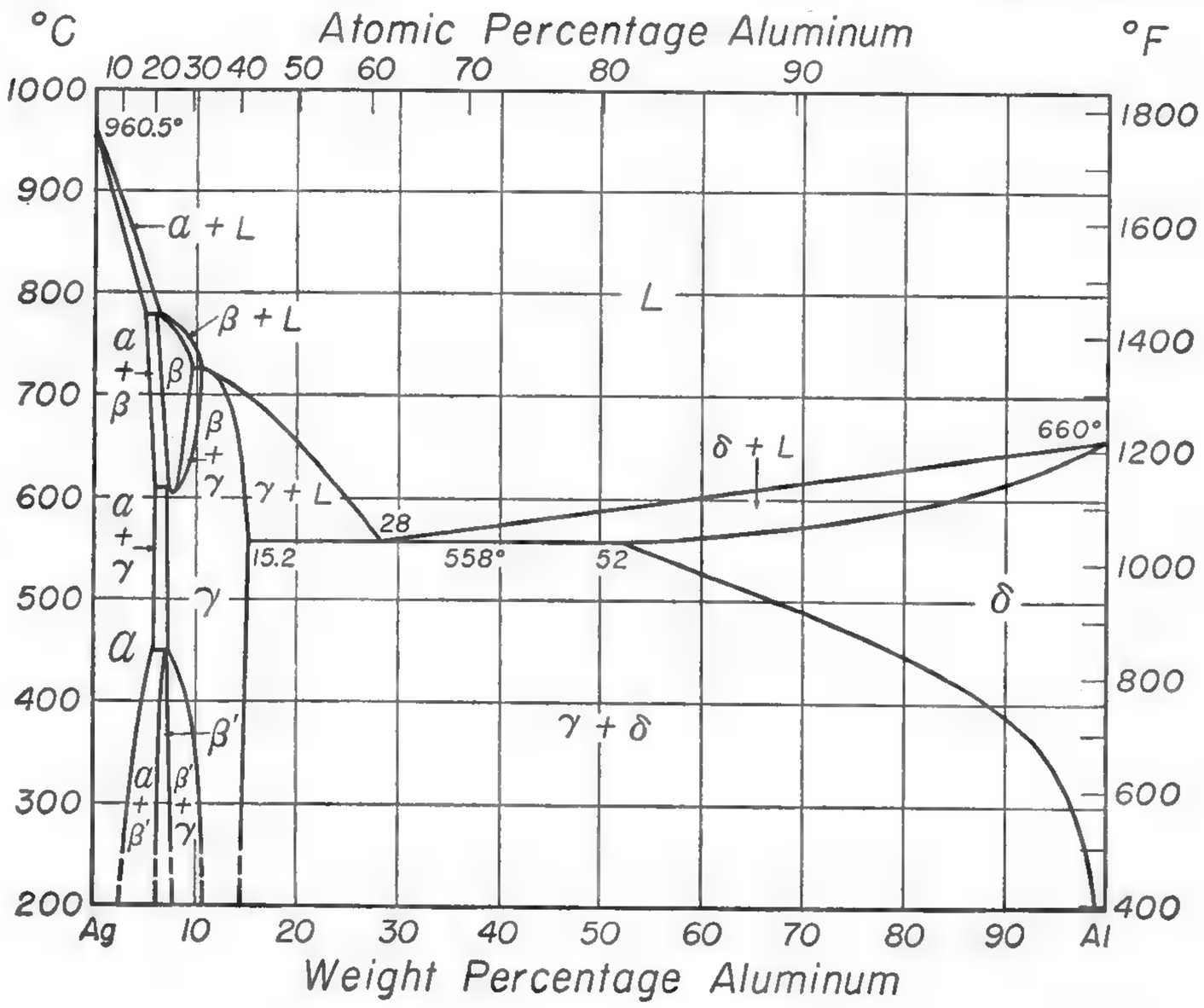

Ag-Au Silver-Gold

By Robert H. Leach*

The curve of lattice parameter versus composition of a passes through a minimum at 19.9% Ag and 4.0672 kX.[3]

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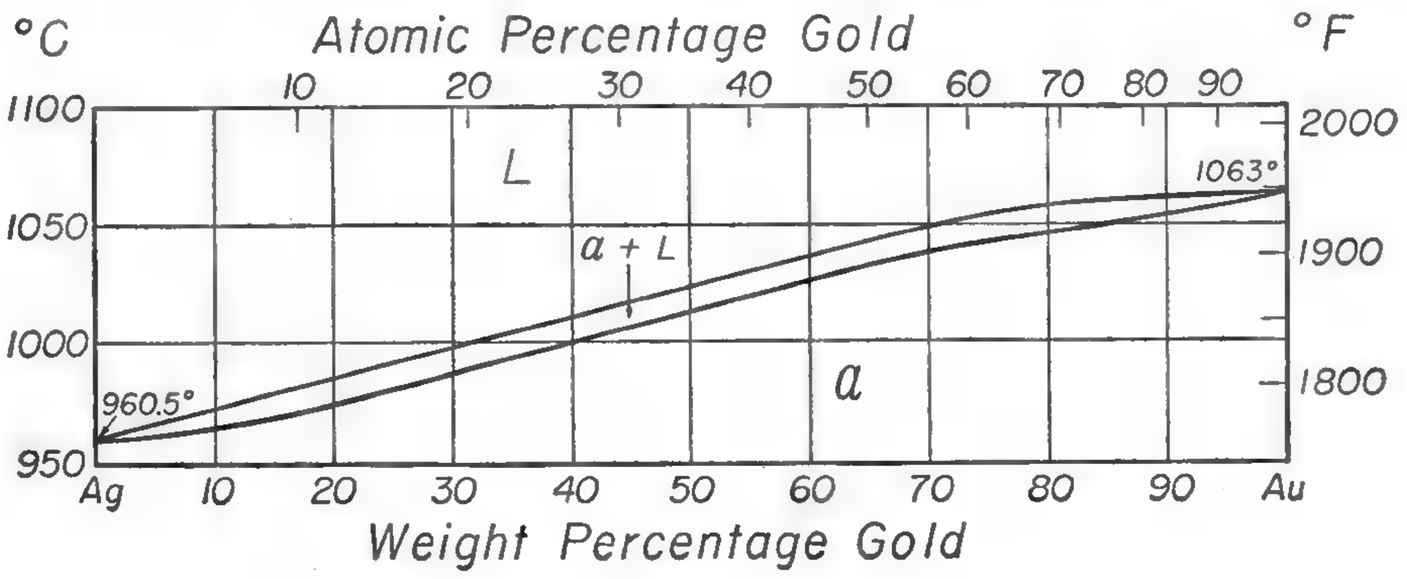
* Vice President, Handy & Harman, Bridgeport, Conn.



Ag-Cd Silver-Cadmium

By F. C. Kracek*

At the liquidus the diagram[1,3,4,5,7] bears a close resemblance to that of silver-zinc. Below the liquidus the relationship is more complex in the β field; microscopic and thermal studies[2,3,4] show the existence of β (disordered?), β' (ordered?) and ζ (complex hexagonal) phases. X-ray studies on quenched powdered samples[8,9,11] do not reveal the ζ phase, which appears not to be retained because of extremely rapid transformation to β' (plus α or γ); measurements obtained with a high-temperature camera indicate the existence of all the three phases (β, β', ζ) in the β field.[10] The phase boundaries that are given in the diagram were deduced from the microscopic examination of quenched specimens.[3,4] These boundaries are not in good agreement with those based on X-ray studies.[11]

* Geophysical Laboratory, Carnegie Institution of Washington, Washington, D.C.

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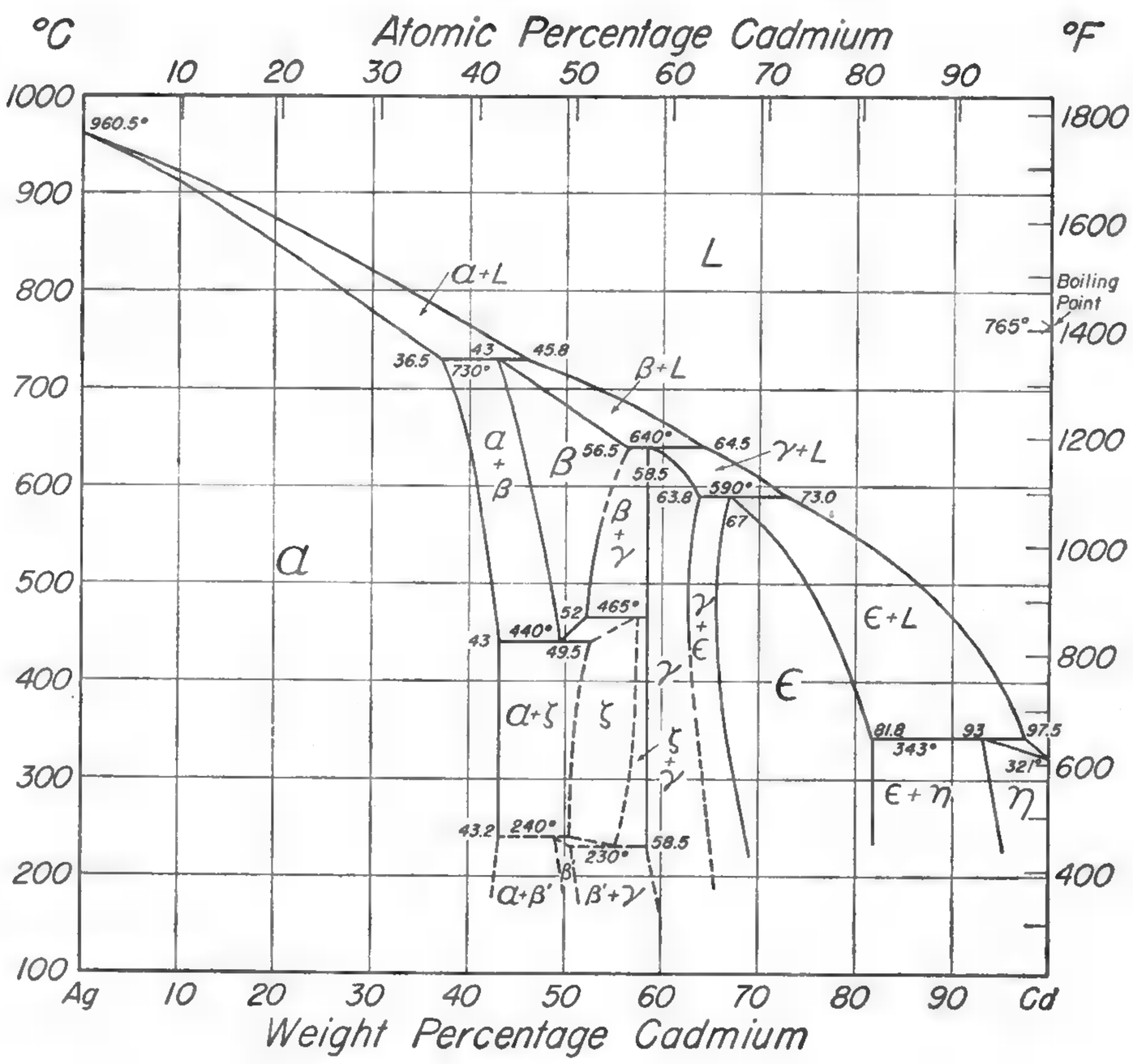


Crystal Structures and Lattice Parameters of Silver-Cadmium Alloys

Phase	Percentage Silver	Crystal Structure	Atoms per Cell	Lattice Parameter a, kX	Lattice Parameter c/a	Reference
α	100	Face-centered cubic	4	4.078	....	8, 9
	69			4.14	....	
	65			4.15	....	
β	55.53	Body-centered cubic	2	3.315 to 3.321	....	8, 9, 11
	51.66			3.320	....	
	49.10			3.326	....	
	43.6			3.336	....	
ζ	49	Close-packed hexagonal	2	3.16	1.56	10
	49			3.01	1.62	8
	52.6			2.973	1.619	9
	43.5			2.989	1.608	
γ	44.6	Complex cubic	52	9.935	....	8
	32.9			9.982	....	
ϵ	33.9	Close-packed hexagonal	2	3.04	1.58	8, 9
	25.75			3.06	1.58	
η	5.0	Close-packed hexagonal	2	2.95	1.89	8, 9
	0.0			2.98	1.89	

Ag-Co Silver-Cobalt

According to Petrenko,[1] silver and cobalt are insoluble in the liquid state at 1600 C. Tammann and Oelsen,[2] using a sensitive magnetic method, determined a solubility between 0.0001 and 0.001% Co in silver after the solidification of silver liquid solutions to which small amounts of cobalt had been added at a temperature of 1000 or 1200 C.

References

1 G. I. Petrenko, Z anorg Chem, 53, 212 (1907)
2 G. Tammann and W. Oelsen, Z anorg allgem Chem, 186, 257 (1930)

Ag-Cr Silver-Chromium

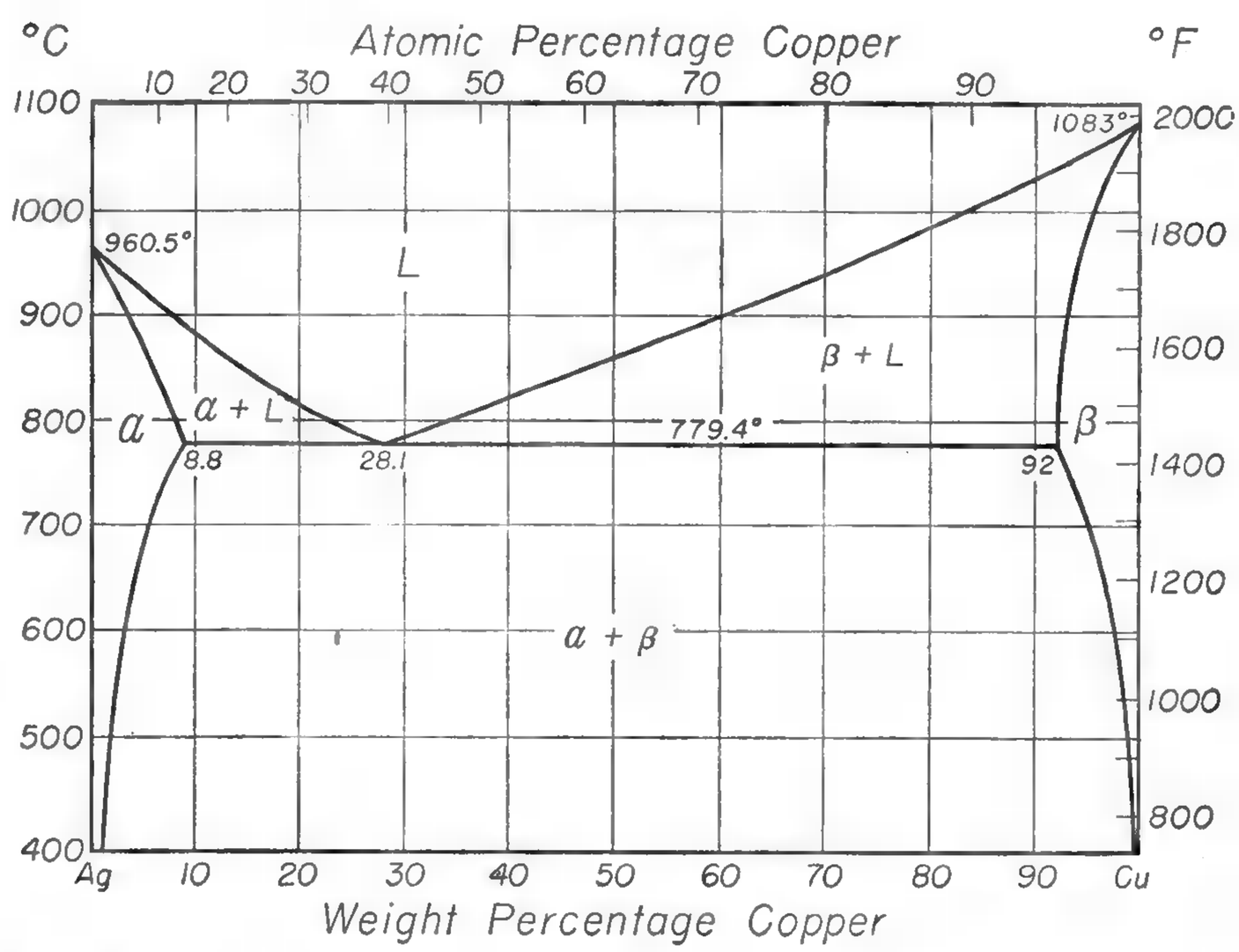
Hindrichs[1] investigated alloys of silver and impure chromium, both of which melted at temperatures considerably lower than the melting points of the pure metals. His results indicate a monotectic reaction about 100 C below the melting point of chromium, and a miscibility gap extending from about 10 to 90% Cr. All solid alloys contained two metallic phases, silver and chromium.

Reference

1 G. Hindrichs, Z anorg Chem, 59, 423 (1908)

Ag-Cu Silver-Copper

By Cyril Stanley Smith*



The liquidus is based on the results of Heycock and Neville[1], Friedrich and Leroux[2] and Hirosé.[3] The eutectic temperature[4] and composition[5] have been the subject of special investigations and are known with unusual accuracy. The extent of solid solution at each end of the diagram has been determined by microscopic examination,[6,7] X-ray[8,9,10] and electrical conductivity[7] methods, all of which are in substantial agreement.

Both solid solutions are face-centered cubic. The lattice parameter of the copper-rich solid solution increases lineally with atomic percentage of silver from 3.608 to 3.633 kX at 8.0% Ag, and that of the silver-rich solution decreases lineally from 4.077 to 4.029 kX at 8.0% Cu.

* Director, Institute for the Study of Metals, University of Chicago, Chicago

References

1 C. T. Heycock and F. H. Neville, Phil Trans Roy Soc (London), A 189, 32 (1897)
2 K. Friedrich and A. Leroux, Metallurgie, 4, 293 (1907)
3 T. Hirosé, Repts Imp Mint, Osaka, 1, 1 (1927)
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9 N. Ageev and G. Sachs, Z Physik, 63, 293 (1930)
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Ag-Fe Silver-Iron

By R. M. Parke*

Silver and iron are insoluble in the liquid state at 1600 C[1] and are virtually insoluble in the solid state. Tammann and Oelsen[2] report that ▮ × 10^{-4}% Fe dissolves in silver at 1600 C and 4 × 10^{-4}% Fe dissolves in silver at 1000 C. Dornblatt[3] reports that 0.01% Ag dissolves in Armco iron, but Wever[4] states diagrammatically, without the inclusion of data on temperature, that silver is insoluble in iron.

* Kellex Corporation, Silver Spring, Md.

References

1 G. I. Petrenko, Z anorg Chem, 53, 212 (1907)
2 G. Tammann and W. Oelsen, Z anorg allgem Chem, 186, 257 (1930)
3 A. J. Dornblatt, discussion of Fink and De Marchi, Trans Electrochem Soc, 74, 271 (1938)
4 F. Wever, Arch Eisenhüttenw, 2, 739 (1929)

Ag-Ga Silver-Gallium

On a scale of atomic percentage, the liquidus and solidus of the α phase are approximately the same as those in the silver-tin system. Close-packed hexagonal ζ forms peritectically at 611 C, and transforms eutectoidally at 378 C into α and ζ'. The ζ' phase has a complex hexagonal structure the same as the ζ phase in the silver-zinc system. The solubility of gallium in silver is 18.7 atomic % at 611 C, 17.6 atomic % at 378 C, and 12.2 atomic % at 211 C.

Reference. Hume-Rothery and Andrews, J Inst Metals, 68, 133 (1942)

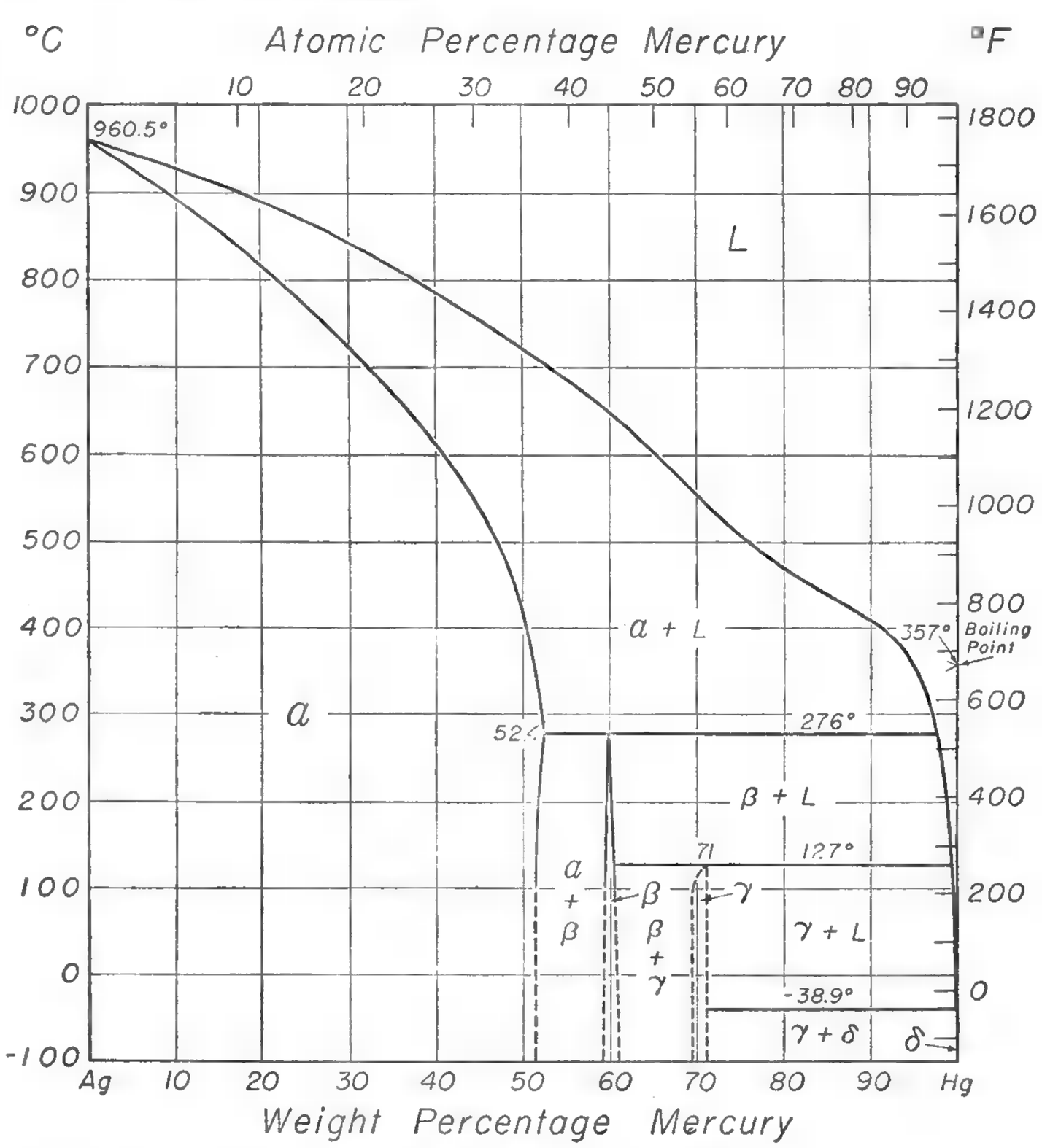
Ag-Ge Silver-Germanium

The phase diagram for the silver-germanium system is similar to that for the gold-germanium system (*see* page 1172). Both diagrams are of the eutectic type with no intermediate phases. The silver-germanium eutectic point is at 19% Ge[1] and 651 C.[2] The α solubility decreases from 7.9 atomic % Ge at 575 C to 1.5 atomic % Ge at 270 C.[3] The solubility of silver in germanium is apparently very slight.

References. (1) T. R. Briggs and others, J Phys Chem, 33, 1080 (1929). (2) W. Hume-Rothery and others, J Inst Metals, 66, 237 (1940). (3) E. A. Owen and V. W. Rowlands, J Inst Metals, 66, 371 (1940)

Ag-Hg Silver-Mercury

By W. Earl Lindlief*



According to Murphy,[1] γ is formed quite rapidly by reaction of mercury with finely divided silver at room temperature. However, in the alloys containing more than 52% Hg there is a strong tendency for metastable conditions to be developed during cooling after fusion. The reaction between α and liquid and that between β and liquid proceed slowly and are entirely suppressed by cooling rates such as those employed in thermal analysis. For example, an alloy containing 95% Hg must be annealed for 3 days at 100 C before the thermal arrest observed on a heating curve is equivalent to that obtained when an unfused amalgam of the same composition is being heated at the same rate.

The solubility of silver in liquid mercury at 19 C is approximately 0.034%.[2,3]

Crystal structures and lattice parameters of the α, β and γ phases are given in the table below the diagram.

References

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* National Bureau of Standards, Washington, D.C.

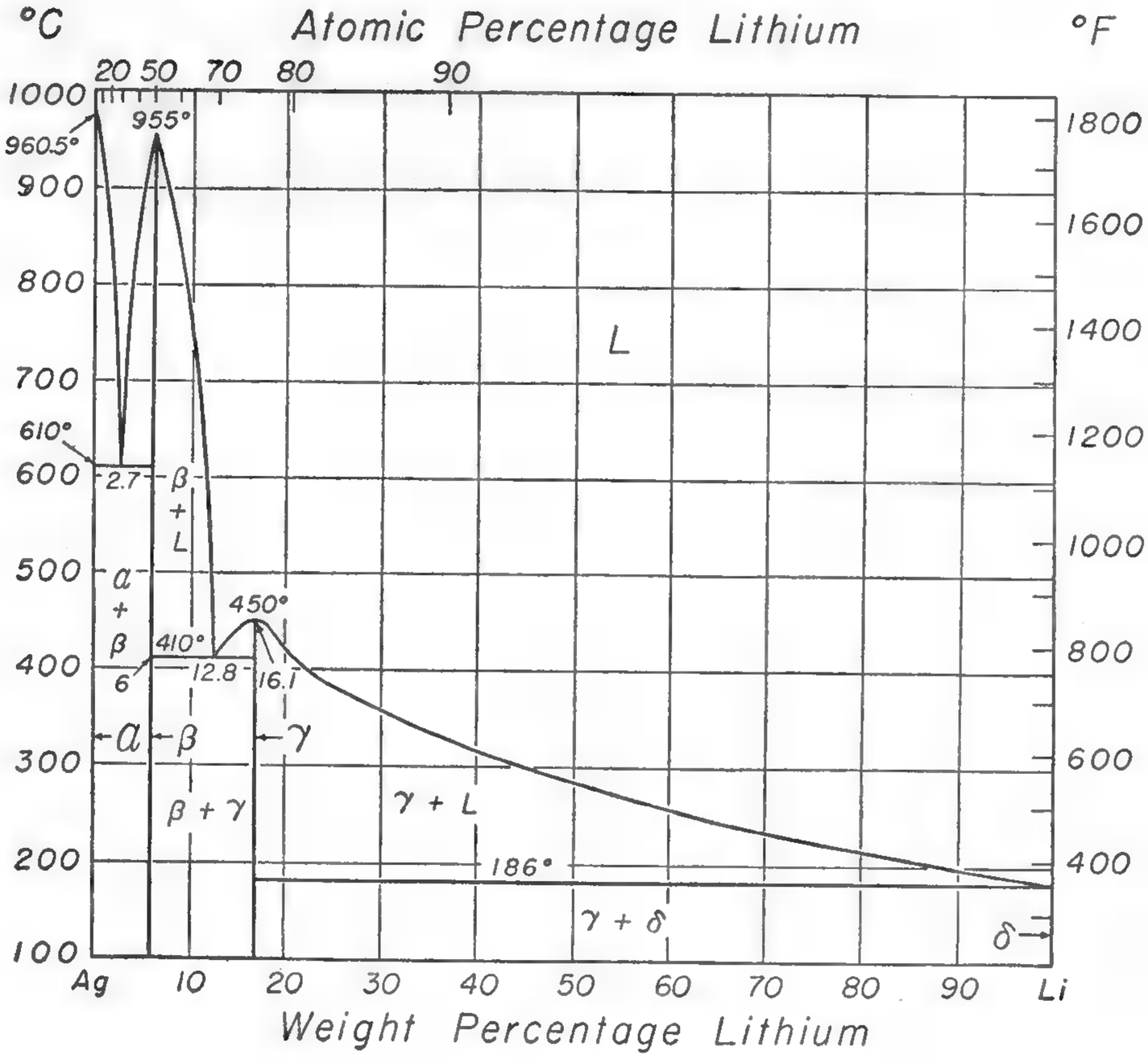
Crystal Structures and Lattice Parameters of Silver-Mercury Alloys[5,6]

Phase	Percentage Mercury	Crystal Structure	Lattice Parameter, kX units	
			a	c
α	9.98	Face-centered cubic	4.0910	....
α	19.97	Face-centered cubic	4.0166	....
α	28.98	Face-centered cubic	4.1263	....
α	40.00	Face-centered cubic	4.1488	....
α	49.15	Face-centered cubic	4.1731	....
β	Ag saturated	Close-packed hexagonal	2.964	4.831
β	Hg saturated	Close-packed hexagonal	2.987	4.830
γ	Ag saturated	Body-centered cubic	10.013	....
γ	Hg saturated	Body-centered cubic	10.031	....

The α-phase alloys were annealed 500 hr at 270 C and quenched; β- and γ-phase alloys were annealed at 100 C.

Ag-Li Silver-Lithium

By H. E. Cleaves*



Data for the liquidus and eutectics of silver-lithium alloys were obtained by Pastorello[1] using lithium melting at 180 C, six degrees below the melting point of pure lithium.[2] Hence the temperatures of the liquidus and eutectics may be slightly in error.

No evidence of solid solubility of lithium in silver or of silver in lithium was observed.[1]

The existence of the compounds β and γ was confirmed and their structures were determined.[3,4] These compounds correspond to the compositions LiAg and Li_3Ag respectively.

The β phase has a body-centered cubic structure of the same type as β brass; the lattice parameter is 3.168 ± 0.003 kX.[3]

The γ phase is simple cubic with a lattice parameter of 9.94 kX.[4]

References

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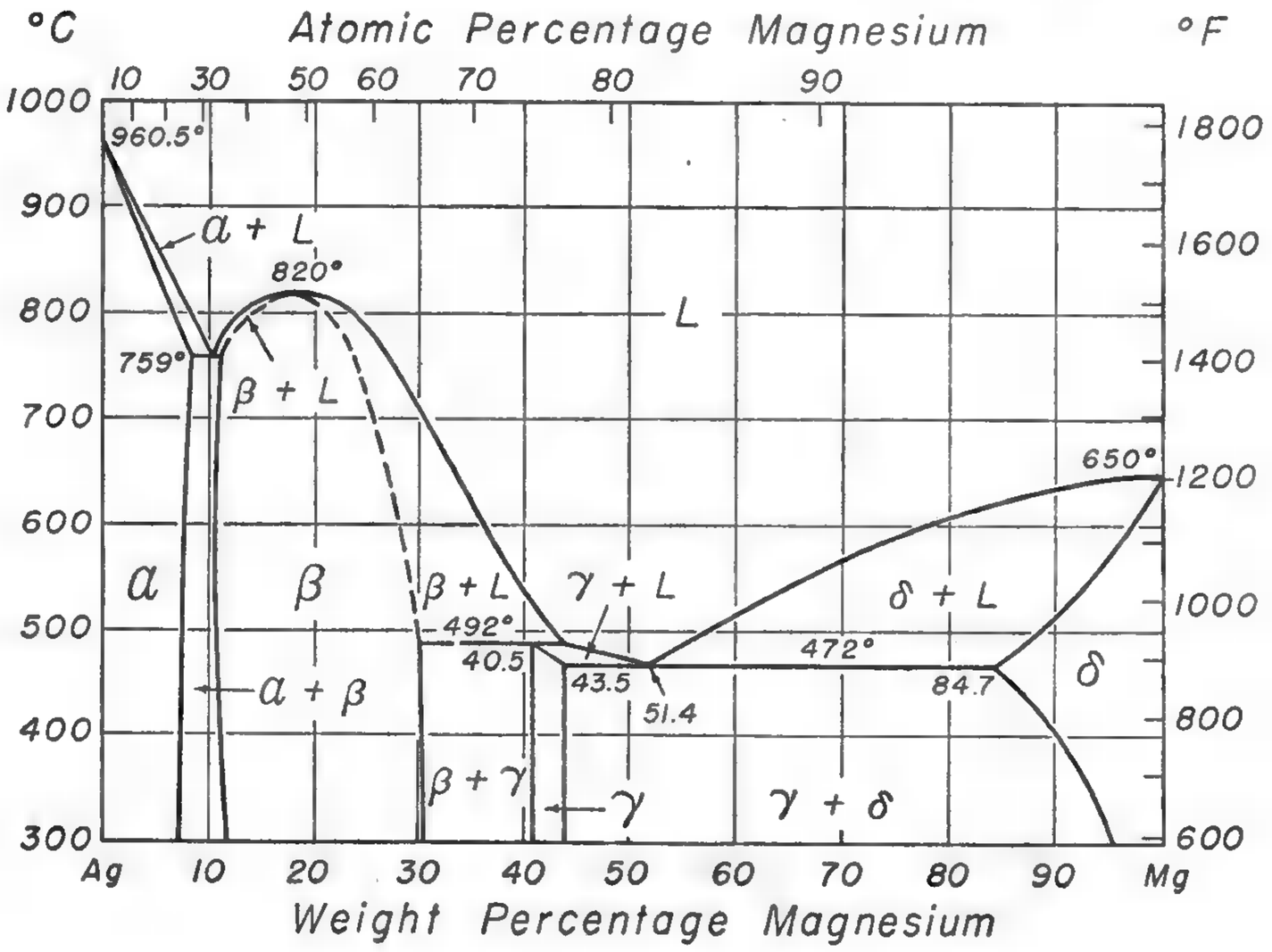
* National Bureau of Standards, Washington, D.C.

Ag-Mg Silver-Magnesium

By G. F. Sager* and B. J Nelson*



The width of the β field is not firmly established. The solubility of magnesium in silver is 8.54% at 759 C, 7.51% at 300 C. The solubility of silver in magnesium is 15.3% at 472 C, 9.0% at 400 C, 3.9% at 300 C, and 1.6% at 200 C.

The β phase is body-centered cubic (CsCl type)[1] with a lattice parameter of 3.28 kX; γ was first reported to be hexagonal,[2] but later work[5] indicates a more complicated structure.

A superstructure has been found in the β phase near 50 atomic % Mg.[5]

References

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* Aluminum Research Laboratories, New Kensington, Pa.

Ag-Ni Silver-Nickel

By John L. Christie*

The limited terminal solubilities have not been determined precisely.[1] The solubility of nickel in solid silver is very low, 0.102% at 922 C and 0.012% at 400 C.[2]

Silver-rich silver-nickel mixtures have characteristics desirable for electrical contacts. Because of the low solubility of each metal in the other, most compositions must be prepared by the methods of powder metallurgy. The properties of these materials, in the composition range from 0 to 40% Ni, are discussed in the article "Silver Materials for Electrical Contacts", on page 1114 in this Handbook.

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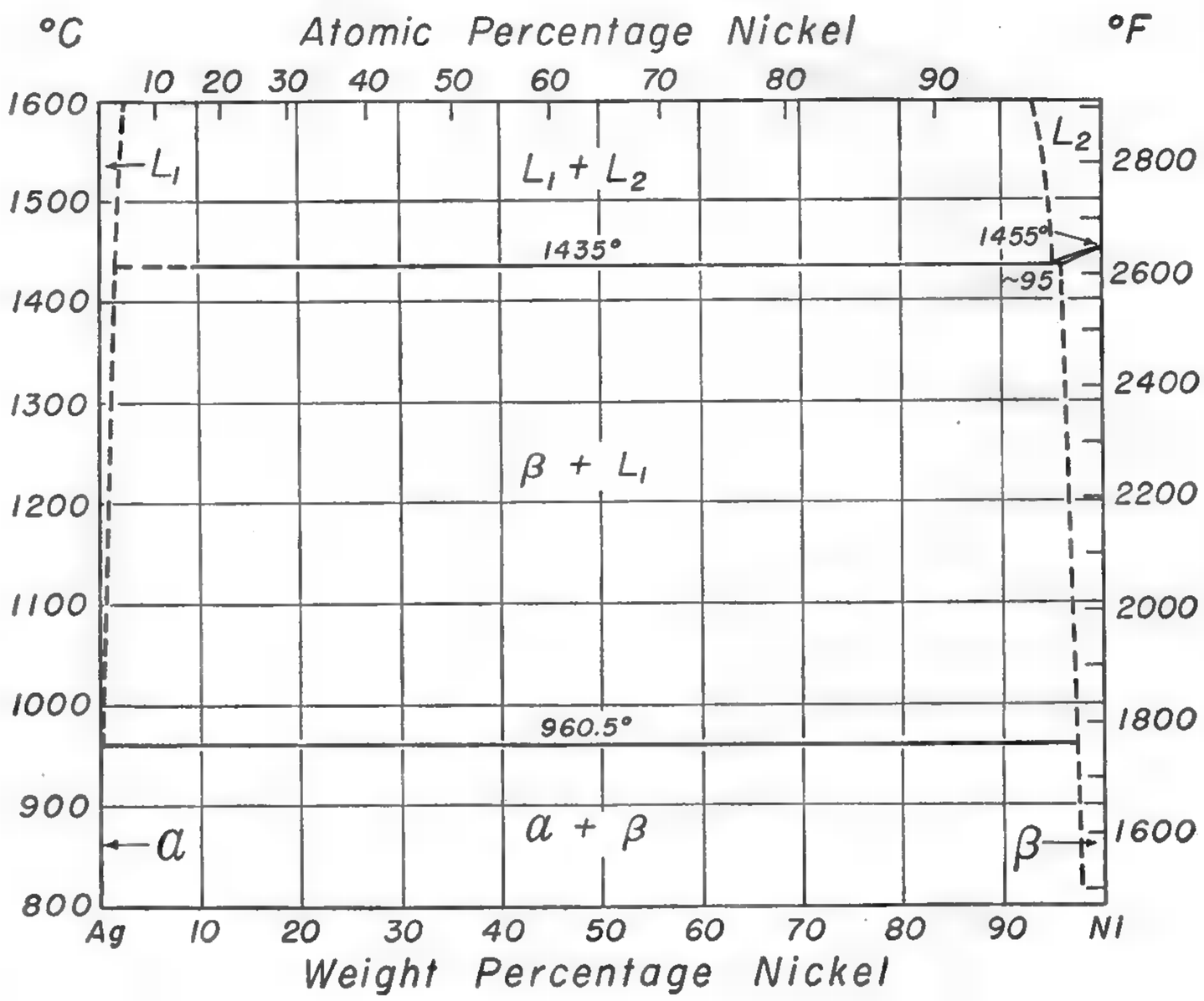
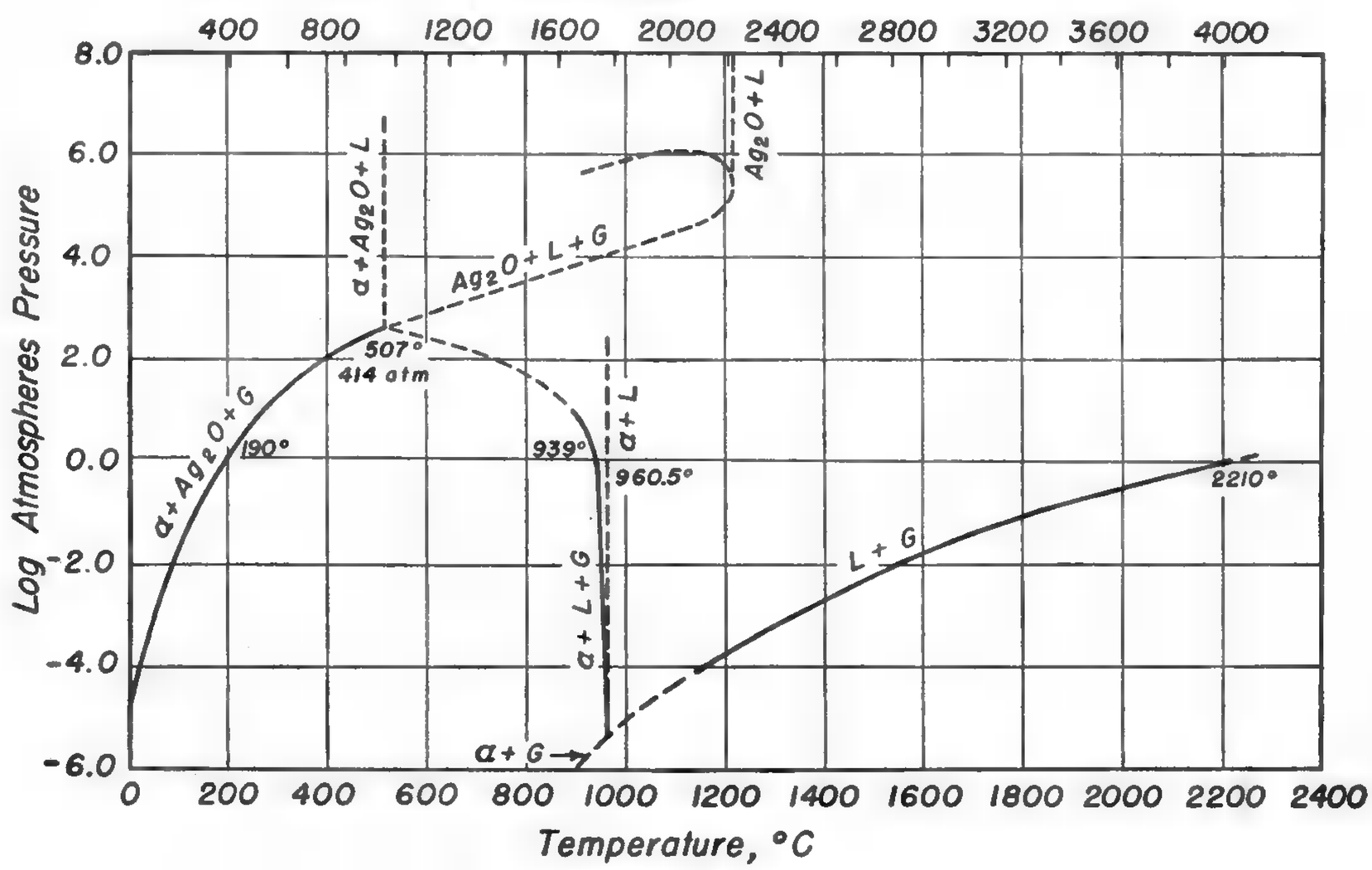
* Metallurgical Manager, Handy & Harman, Bridgeport, Conn.

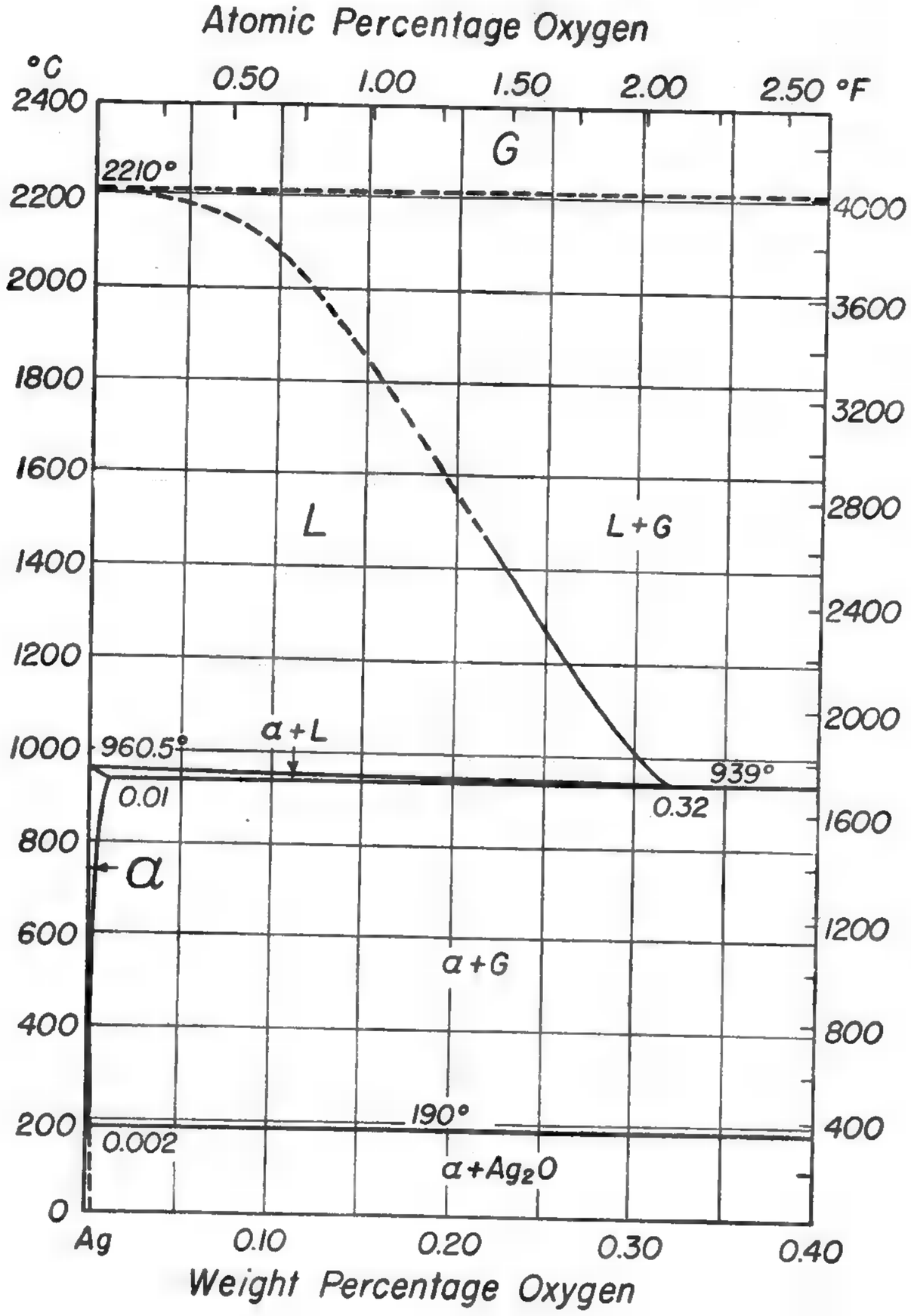


Ag-O Silver-Oxygen

By H. C. Vacher*



* National Bureau of Standards, Washington, D.C.



Available information on the silver-oxygen system is summarized by two diagrams: temperature versus composition at one atmosphere pressure, and pressure versus temperature.

The solubility of oxygen in silver is based on the work of Steacie and Johnson.[3] Their results, obtained between 200 and 800 C and at pressures between 20 and 80 cm Hg, indicated that the solubility was lowest at 400 C, and from the curves, these authors concluded that it was greater at room temperature than at 200 C. These authors admit that the reversal in the solubility curve is difficult to explain, and suggest, after thermodynamic considerations, that it is associated with the possible existence of oxygen dissolved as Ag_2O at low temperatures and as atomic oxygen at temperatures above 400 C.

Silver oxide crystallizes in the cubic system; $a = 4.72$ kX units. The unit cell contains four silver and two oxygen atoms arranged in the $2a$ and $2d$ special positions of the O_h^4 space group.[4]

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7 K. K. Kelley, U. S. Bur Mines Bull 383, 1935

Ag-Pb Silver-Lead

By A. A. Smith, Jr.*

The diagram is based largely on the work of Heycock and Neville,[1] Friedrich,[2] and Petrenko.[3] The solubility of lead in solid silver is about 1.6% at the eutectic temperature.[4,5] Silver has very restricted solubility in solid lead; according to Seith and Keil[6] it is about 0.1% at the eutectic temperature and 0.05% at 200 C.

The solubility curve of lead in silver above the eutectic temperature passes through a maximum at about 650 C and 5% Pb.[4] This retrograde solubility is unusual, but appears to have been firmly established by the microscopic and X-ray results of Raub and Polaczek-Wittek.[4]

A lead-silver alloy (containing 1% Sn to improve the resistance to humid air) is used commercially for coating and joining. Some properties of this alloy (97.5 Pb – 1.5 Ag – 1 Sn) are listed in the Lead Section, page 964.

* Central Research Laboratory, American Smelting and Refining Company, Barber, N.J.

References

1 C. T. Heycock and F. H. Neville, Phil Trans Roy Soc (London), A 189, 37 (1897)
2 K. Friedrich, Metallurgie, 3, 396 (1906)
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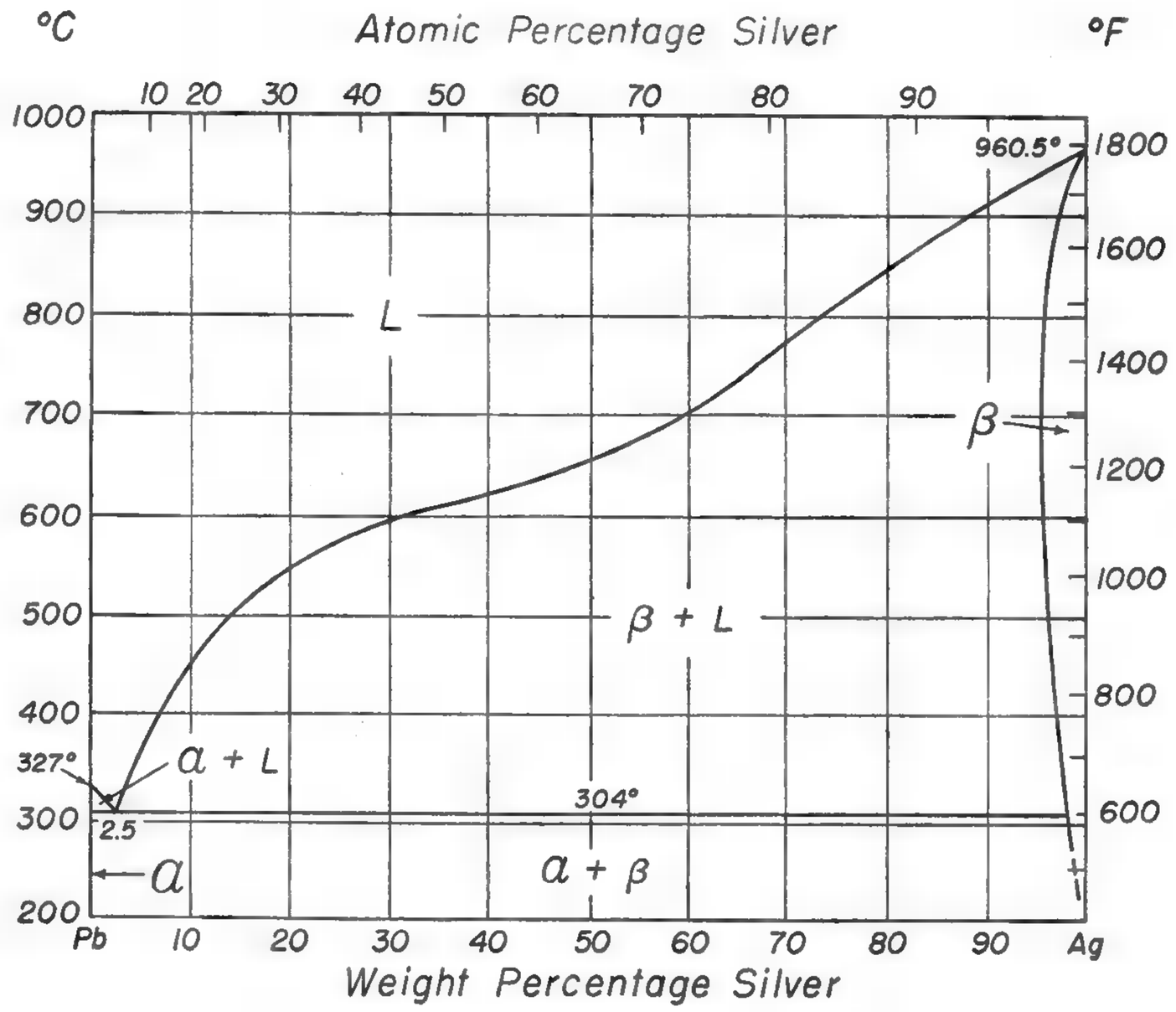
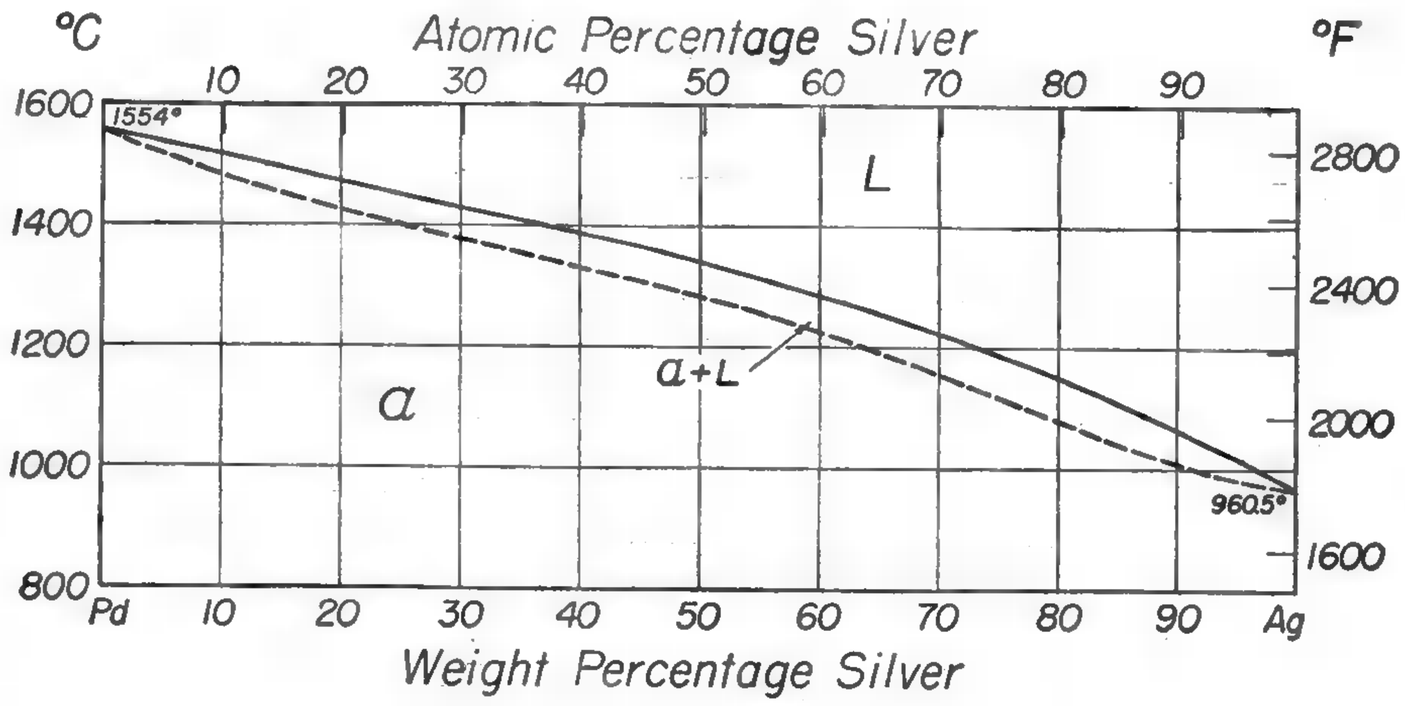


Ag-Pd Silver-Palladium

By E. M. Wise*



The liquidus has been established by Ruer[1] and modern investigators. The location of the solidus is less exactly known, but it is close to the liquidus throughout.

Lattice parameter measurements plotted against composition in atomic per cent are almost linear; the parameter of the 50% alloy is only slightly less than the mean of the end members.[3]

The hardness and tensile strength of silver-palladium alloys are maximum at about 30% Ag — 100 Bhn and 55,000 psi in the annealed condition, 180 Bhn after 66% reduction and 99,000 psi after 50% reduction by cold working.[4]

The electrical resistivity has a maximum value of 42 microhm-cm at about 40% Ag.[5–9] The temperature coefficient of resistivity reaches a very low value of 0.00002 per °C (0 to 100 C) at 44% Ag.*

* The International Nickel Company, Inc., New York

References

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2 L. W. McKeehan, Phys Rev, 20, 424 (1922)
3 W. Stenzel and J. Weerts, "Festschrift zum 50-jähr Bestehen der Platinschmelze G. Siebert", Hanau, 1931, p 288
4 R. F. Vines and E. M. Wise, "Platinum Metals and Their Alloys". The International Nickel Company, Inc., New York, 1941, p 126–127
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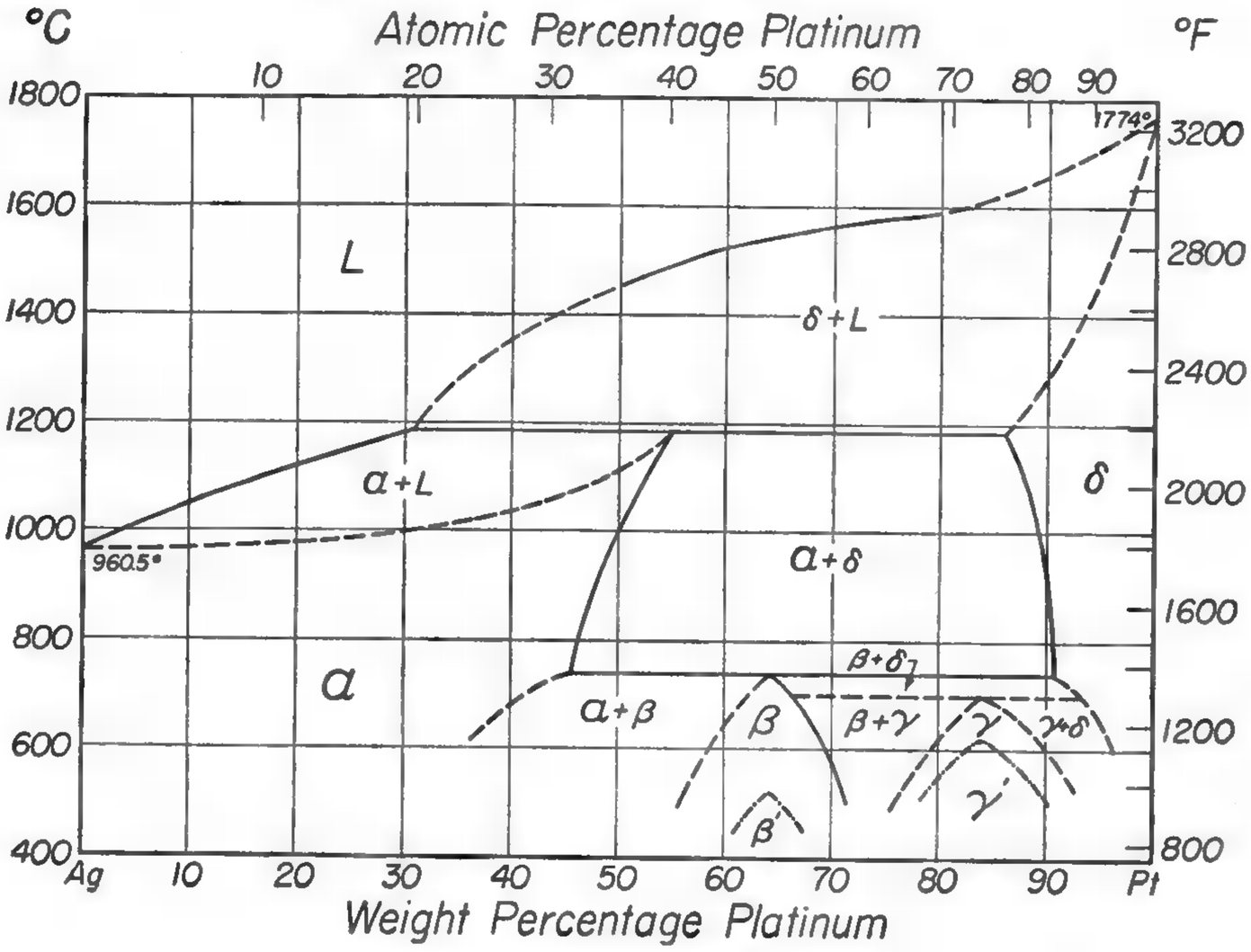
* F. E. Carter, unpublished data

Ag-Pt Silver-Platinum

By E. M. Wise*



The general form of the liquidus and solidus was established by Doerinckel.[1] Schneider and Esch[2] have confirmed many of the results of Johansson and Linde[3] concerning the low-temperature intermediate phases and have reported the ordered phases β' and γ'. Other phases reported below the peritectic temperature have been omitted from the diagram, since X-ray, microscopic, and electrical measurements are not in agreement.

The 20% Ag alloy has a Brinell hardness number of 360 after quenching and aging at about 550 C.

References

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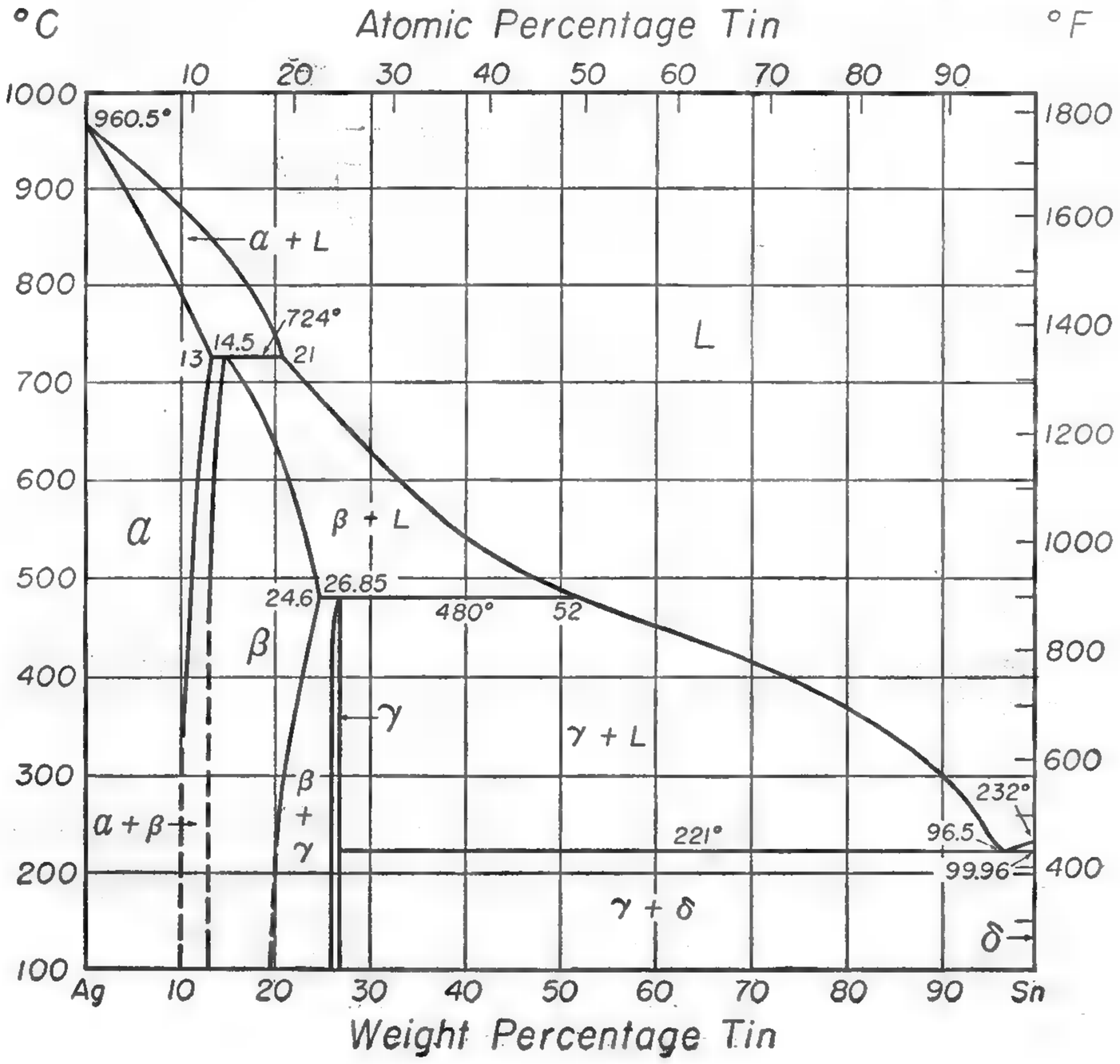
* The International Nickel Company, Inc., New York

Ag-Sn Silver-Tin

By R. I. Jaffee* and H. P. Nielsen†



Petrenko reported a polymorphic change in γ at 232 C, but Murphy, through extensive tests, could not find evidence for such a change, except a discontinuity at 60 C in the curve of electrical conductivity versus temperature.

Murphy found that as little as 0.2% Ag inhibited the allotropic change of tin to its brittle form.

The β phase containing 21.3% Sn is close-packed hexagonal with $a = 2.925$ kX and $c/a = 1.616$.[5] The γ phase (Ag_3Sn) is rhombohedral with $a_1 = 2.985$ kX, $a_2 = 5.144$ kX, and $a_3 = 4.771$ kX.[5]

A tin-silver alloy containing 5% Ag is in commercial use as a solder (*see* page 1073 in this Handbook).

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5 O. Nial, A. Almin, and A. Westgren, Z physik Chem, 14, 81 (1931)

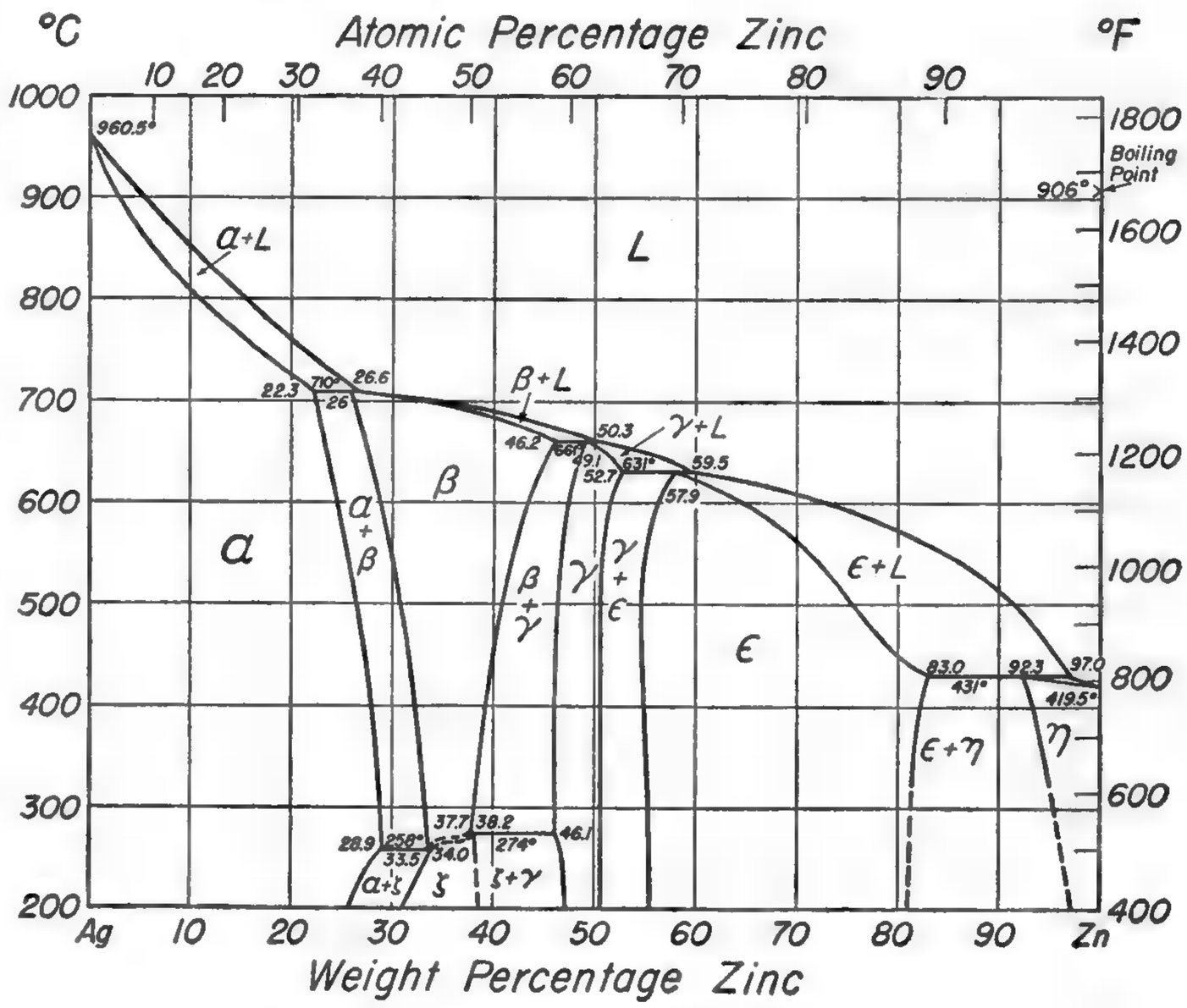
* Battelle Memorial Institute, Columbus, Ohio
† University of Southern California, Los Angeles

Ag-Zn Silver-Zinc

By F. C. Kracek*

The phase diagram[1-8,13,20] is closely analogous to that of copper-zinc; the delta phase of the latter system is absent, however. Phase boundaries evaluated from X-ray data on quenched alloys[14-19] have been shown to be inexact.[20]

In the β field a transformation on slow cooling normally occurs from a disordered β phase (cubic) to a hexagonal ζ phase; between 28 and 34% Zn, β appears to transform below 200 to 227 C unstably to an ordered β' phase of CsCl type on quenching[17,18,21,22] from above 380 C. The β–ζ transformation is much less rapid than β–β', and has a wide hysteresis range. Equilibrium values of the transformation temperatures[20] are given in the diagram.



Crystal Structures and Lattice Parameters of Silver-Zinc Alloys

Phase	Percentage Silver	Crystal Structure	Atoms per Cell	Lattice Parameter a, kX	Lattice Parameter c/a	Reference
α	100	Face-centered cubic	4	4.078	....	4, 14, 15
	94.5			4.063	....	16, ■
	80.0			4.024	....	
	70.0			4.004	....	
β	65	Body-centered cubic	2	3.156	....	16, 17
β'	66.96	Body-centered cubic	2	3.1607	....	17, 18
	65.00	ordered CsCl type		3.1563	....	
	62.50			3.1499	....	
ζ	66.0	Complex close-packed	■■	7.609	0.746	18, ■■
	64.1	hexagonal		7.615	0.742	
	62.3			7.621	0.738	
γ	55.0	Complex cubic	52	9.348	....	14
	46.0			9.317	....	
ϵ	46	Close-packed hexagonal	2	2.819	1.588	14
	21.9			2.815	1.557	
	20			2.812	1.550	
η	9.7	Close-packed hexagonal	2	2.700	1.765	14
	0.0			2.659	1.856	

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* Geophysical Laboratory, Carnegie Institution of Washington, Washington, D.C.

Al-B Aluminum-Boron

By W. L. Fink* and L. A. Willey*

At least two intermetallic phases appear in the aluminum-boron system. These have compositions that correspond to the formulas AlB_2[1] and AlB_{12}.[2] The AlB_2 phase apparently forms at about 1350 C by peritectic reaction between the AlB_{12} phase and liquid containing less than 4% B in solution.[1] Boron is only slightly soluble in liquid aluminum. Saturation limits of about 2% at 1300 C, 0.7% at 1100 C, 0.35% at 950 C, 0.17% at 785 C and 0.09% ■ in aluminum at 730 C have been observed in unpublished research at the Aluminum Research Laboratories.

AlB_2 is hexagonal,[1] with $a = 3.00$ kX, $c = 3.24$ kX. AlB_{12} is monoclinic[2] with $a = 17.01$, $b = 10.98$, $c = 18.80$ kX, $\beta = 110°\ 54' \pm 6'$.

* Aluminum Research Laboratories, New Kensington, Pa.

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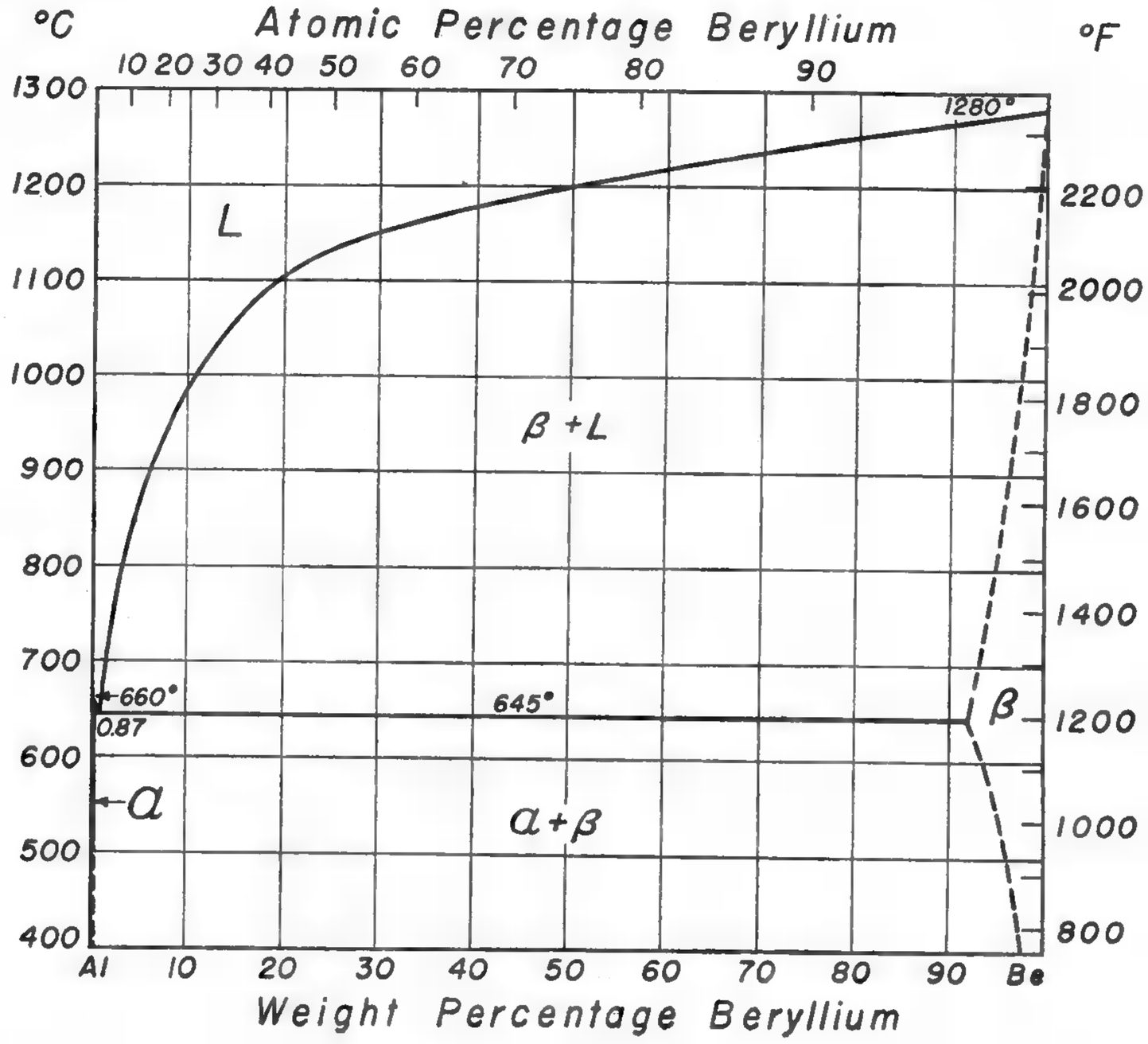
Al-Be Aluminum-Beryllium

By W. L. Fink* and L. A. Willey*



The solid solubility of beryllium in aluminum is from 0.04 to 0.05% at 630 C.[2,5] It decreases to about 0.005% Be at 500 C. A thorough investigation of the solubility of aluminum in solid beryllium has not been made but it is reported as up to 8%[1,3] and also as less than 1.27% Al at 650 C.[4]

The Brinell hardness of a quenched alloy containing 0.75% Be increases from 27 to 43 after aging at room temperature.[2]

The use of beryllium in aluminum has often been suggested as a means for increasing the modulus of elasticity, decreasing the coefficient of thermal expansion and decreasing the density, but the high cost of beryllium and the high liquidus temperatures of alloys containing large amounts of beryllium have prevented the use of such alloys.

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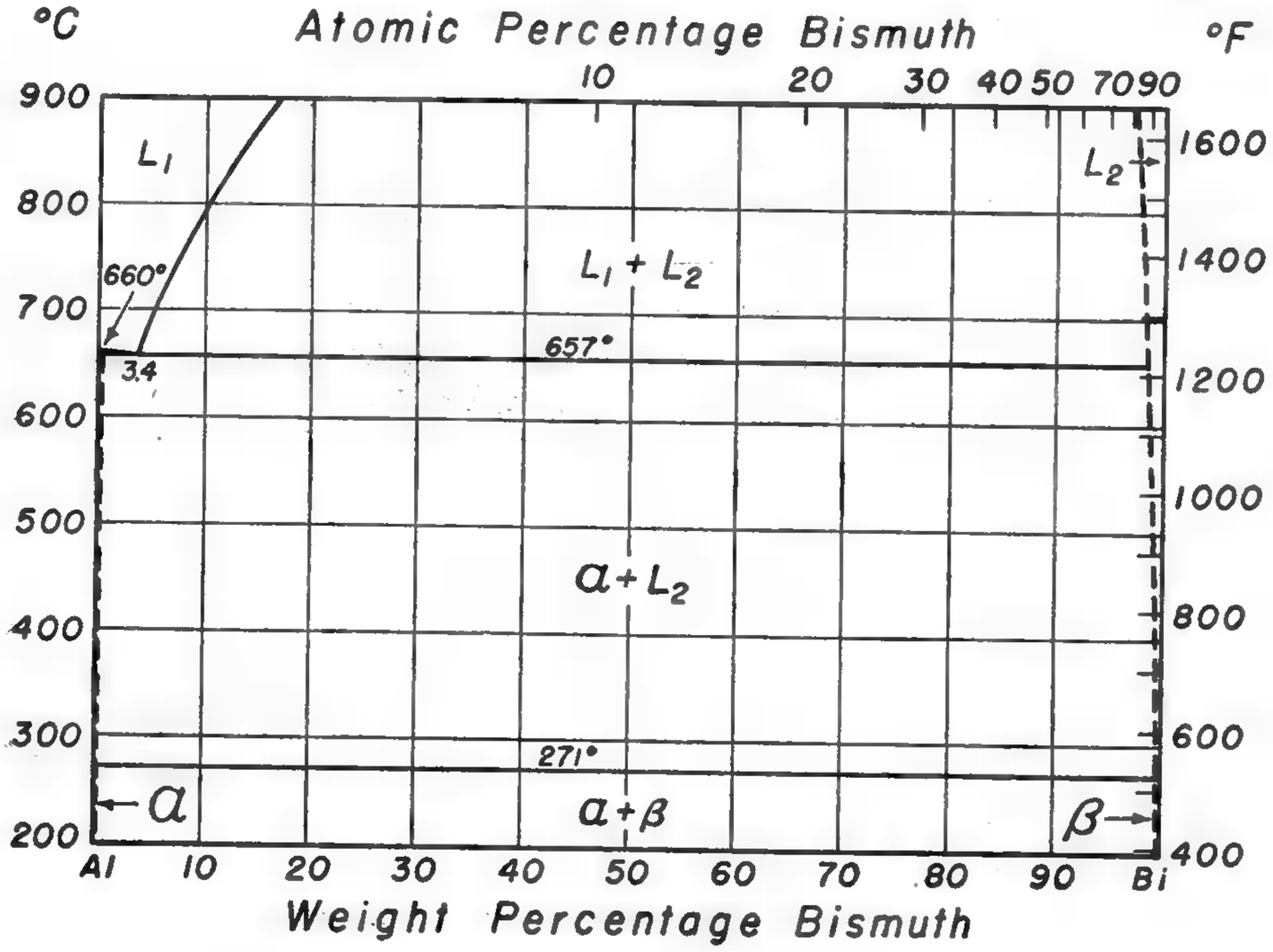
Al-Bi Aluminum-Bismuth

By W. L. Fink* and L. A. Willey*



The solid solubility of bismuth in aluminum has not been thoroughly investigated. It is, however, reported to be less than 0.2% at the monotectic temperature (657 C).[2] Neither the liquid nor the solid solubility of aluminum in bismuth has been determined. These are probably low.

The solubility of bismuth in liquid aluminum is decreased slightly by the presence of about 5% Cu.[2]

Bismuth is used in aluminum alloys only for the purpose of improving the machining characteristics. It is usually employed with lead, which has a similar phase diagram with aluminum, and which has the same beneficial effect on machinability.

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* Aluminum Research Laboratories, New Kensington, Pa.

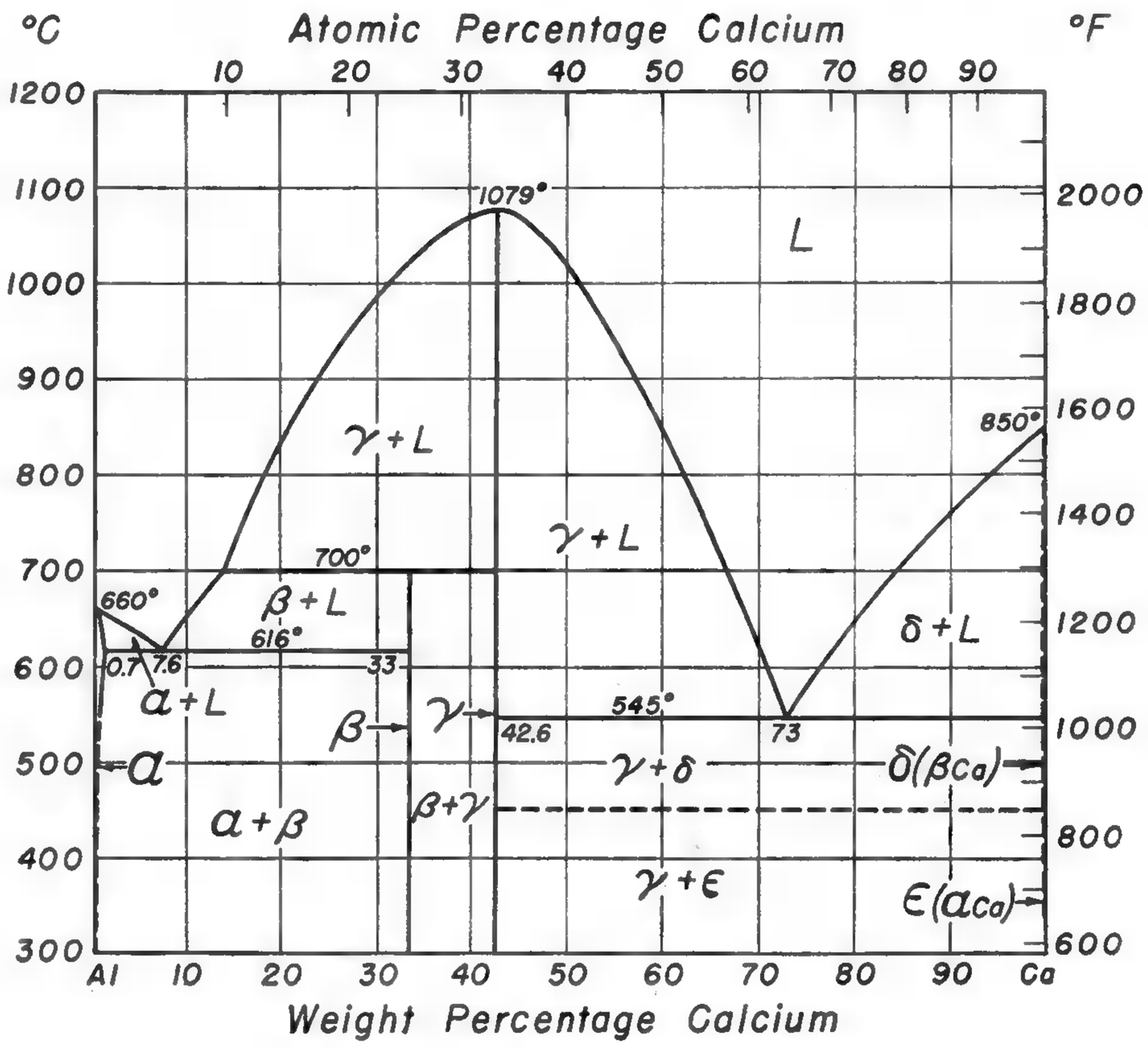
Al-Ca Aluminum-Calcium

By W. L. Fink* and L. A. Willey*

The solubility of calcium in solid aluminum has been reported to be as low as 0.6% at 600 C[3] and as high as 2.8% at 616 C.[4] The latter value appears to be excessive. No determination of the calcium-rich solid solution has been made.

According to most investigators[1,2,3] the β phase corresponds to the formula Al_3Ca but it has been more recently reported as Al_4Ca.[4] This phase is tetragonal with $a = 4.35$, $c = 11.07$ kX.[4] γ is face-centered cubic with $a = 8.022$ kX.[4]

Alloys of aluminum and calcium have no commercial importance. However, calcium has been used commercially as a minor alloying addition to duralumin-type aluminum-base alloys, to improve the hot workability.



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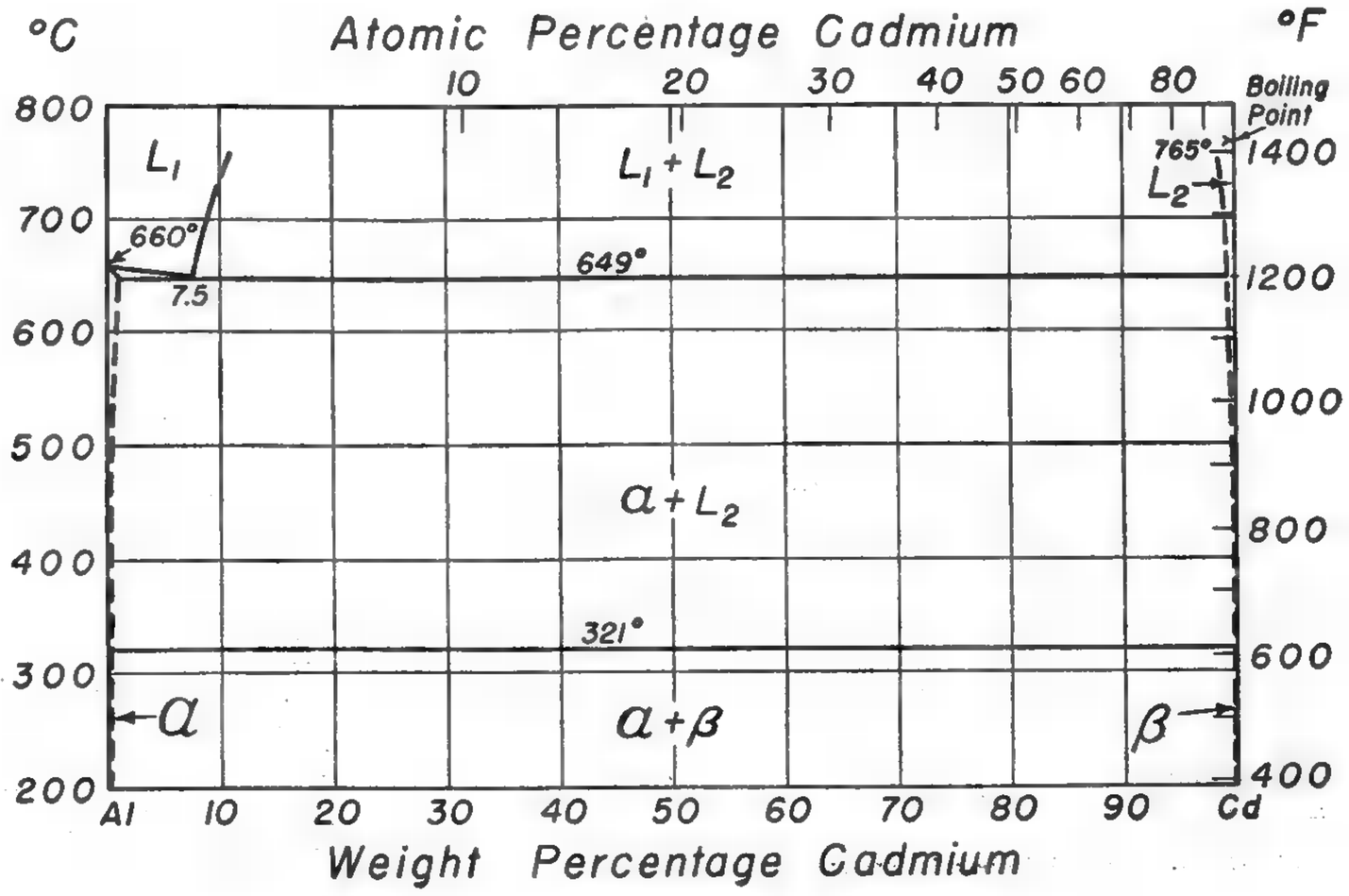
Al-Cd Aluminum-Cadmium

By W. L. Fink* and L. A. Willey*

The system has received relatively little attention. The type of diagram has been established but many of the details have not been determined with sufficient accuracy.

The solubility of cadmium in solid aluminum has been found to be less than 1% at the monotectic temperature (649 C).[1] Information pertaining to the solubility of aluminum in either liquid or solid cadmium is lacking. These solubilities are probably very small.

Cadmium has been recommended for use in aluminum solders, aluminum-base bearing alloys, and in free-cutting aluminum alloys.



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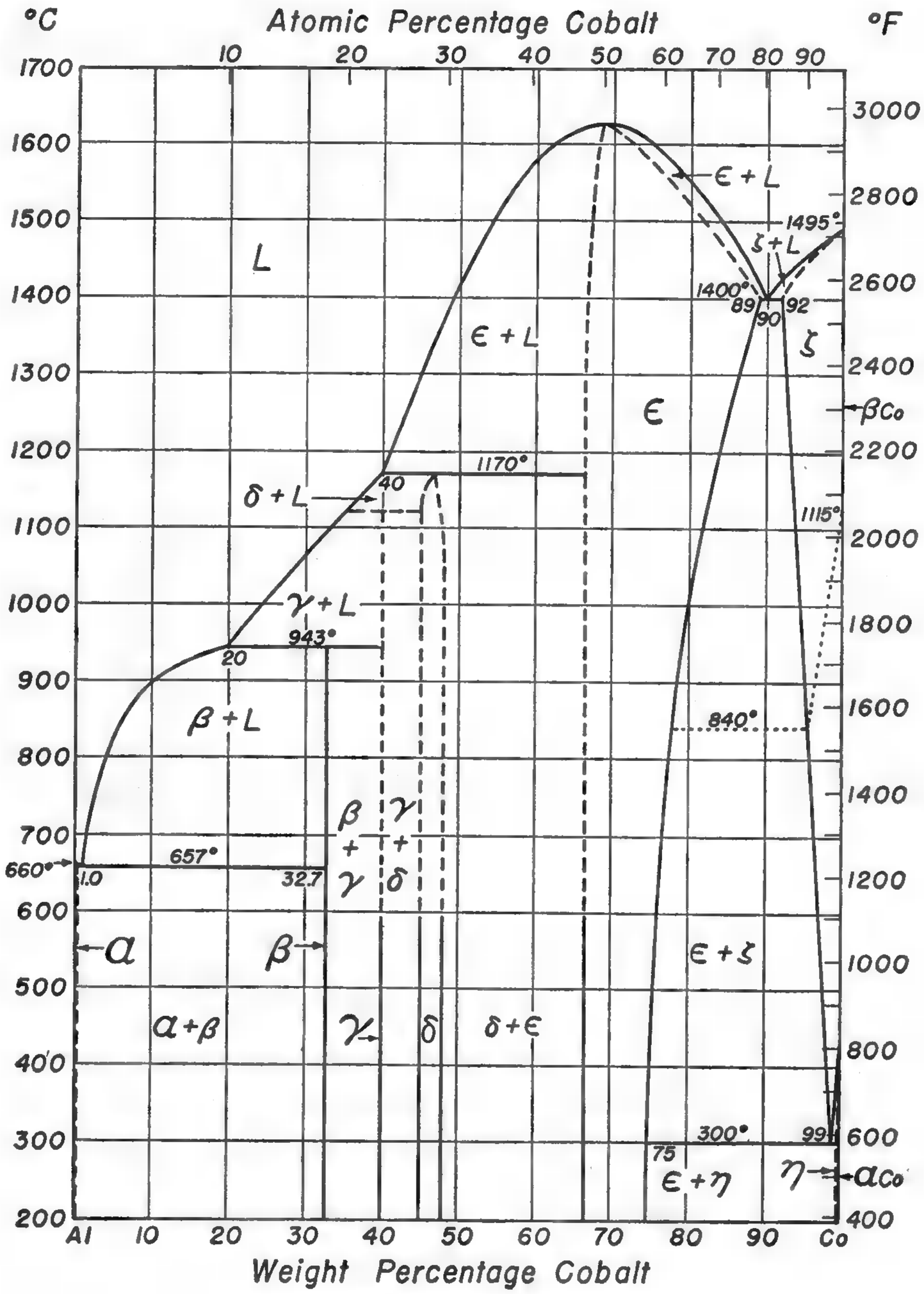
* Aluminum Research Laboratories, New Kensington, Pa.

Al-Co Aluminum-Cobalt

By W. L. Fink* and L. A. Willey*



In addition to the four intermetallic phases shown in the diagram the presence of another in alloys containing from 42 to 44% Co has been reported.[2] This phase has not been isolated or definitely identified and cannot be reconciled with the present knowledge of the system above 600 C.

The solid solubility of cobalt in aluminum is less than 0.02% at the eutectic temperature (657 C).[1] The solubility of aluminum in the hexagonal form of cobalt is slight.[2] The solubility of aluminum in cubic cobalt is 7, 4, and 2% at 1300, 800 and 500 C, respectively.[3]

The ζ phase is hexagonal; ϵ is body-centered cubic with $a = 5.8565$ kX.[3]

* Aluminum Research Laboratories, New Kensington, Pa.

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Al-Cr Aluminum-Chromium

By W. L. Fink* and L. A. Willey*

Only the aluminum end of this diagram has been investigated sufficiently for complete and accurate reproduction. The β phase, existing in equilibrium with aluminum-rich solutions, has been found to correspond to the formula $CrAl_7$.[2] Some investigators[1,3] have found evidence that this phase forms by peritectic reaction between liquid and a solid phase of higher chromium content at a temperature between 710 and 800 C. The reaction was not observed in alloys containing up to 2% Cr.[3]

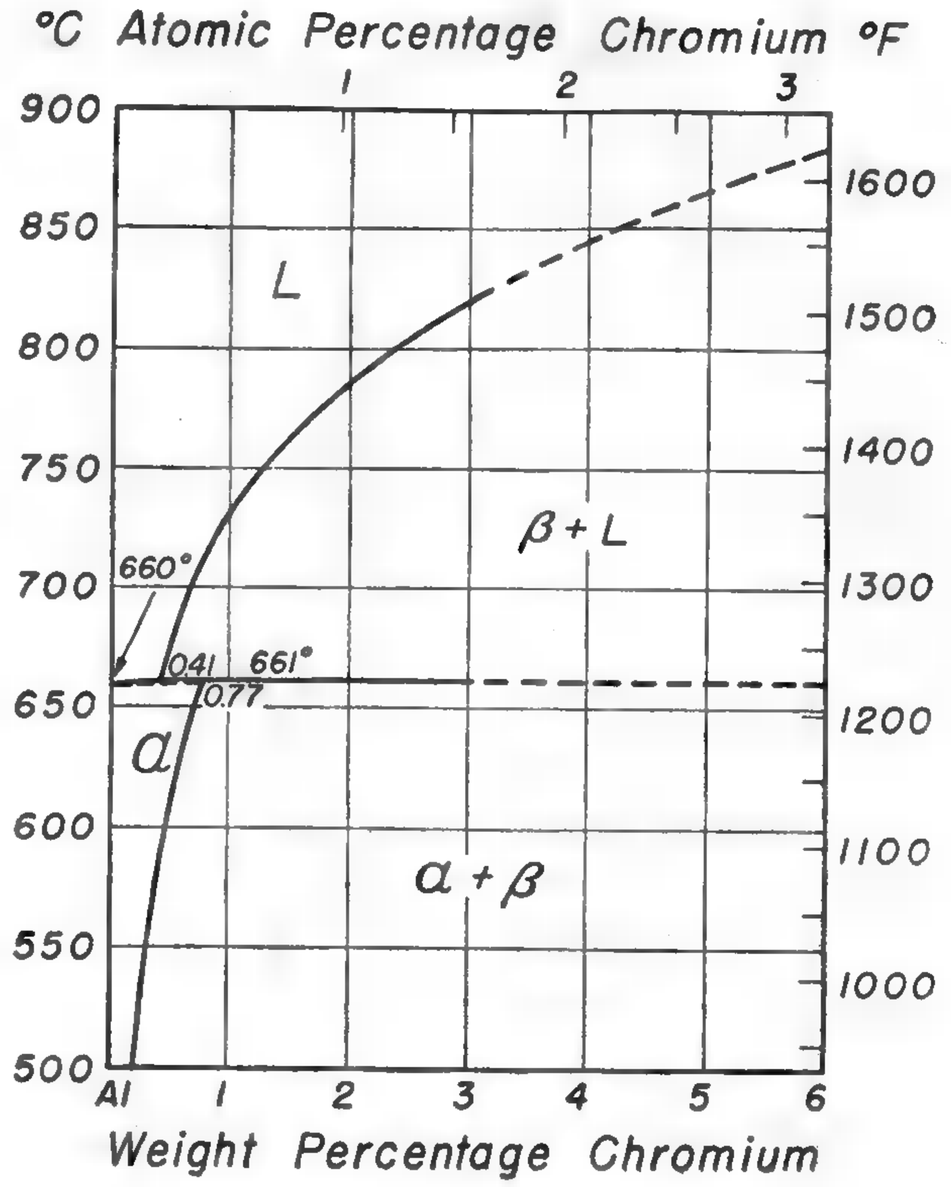
X-ray analysis[3] of aluminum-chromium alloys indicates the existence of at least nine different intermetallic phases in addition to the two terminal solid solutions. The maximum solid solubility of aluminum in chromium is given[3] as about 29% in the range 975 to 1350 C.

The solubility of chromium in solid aluminum is, as follows:[2,4]

Temperature, °C	630	580	530	480	400
Percentage Chromium	0.61	0.38	0.21	0.14	0.07

The β phase is orthorhombic with $a = 19.99$, $b = 34.51$, and $c = 12.47$ kX.[3]

A few commercial aluminum alloys contain small amounts of chromium (0.1 to 0.3%). In some alloys, the addition of chromium causes a decided improvement in resistance to corrosion. Substantial quantities of chromium, however, increase the liquidus temperature beyond commercial limits.



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* Aluminum Research Laboratories, New Kensington, Pa.

Al-Cu Aluminum-Copper

By W. L. Fink,* L. A. Willey* and C. S. Smith*

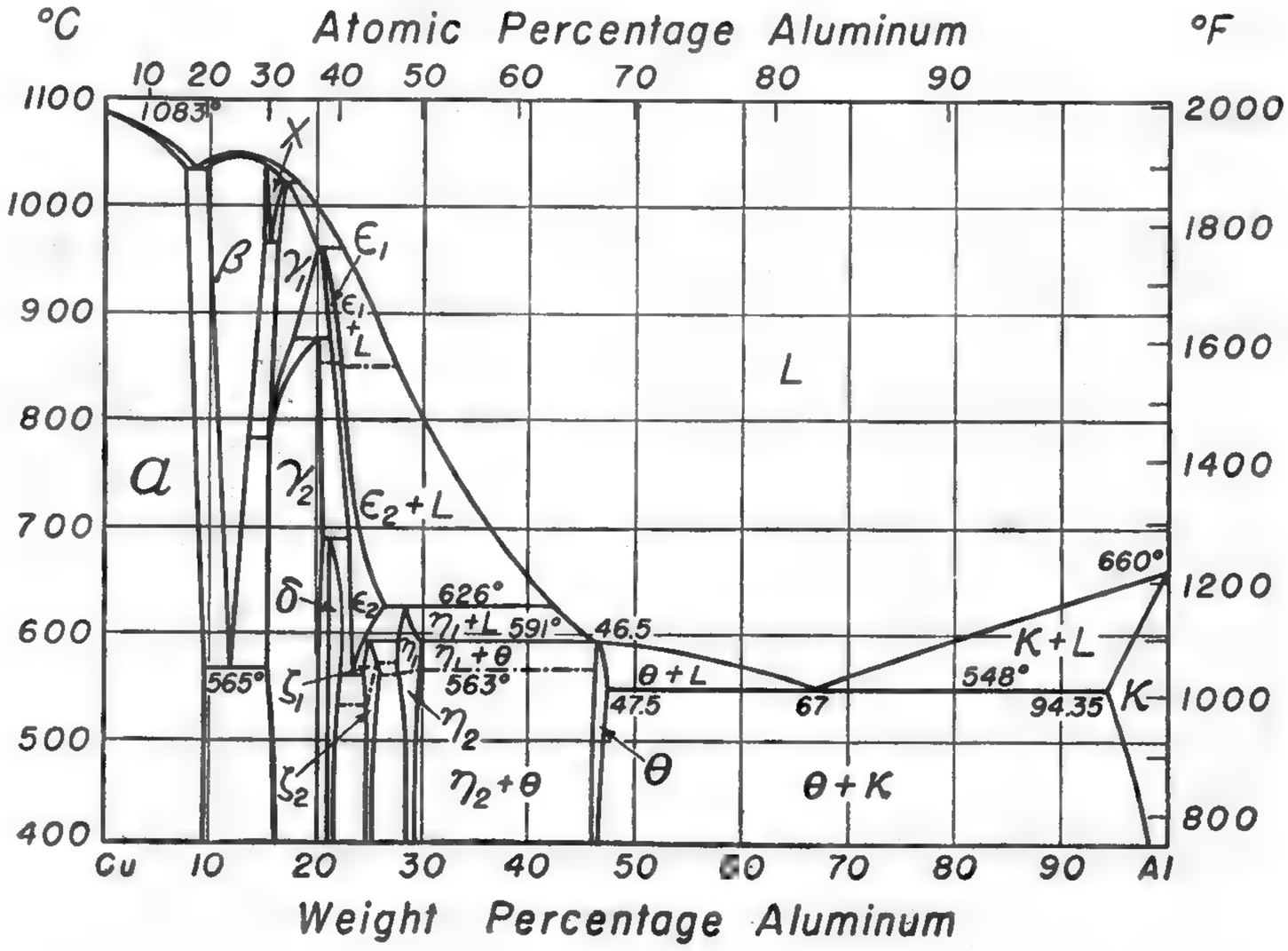
The diagram shown is similar to that proposed by Raynor.[1] The equilibrium relations in the range between 20 and 30% Al are complex and have not been firmly established.

During rapid cooling the β phase transforms to one of three metastable phases, each bearing some relation in structure to one of the stable phases. For a summary of these transitional structures, see the paper by Greninger,[2] and also the article "The Martensite Transformation", page 263 in this Handbook.

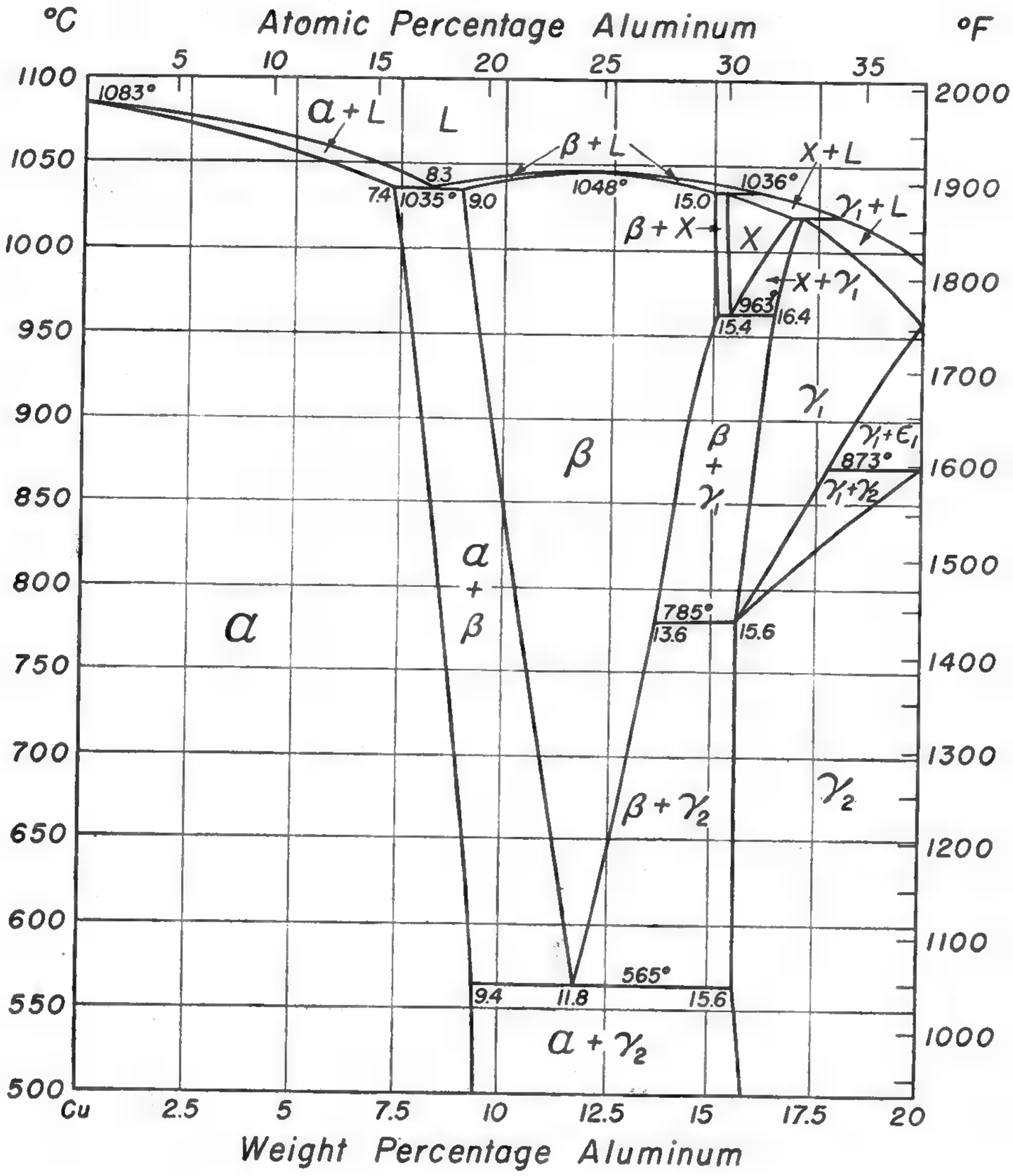
The solubility of copper in solid aluminum is, as follows: 4.10% at 500 C, 2.60 at 450, 1.50 at 400, 0.85 at 350, and 0.45 at 300.[3,4]

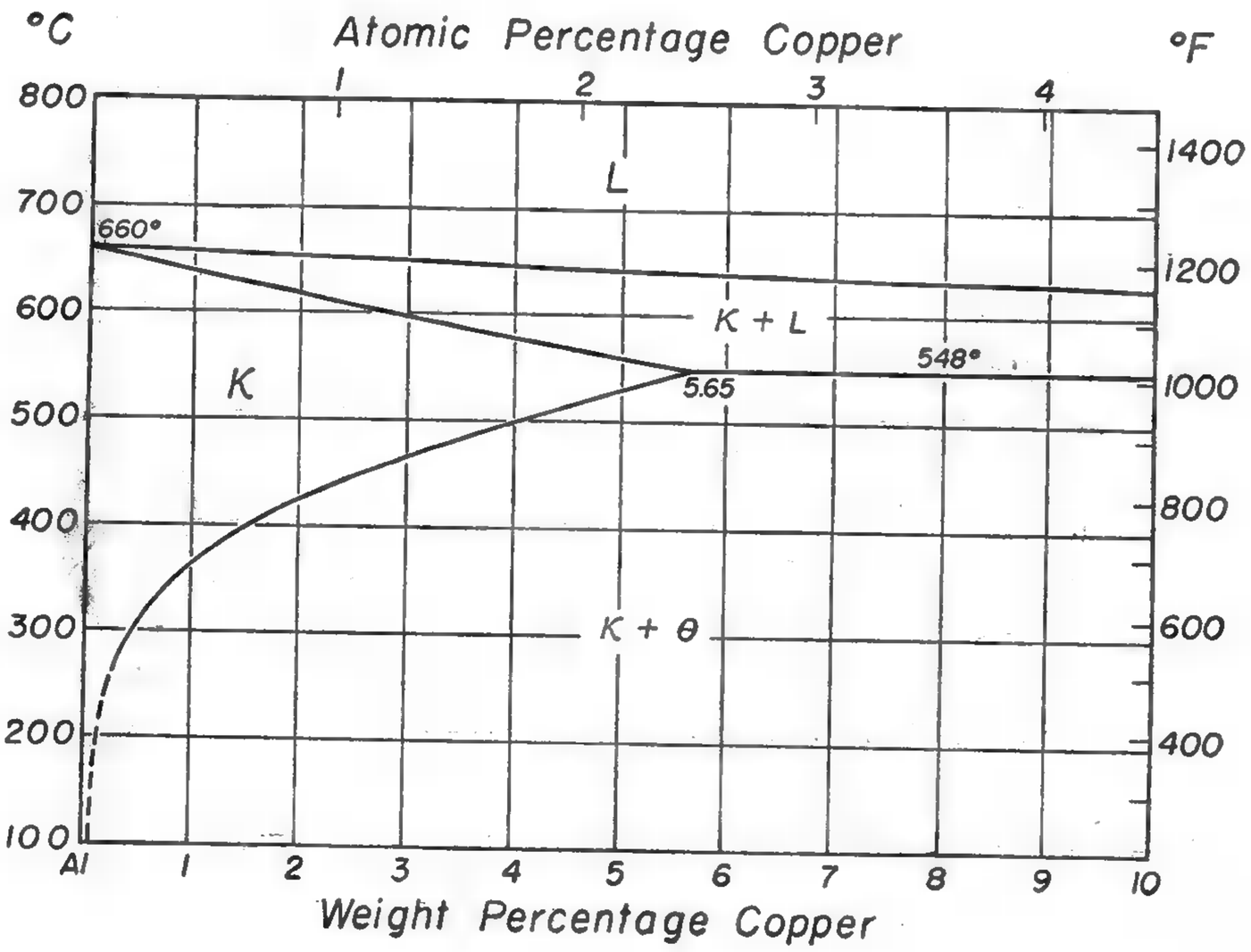
The solubility of aluminum in solid copper is, as follows: 8.0% at 890 C, 8.5 at 795, 9.0 at 690, and 9.4 at 565.[1,5,6,7]

(*continued on the next page*)



* Aluminum Research Laboratories, New Kensington, Pa.
* University of Chicago, Chicago





The structures of the intermediate phases are: β, body-centered cubic,[8] $a = 2.94$ kX; γ_2, cubic,[9,10] $a = 8.7$ kX; ϵ_1 cubic;[9] ζ_2, hexagonal;[10] η_2, orthorhombic;[10] θ, tetragonal,[5] $a = 6.04$ kX, $c = 4.86$ kX.

Highly important commercial alloys are found at both ends of the aluminum-copper system.

The copper-rich alloys are aluminum bronzes, containing from 4 to 11% Al with or without other alloying elements, principally iron or iron and nickel. For additional information concerning commercial aluminum bronzes, the reader may refer to pages 928 to 933 (wrought alloys) and 941, 942 (castings).

The aluminum-rich alloys of this system may contain as much as 12 to 15% Cu, although the wrought alloys generally do not contain more than 5% Cu. Both the wrought and the cast aluminum-rich alloys are subject to improvement in strength and hardness by heat treatment. (*See* "Properties of Aluminum-Copper Alloys", page 803.)

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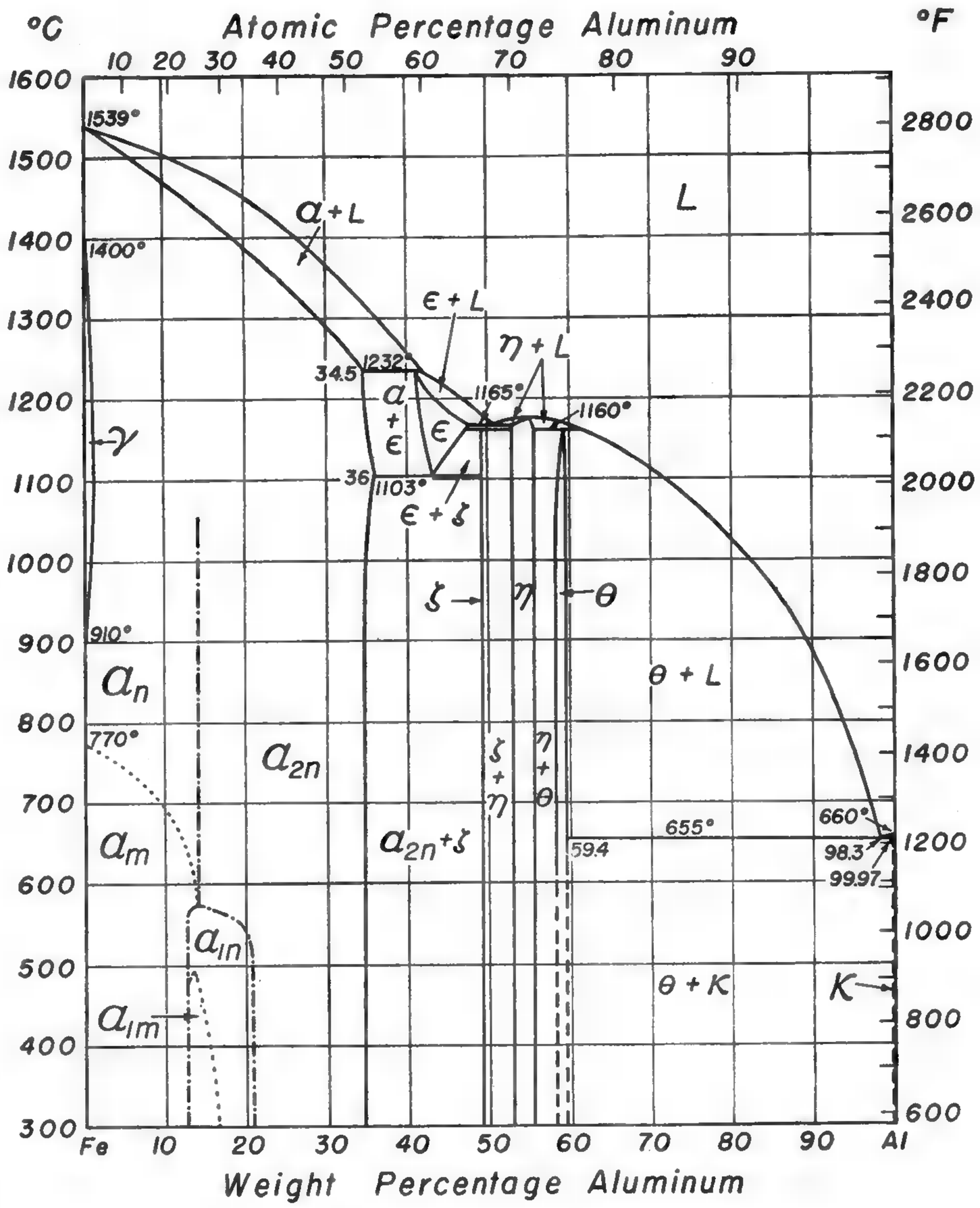
Al-Fe Aluminum-Iron

By W. L. Fink* and L. A. Willey*



Evidence has been presented [12] that the θ phase, which corresponds approximately to the formula $FeAl_3$, is converted to Fe_2Al_7 at a temperature somewhat below 600 C. The mechanism of this conversion has not been established.

The solubility limit of iron in high-purity aluminum has been found to be about 0.03% at the eutectic temperature (655 C).[13] It was also established that this limit decreased at lower temperatures.

In the solid solution field of aluminum in α iron, order-disorder as well as magnetic to nonmagnetic transformations have been shown to exist.[7, 8, 9, 11, 12] Since no phase changes are involved in these transformations, the boundaries have been shown in the diagram as dashed and dotted lines. After Bradley and Taylor,[12] the regions of the α phase field have been marked with subscripts: *m* and *n* indicating the magnetic and nonmagnetic phases respectively, and *1* and *2* indicating ordered structures of the type Fe_3Al and FeAl respectively.

* Aluminum Research Laboratories, New Kensington, Pa.

The θ phase is orthorhombic[10] with $a = 47.43$ kX, $b = 15.46$ kX and $c = 8.08$ kX.

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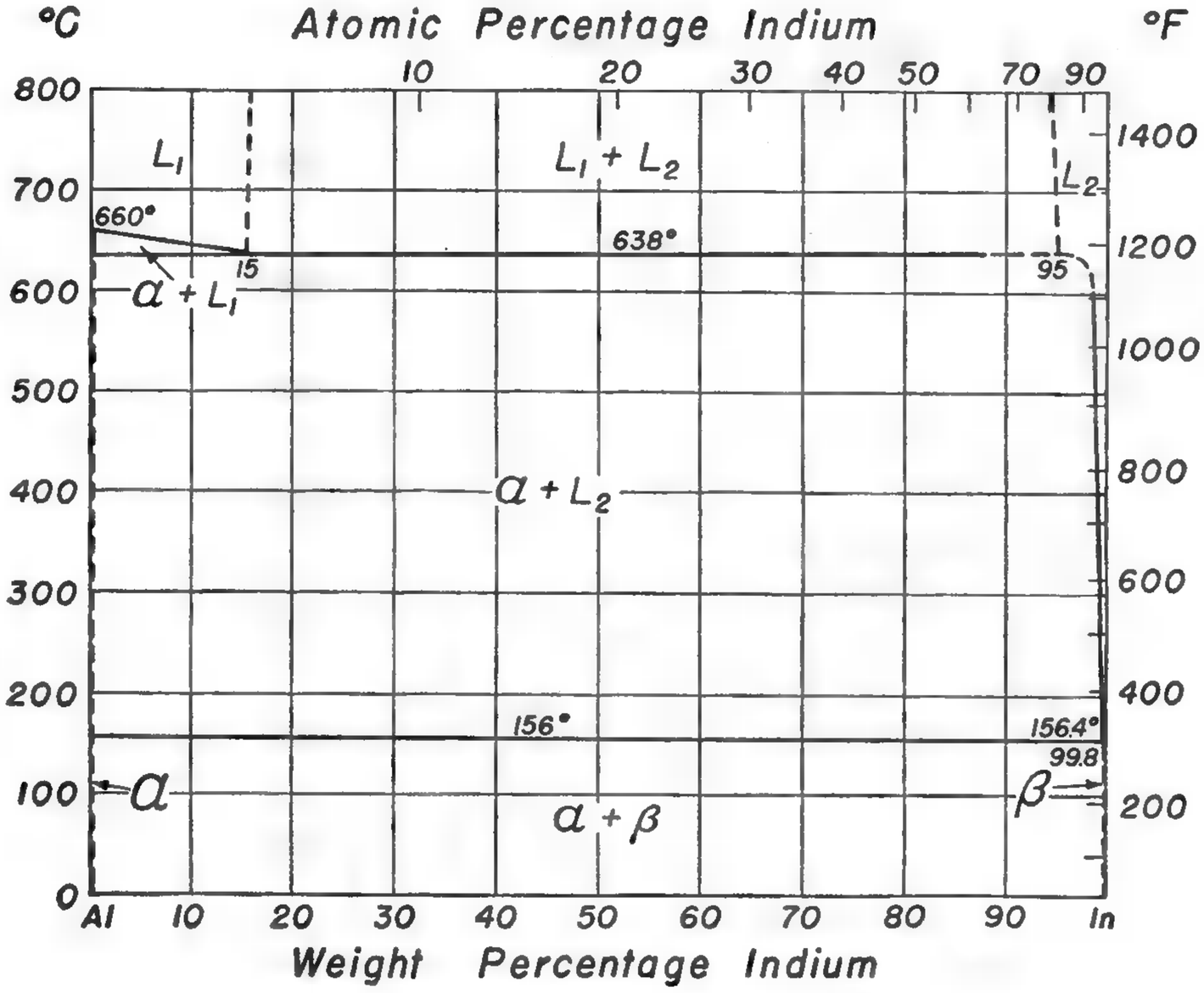
Al-In Aluminum-Indium

By H. M. Davis*



The diagram for the aluminum-indium system has been constructed entirely from unpublished work by H. M. Davis and G. H. Rowe.*

Indium apparently has a slight solubility in aluminum. The α phase at 250 C contains enough indium to produce a barely discernible shift in the X-ray diffraction pattern from that of high-purity aluminum.

Note Added in Proof. A report[1] published after the construction of this diagram, generally confirms it. The eutectic temperature and the monotectic temperature are reported as 156 C and 634 C, respectively. The miscibility gap is reported to extend from 13 to 98% In at 634 C.

Reference

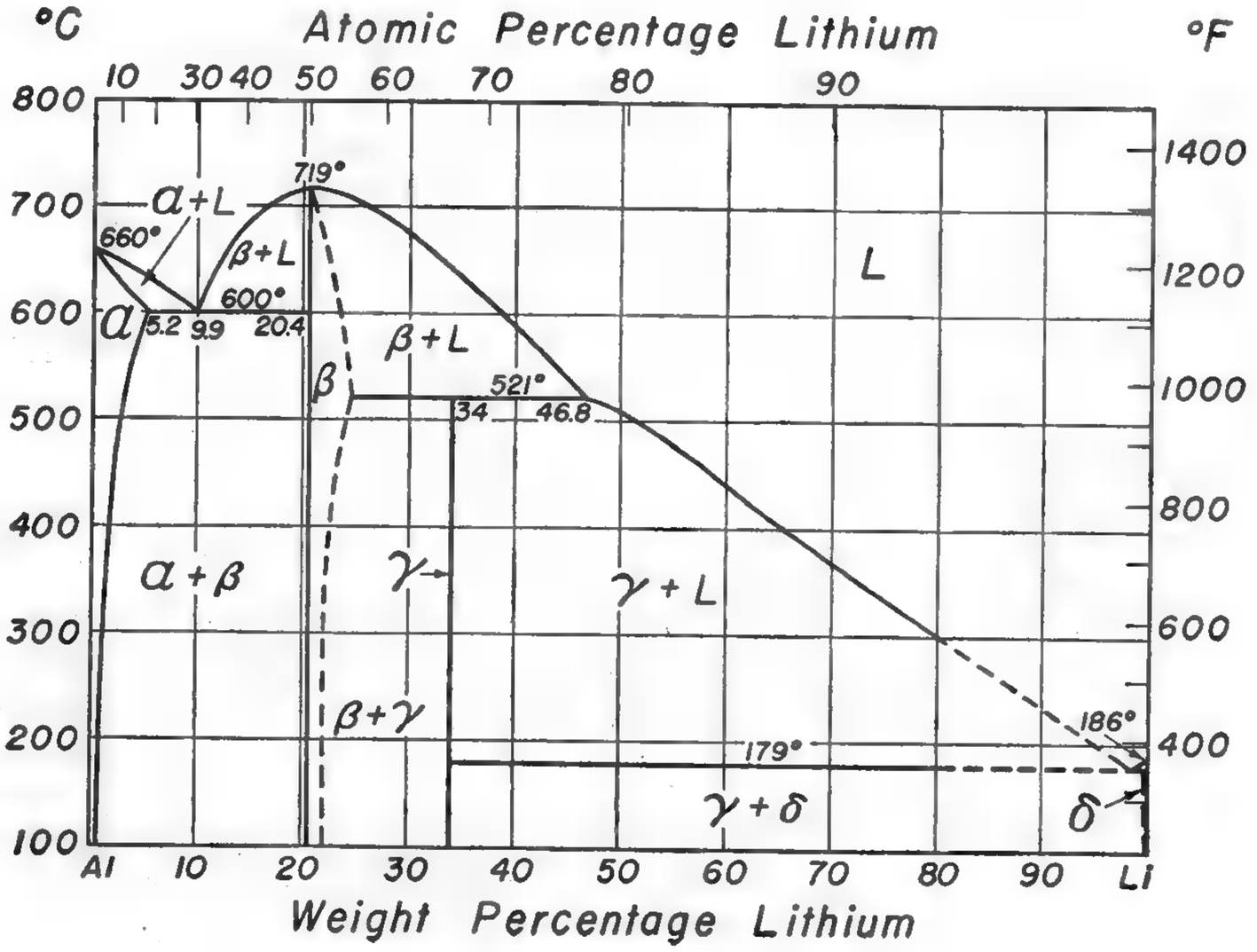
1 S. Valentiner and I. Pazicha, Metallforschung, 2, 127 (1947)

* Associate Professor of Metallurgy, The Pennsylvania State College, State College, Pa.

* Editor's Note. In the original work, the melting point of indium was determined as 157.3 C, and the eutectic temperature as 156.9 C. On the diagram shown here, these temperatures have been changed to be consistent with the melting point of indium as employed elsewhere in this Handbook, 156.4 C.

Al-Li Aluminum-Lithium

By W. L. Fink† and L. A. Willey†



The β phase, which has a composition corresponding to the formula LiAl, appears to form a rather extensive solid solution with lithium.[2,3] It has also been reported[4] to dissolve appreciable aluminum but this has not been confirmed.

A lack of agreement exists in regard to the location of the eutectic between the γ phase and the lithium-rich solid solution. The solubility of aluminum in solid lithium has not been determined.

The solubility of lithium in solid aluminum is, as follows:[1] 5.2% at 600 C, 3.6 at 550, 2.5 at 500, 1.7 at 400, 0.9 at 220. The β phase is body-centered cubic[4,5] with $a = 6.36$ kX.

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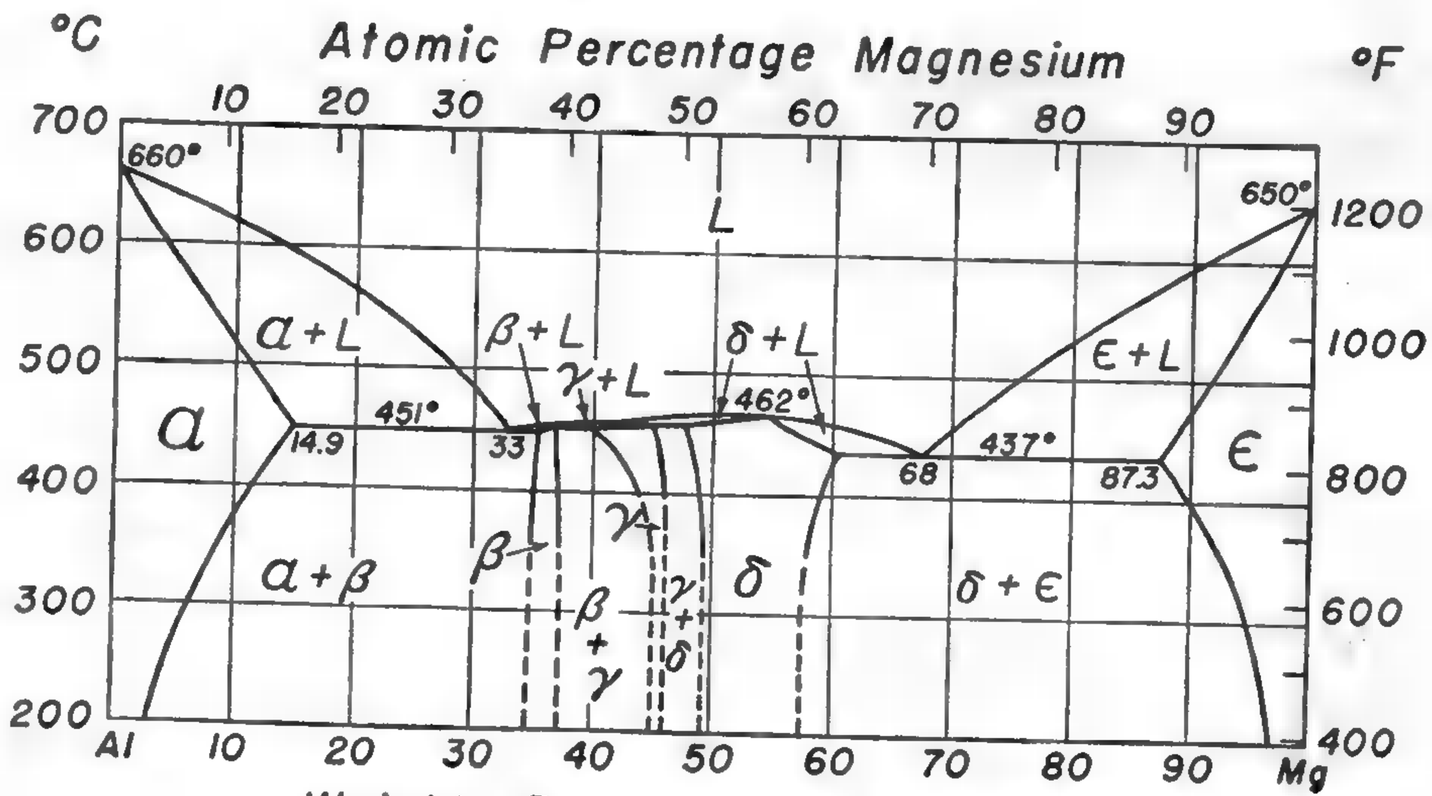
† Aluminum Research Laboratories, New Kensington, Pa.

Al-Mg Aluminum-Magnesium

By W. L. Fink* and L. A. Willey*



The diagram from 38 to 49% Mg has not been well established. γ may be unstable below 300 C; it has been reported to decompose into β and a fourth intermetallic phase containing approximately 40% Mg.[5] The latter phase apparently decomposes into β and γ at 390 C.

The solubility of magnesium in solid aluminum is, as follows:[2] 11.5% at 400 C, 8.7 at 350, 6.4 at 300, 4.3 at 250, 2.9 at 200.

The solubility of aluminum in magnesium is, as follows:[3,6] 10.6% at 400 C, 7.3 at 350, 5.3 at 300, 4.1 at 250, 3.2 at 200.

The β phase is hexagonal with $a = 11.38$ kX, $c = 17.87$ kX;[8] δ is body-centered cubic with $a = 10.52$ kX.[8]

The aluminum-rich alloys are discussed in the article on page 807.

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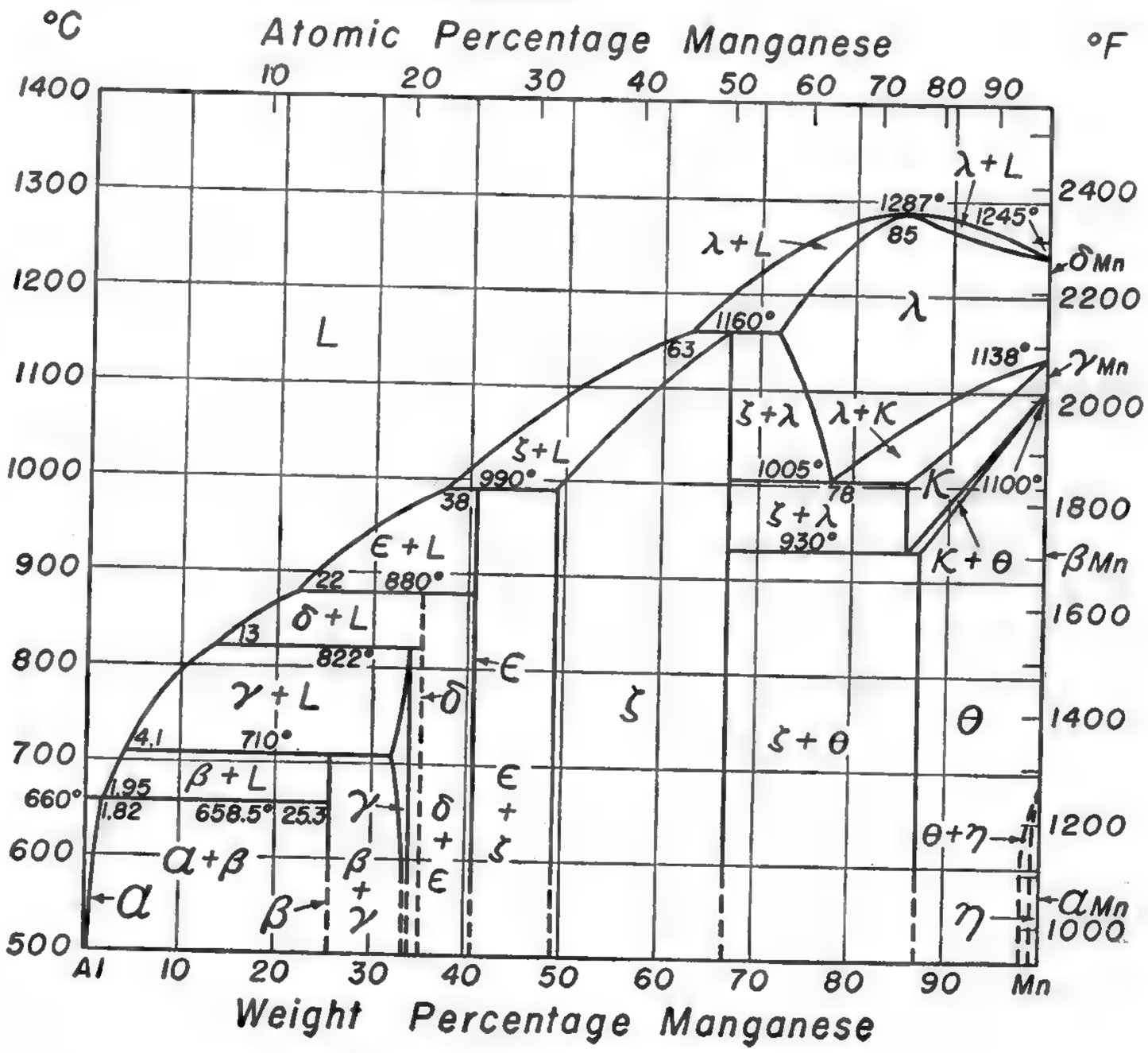
Al-Mn Aluminum-Manganese

By W. L. Fink* and L. A. Willey*



The composition of δ is not known; this phase has been observed only in specimens containing either γ or ϵ.

The solubility of aluminum in alpha manganese is reported to be low;[1] the actual boundaries of the $\theta + \eta$ field have not been determined. The solubility of manganese in aluminum is, as follows:[2] 1.35% at 626 C, 0.78 at 570, 0.36 at 500.

The β phase ($MnAl_6$) is orthorhombic with $a = 6.51$ kX, $b = 7.57$ kX, $c = 8.87$ kX;[3] γ ($MnAl_4$) is hexagonal with $a = 28.35$ kX, $c = 12.36$ kX;[3] ϵ ($MnAl_3$) is orthorhombic with $a = 14.79$ kX, $b = 12.6$ kX, $c = 12.43$ kX;[3] ζ is body-centered cubic.[7]

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* Aluminum Research Laboratories, New Kensington, Pa.

Al-Na Aluminum-Sodium

By W. L. Fink* and L. A. Willey*

Aluminum and sodium are practically immiscible in each other in both the liquid and solid states.[1] No binary intermetallic phases are formed between these two elements. The eutectic apparently lies very near 100% Na and at a temperature close to its melting point. The monotectic occurs at less than 0.1% Na and near the melting point of aluminum. The solubility of sodium in liquid aluminum has been found to decrease from about 0.13% at 800 C, to about 0.1% at 700 C.[2]

* Aluminum Research Laboratories, New Kensington, Pa.

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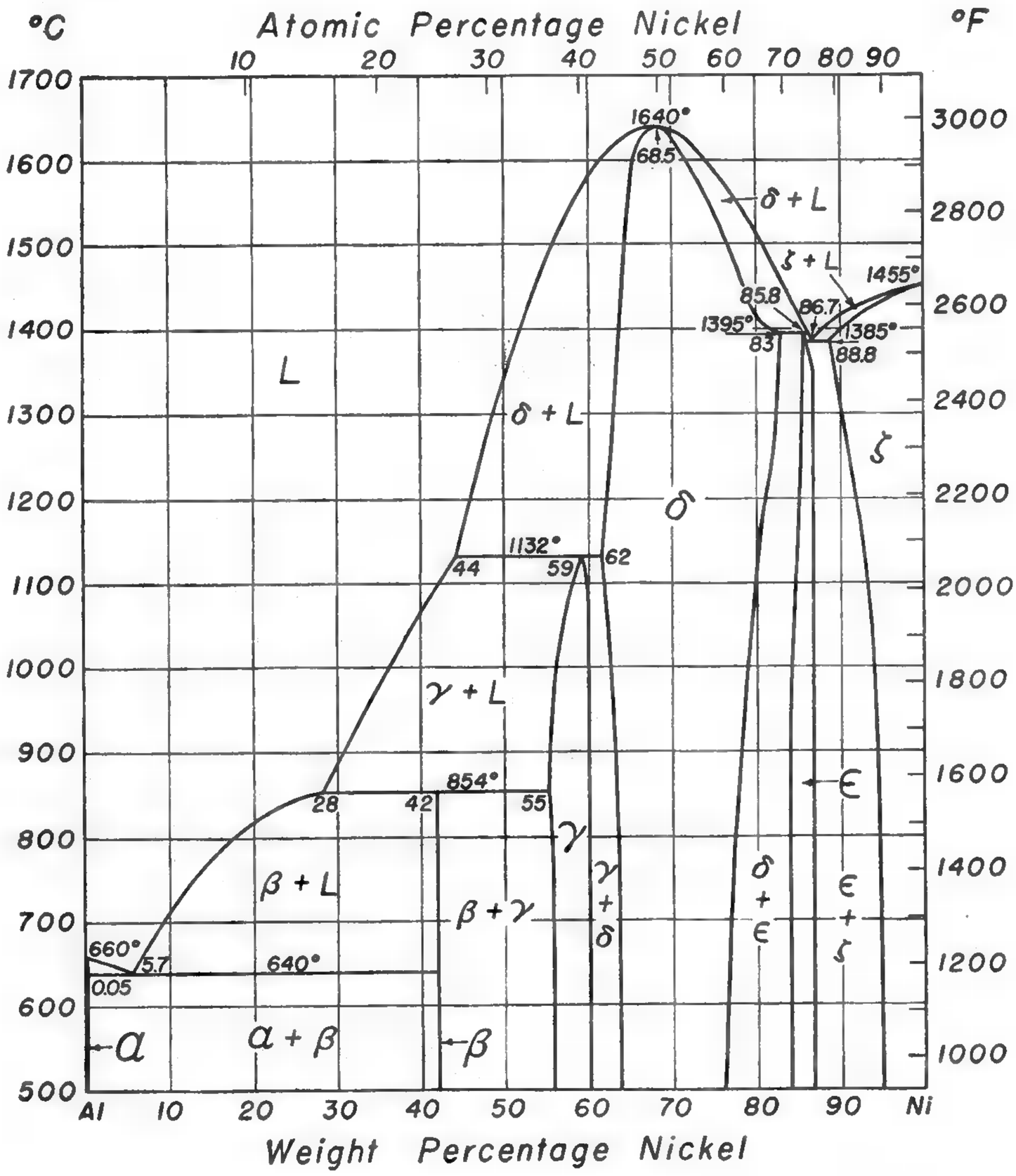
Al-Ni Aluminum-Nickel

By W. L. Fink* and L. A. Willey*



The diagram shown is from investigations by Alexander and Vaughan,[2] Schramm,[3] and Fink and Willey.[1]

The Curie temperature of nickel is decreased linearly from 360 to 70 C by the addition of 4.6% Al in solid solution.[3]

The solubility of nickel in solid aluminum is, as follows:[1] 0.040% at 625 C, 0.018 at 570, 0.006 at 505. The solubility of aluminum in solid nickel is:[3] 9.7% at 1300 C, 8.0 at 1200, 6.5 at 1080, 6.0 at 980, 5.0 at 700.

Nickel is used as an alloying element in a few commercial aluminum-base alloys, principally in aluminum-copper-magnesium alloys and aluminum-silicon-magnesium alloys. Nickel increases the strength of these alloys at elevated temperature and decreases the coefficient of thermal expansion, but usually decreases the resistance to corrosion.

At the other end of the system there are a few commercial alloys that are used principally for thermocouple wires.

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* Aluminum Research Laboratories, New Kensington, Pa.

Crystal Structures and Lattice Parameters of Aluminum-Nickel Alloys

Phase	Crystal Structure	Lattice Parameter, kX units		
		a	*b*	*c*
β	Orthorhombic	6.598	7.352	4.802
γ	Trigonal	4.028	4.891	....
δ	Body-centered cubic	2.881	....	....
ε	Face-centered cubic	3.58	....	....

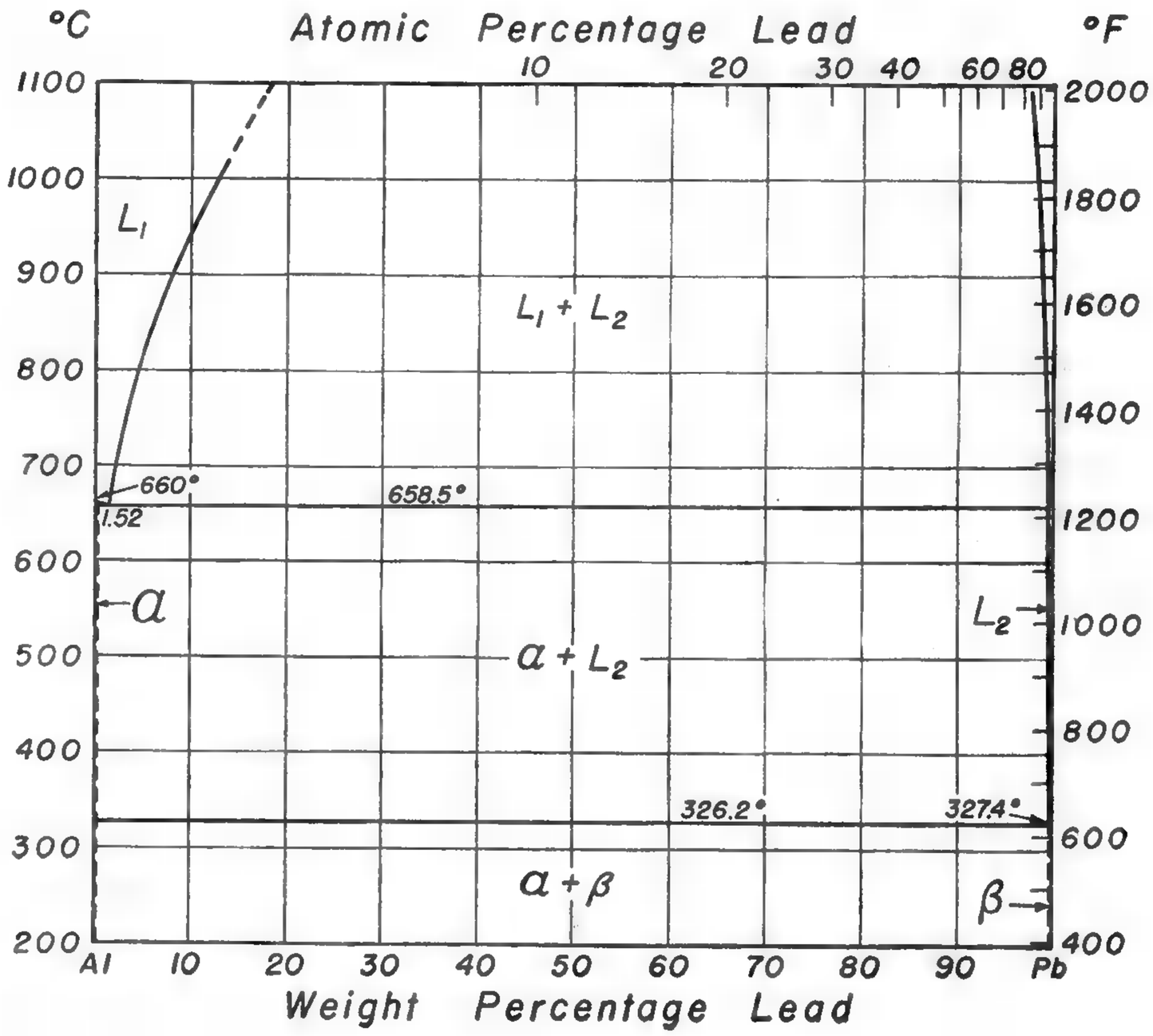
Al-Pb Aluminum-Lead

By W. L. Fink* and L. A. Willey*

The diagram shown is from investigations by Van Horn,[1] Campbell and Ashley,[2] and Dardel.[4] The system is of the monotectic type. The miscibility gap extends from 1.52% to greater than 99% Pb at the monotectic temperature (658.5 C).

The eutectic of this system has been reported at 99.98% Pb.[3, 4] The solubility of lead in solid aluminum does not exceed 0.2% at the monotectic temperature (658.5 C).[1] The solubility of lead in liquid aluminum is decreased slightly by the presence of about 5% Cu.[1]

Lead is used along with bismuth as a minor alloying element in a few commercial aluminum alloys to improve the machinability. The amounts added do not exceed about 0.5%. There are no other commercial applications of aluminum-lead alloys.



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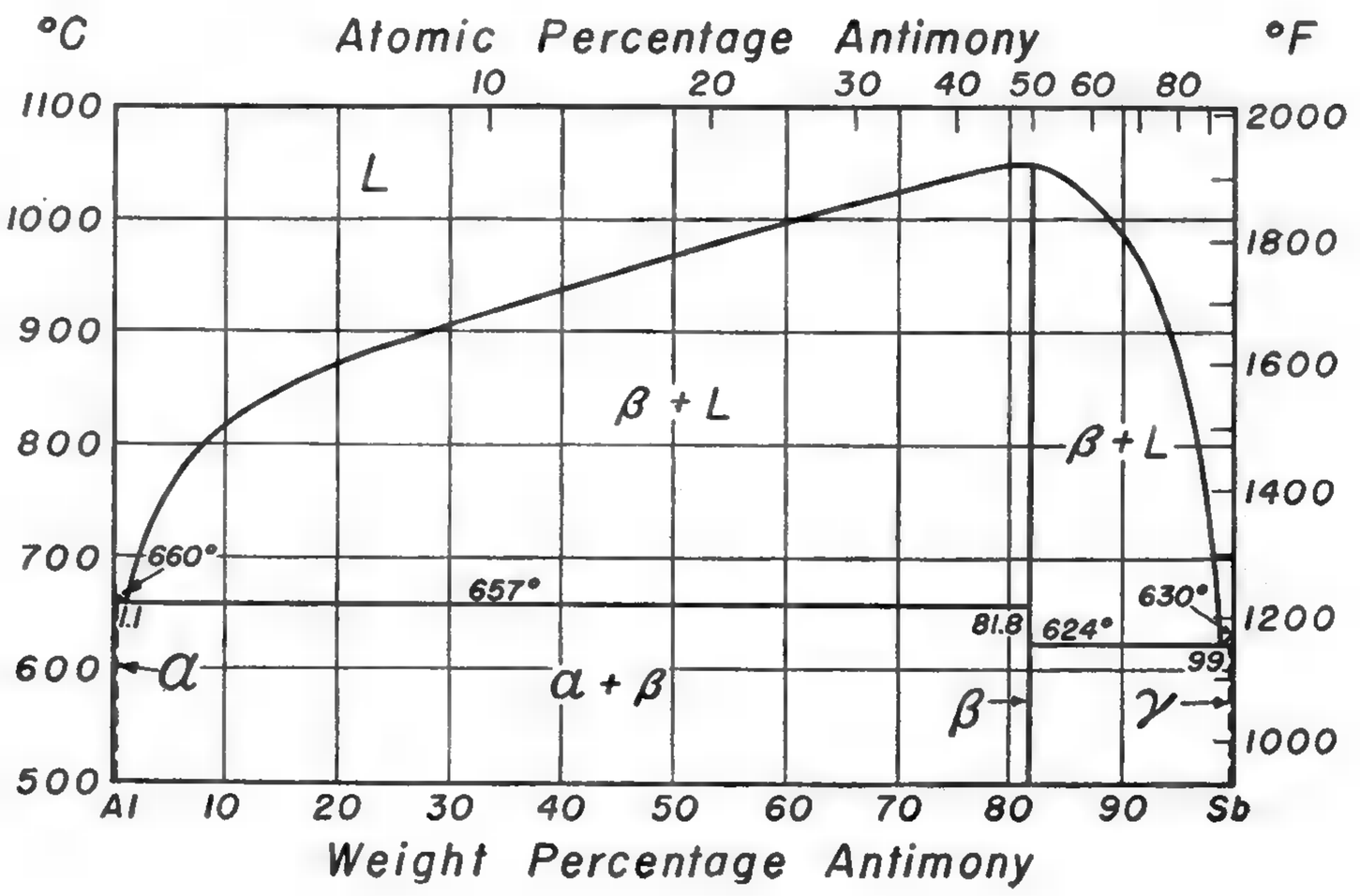
Al-Sb Aluminum-Antimony

By W. L. Fink* and L. A. Willey*

Aluminum and antimony form an intermetallic phase, β, at 50 atomic per cent. The melting point of β has not been definitely established but it is approximately 1050 C.

The solubility of antimony in solid aluminum has been found to be less than 0.1% at 645 C.[2] A determination of the solubility of aluminum in solid antimony has not been made; however, this solubility is probably less than 0.1% at the eutectic temperature.

The crystal structure of the β phase has been reported to be face-centered cubic.[1]



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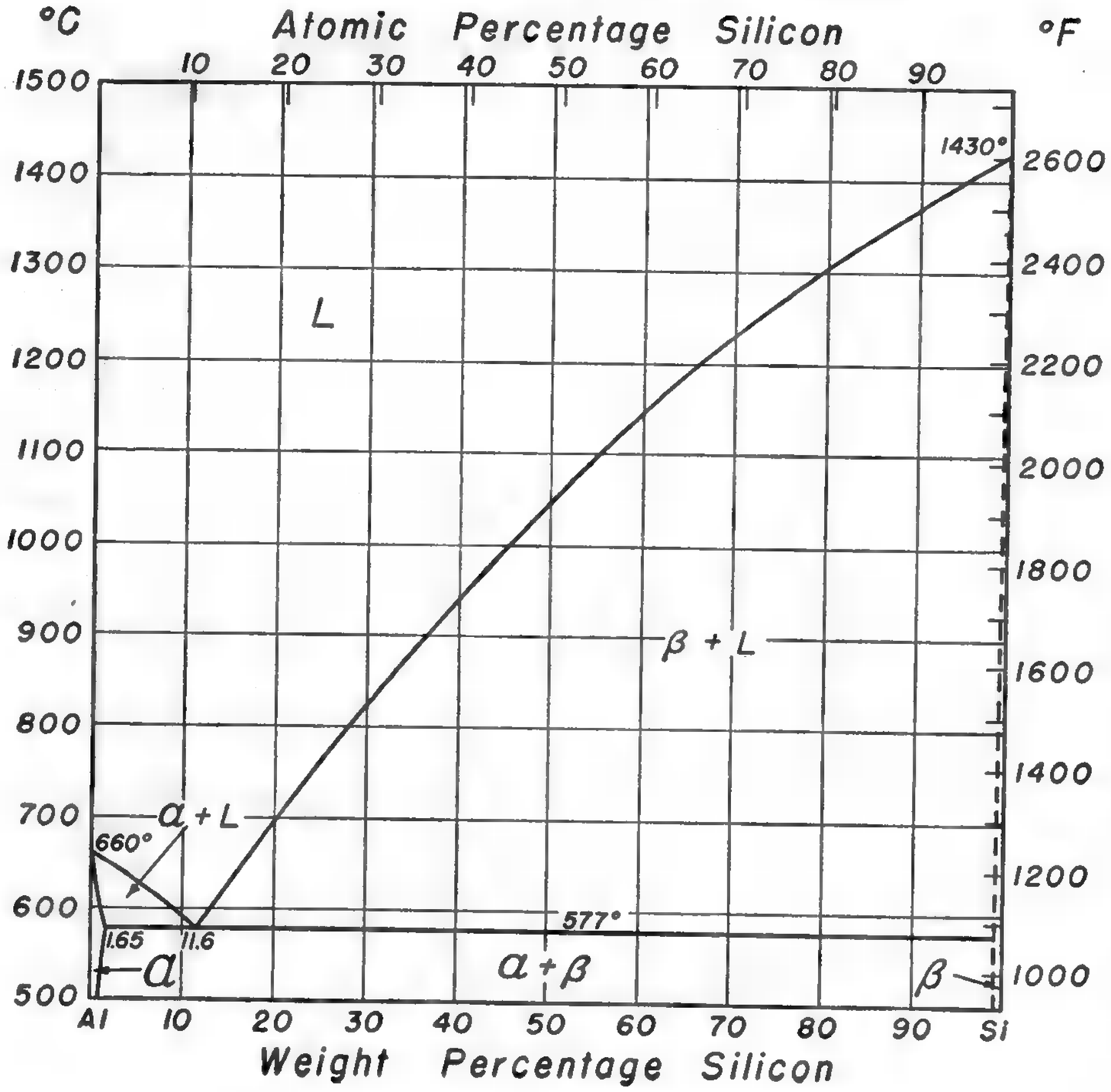
* Aluminum Research Laboratories, New Kensington, Pa.

Al-Si Aluminum-Silicon

By W. L. Fink* and L. A. Willey*



The solubility of aluminum in solid silicon has never been thoroughly investigated; however it has been reported that silicon dissolves about 4% Al at the eutectic temperature.[4] From other evidence this value would appear to be excessive.[7]

The solubility of silicon in solid aluminum is, as follows:[8] 1.30% at 550 C, 0.80 at 500, 0.48 at 450, 0.29 at 400, 0.17 at 350, 0.10 at 300, 0.05 at 200.

Silicon inevitably occurs as an impurity in all commercial aluminum alloys and is used as an alloying element in many of the commercial casting alloys. Silicon is also used as an alloying element in wrought alloys that depend on magnesium silicide as the hardening agent. (*See* page 805.)

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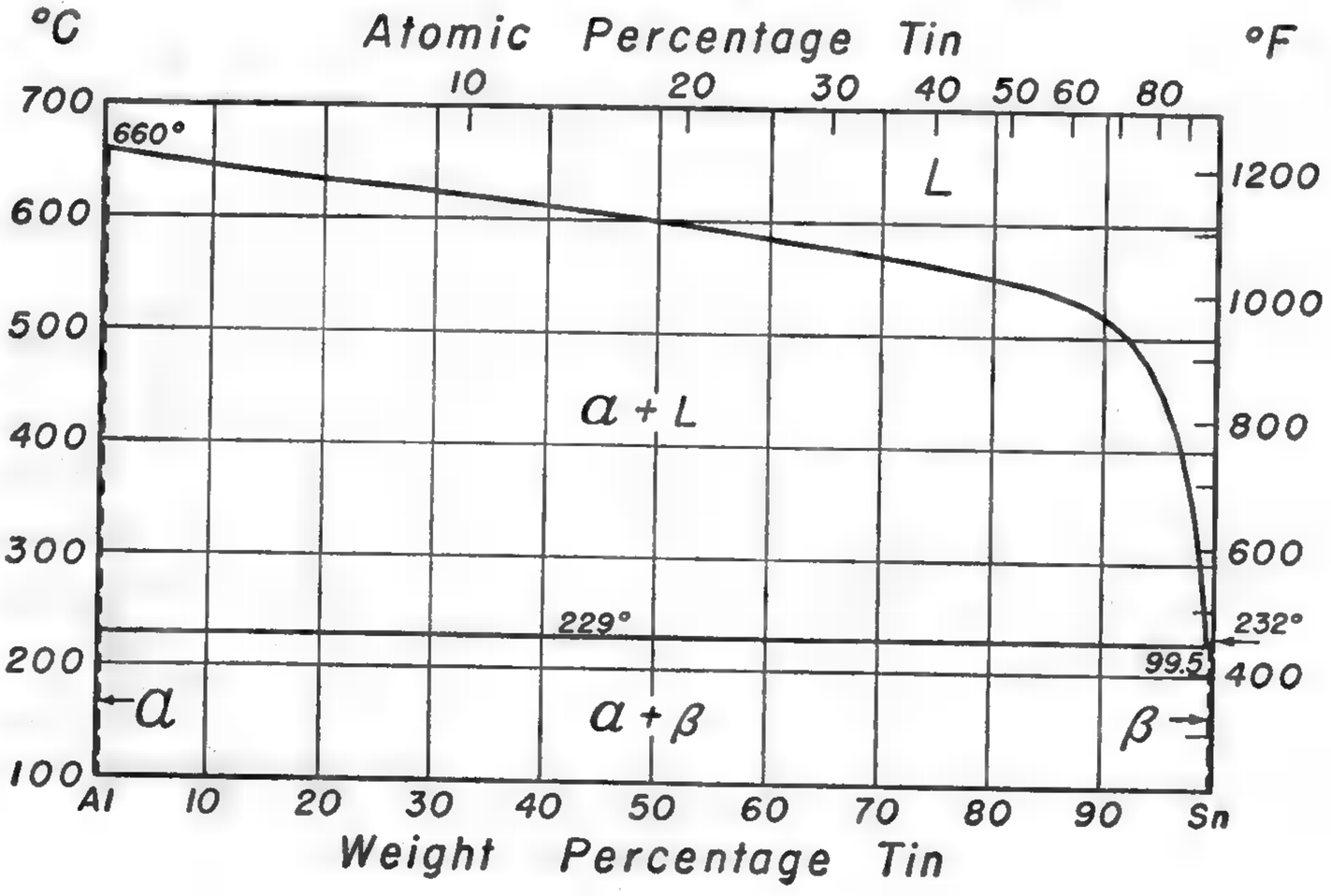
* Aluminum Research Laboratories, New Kensington, Pa.

Al-Sn Aluminum-Tin

By H. P. Nielsen* and R. J. Nekervist†



Reported values for the solubility of tin in solid aluminum vary considerably.[1,3,5,10] Unpublished results by Wm. L. Fink indicate that the solubility is approximately 0.05% Sn at 500 C, and not more than a few thousandths per cent at the eutectic temperature (229 C). At still lower temperatures the solubility is nil.

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* University of Southern California, Los Angeles
† Battelle Memorial Institute, Columbus, Ohio

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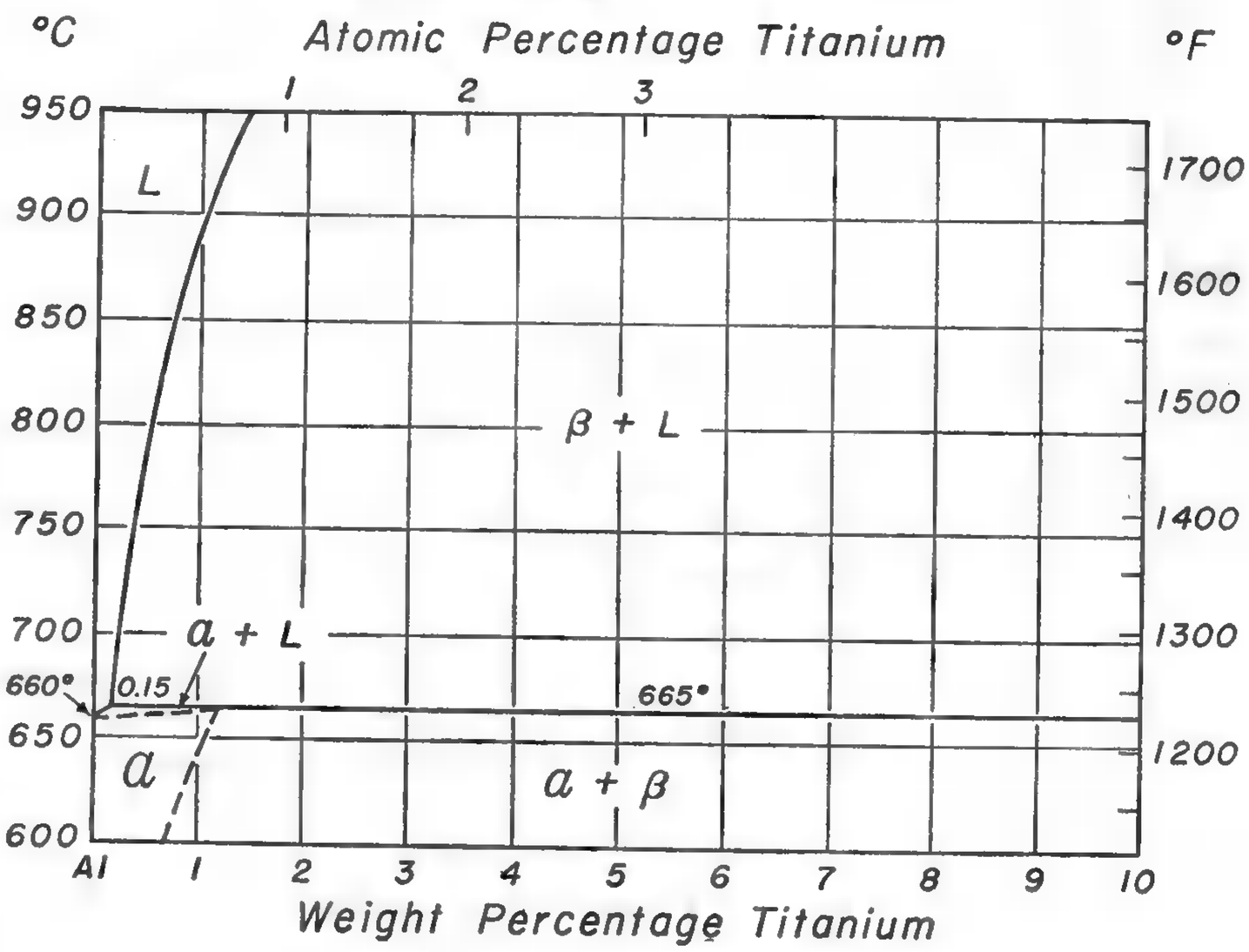
Al-Ti Aluminum-Titanium

By W. L. Fink* and L. A. Willey*

Attempts to determine accurately the solid solubility of titanium in aluminum have not been successful, apparently because of the extremely slow rate of diffusion. A determination, however, has indicated a solubility of 0.24% Ti at 510 C. Calculations indicate a solid solubility at the peritectic temperature of between 1 and 1.5% Ti.

The β phase contains 37.2% Ti and therefore may be represented by the formula $TiAl_3$.[1] Nothing is known of the diagram beyond approximately 40% Ti.

The β phase is tetragonal with $a = 5.424$ kX and $c = 8.574$ kX.[1]



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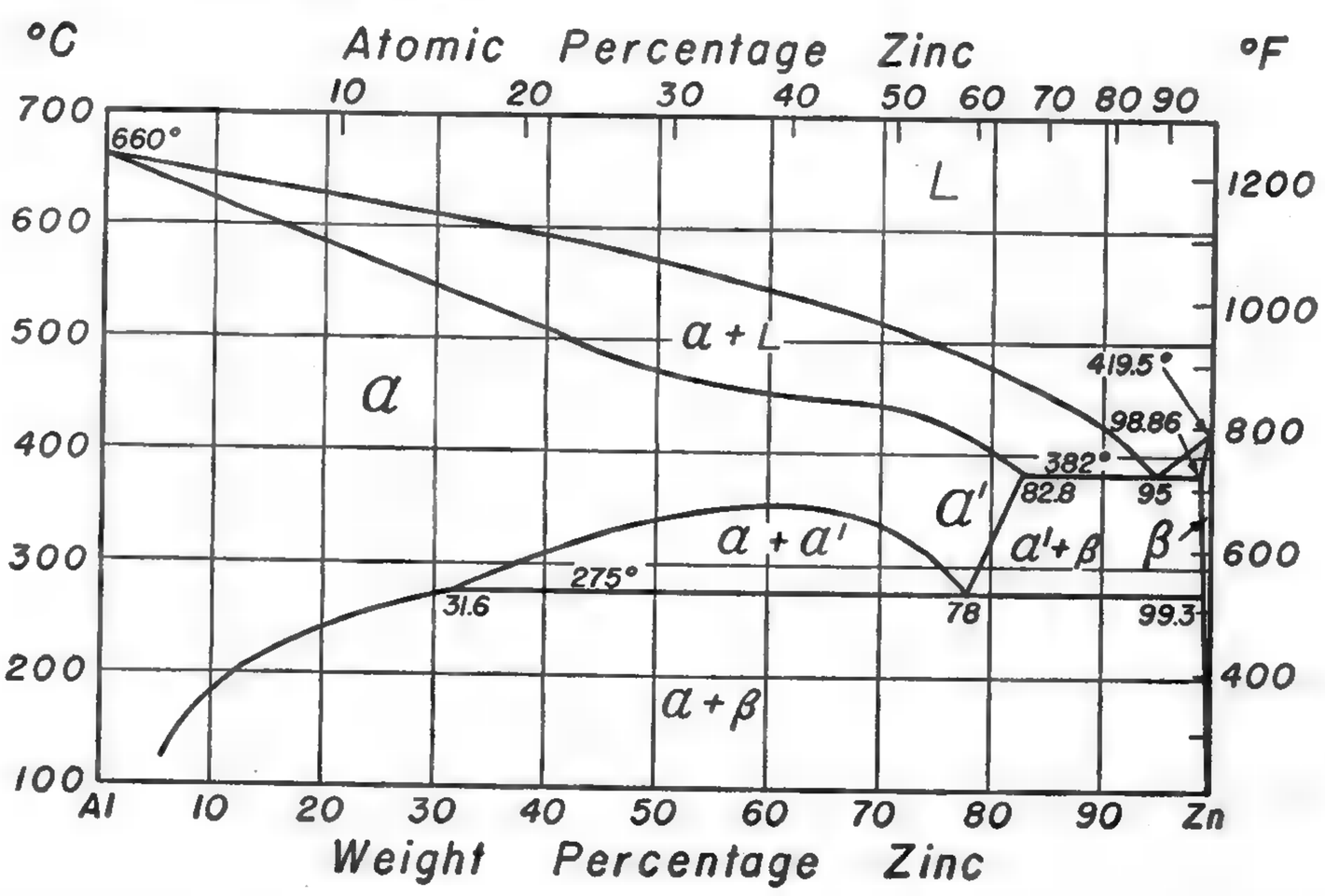
Al-Zn Aluminum-Zinc

By E. A. Anderson*

The diagram is that selected by Raynor.[1] Efforts to detect an alleged peritectic at 443 C previously reported[4] have been unsuccessful.[5] Heat effects at 443 C have not been explained convincingly. The existence of a two-phase region between 31.6 and 78% Zn above 275 C seems well established.[2,3] The two phases are face-centered cubic and have nearly the same lattice parameter.



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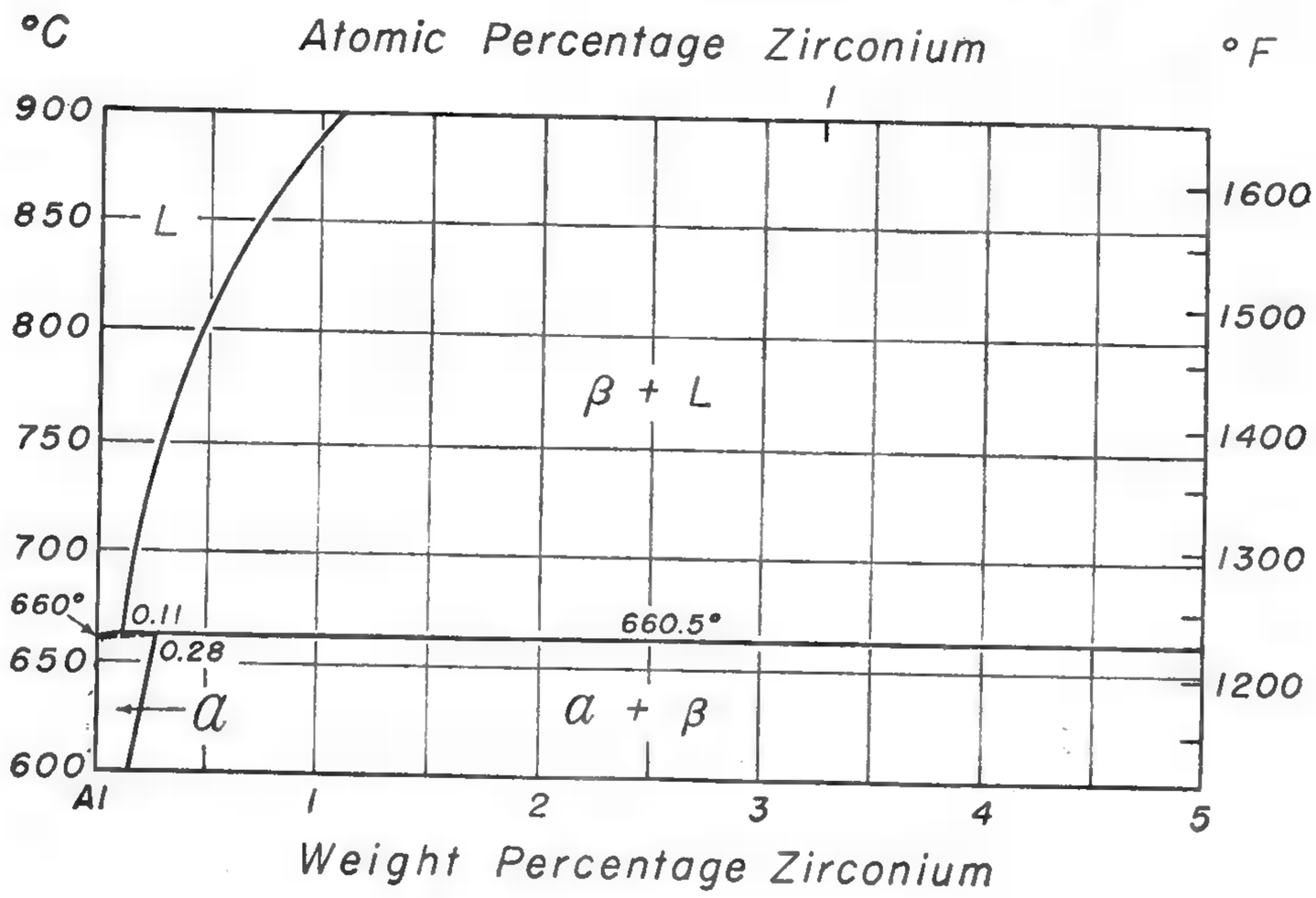
* The New Jersey Zinc Company (of Pa.), Palmerton, Pa.

Al-Zr Aluminum-Zirconium

By W. L. Fink* and L. A. Willey*



The β phase (tetragonal) contains 53% Zr and therefore corresponds to the formula $ZrAl_3$. This constituent is not discolored or attacked by ordinary etching reagents. No investigations of the system at temperatures above 1000 C or beyond 53% Zr have been made. The solubility of zirconium in solid aluminum is as follows:

Temperature, deg Cent	Percentage Zirconium
660.5	0.28
640	0.23
600	0.15
550	0.084
500	0.050

Reference

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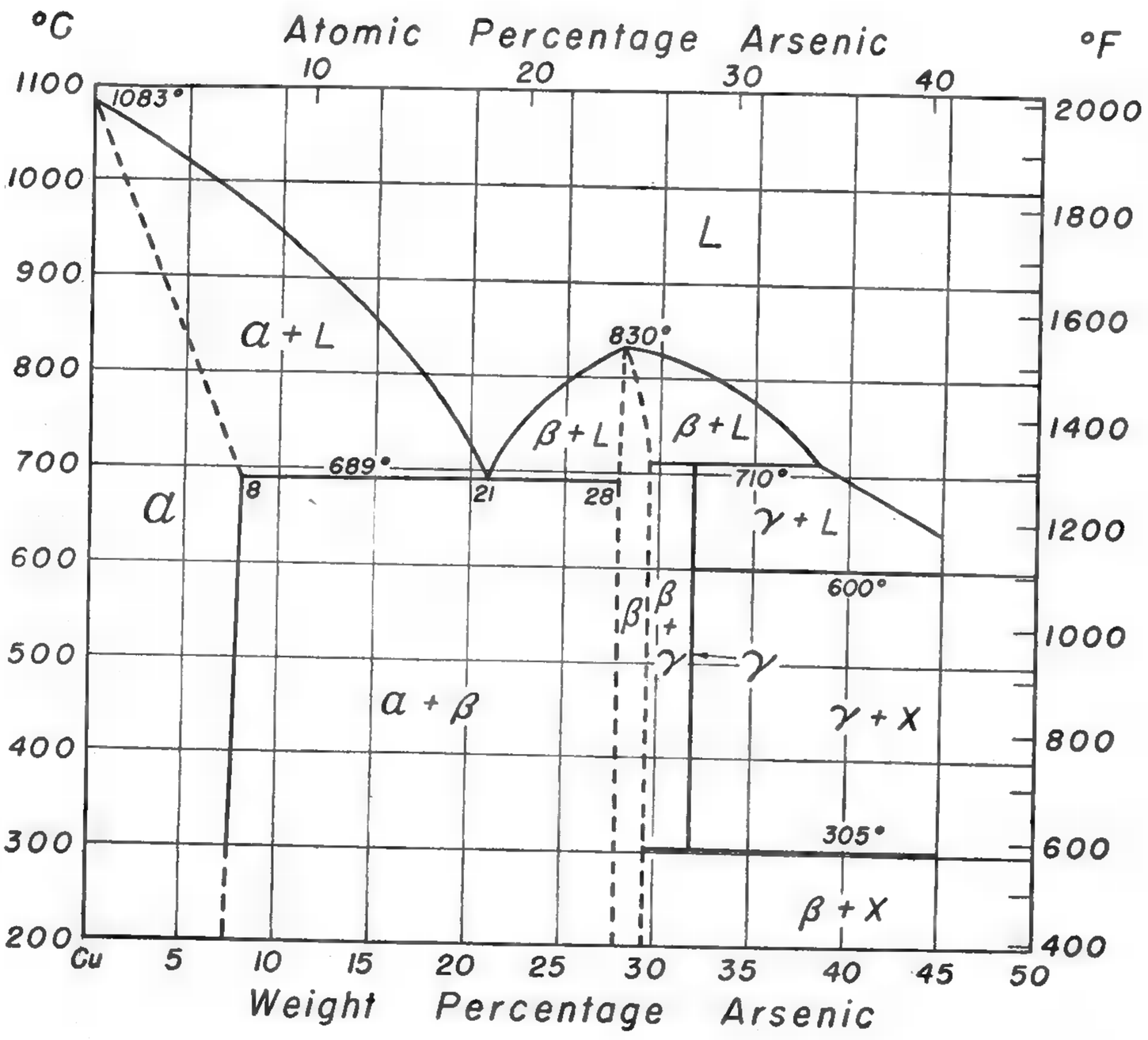
* Aluminum Research Laboratories, New Kensington, Pa.

As-Cu Arsenic-Copper

By H. L. Burghoff*



This diagram is essentially as given by Hansen,[1] except that the alpha solid solubility boundary is as determined by Mertz and Mathewson.[5] The constitution of copper-arsenic alloys containing more than 28% As is uncertain, for the evidence concerning the existence of the γ phase (the compound Cu_5As_2) is contradictory. The β phase region includes the composition Cu_3As.

Alloys containing up to about 0.5% As are used commercially.

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* Research Metallurgist, Chase Brass & Copper Co., Waterbury, Conn.

From a diffusion study, it was estimated that the limit of the γ loop is between 3½ and 4% As at 1150 C.[1]

The η phase (FeAs) crystallizes in a simple rhombic lattice.[2] The elementary cell contains four FeAs groups.[3] The ϵ phase (Fe_2As) has a simple tetragonal lattice with two Fe_2As groups per cell.[3]

Natural $FeAs_2$ (72.86% As) is isomorphous with marcasite (FeS_2) and with $FeSb_2$.[4,5]

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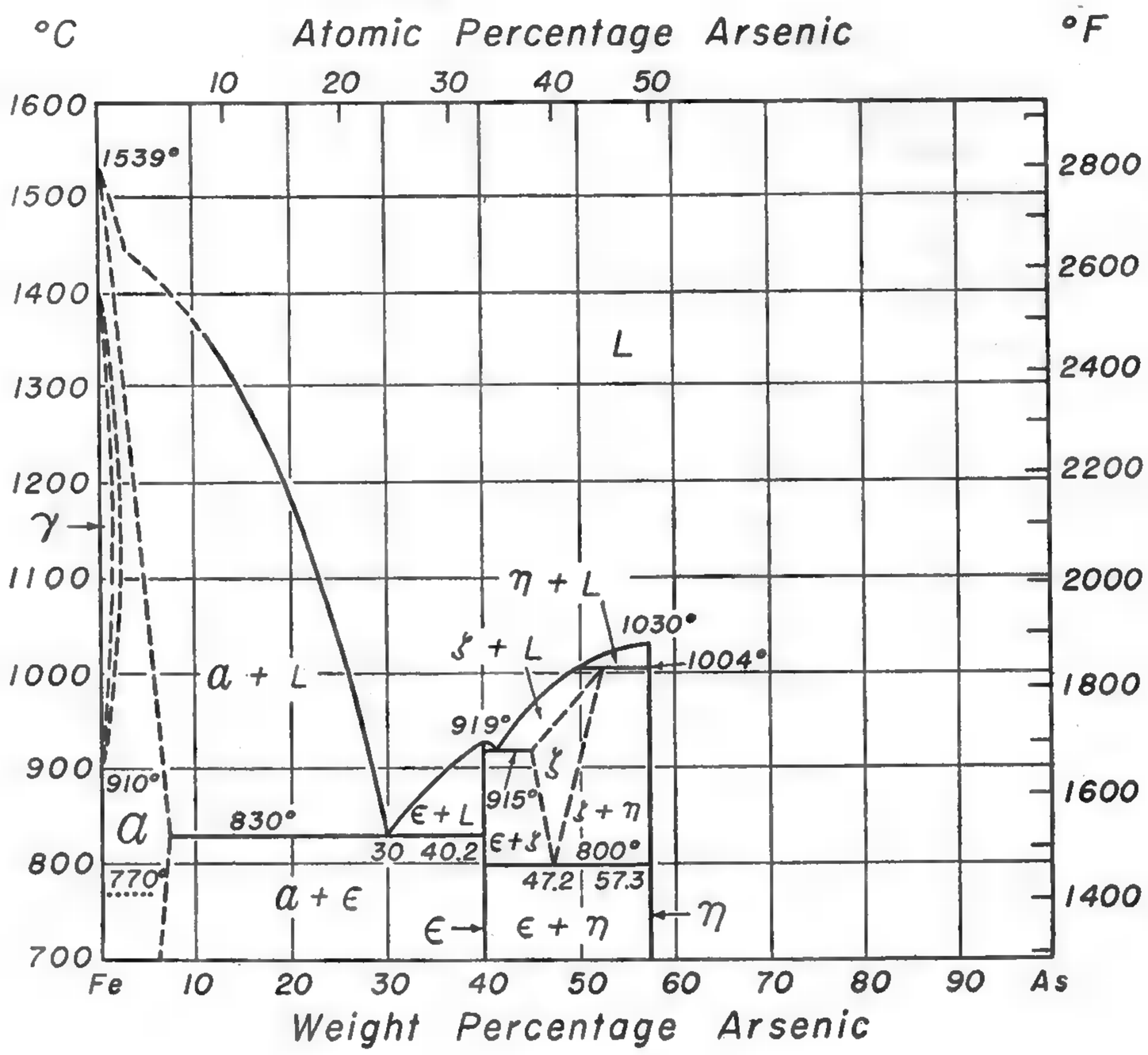
* Kellex Corporation, Silver Spring, Md.

As-Fe Arsenic-Iron

By R. M. Parke*



As-Pb Arsenic-Lead

By A. A. Smith, Jr.*

Lead and arsenic form a simple eutectic system as determined by Heycock and Neville,[1] Heike,[2] and Bauer and Tonn.[3] No detailed study has been made on the arsenic end of the system, since arsenic sublimes under atmospheric pressure above 610 C.

Arsenic has but slight solubility in solid lead—approximately 0.05% at the eutectic temperature and probably less than 0.01% at 25 C.[3]

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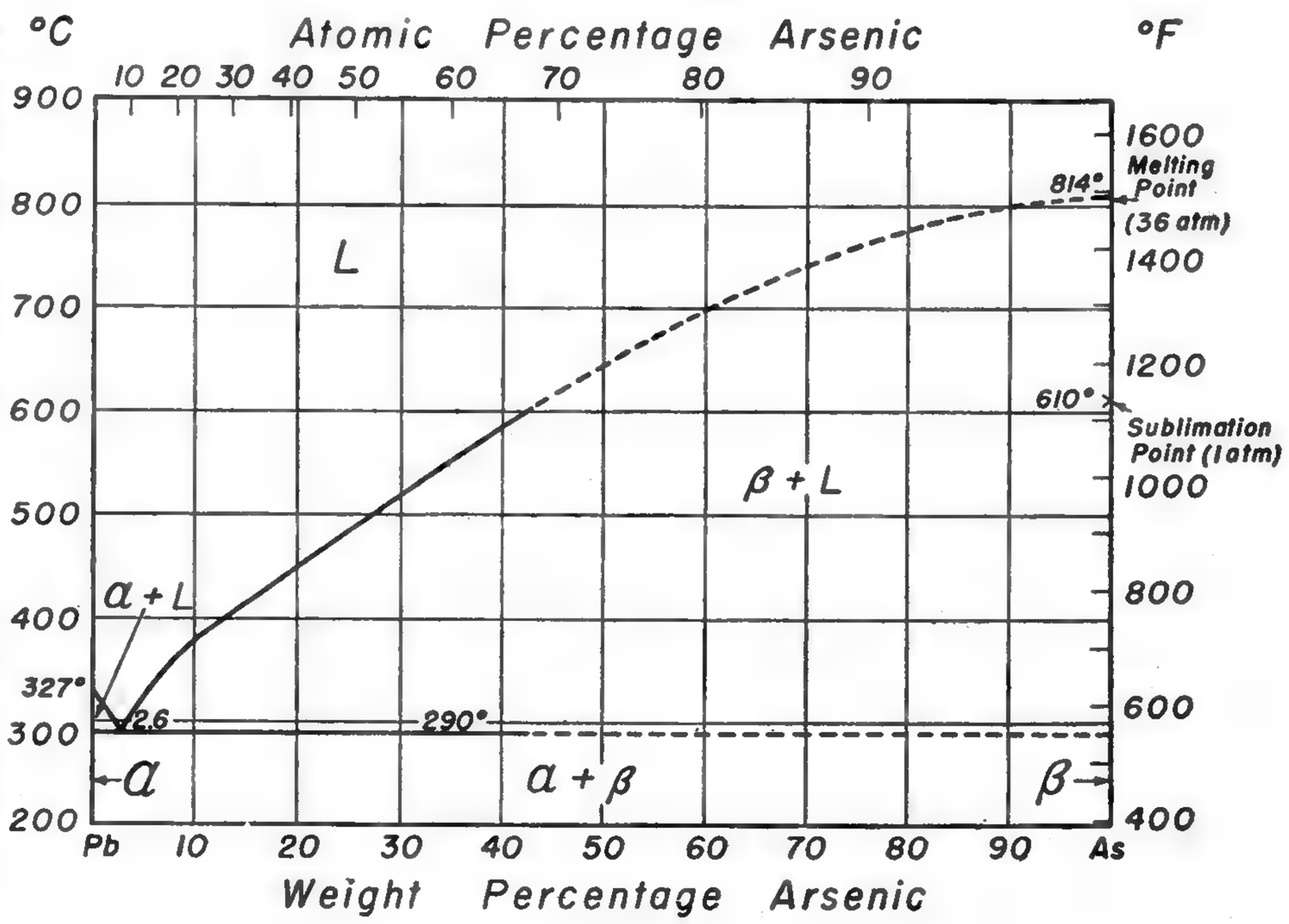

Au-Bi Gold-Bismuth

By W. Earl Lindlief*

The only known data for the liquidus and eutectic are those of Vogel.[1] The melting point of the bismuth used in his determinations was 266 C, which is 5.3 C lower than the melting point of pure bismuth. The liquidus and eutectic temperatures may therefore be somewhat in error.

Jurriaanse[2] found the solubility of bismuth in solid gold to be less than 0.2% by metallographic methods. His X-ray work indicated the solubility to be nil and this has been verified by the more recent work of Owen and Roberts.[3]

The β phase (Au_2Bi, 34.64 weight % Bi) is face-centered cubic with $a = 7.942$ kX units.[3]

* National Bureau of Standards, Washington, D.C.

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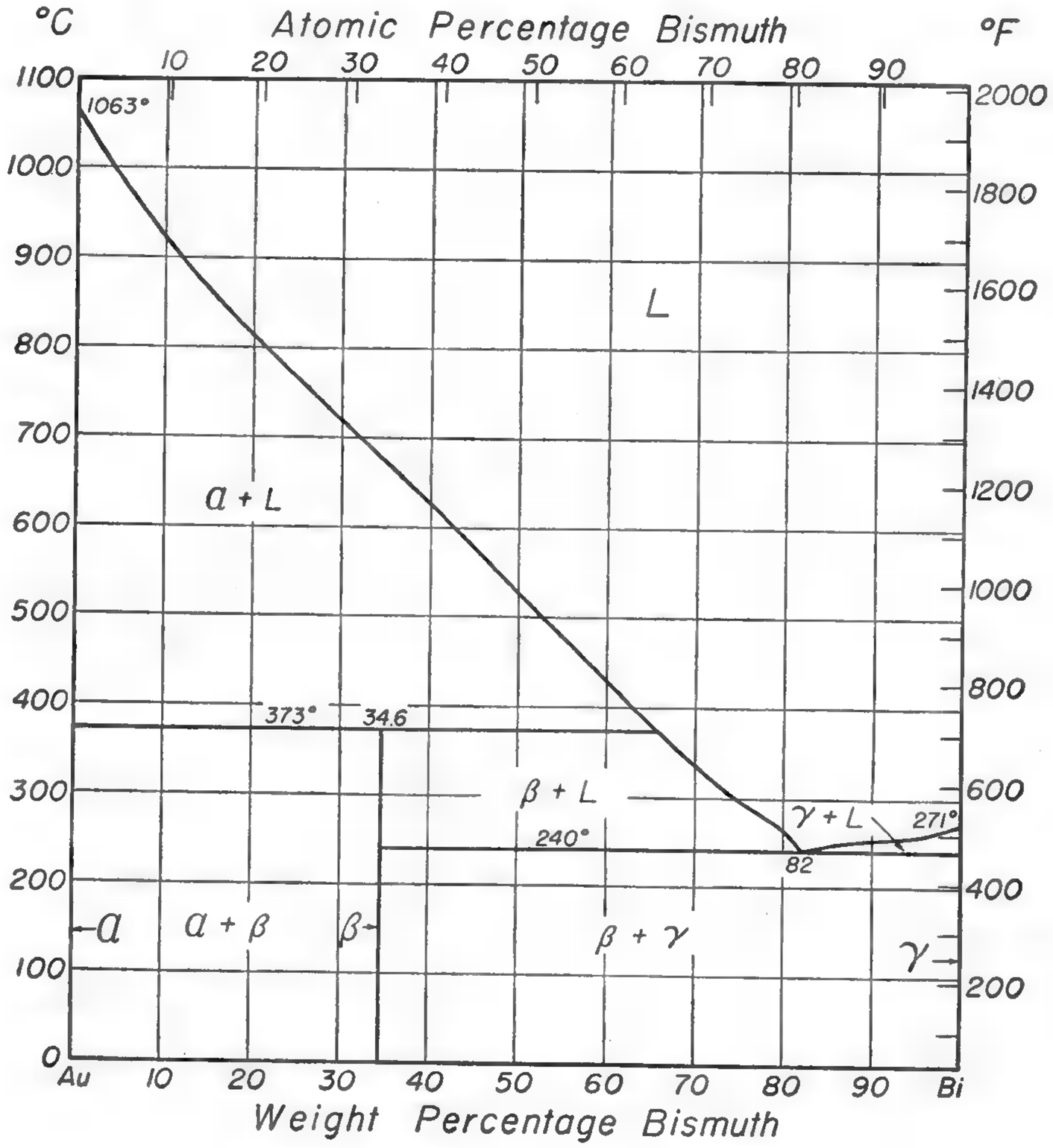


Au-Cu Gold-Copper

By David Harker*

Lattice Parameters of Gold-Copper Alloys Quenched from 600 C
(Lattice parameters of the α' structure are within 0.005 kX of those of α)

Gold, wt %	0	10	20	30	40	50	60	70	80	90	100
Lattice constant, kX	3.608	3.631	3.655	3.680	3.709	3.743	3.785	3.837	3.894	3.969	4.070

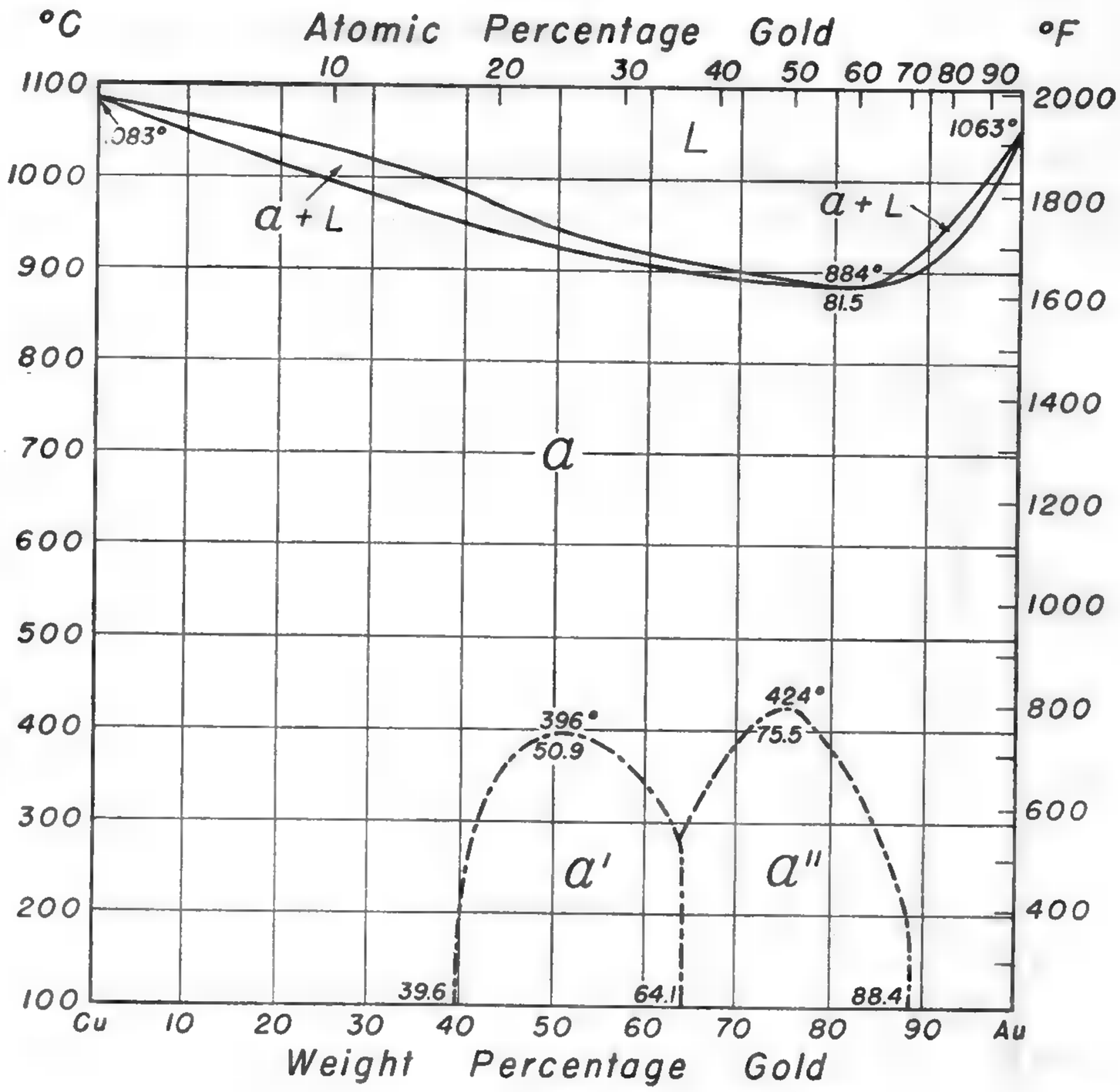
Lattice Parameters of Gold-Copper Alloys Quenched from 200 C (Tetragonal α'')

Gold, wt %	65	70	75	80	85
a, kX units	3.846	3.914	3.956	3.978	3.950
c/a	0.976	0.934	0.926	0.933	0.981

* Research Laboratory, General Electric Company, Schenectady

Both α' and α'' are ordered states of the face-centered cubic α' phase; α' is cubic with the ideal formula $AuCu_3$; α'' is tetragonal with the ideal formula AuCu. There is also an orthorhombic structure at the equiatomic composition.[4,6] According to the results of Hultgren and Tarnopol[8] this structure is stable over a temperature range of nearly 50 C in the vicinity of 400 C. The b/a axial ratio of the orthorhombic crystals increases on standing six months at room temperature.[6]

There is some evidence for the existence of another ordered state with the ideal formula Au_2Cu_3. If it exists, there would be almost a smooth continuation of the α'' region.



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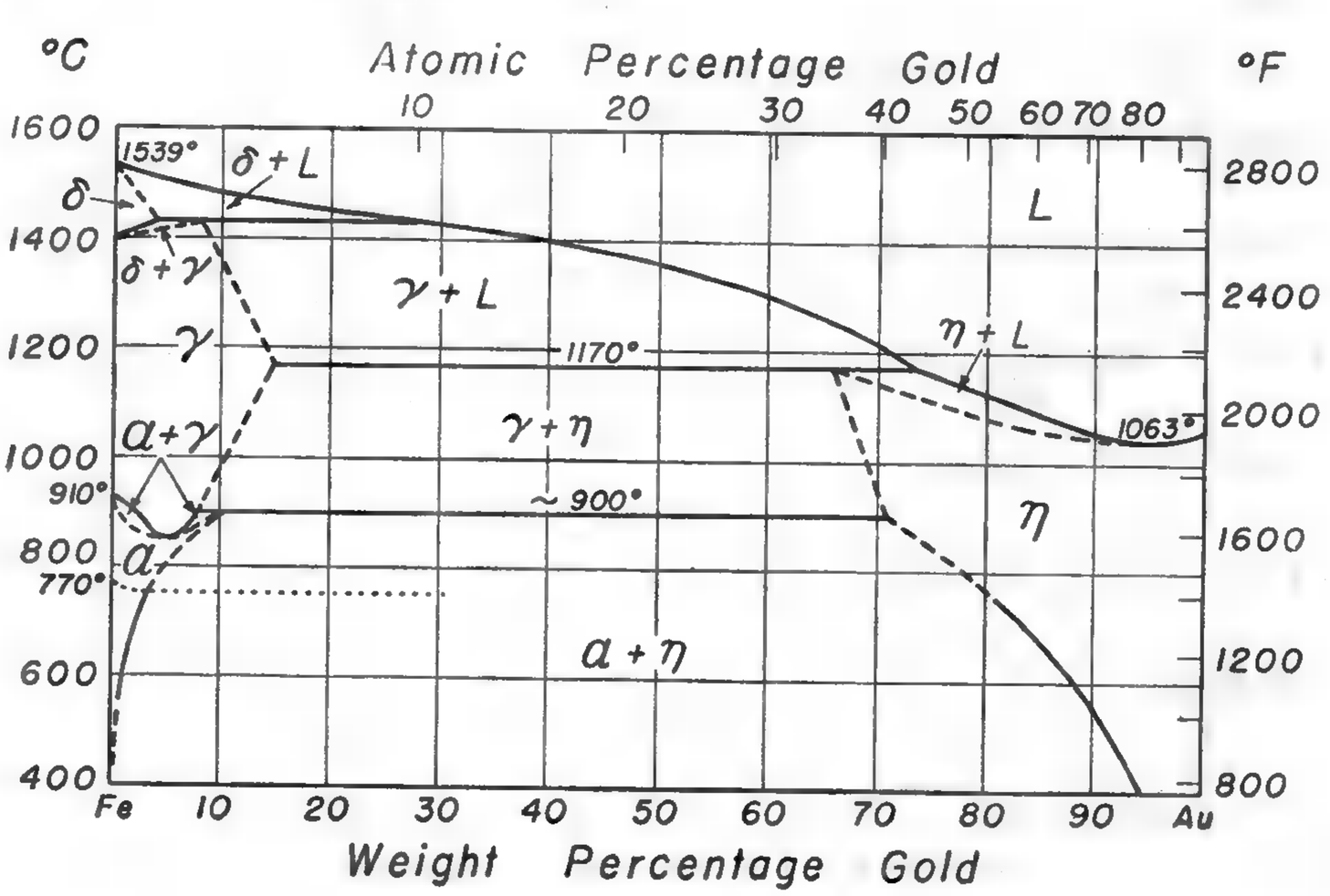
Au-Fe Gold-Iron

By R. M. Parke*

Although the diagram of the gold-iron system given by Hansen[1] shows a compound $AuFe_3$, based on the work of Wever (reported by Nowack[2]), the data of Jette, Bruner, and Foote[3] and of Pan, Kaufmann, and Bitter[4] are convincing that no compound exists. The η solid solutions containing from 10 to 15% Fe are ferromagnetic.[3]



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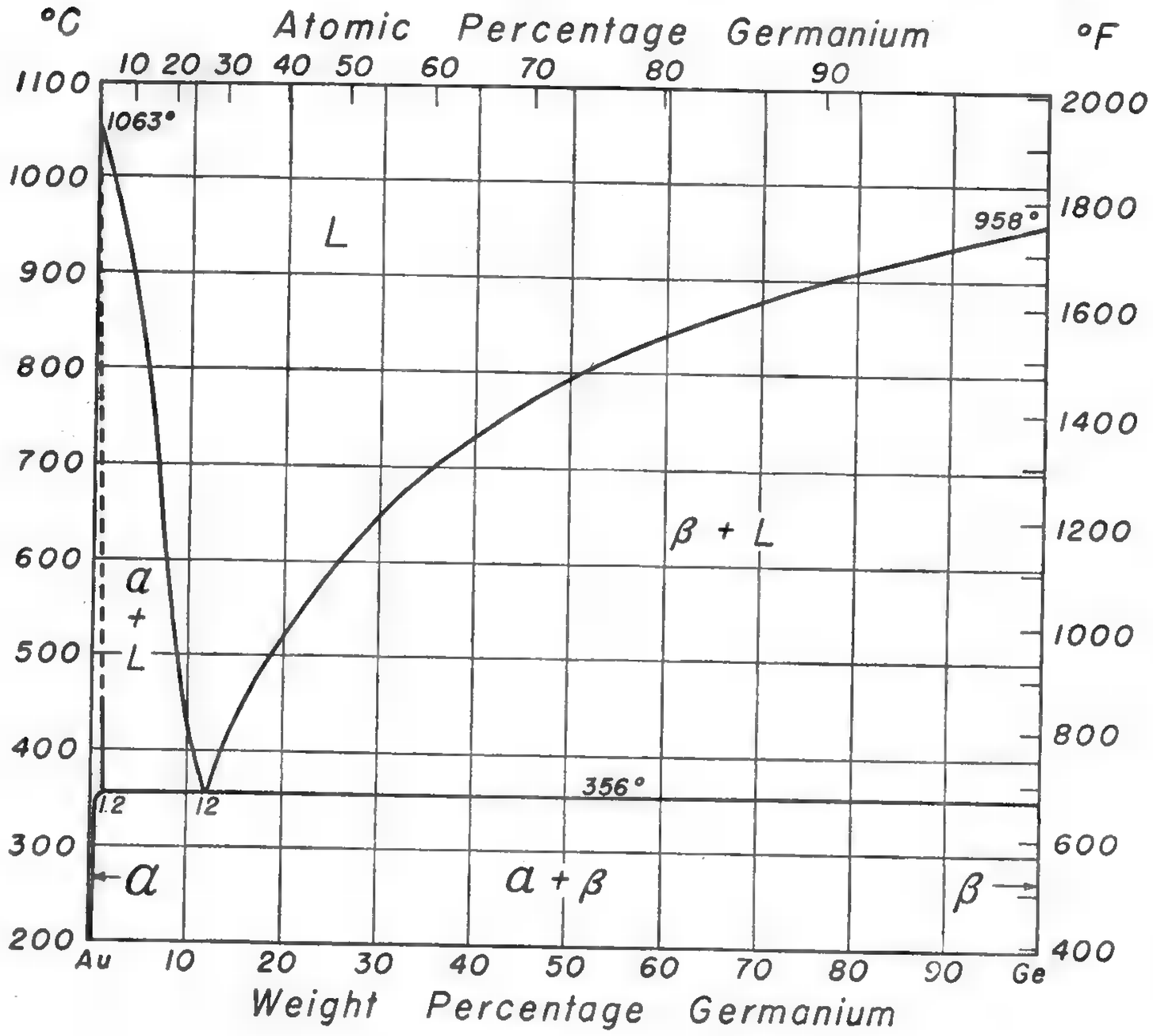
*Kellex Corporation, Silver Spring, Md.

Au-Ge Gold-Germanium

By R. I. Jaffee* and Bruce W. Gonser*



The solubility of germanium in gold is 0.1% or less at room temperature.

The solubility of gold in germanium has not been investigated. Germanium[3] and the gold-germanium eutectic alloy[1] expand on solidification, resulting in so-called "sprouting" on the free surface of solidification. The alloys retain their gold color up to the eutectic composition.

The structure of the eutectic is extremely fine-grained at the eutectic composition, and on the gold side of the eutectic, but is quite coarse on the germanium side. Up to about 5% Ge the alloys are malleable. The hardness increases to about 200 Vickers at 12% Ge.

The addition of 1.16% Ge to gold increases the lattice parameter of the face-centered cubic solid solution from 4.0700 to 4.0724 kX.[2]

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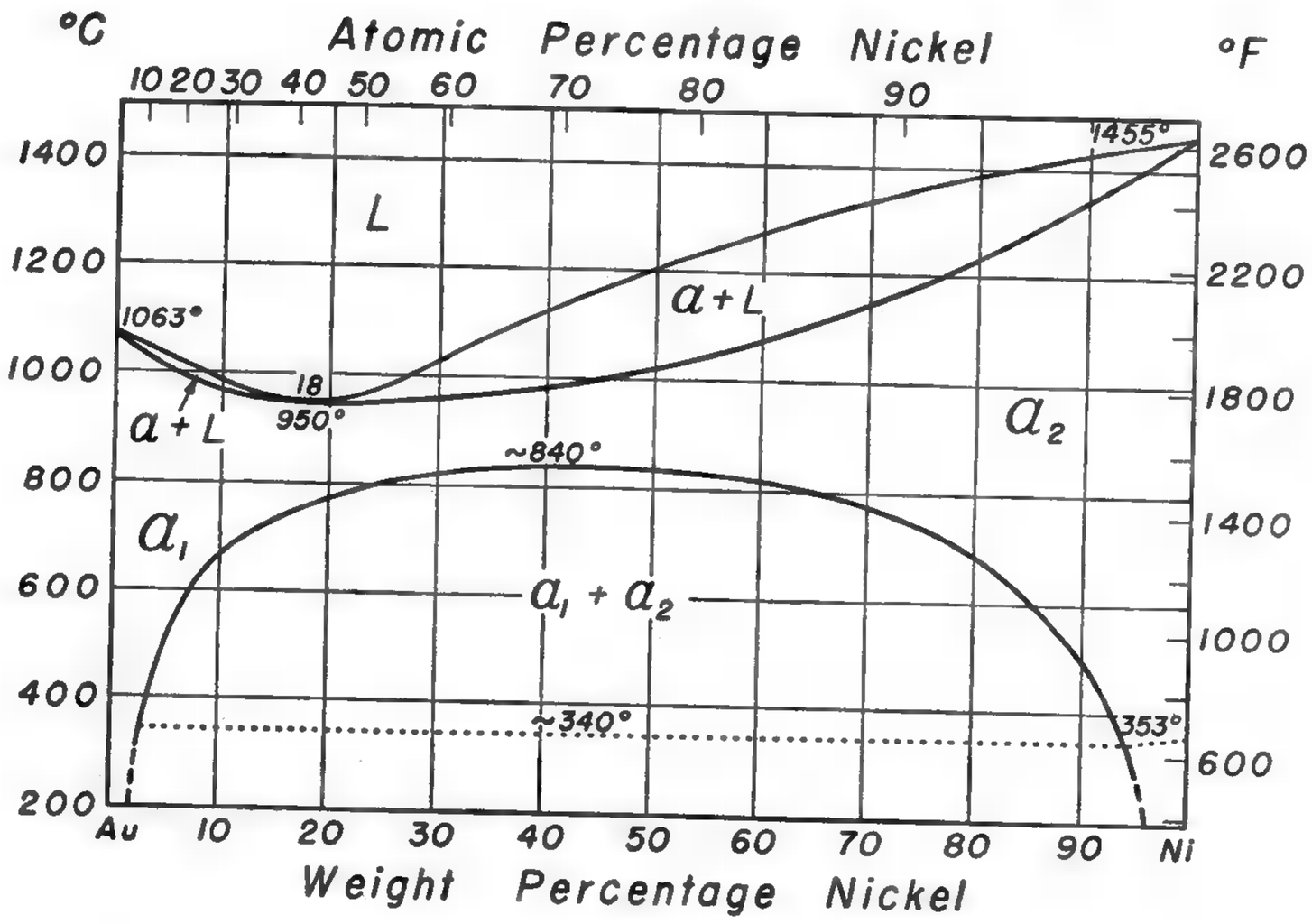
* Battelle Memorial Institute, Columbus, Ohio

Au-Ni Gold-Nickel

By Louis A. Carapella*



At about 340 C, the α_2 phase in equilibrium with α_1 becomes ferromagnetic during cooling. A second magnetic change has also been detected at lower temperatures[4, 8] in alloys with approximately 40 to 95% Ni quenched from the single-phase range. This is not an equilibrium magnetic change.

Lattice parameters have been reported.[4]

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2 W. Fraenkel and A. Stern, Z anorg allgem Chem, 166, 161 (1927)
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4 W. Köster and W. Dannöhl, Z Metallkunde, 28, 248 (1936)
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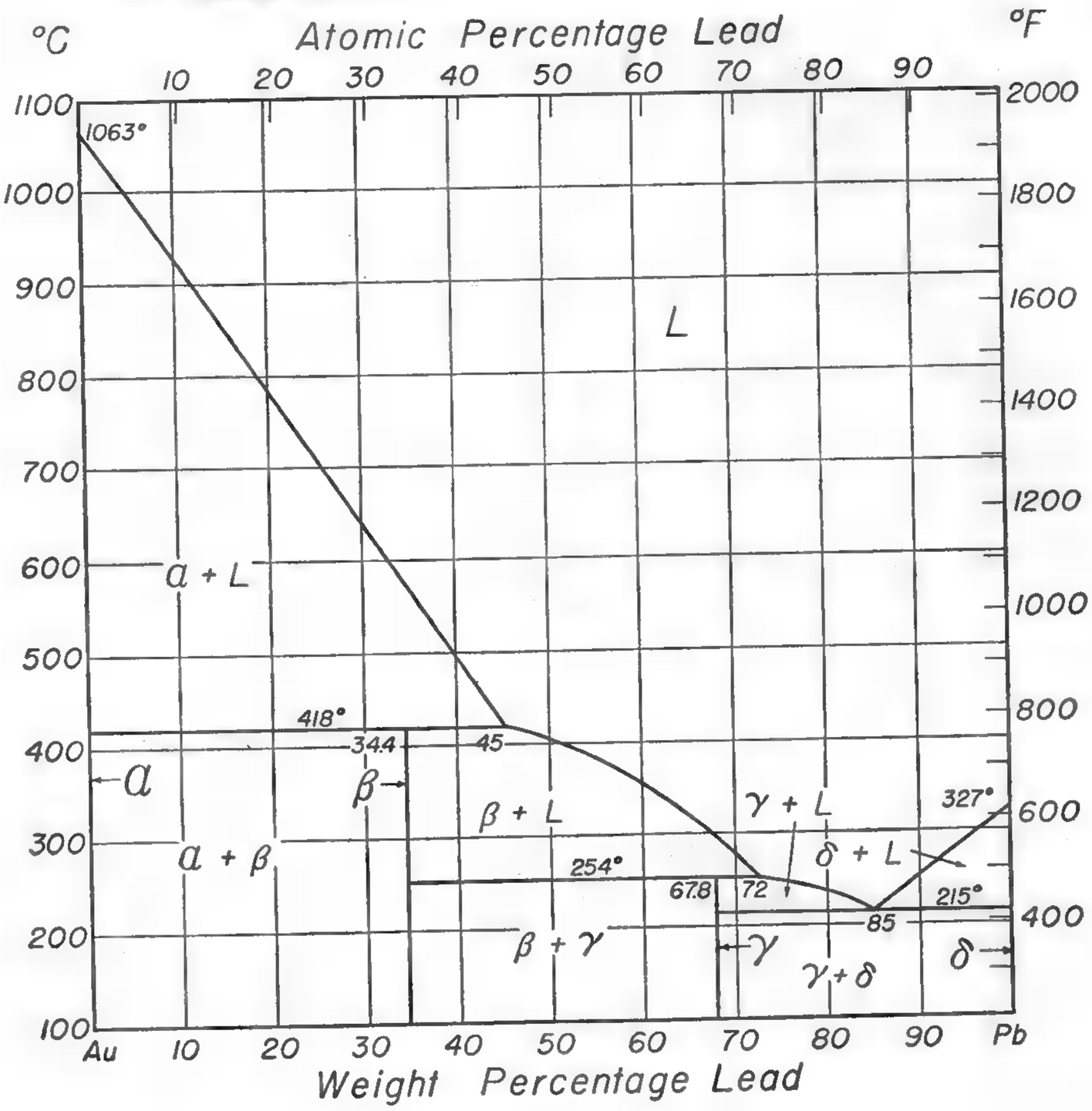
* Mellon Institute of Industrial Research, Pittsburgh

Au-Pb Gold-Lead

By Charles L. Gordon*



The phase diagram is based mainly on the work of Vogel.[1] The solubility of lead in solid gold is probably less than 0.005%.[2,3,8] The suggested solubility of gold in lead ranges from 0.09% near the eutectic temperature (215 C) to 0.03% at 170 C.[5]

The β phase (Au_2Pb) is face-centered cubic with 16 gold and 8 lead atoms in a unit cell that is identical with those of $MgCu_2$ and KBi_2. The lattice parameter is 7.910 kX units.[9] The γ phase ($AuPb_2$) is tetragonal[6] with $a = 7.319$ kX and $a/c = 1.297$.

References

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2 L. Nowack, Z Metallkunde, 19, 238 (1927)
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4 H. Perlitz, Acta Commentationes Univ Tartu, A 27, No. 11, 15 pages (1934)
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7 O. Kubaschewski, Z physik Chem, 192, 292 (1943)
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9 H. Perlitz, Keemia Teated, 2, 11 (1934)

* National Bureau of Standards, Washington, D.C.

Au-Pd Gold-Palladium

By E. M. Wise*

The liquidus has been drawn according to the results of Ruer[1] and of Fraenkel and Stern.[2] Measurements of the lattice parameter[4,5] indicate a nearly linear function of the composition expressed in atomic percentage.

The maximum electrical resistivity of about 27.5 microhm-cm occurs at about 50% Au.[6-10] The temperature coefficient of electrical resistivity has a minimum value of about 0.00034 per degree centigrade (0 to 100 C) at about 60% Au.[6,†] In the curves of these two electrical properties versus composition, peculiar changes in slope near 70% Au have not been explained.

Hardness and tensile strength are maximum at about 55% Au. The maximum values are 88 Bhn and 50,000 psi tensile strength for annealed material, and 160 Bhn and 83,000 psi for alloys reduced 66% in cold working.

Only the alloys containing less than about 15% Pd are yellow in color.

Palladium-gold alloys have been used in dentistry and for electrical contacts.

* The International Nickel Company, Inc., New York
† F. E. Carter, unpublished data

References

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2 W. Fraenkel and A. Stern, Z anorg allgem Chem, 166, 166 (1927)
3 S. Holgersson and E. Sedström, Ann Physik, 75, 149 (1924)
4 W. Stenzel and J. Weerts, "Festschrift zum 50-jähr. Bestehen der Platinschmelze G. Siebert", Hanau, 1931, p 288
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7 E. Sedström, Dissertation, Stockholm, 1924
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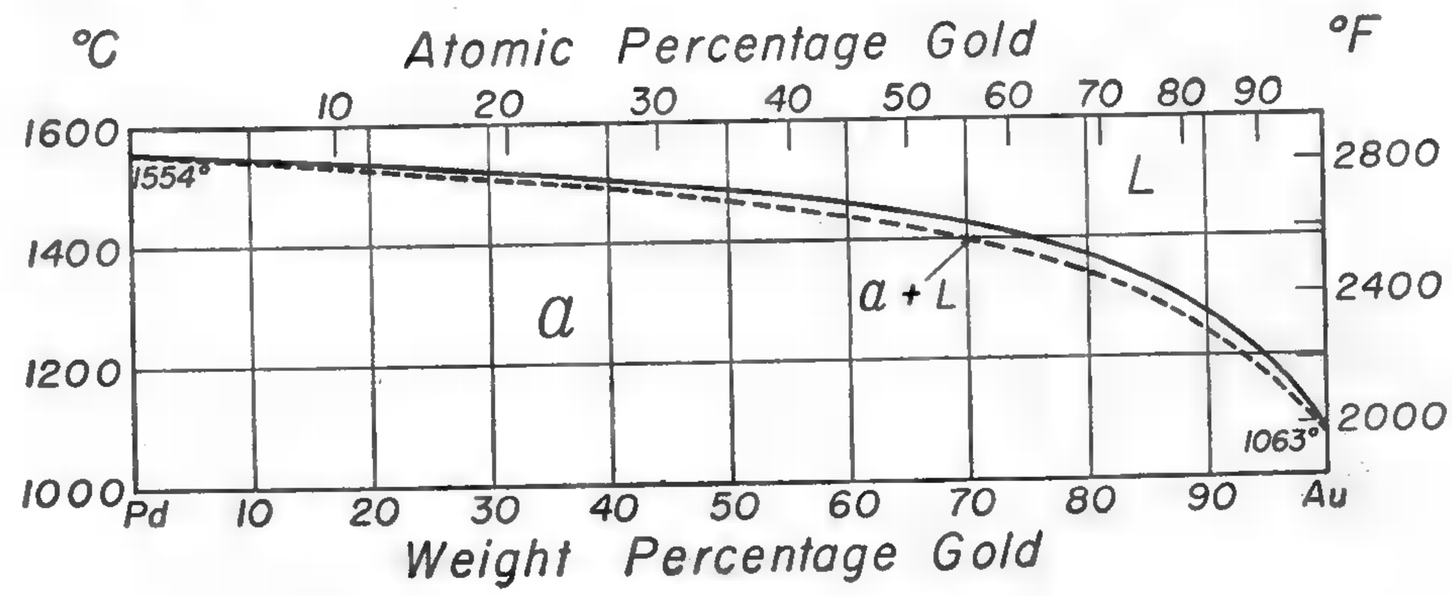
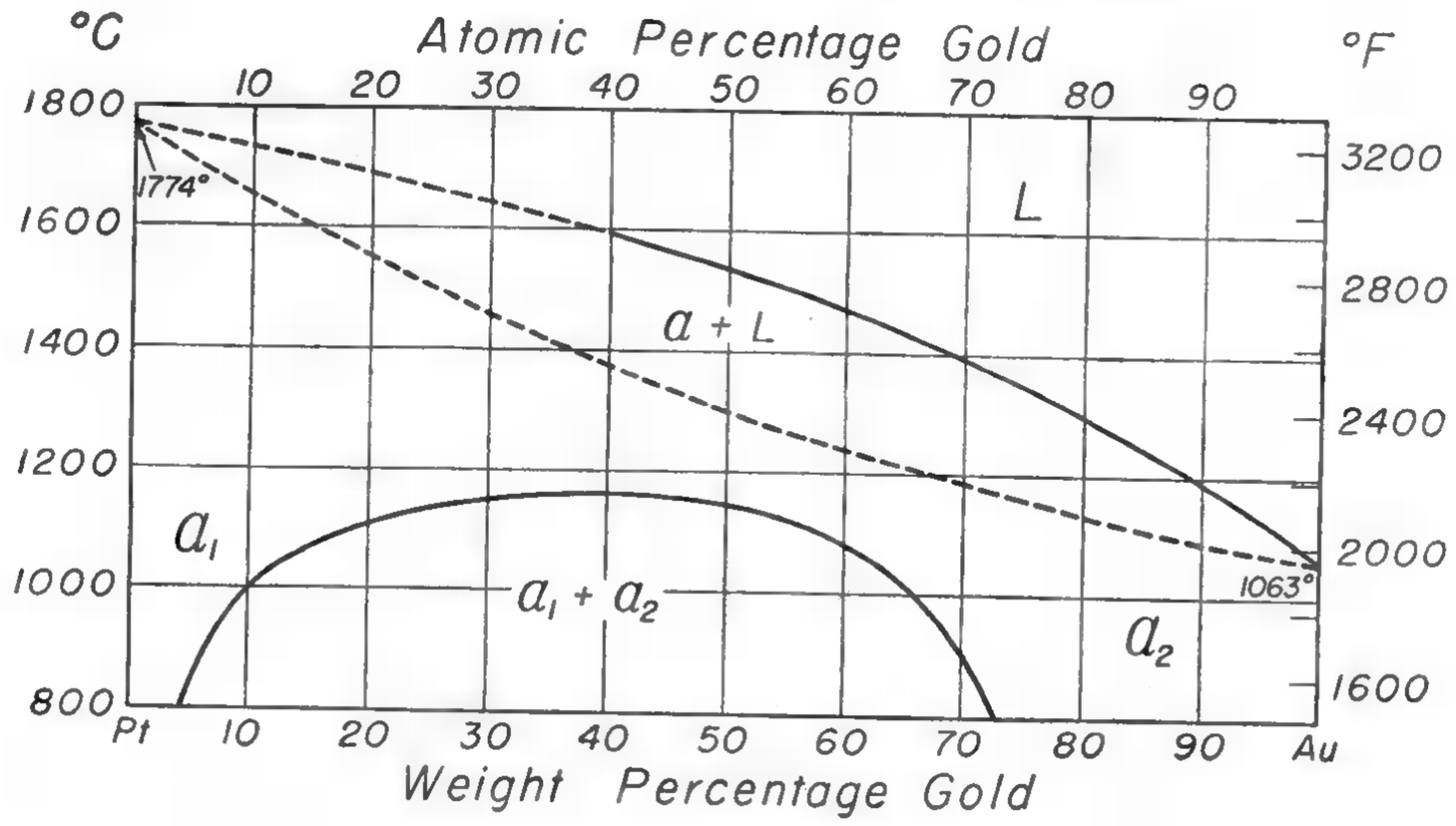


Au-Pt Gold-Platinum

By E. M. Wise*



The shape of the duplex $a_1 + a_2$ region is based on the closely agreeing work of Johansson and Linde[2] and Stenzel and Weerts.[3] It appears that at low temperature the domain of heterogeneity extends from 3% to 85 or 90% Au. At temperatures below about 600 C some additional transformations—perhaps involving ordering—may occur.

References

1 F. Doerinckel, Z anorg Chem, 54, 345 (1907)
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3 W. Stenzel and J. Weerts, "Festschrift zum 50-jähr Bestehen der Platinschmelze G. Siebert", Hanau, 1931, p 300
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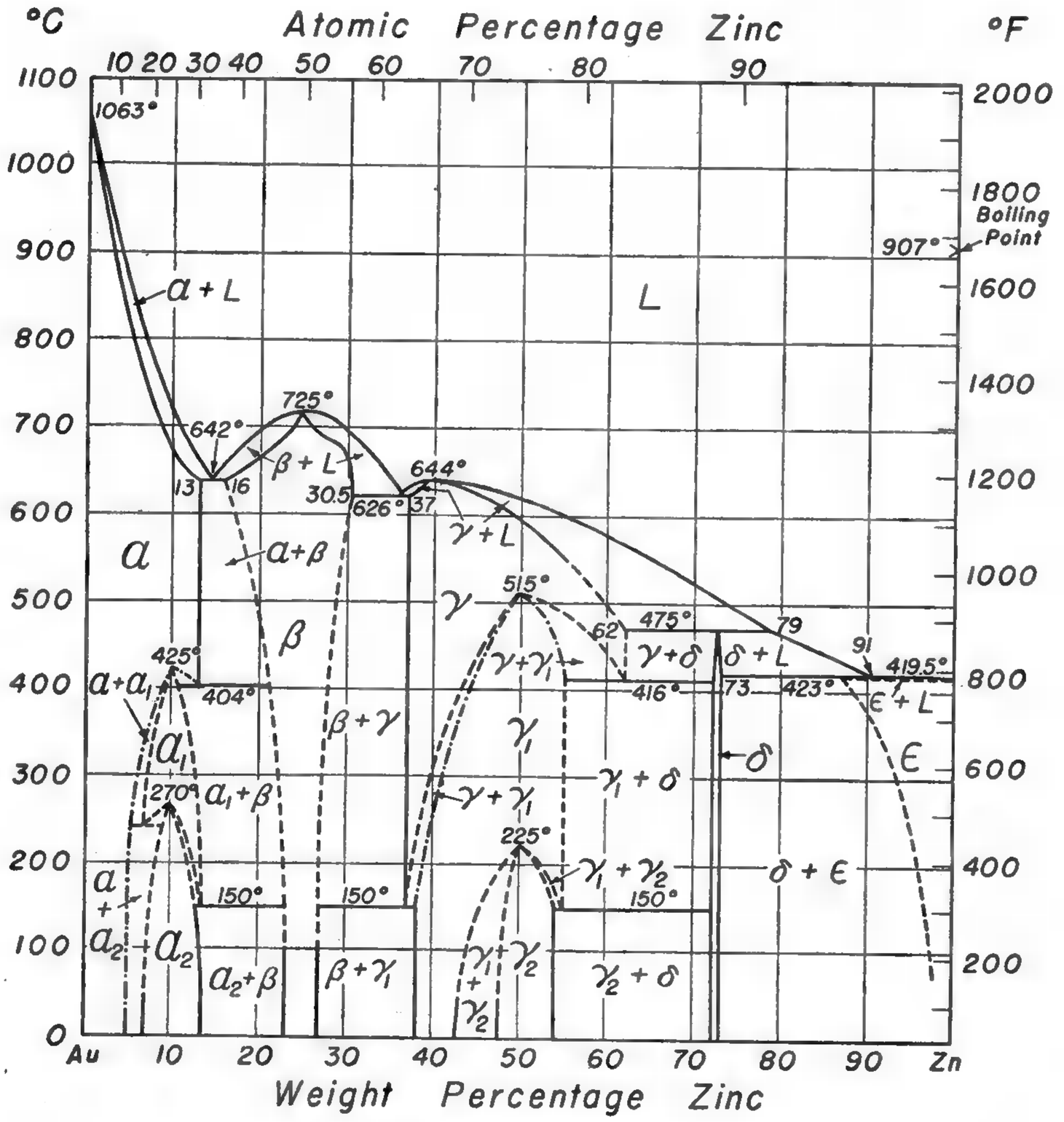
* The International Nickel Company, Inc., New York

Au-Zn Gold-Zinc

By Fred M. Reinhart*



The gold-zinc system is analogous to copper-zinc but is complicated by the formation of several ordered phases at low temperature. There are five types of structure common to both systems.[1]

A superstructure is present in the β-phase alloys quenched from temperatures up to the melting point.[5]

The diagram is based on Hansen's[3] review of the work of Vogel[4] and of Soldau[2] and on more recent work by Ageew and Shoykhet.[6]

The β phase is body-centered cubic (CsCl type) with ■ = 3.146 kX at 30.2% Zn. γ is cubic with 52 atoms per unit cell; the lattice parameter is 9.223 kX at 41.1% Zn. γ_1 and γ_2 have complex cubic crystal structures that contain, respectively, 90 and 32 atoms per unit cell. The δ and ϵ phases are close-packed hexagonal with axial ratios of 1.55 to 1.60 and 1.80 to 1.90, respectively.

References

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2 P. Soldau, J Inst Metals, 30, 351 (1923)
3 M. Hansen, "Der Aufbau der Zweistofflegierungen", J. Springer, Berlin, 1936
4 R. Vogel, ■ anorg Chem, 48, 319 (1906)
■ E. A. Owen and I. G. Edmunds, Proc Phys Soc (London), 50, 389 (1938)
6 N. V. Ageew and D. N. Shoykhet, Izvest Sektor Fiz-Khim Anal, 13, 165 (1940)

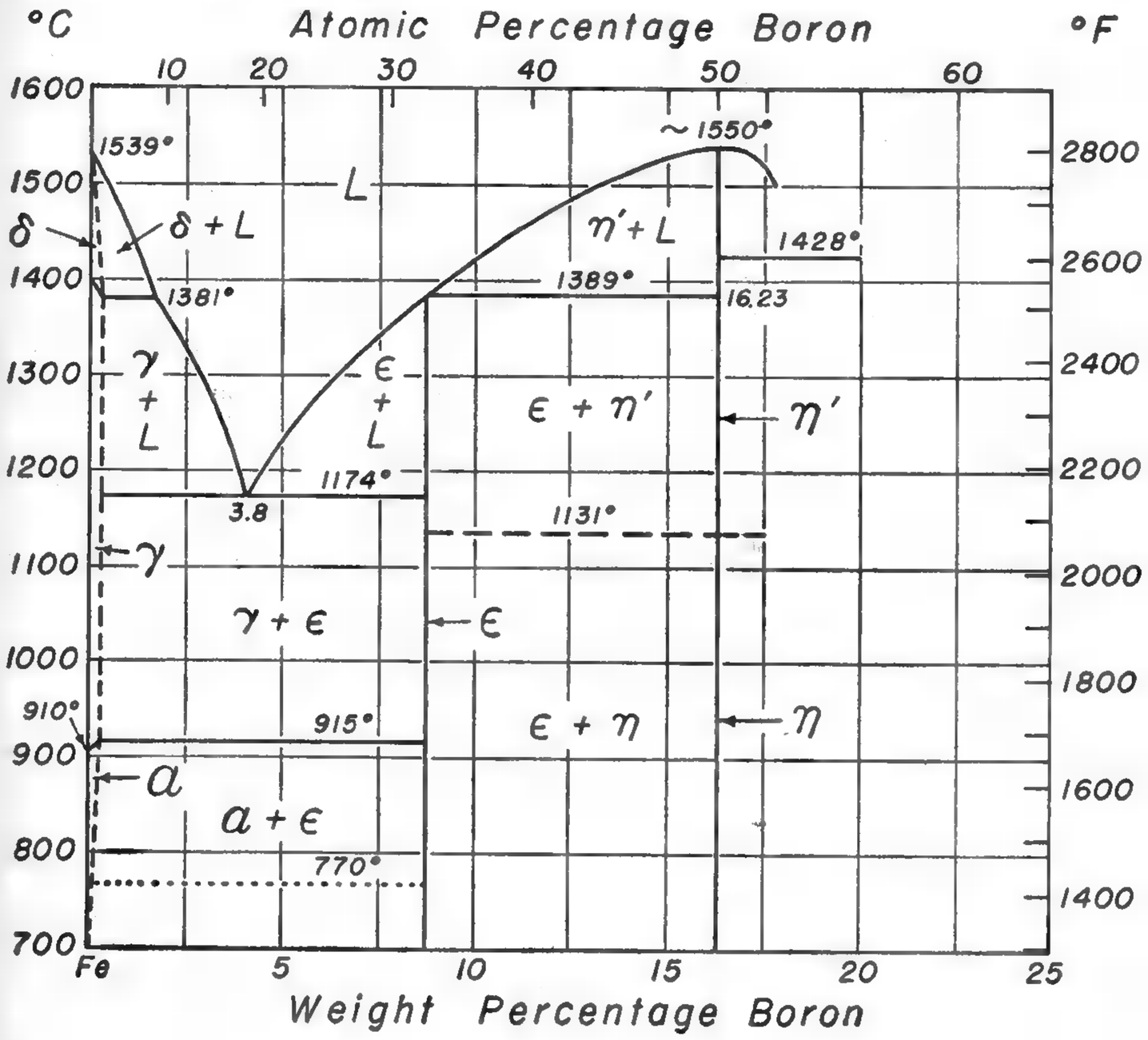
* National Bureau of Standards, Washington, D.C.

B-Fe Boron-Iron

By R. M. Parke*

Wever and Müller[1,2] determined that the compound Fe_2B has a body-centered tetragonal structure with four Fe_2B groups in the unit cell. Bjurstrom and Arnfelt[3] verified the structure of Fe_2B and also determined that the monoboride FeB has a rhombic structure with four FeB groups to the unit cell. Unlike carbon, boron forms substitutional solid solutions with alpha iron and probably with gamma iron.[4] The solubility of boron in delta iron is 0.15% at 1381 C. In gamma iron the maximum solubility is about 0.1%. The solubility of boron in alpha iron is less than 0.15% at 915 C.[4]

With five alloys containing 0.06 to 2.5% B, Wasmuht[8] studied precipitation hardening after quenching from 750 C. No hardening was observed, and it is concluded therefore that there is very little decrease in the solubility of boron in alpha iron as the temperature decreases below 750 C.



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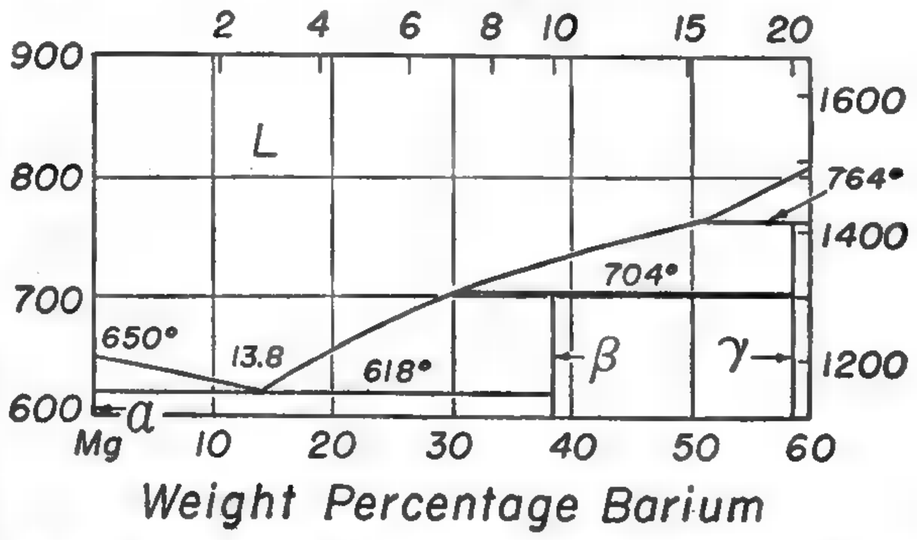
*Kellex Corporation, Silver Spring, Md.

Ba-Mg Barium-Magnesium

By Louis A. Carapella*



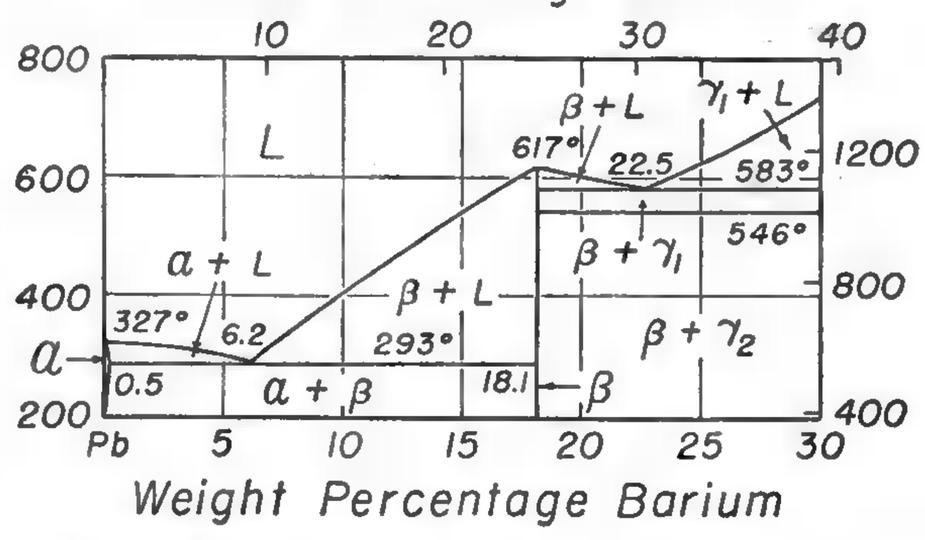
The diagram is based on the results of Grube and Dietrich [Z Elektrochem, 44, 755 (1938)], who investigated the range of composition up to approximately 80% Ba.

The β phase corresponds to the composition $BaMg_9$ (38.56% Ba); γ is $BaMg_4$ (58.54% Ba). The compound Ba_2Mg_5 (about 69% Ba) melts congruently at 855 C, and forms a eutectic with a barium-rich phase at 76.1% Ba (746 C).

* Mellon Institute of Industrial Research, Pittsburgh

Ba-Pb Barium-Lead

By Louis A. Carapella*



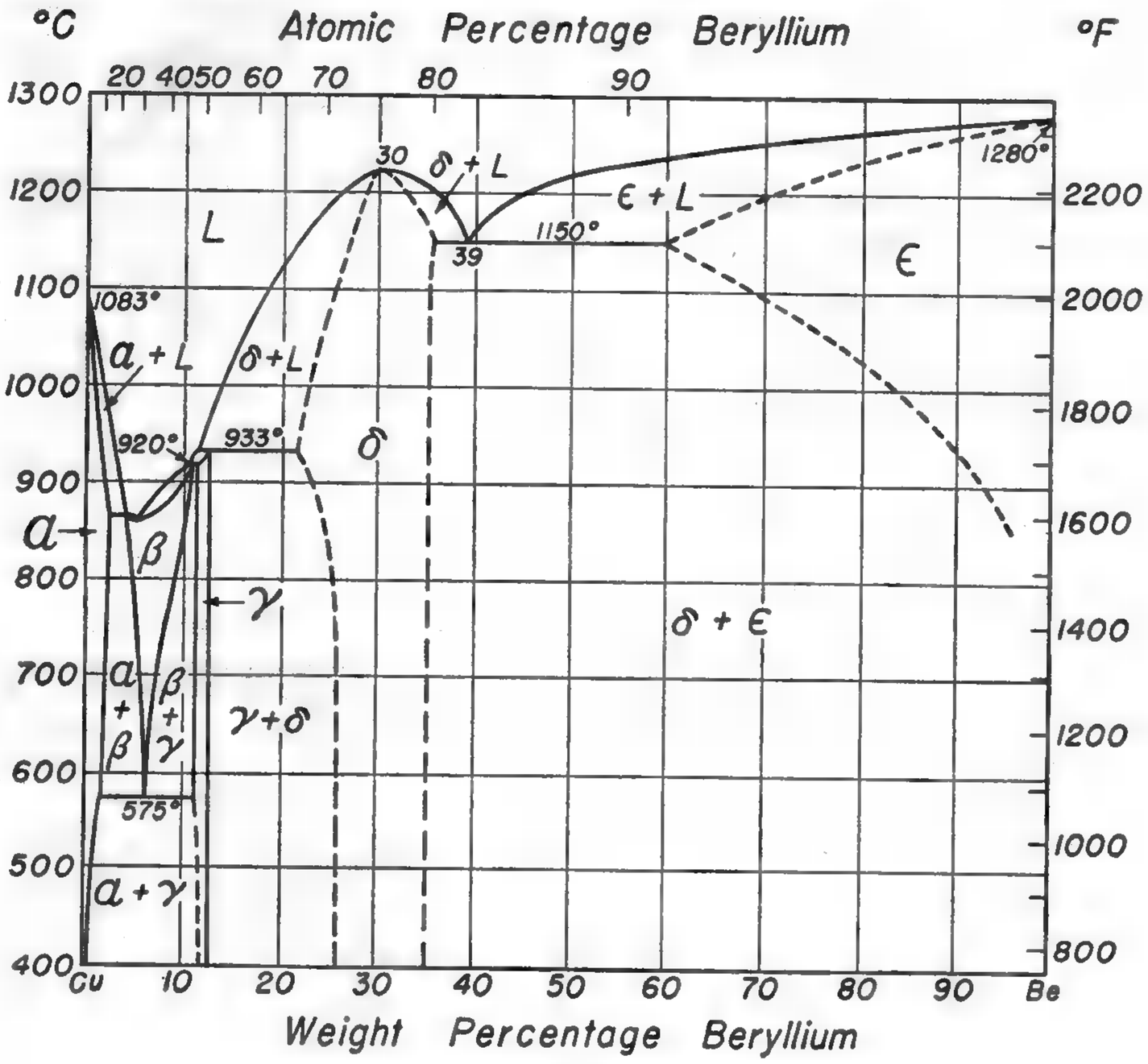
The diagram is based on the results of Grube and Dietrich [Z Elektrochem, 44, 755 (1938)], who investigated the entire range of composition in the barium-lead system.

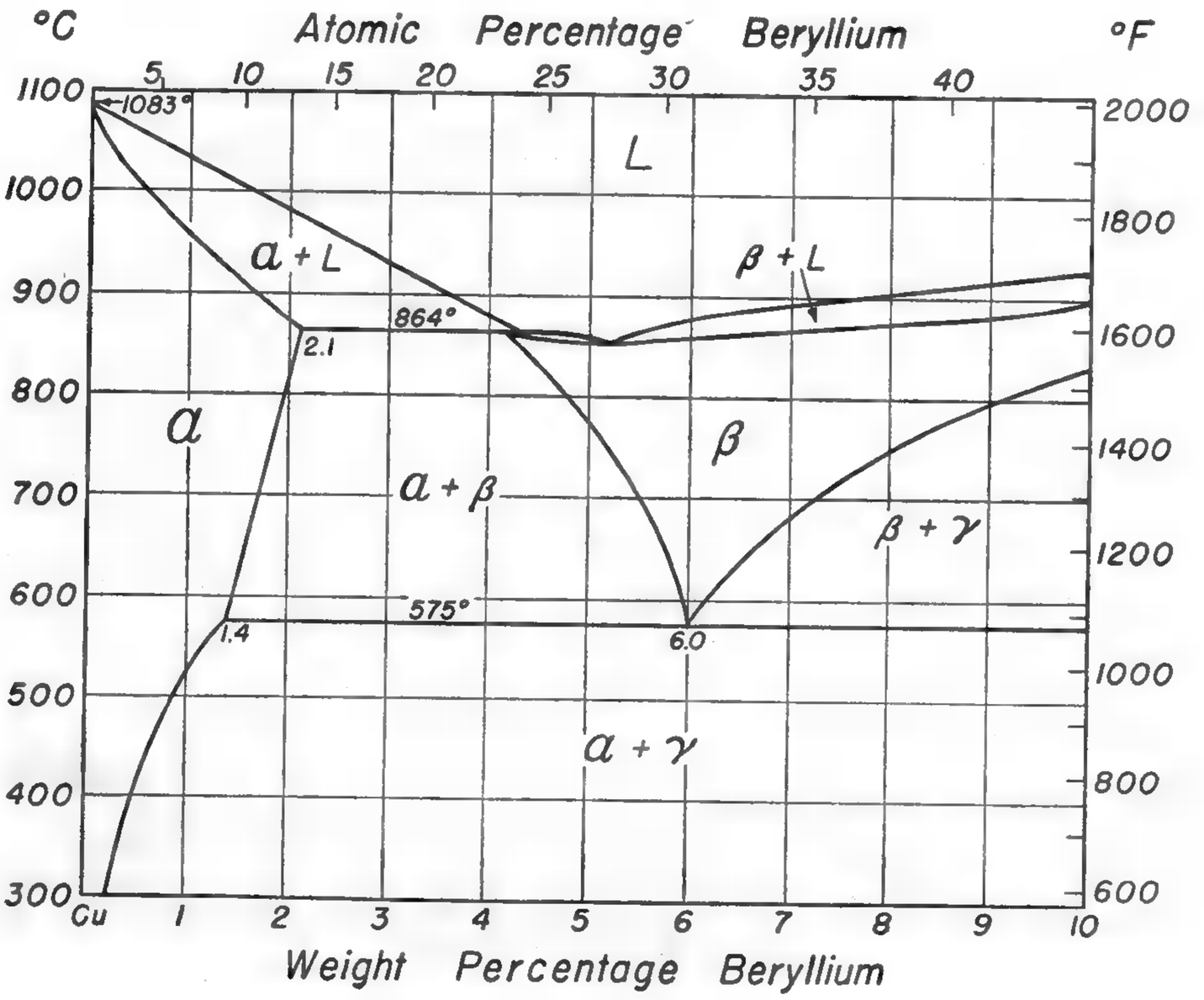
The β phase is $BaPb_3$. The γ phase (BaPb) undergoes allotropic transformation at 546 C, and melts peritectically at 850 C. The compound Ba_2Pb melts congruently at 928 C and forms a eutectic with barium at 75% Ba (595 C).

* Mellon Institute of Industrial Research, Pittsburgh

Be-Cu Beryllium-Copper

By H. F. Silliman*





The diagram is relatively well established except for the extent of δ phase and the solubility of copper in beryllium. The liquidus and the eutectic horizontal at 1150 C are based solely on the work of Losana and Venturello.[10] The high solubility of copper in solid beryllium, as suggested by these investigators, was based on thermal analysis alone; the values appear doubtful. Thermal arrests in high-beryllium alloys between 500 and 800 C indicate that the diagram is more complex than shown here.

The minimum in the liquidus curve for the β phase has been questioned[5] but the weight of evidence favors it. The α boundary is from the work of Tanimura and Wassermann.[4] The curvature of the boundary between the $\alpha + \gamma$ and γ fields, suggested by Iwasé and Okamoto,[5] gains some support from X-ray studies on aged samples.[6]

The γ phase corresponds to the composition CuBe. Although the maximum in the liquidus of the δ phase is at the composition $CuBe_3$, the structure is said to be of the same type as $CuMg_2$, and the phase is reported to include the composition $CuBe_2$.[7,10]

The lattice parameter of the face-centered cubic α phase is 3.566 kX at 2.1% Be.[4,6] The β phase is body-centered cubic, disordered, with $a = 2.79$ kX at 7.2% Be and 750 C.[9]

The γ phase is body-centered cubic with the CsCl type of ordering. The lattice parameter is 2.70 kX.[6,7] The cubic δ phase ($CuMg_2$-type) has a lattice parameter of 5.940 to 5.887 kX.[7,10]

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5 K. Iwasé and M. Okamoto, Nippon Kinzoku Gakkai-Si, 5, 82 (1941)
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7 L. Misch, Z physik Chem, B 29, 42 (1935)
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9 G. F. Kossolapov and A. K. Trapesnikov, Metallwirtschaft, 14, 45 (1935)
10 L. Losana and G. Venturello, Alluminio, 11, 9 (1942); Chem Abs, 37, 5004 (1943)

* The American Brass Company, Waterbury, Conn.

Be-Fe Beryllium-Iron

By R. M. Parke*

Beryllium in iron closes the "gamma loop". The γ field does not extend beyond 0.4% Be.[1] The solubility of beryllium in α is 7.5 to 8% at 1150 C and 4.5 to 5% at low temperature. A eutectic is formed between the α phase and the hexagonal compound $FeBe_2$ at 10% Be and 1150 C.[2]

References

1 I. S. Gaev and R. S. Sokolov, Metallurg, (4), 42 (1937)
2 M. Hansen, "Der Aufbau der Zweistofflegierungen", J. Springer, Berlin, 1936

* Kellex Corporation, Silver Spring, Md.

Be-Mg Beryllium-Magnesium

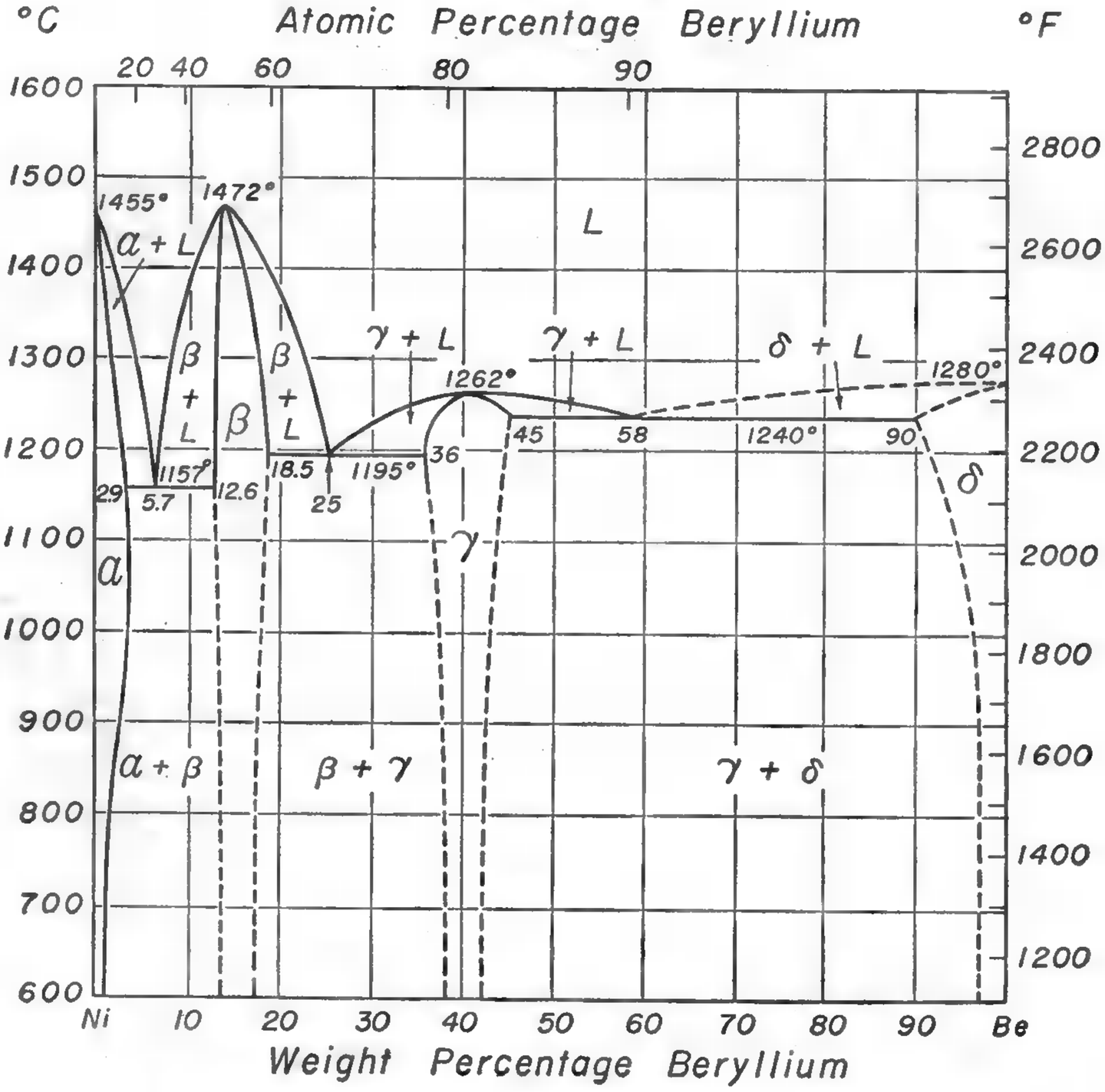
By Taylor Lyman*

It is impossible to produce magnesium-beryllium alloys by the usual methods because the boiling point of magnesium (1110 C) is below the melting point of beryllium (1280 C). A process has been described [*see* Met Abs, 7, 109 (1940)] for producing such alloys under a pressure of more than 100 atmospheres of hydrogen. Small amounts of beryllium, contained in an aluminum-beryllium master alloy, are sometimes added during the melting of commercial magnesium alloys that are to be wrought (*see* page 974). The solubility of beryllium in magnesium is very small.

* Editor, Metals Handbook

Be-Ni Beryllium-Nickel

By E. N. Skinner†



Interest in the constitution of beryllium-nickel alloys has been confined principally to the study of the nickel-rich α solid solution,[1,2] which exhibits exceptional precipitation hardening.

Losana and Goria[3] have investigated this system in the range from 10 to 100% Be. These investigators observed isothermal reactions at 1157, 1195 and 1240 C, involving intermetallic phases designated as β and γ. These phases include the compositions NiBe and Ni_5Be_{21} respectively. Both phases melt congruently — β at 1472 C and γ at 1262 C. Because of the experimental difficulties in the preparation of beryllium-nickel alloys, there is some uncertainty concerning the shapes of the liquidus, solidus and solvus curves shown for the beryllium-rich compositions.

† The International Nickel Company, Inc., New York.

Beryllium dissolved in high-purity nickel depresses the Curie temperature, as follows:[4]

Weight % Be	0	0.5	1.0	1.5	2.0	2.5
Curie temperature, °C	350	280	220	160	95	35

The β phase has the CsCl type of body-centered cubic structure with $a = 2.603 \pm 0.003$ kX.[5] The γ phase has a deformed gamma-brass type of cubic structure with a lattice parameter of 7.56 kX.

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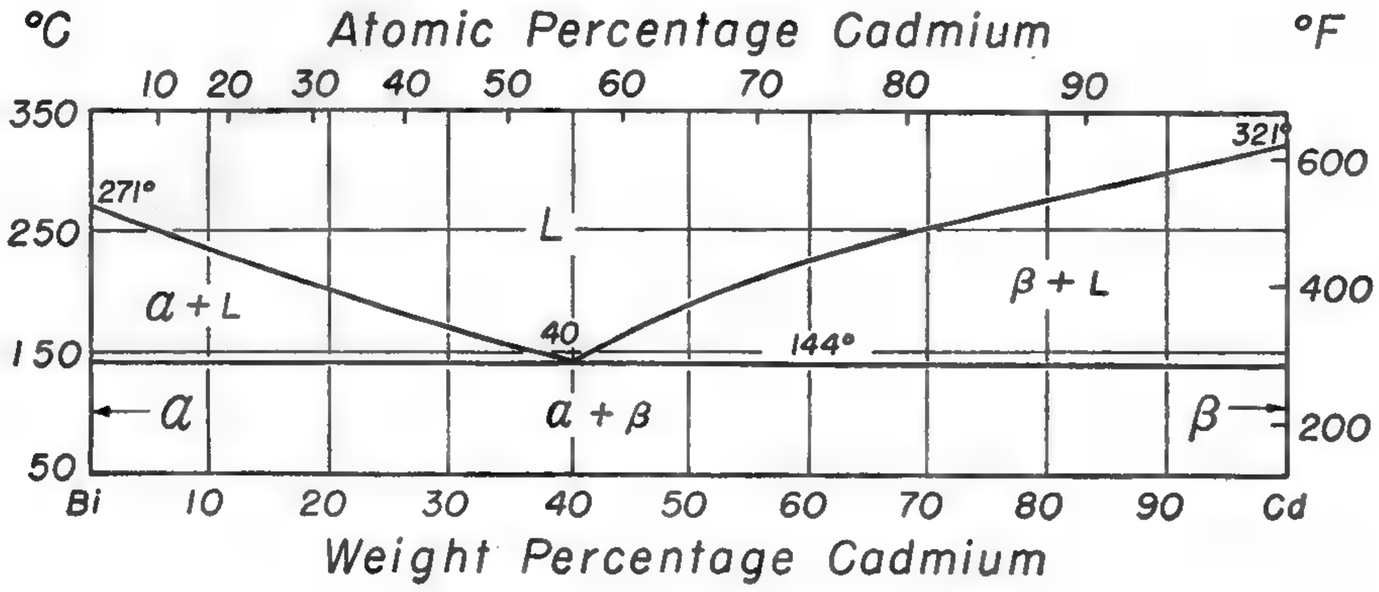
Bi-Cd Bismuth-Cadmium



The diagram has been taken without change from Hansen,[1] who states that the liquidus temperatures are accurate to less than 5 C. According to Tammann and Rocha,[2] the solubility of bismuth in cadmium is less than 0.05% at the eutectic temperature (144 ± 2 C[1]).

References

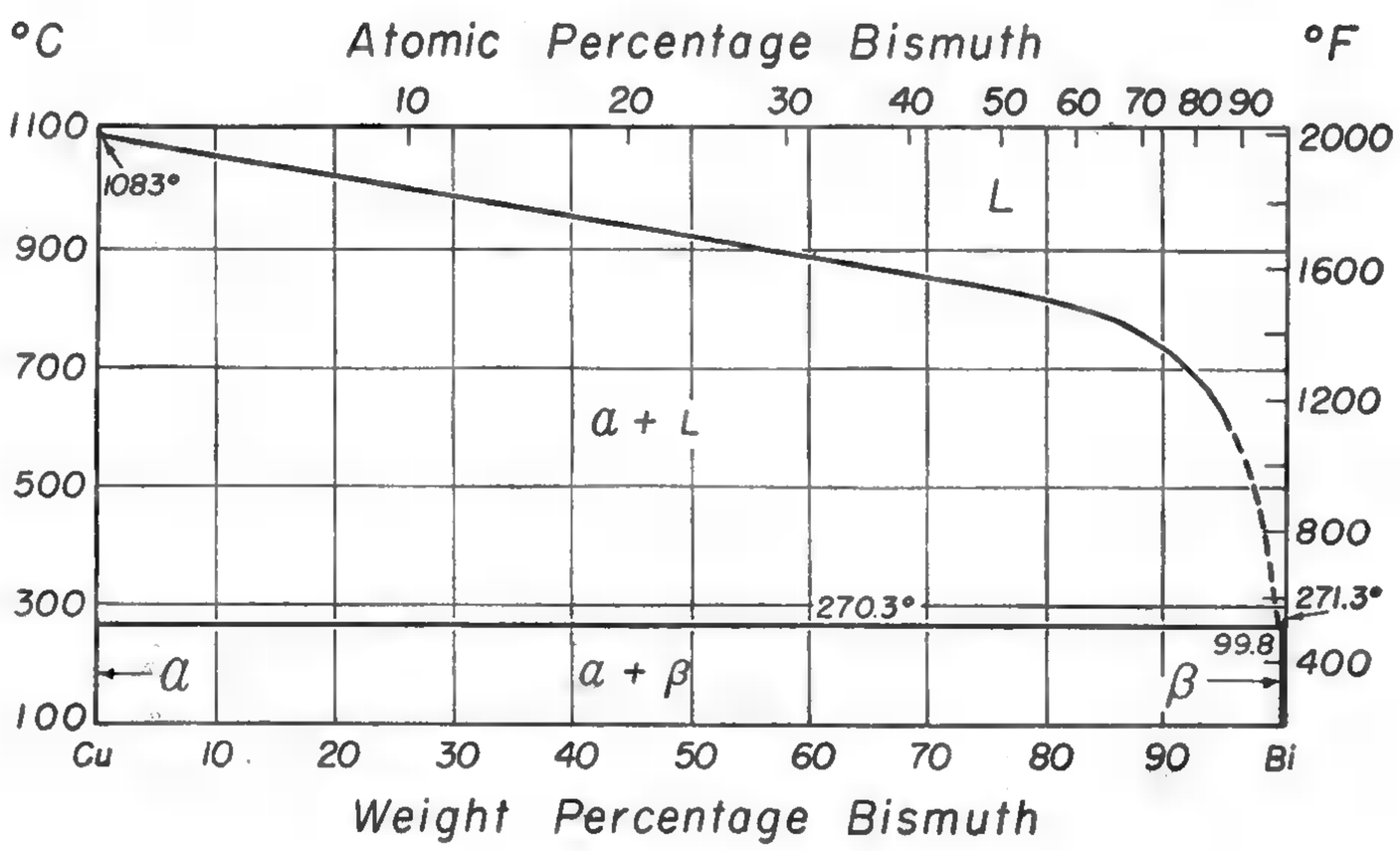
1 M. Hansen, "Der Aufbau der Zweistofflegierungen", J. Springer, Berlin, 1936, p 295
2 G. Tammann and H. J. Rocha, Z Metallkunde, 25, 133 (1933)

Bi-Cu Bismuth-Copper

By A. C. Vaughan*

The eutectic temperature is about one degree Centigrade lower than the melting point of bismuth.[3] Liquidus temperatures are reported in references 4, 5, 6, 7 and 8.

The solubility of bismuth in solid copper was determined by Hanson and Ford,[1] with microscopic methods, as about 0.001% after quenching from 980 C. Blazey[9] showed that the amount of bismuth necessary to cause hot shortness in arsenical deoxidized copper (and presumably closely related to the solubility) decreases from 0.006% at 725 C to less than 0.002% at 600 C. The practical insolubility of either metal in the other was indicated by measurements of the lattice parameter by Ehret and Fine.[2]



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9 C. Blazey, J Inst Metals, 46, 353 (1931)

* American Smelting and Refining Company, Barber, N. J.

Bi-Fe Bismuth-Iron

By R. M. Parke*

According to Isaac and Tammann,[1] bismuth and iron are virtually insoluble in each other in the molten state, and this has been confirmed by Hägg.[2] Using a magnetic method, Tammann and Oelsen[3] determined that 0.0002 to 0.0004% Fe dissolved in bismuth heated to 400 and 1600 C under a hydrogen atmosphere.

References

1 E. Isaac and G. Tammann, Z anorg Chem, 55, 59 (1907)
2 G. Hägg, Z Krist, 68, 472 (1928)
3 G. Tammann and W. Oelsen, Z anorg allgem Chem, 186, 277 (1930)

* Kellex Corporation, Silver Spring, Md.

Bi-Hg Bismuth-Mercury

By Louis A. Carapella†

A continuous liquidus curve with no evidence of compound formation has been established.[1,2] A eutectic point at 99.9% Hg has been suggested.[3] There is some indication of a solidus temperature at minus 39.2 C for mercury-rich alloys.[3,4,5] Data are lacking for the bismuth-rich alloys.

References

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2 C. T. Heycock and F. H. Neville, J Chem Soc, 61, 888 (1892)
3 G. Tammann, Z physik Chem, 3, 441 (1889)
4 D. Mazzotto, Z physik Chem, 13, 572 (1894)
5 K. Bornemann, Metallurgie, 7, 109 (1910)

† Mellon Institute of Industrial Research, Pittsburgh

Bi-Mg Bismuth-Magnesium

By G. F. Sager* and B. J Nelson*

The extent of the $\beta + \gamma$ field has not been firmly established.

The solubility of bismuth in magnesium is, as follows:

Temperature, °C	553	525	500	450
% Bi	9.05	6.56	4.95	2.81
Temperature, °C	400	350	300	250
% Bi	1.53	0.79	0.33	0.1

The γ phase is hexagonal with $a = 4.666$ kX, $c = 7.401$ kX.[3]

Bismuth has little effect on the mechanical properties of magnesium. There are no magnesium-bismuth alloys of commercial importance.

References

1 R. Kremann and H. Eitel, Z Metallkunde, 12, 363 (1920)
2 E. Zintl and E. Husemann, Z physik Chem, B 21, 138 (1933)
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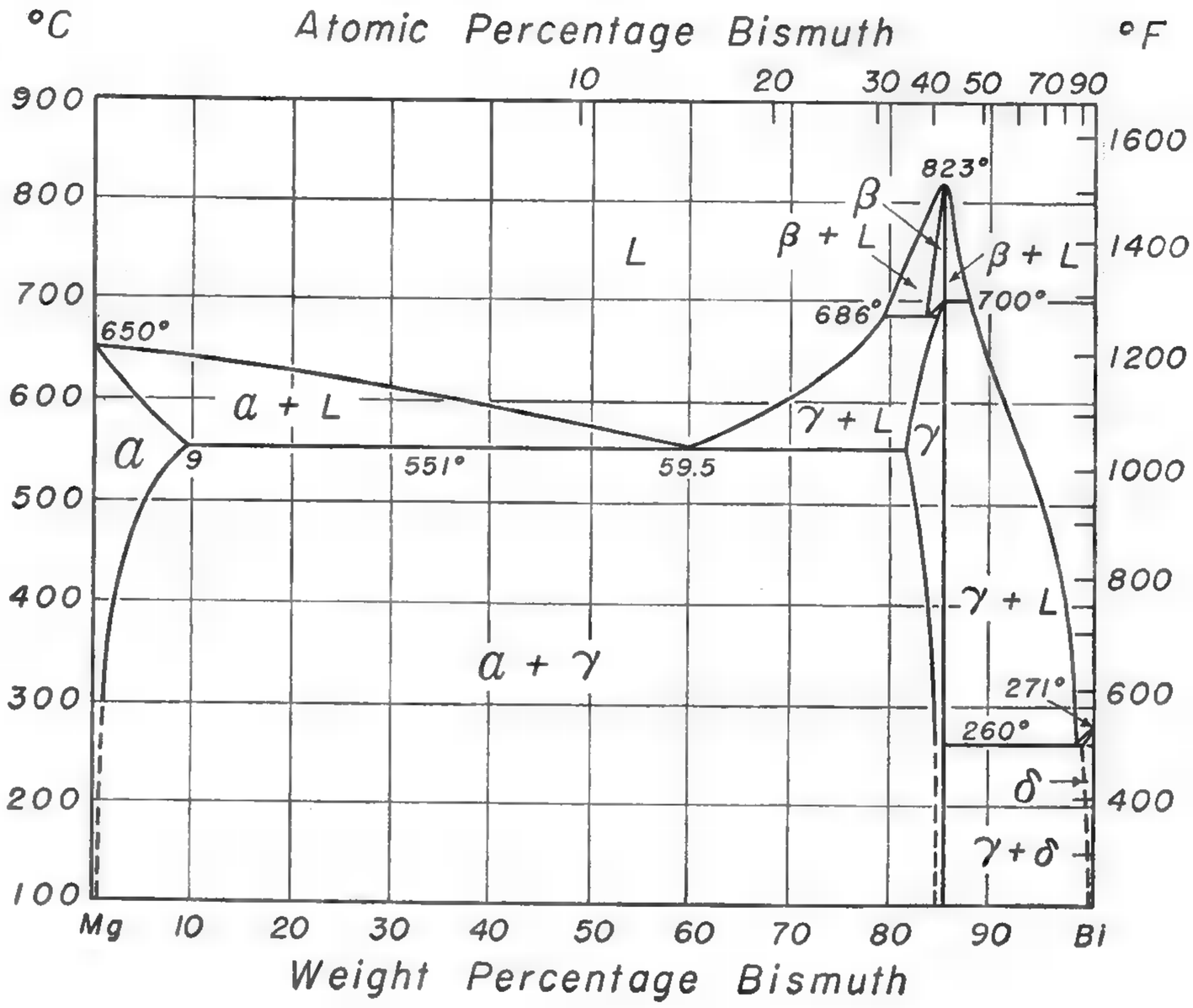
5 H. Vosskühler, Metallwirtschaft, 22, 545 (1943)

* Aluminum Research Laboratories, New Kensington, Pa.



Bi-Pb Bismuth-Lead

By G. O. Hiers*

The diagram is based on the references listed and on unpublished data of W. C. Smith concerning the eutectic.

The solubility of bismuth in lead is 21.5% at 184 C and 18.8% at 20 C.

The β phasé has been reported to be hexagonal with $a = 3.507$ kX and $c/a = 1.646$.

Bismuth-lead compositions are used as "low-melting alloys" (*see* page 744).

References

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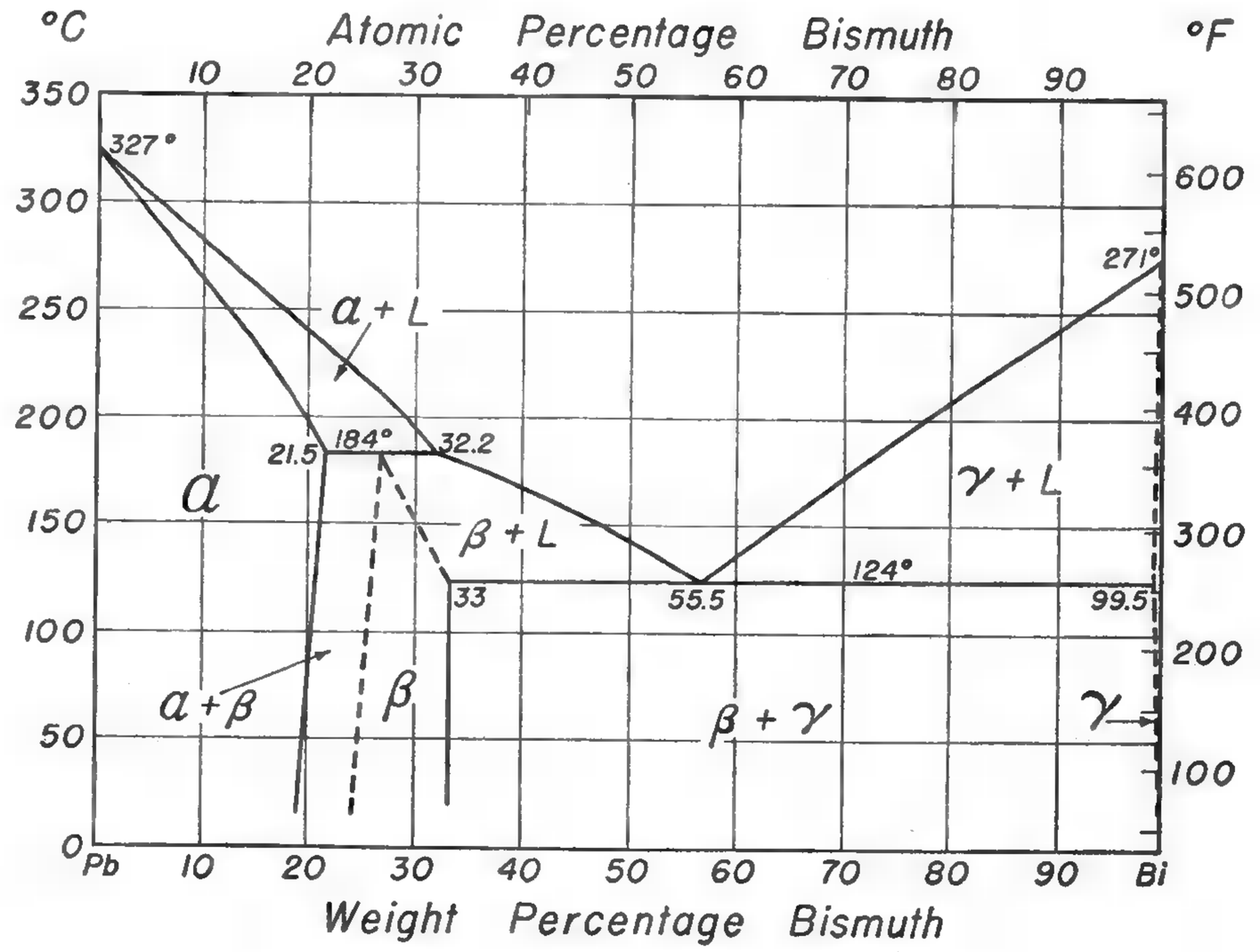
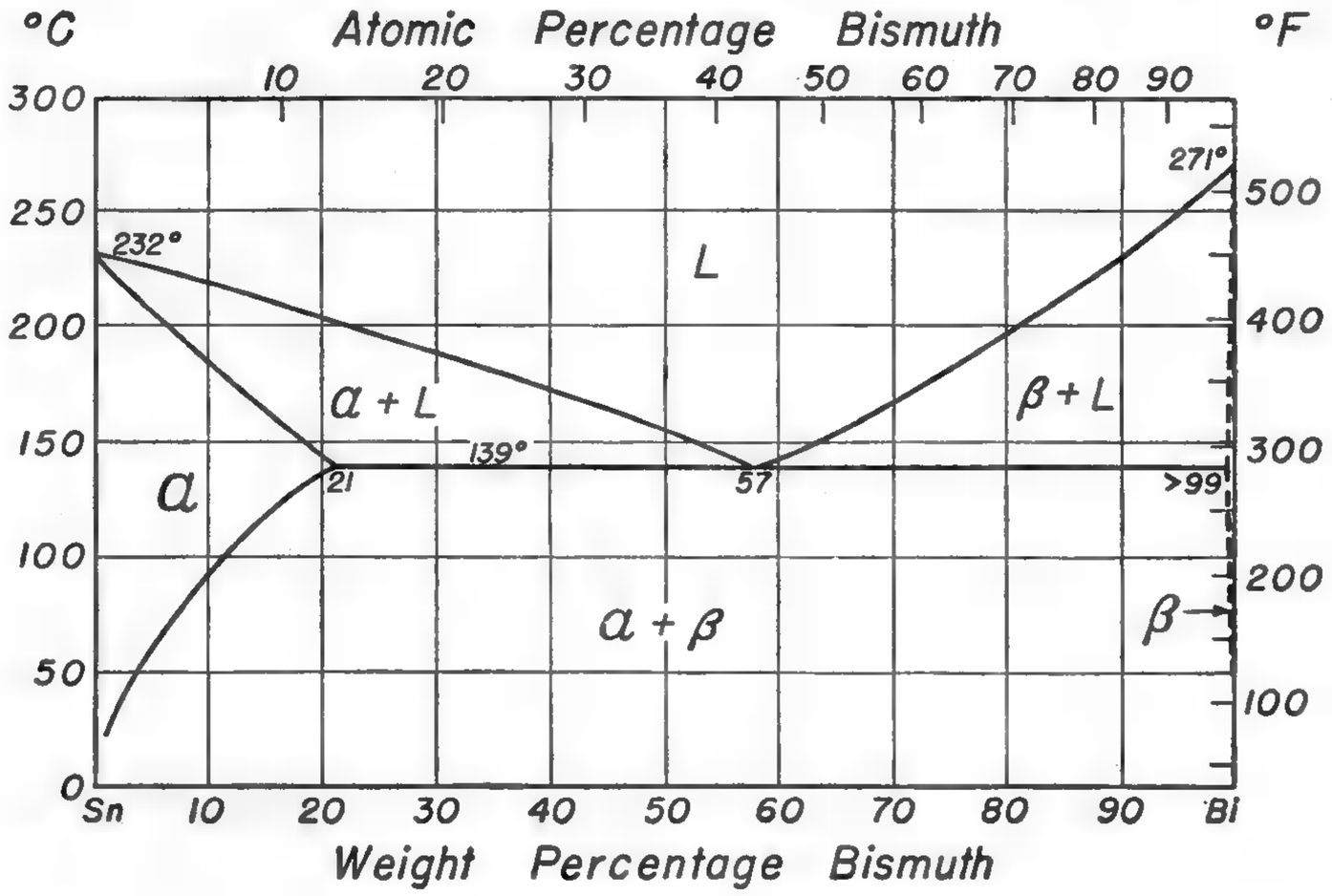
* Metallurgist, National Lead Company, Brooklyn



Bi-Sn Bismuth-Tin

By R. I. Jaffee* and Bruce W. Gonser*



Long annealing at the eutectic temperature is required for attainment of the maximum solubility of bismuth in α. Chill-cast specimens containing as little as 8% Bi show some eutectic.[2] The maximum solubility of tin in β is probably about 0.1%.

An alleged eutectoid transformation at 95 C is now generally discredited, and thermal arrests at that temperature are believed to be the result of precipitation of β from the supersaturated α solid solution.

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2 A. C. Davidson, The Constitution of the Alloys of Tin with Bismuth, Intern Tin Research Development Council, Tech Pub A77, 1938
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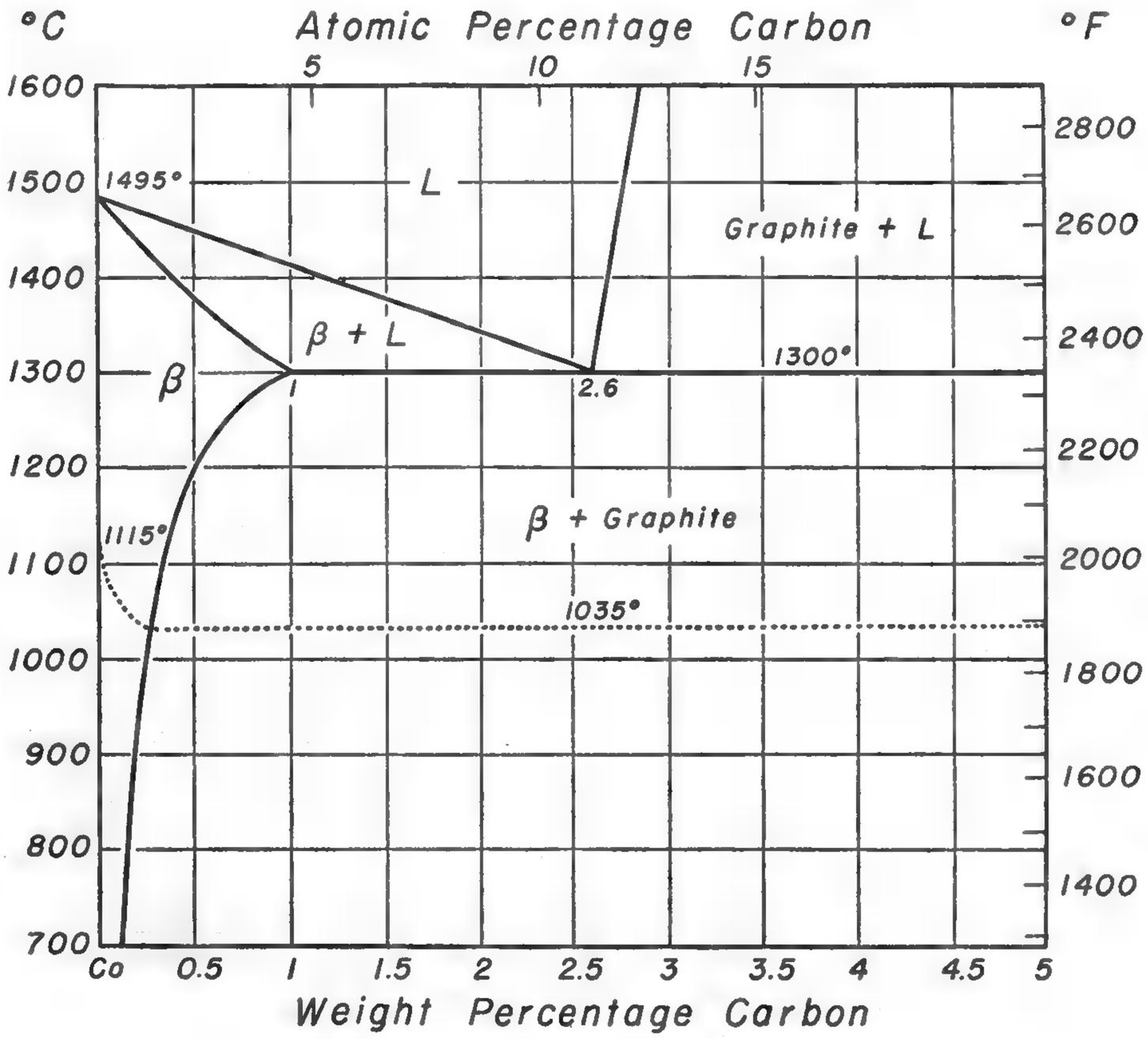
* Battelle Memorial Institute, Columbus, Ohio

C-Co Carbon-Cobalt

By W. P. Sykes*



The accompanying diagram is based on the extremely meager amount of data appearing in the literature.[1,2] One investigator[2] thinks it likely that a carbide, Co_3C, forms the second solid phase of the eutectic, but that this carbide decomposes so readily that it can be retained only by a most drastic quench from the molten state.

As indicated by the dotted line on the diagram, carbon in solution in β cobalt lowers the magnetic transformation temperature from 1115 to 1035 C.

Recently a new cobalt carbide, described as Co_2C (9.3% C), has been prepared by reacting carbon monoxide with cobalt at 230 C.[3] The stability of this phase with respect to α cobalt and graphite is not known. Measurements of the lattice parameter of carburized α cobalt give no evidence of any solid solubility of carbon in α cobalt.[3]

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* Lamp Department, General Electric Company, Cleveland

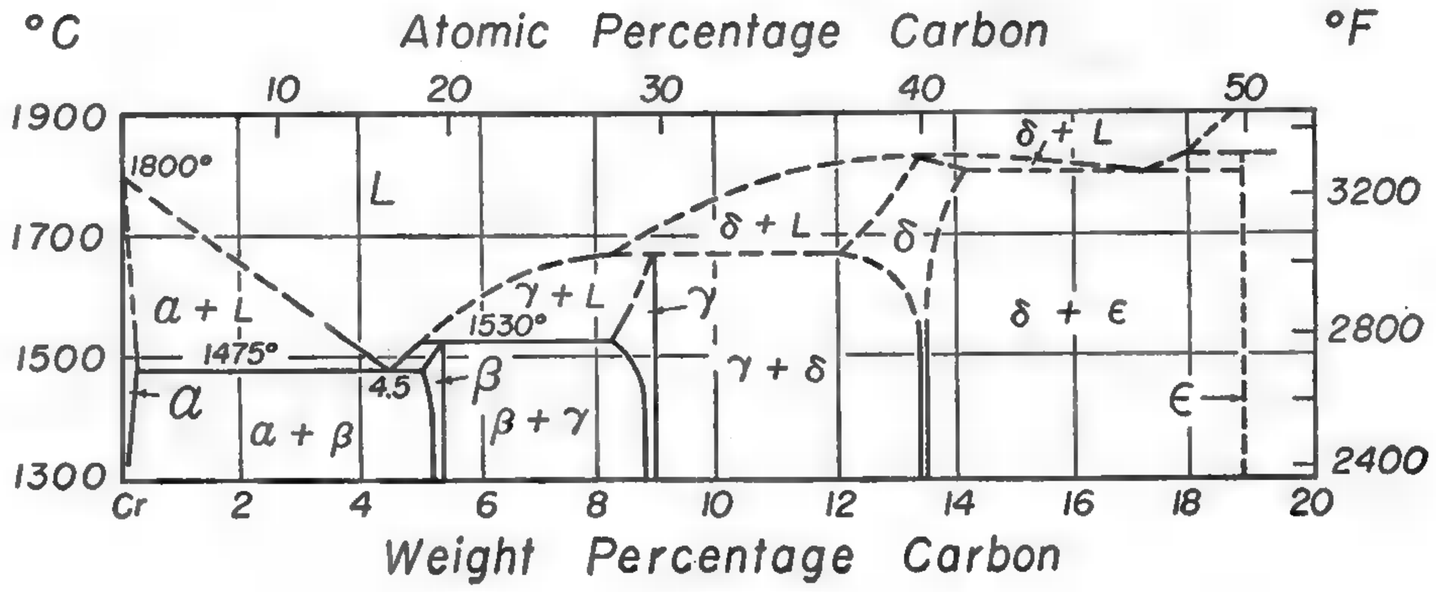
C-Cr Carbon-Chromium

By W. P. Sykes*

The solubility of carbon in solid chromium is probably less than 0.1%.

The existence of the ϵ phase is questionable.

The β phase (Cr_4C or $Cr_{23}C_6$) is cubic with $a = 10.64$ kX; γ (Cr_7C_3) is hexagonal with 80 atoms per unit cell; and δ (Cr_3C_2) is orthorhombic with 20 atoms per unit cell.



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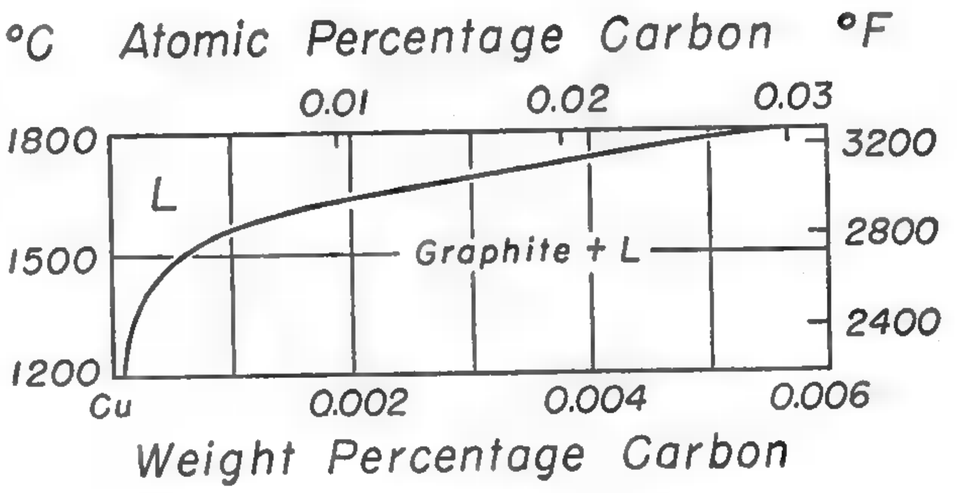
*Lamp Department, General Electric Company, Cleveland

C-Cu Carbon-Copper

The solubility of carbon in liquid copper is shown in the adjoining diagram according to the results of Bever and Floe [Trans AIME, 166, 128 (1946)]. These investigators reported also that the solubility of carbon in molten tin bronzes is approximately the same as in pure copper. It is not known whether the carbon-copper system is of the eutectic or peritectic type.

This system is of interest principally because of the relation between the solubility of carbon and the formation of insoluble carbonaceous gases when the carbon-bearing copper is exposed to oxidizing conditions.



C-Fe Carbon-Iron

By J. B. Austin*

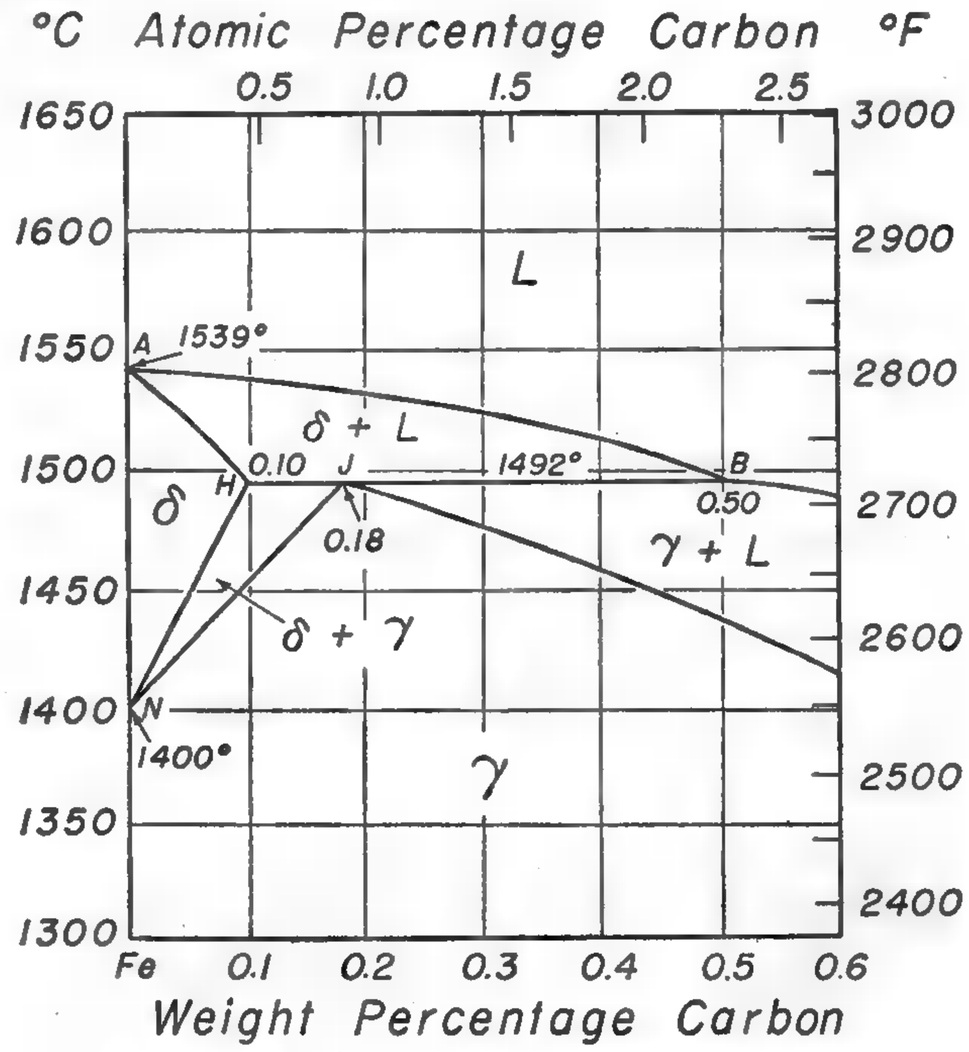
The common names for the alpha, gamma and Fe_3C phases are, respectively, ferrite, austenite and cementite. Cementite is unstable with respect to graphite and the iron solutions. The dashed lines on the diagram represent equilibriums in the stable system iron-graphite; the solid lines represent the metastable iron-cementite system.

Ferrite dissolves 0.025% C at the eutectoid temperature;[6] the solubility is undoubtedly less at lower temperatures.

The crystal structures and lattice parameters of the phases are, as follows: α, body-centered cubic, $a = 2.8610$ kX at 20 C; γ, face-centered cubic, $a = 3.64$ at 910 C; δ, body-centered cubic, $a = 2.92$ at 1400 C; Fe_3C, orthorhombic, $a = 4.5155$, $b = 5.0773$, $c = 6.7265$ at 25 C; graphite, hexagonal, $a = 2.46$, $c = 6.78$ at 20 C.

The variation of the lattice parameter of austenite with carbon content in the range 750 to 1100 C, can be expressed approximately by the relation:

$$Increase\ in\ parameter = 0.0027 \times (\%C \times 10)^3$$



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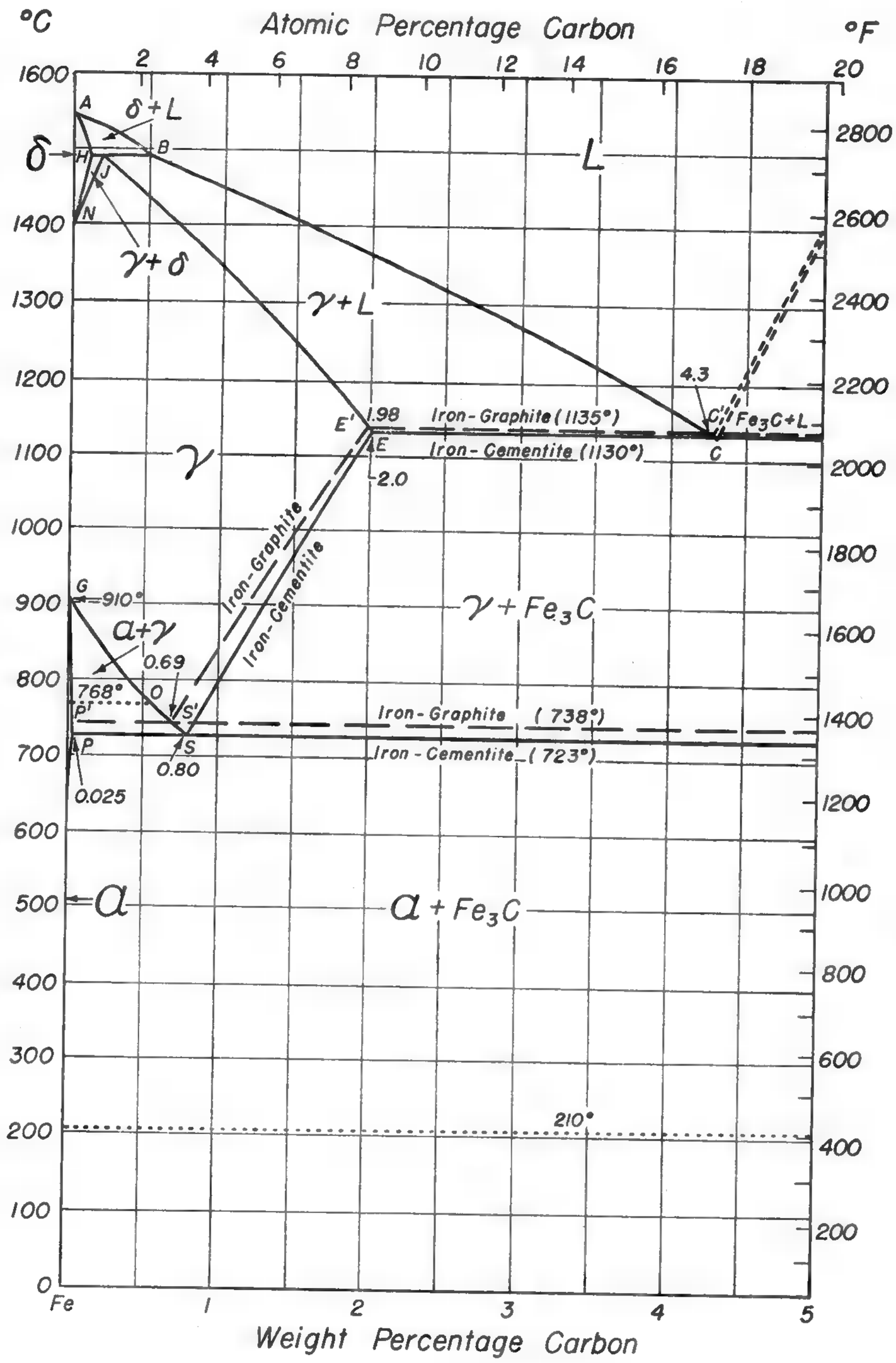
4 R. W. Gurry, Trans AIME, 150, 147 (1942)
5 H. E. Cleaves and J. M. Hiegel, J Research Nat Bur Standards, 28, 643 (1942)
6 R. P. Smith, J Am Chem Soc, 68, 1163 (1946)

* United States Steel Corporation, Research Laboratory, Kearny, N.J.

(The principal iron-carbon diagram is on the next page.)



C-Mn Carbon-Manganese

By W. P. Sykes*

The available data on this system do not warrant the construction of a phase diagram. However two carbides of manganese have been isolated and identified.[1,2] These were prepared by dissolving carbon in molten manganese, and are isomorphous with $Cr_{23}C_6$ and Cr_7C_3. The following lattice dimensions are reported: $Mn_{23}C_6$, cubic, $a = 10.564$ kX; Mn_7C_3, trigonal, $a = 13.87$ kX, $c = 4.53$ kX.

* Lamp Department, General Electric Company, Cleveland

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2 E. Öhman, Jernkontorets Ann, 123, 13 (1944); Translation No. 191, Iron Steel Inst (London)

C-Mo Carbon-Molybdenum

By W. P. Sykes*

Solid molybdenum dissolves about 0.1% C at 2000 to 2100 C.[1] The β phase appears to be a solid solution dissolving carbon interstitially in a close-packed hexagonal lattice.[1,2,3] The limiting composition on the carbon-rich side is probably 5.88% C, represented by the formula Mo_2C.

The higher-carbon intermediate γ phase appears to form most readily at temperatures above 2400 C, but the homogeneity range and the crystal structure of this phase have not been determined.[1]

* Lamp Department, General Electric Company, Cleveland

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1 W. P. Sykes, K. R. Van Horn and C. M. Tucker, Trans AIME, 117, 173 (1935)
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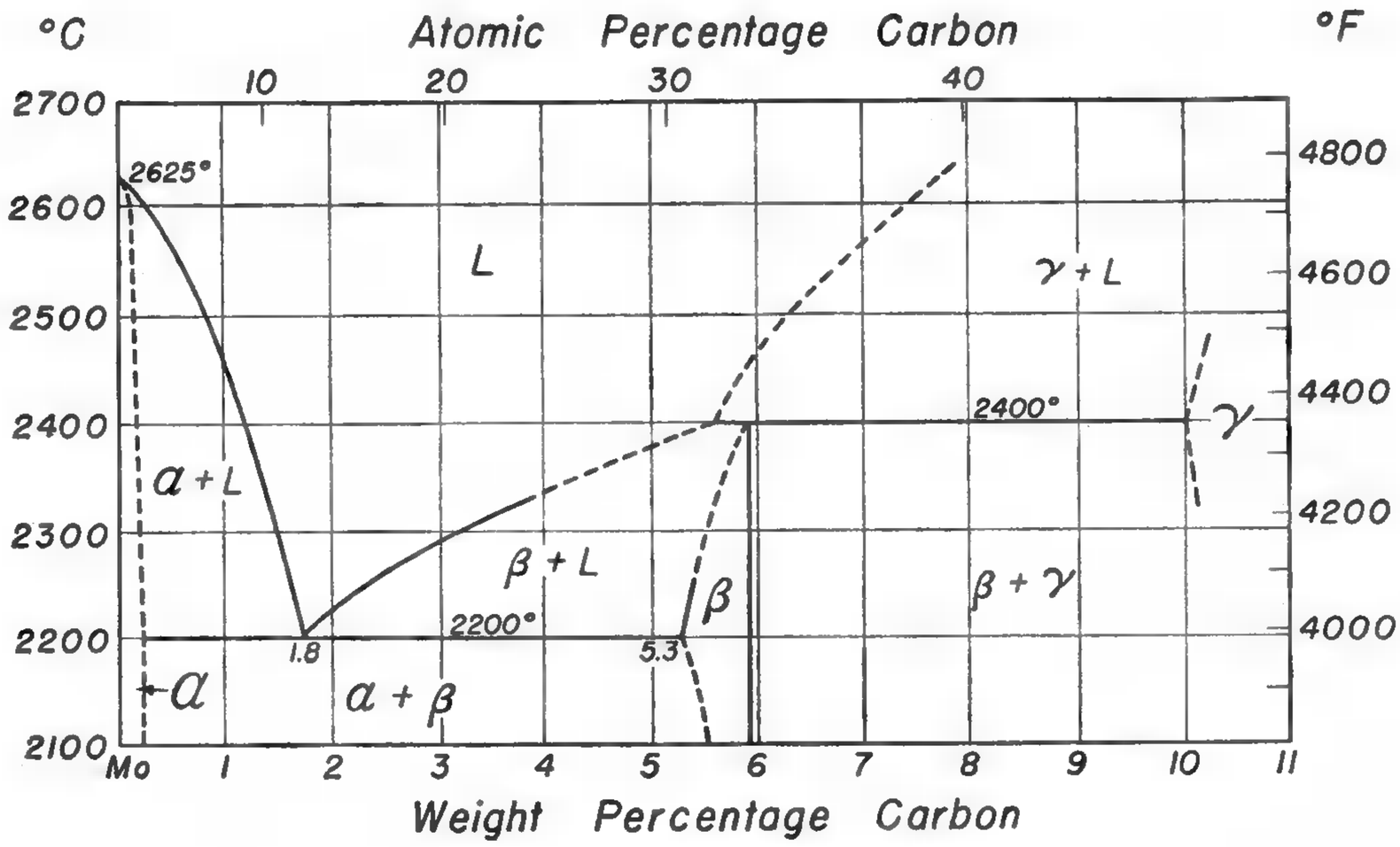

C-Ni Carbon-Nickel

By T. E. Kihlgren* and J. T. Eash*

The system presented is based principally on the work of Ruff and others, and Kasé. The solid solubility of carbon in nickel between 1300 and 995 C is represented according to unpublished results obtained by R. H. Schaefer. The solid solubility of carbon at 500 C is estimated to be about 0.03%.

The compound Ni_3C containing 6.42% C has been reported to exist between 1500 and 2500 C, but it is endothermic and very unstable.[2,4]

The Curie temperature of nickel (353 C) is not affected appreciably by carbon.

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2 O. Ruff and E. Gersten, Ber, 46, 406 (1913)
3 O. Ruff, Ber, 45, 3139 (1912)
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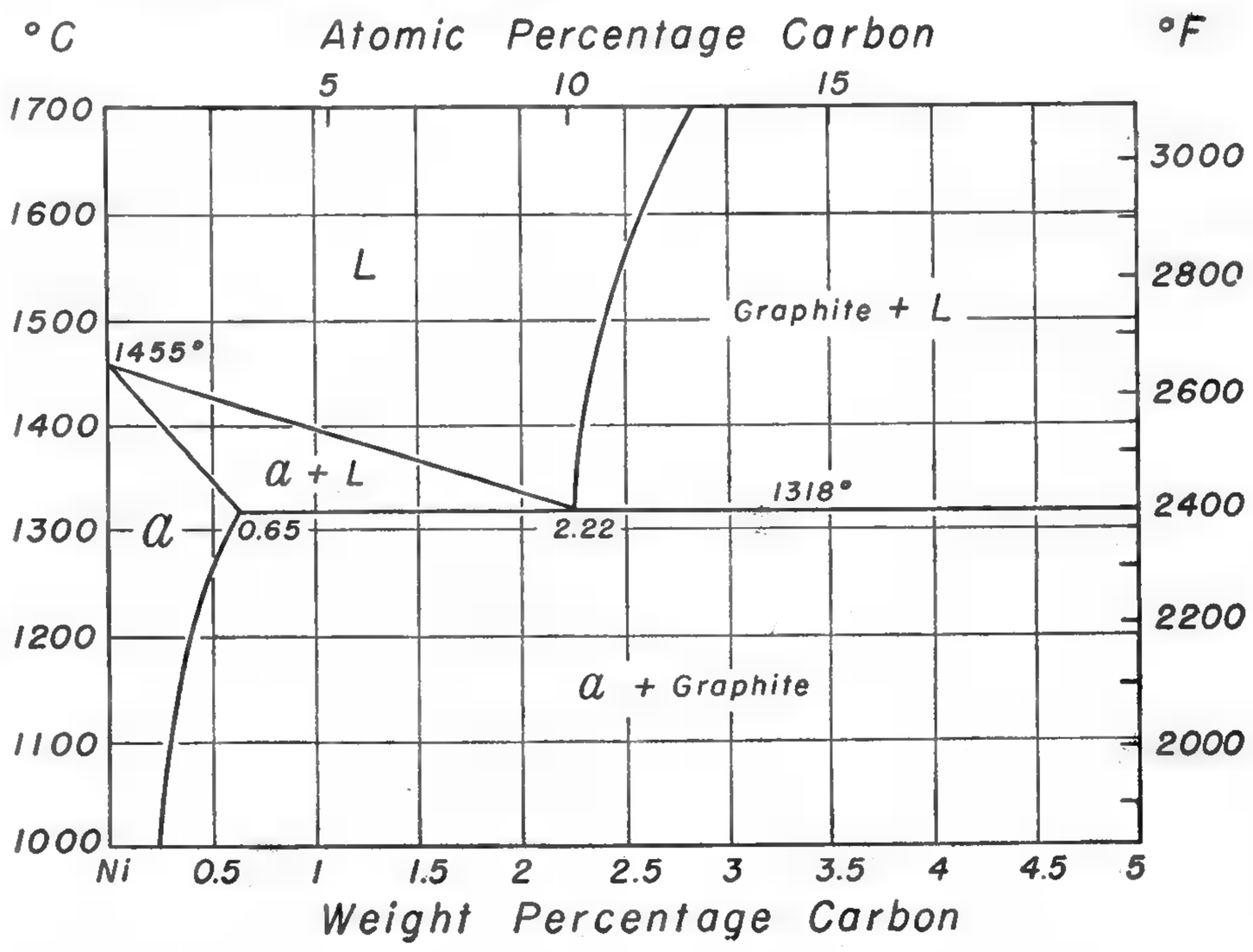
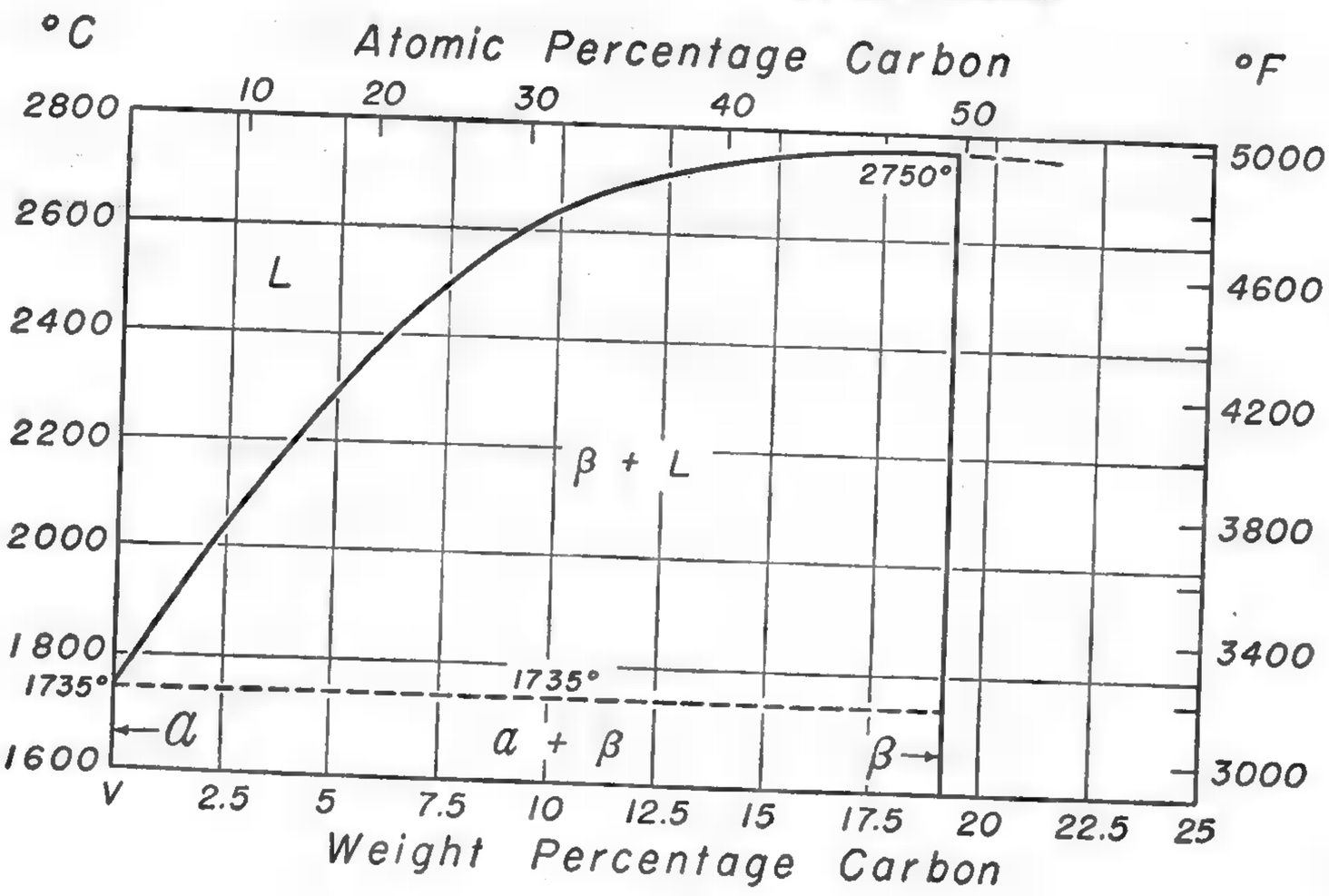
5 T. Kasé, Science Repts Tôhoku Imp Univ, 14, 173 (1925)

* Research Laboratory, The International Nickel Company, Inc., Bayonne, N.J.



C-V Carbon-Vanadium

By W. P. Sykes*



Carbon is soluble to a very limited extent in solid vanadium.[1] No quantitative data regarding such solubility have been reported. The solidus and liquidus temperatures are shown in the diagram as determined by Ruff and Martin.[2]

The β phase is apparently the carbide VC, having a theoretical carbon content of 19.1%.[2,3,4] Phases corresponding to the formulae V_5C, V_4C_3 and V_2C have been reported,[2,5] but the existence of these phases has not been confirmed. The β phase is cubic (NaCl type) with $a = 4.30$ kX.

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4 K. Becker and F. Ebert, Z Physik, 31, 268 (1925)
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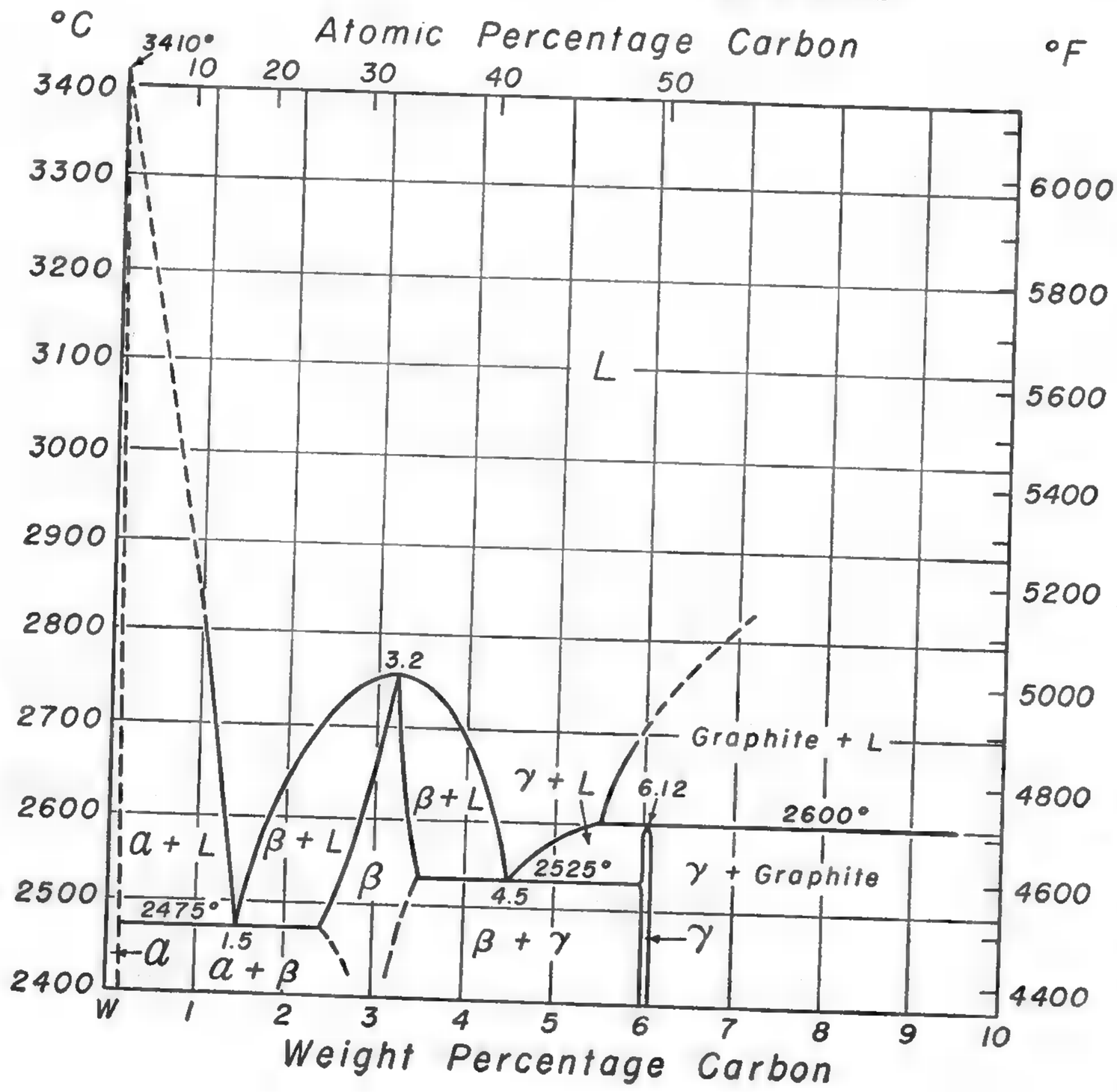
C-W Carbon-Tungsten

By W. P. Sykes*



The solubility of carbon in solid tungsten is less than 0.1% at the eutectic temperature.[1,2] The β phase, corresponding to the formula W_2C, has been reported[3] to undergo an allotropic transformation at about 2400 C but this observation has not been confirmed.

Upon heating to 2600 C the γ phase, corresponding to WC in composition, decomposes into graphite and liquid.

Although both W_2C and WC are rated on the Mohs hardness scale as 9+ it was reported that W_2C is less effective than WC as an abrasive.[4]

The β phase is close-packed hexagonal with $a = 2.99$ kX, $c = 4.71$, $c/a = 1.57$; γ is hexagonal with $a = 2.90$, $c = 2.83$, $c/a = 0.97$.

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*Lamp Department, General Electric Company, Cleveland

Ca-Cu Calcium-Copper

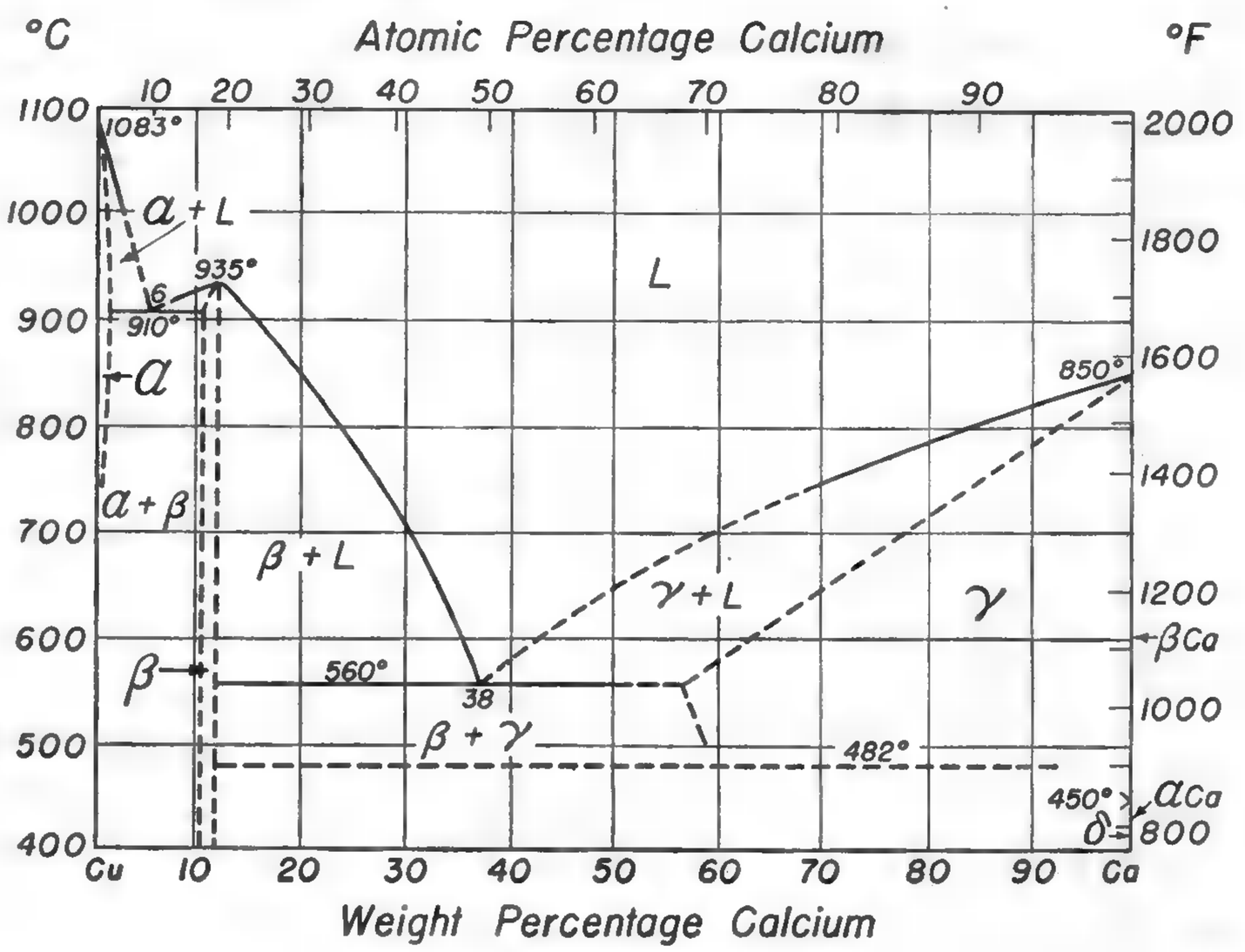
By A. C. Vaughan*

The diagram is essentially that of Baar[1] and indicates some uncertainties. Copper is appreciably soluble in calcium but the boundaries of this terminal solid solution (γ) have been extrapolated from determined eutectic points at 560 C.

The compound β found by Baar to be $CaCu_4$, using thermal and microscopic methods, has been revised by Haucke[2] and Nowotny,[3] using X-ray methods, to $CaCu_5$ (88.8% Cu) and is so shown in the diagram. The compound is hexagonal with unit cell dimensions by Haucke, $a = 5.082$ kX, $c = 4.078$ kX; by Nowotny $a = 5.097$ kX, $c/a = 1.579$. The diagram shows eutectic mixtures of β and γ at 38% Ca and 560 C, and of α and β at 94% Cu and 910 C.

Baar observed weak thermal effects at 482 C on the cooling curves of alloys containing 10 to 76.5% Cu, which Hansen[4] states have not been explained satisfactorily.

Solid copper dissolves less than 0.1% Ca.[5]



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4 M. Hansen, "Der Aufbau der Zweistoffiegierungen", J. Springer, Berlin, 1936

5 E. E. Schumacher, W. C. Ellis and J. F. Eckel, Trans AIME, Inst Metals Div, 151 (1930), (TP 240, 1929)

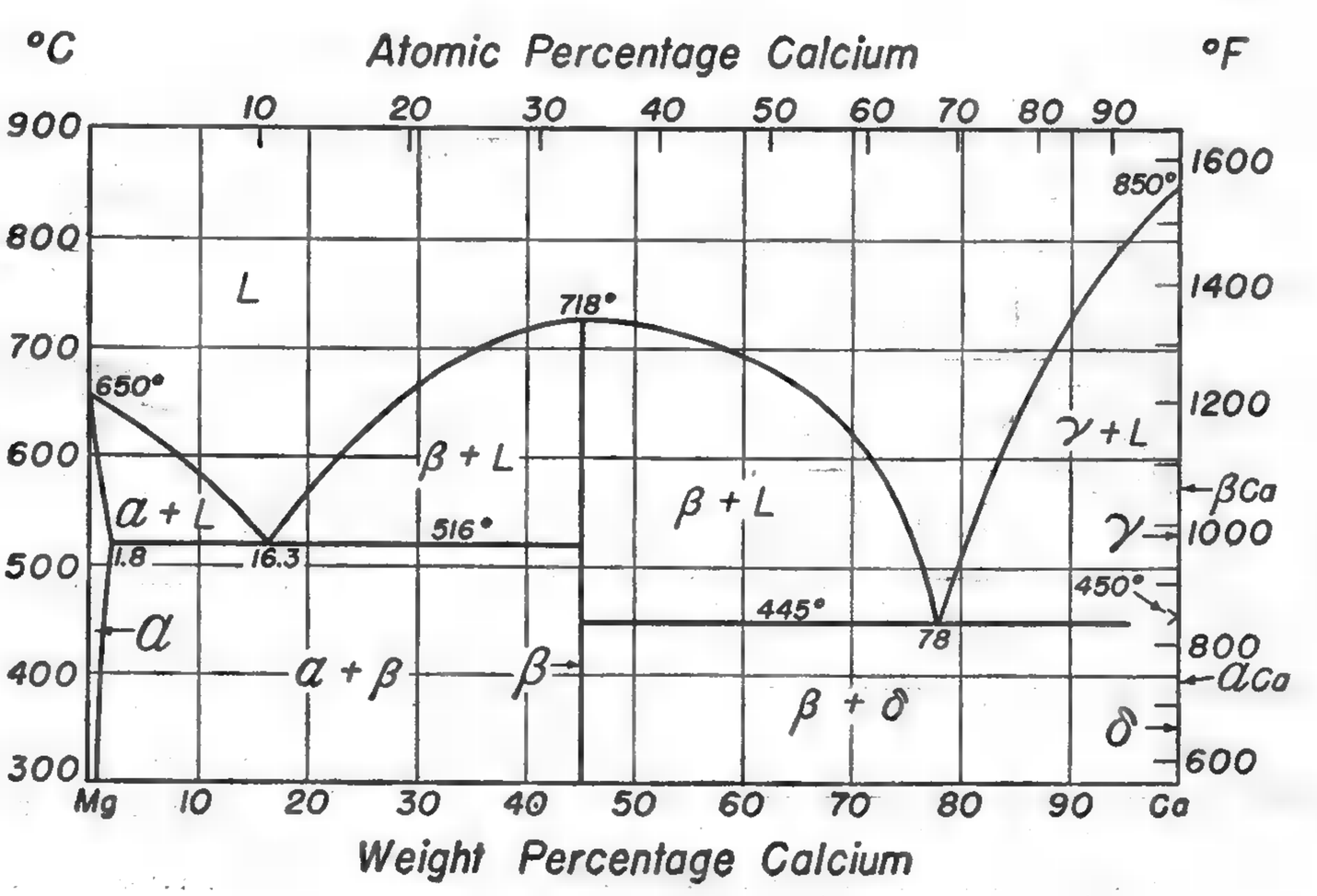
* Central Research Laboratory, American Smelting and Refining Company, Barber, N.J.

Ca-Mg Calcium-Magnesium

By G. F. Sager† and B. J Nelson†

The solubility of magnesium in solid calcium has not been determined. The solubilities of calcium in solid magnesium have been reported, as follows: 1.8% at 517 C, 1.2 at 500, 0.8 at 300, 0.5 at 250.

The β phase ($CaMg_2$) is hexagonal with $a = 6.22$ kX and $c = 10.10$ kX.[7]



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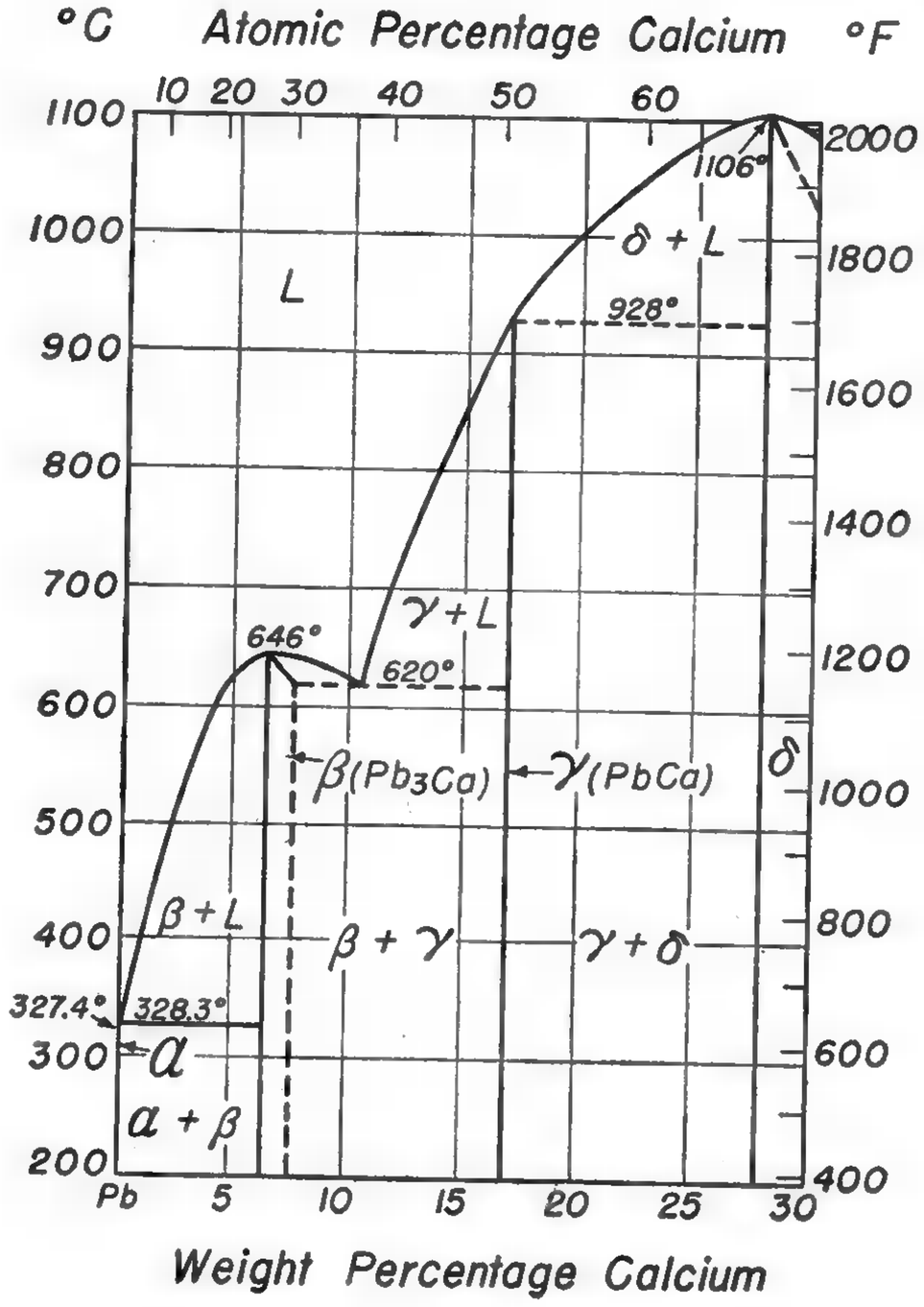
† Aluminum Research Laboratories, New Kensington, Pa.

Ca-Pb Calcium-Lead

By E. E. Schumacher* and G. M. Bouton*



The γ and δ phases disintegrate rapidly in moist air. The β phase is not rapidly affected. The rate at which β precipitates from supersaturated α is greatly affected by the cooling rate; slowly cooled alloys with 0.03% Ca may not show precipitation for a year, but agglomeration is rapid at 220 C in alloys that contain 0.01 to 0.1% Ca.

In the calcium-rich portion of the system, there is a eutectic reaction at about 700 C involving δ (about 38% Ca), liquid (about 58% Ca), and calcium.

β, γ and δ are Pb_3Ca, PbCa and $PbCa_2$ respectively.

References

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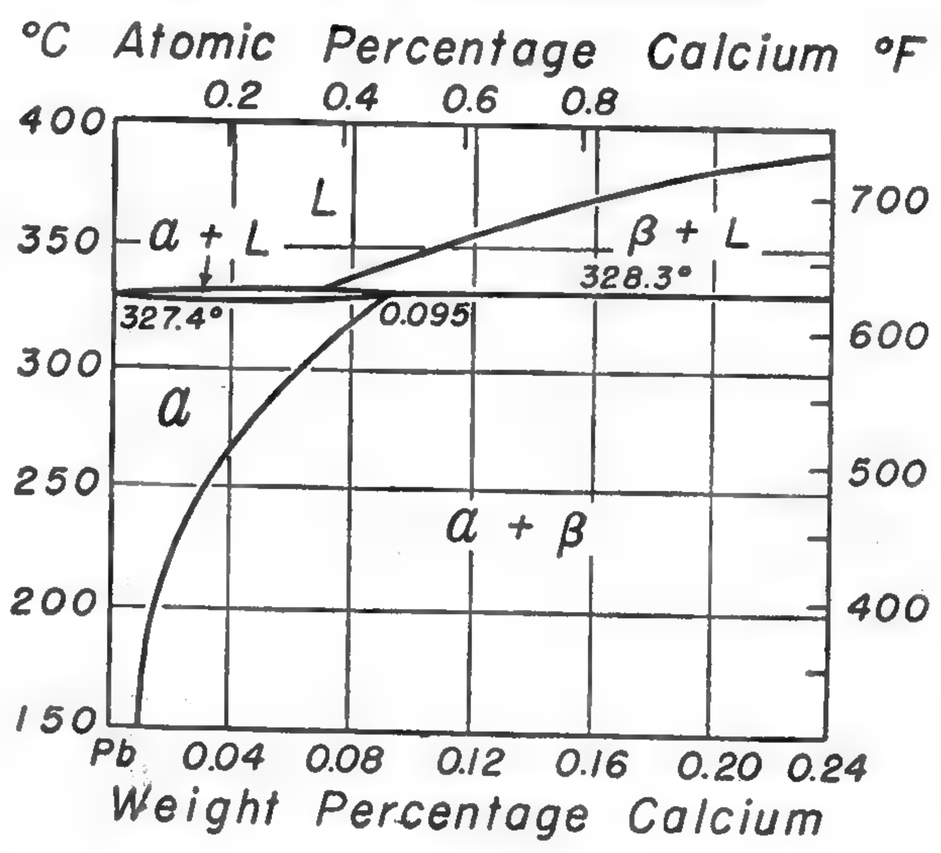
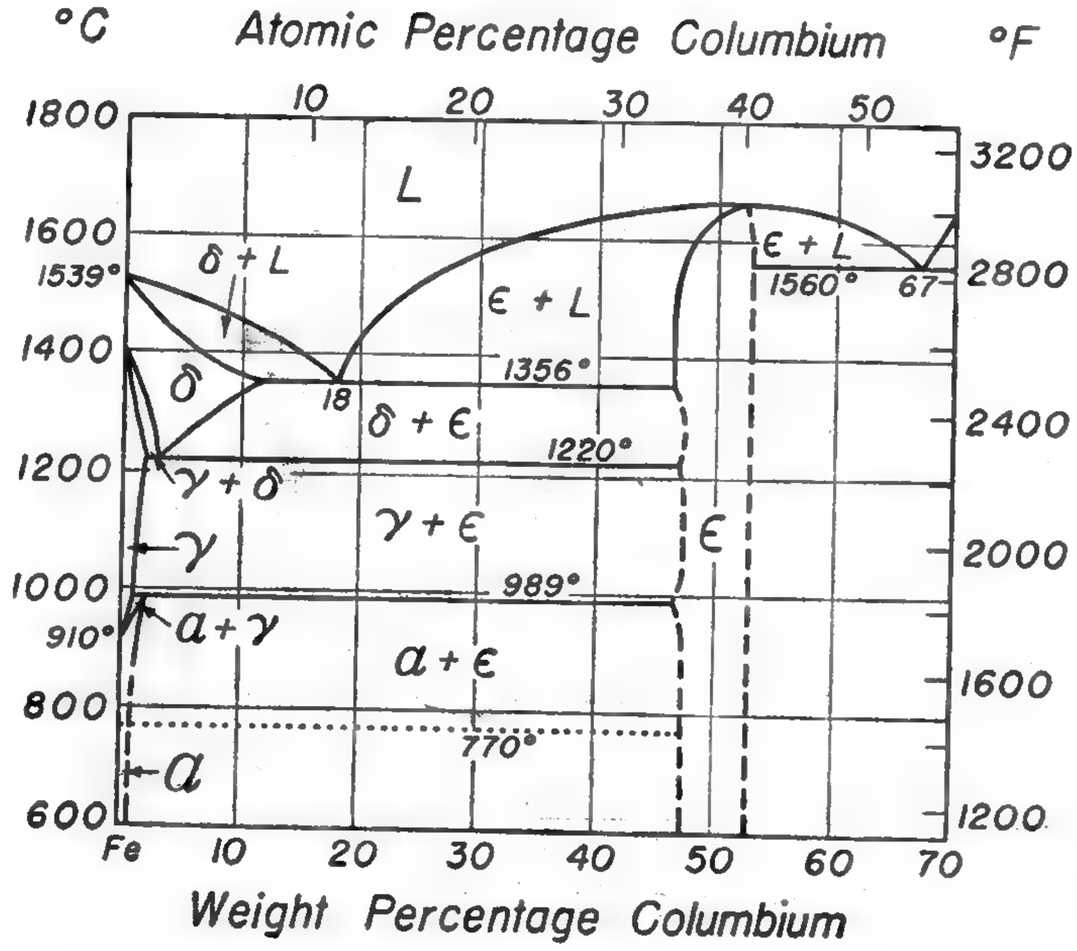
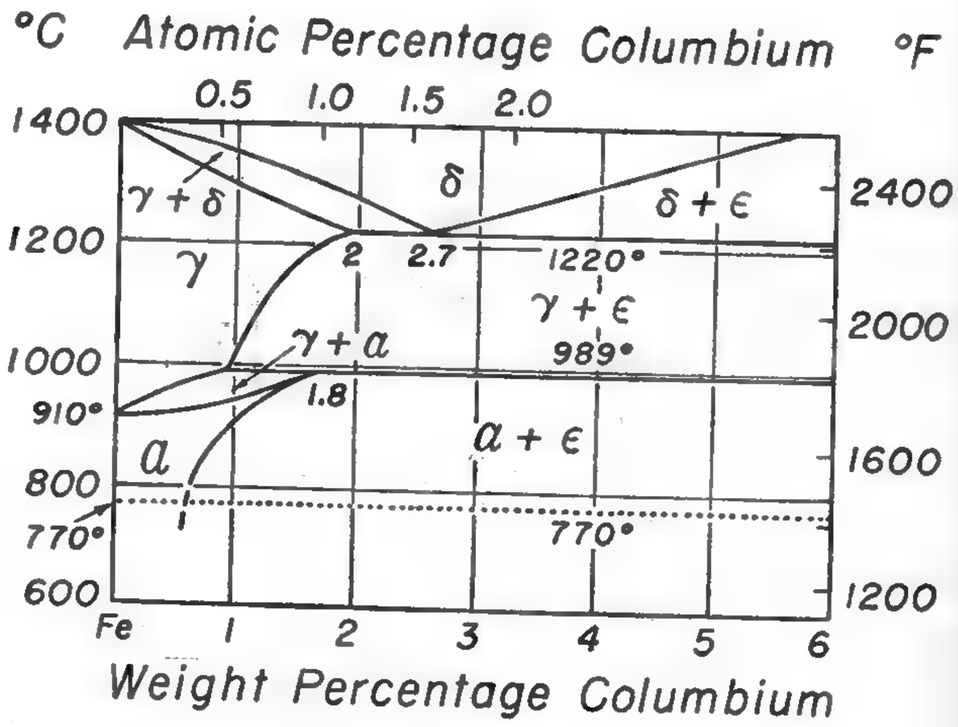
* Bell Telephone Laboratories, Inc., Murray Hill, N.J.



Cb-Fe Columbium-Iron

By R. M. Parke*





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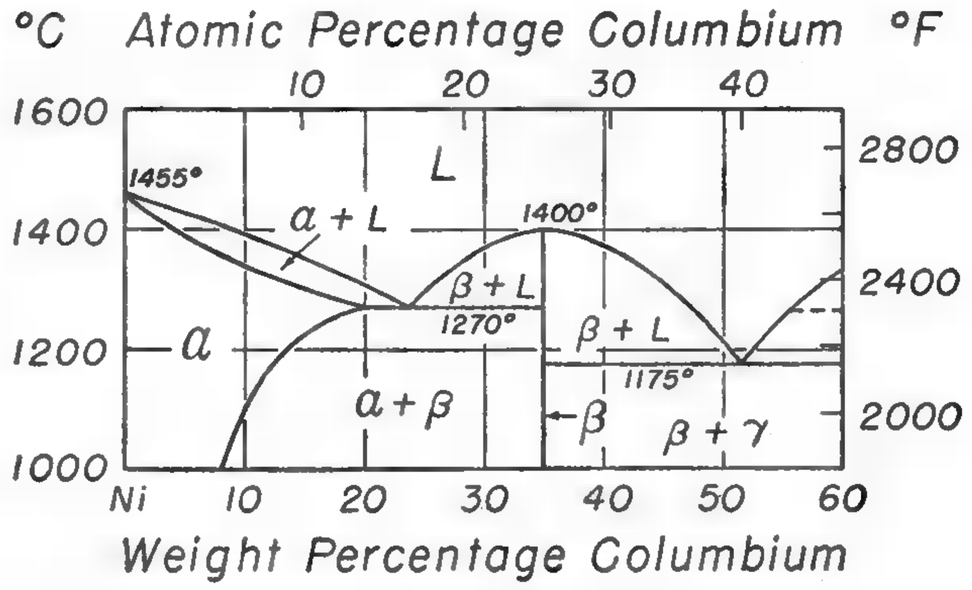
* Kellex Corporation, Silver Spring, Md.

Cb-Ni Columbium-Nickel*

The β phase (Ni_3Cb) may exist over a range of composition of about 5%.[1] The γ phase, apparently based on NiCb, forms by peritectic reaction of liquid and δ.[1] The δ phase, not shown in the accompanying diagram, may be the terminal solid solution of nickel in columbium. The system has not been investigated beyond 65% Cb.

The solubility of columbium in solid nickel is from the X-ray diffraction results of Grube, Kubaschewski and Zwiauer.[2] Pogodin and Selikmann[1] reported a solid solubility somewhat greater than this at the lower temperatures.



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2 G. Grube, O. Kubaschewski and K. Zwiauer, Z Elektrochem, 45, 881 (1939)

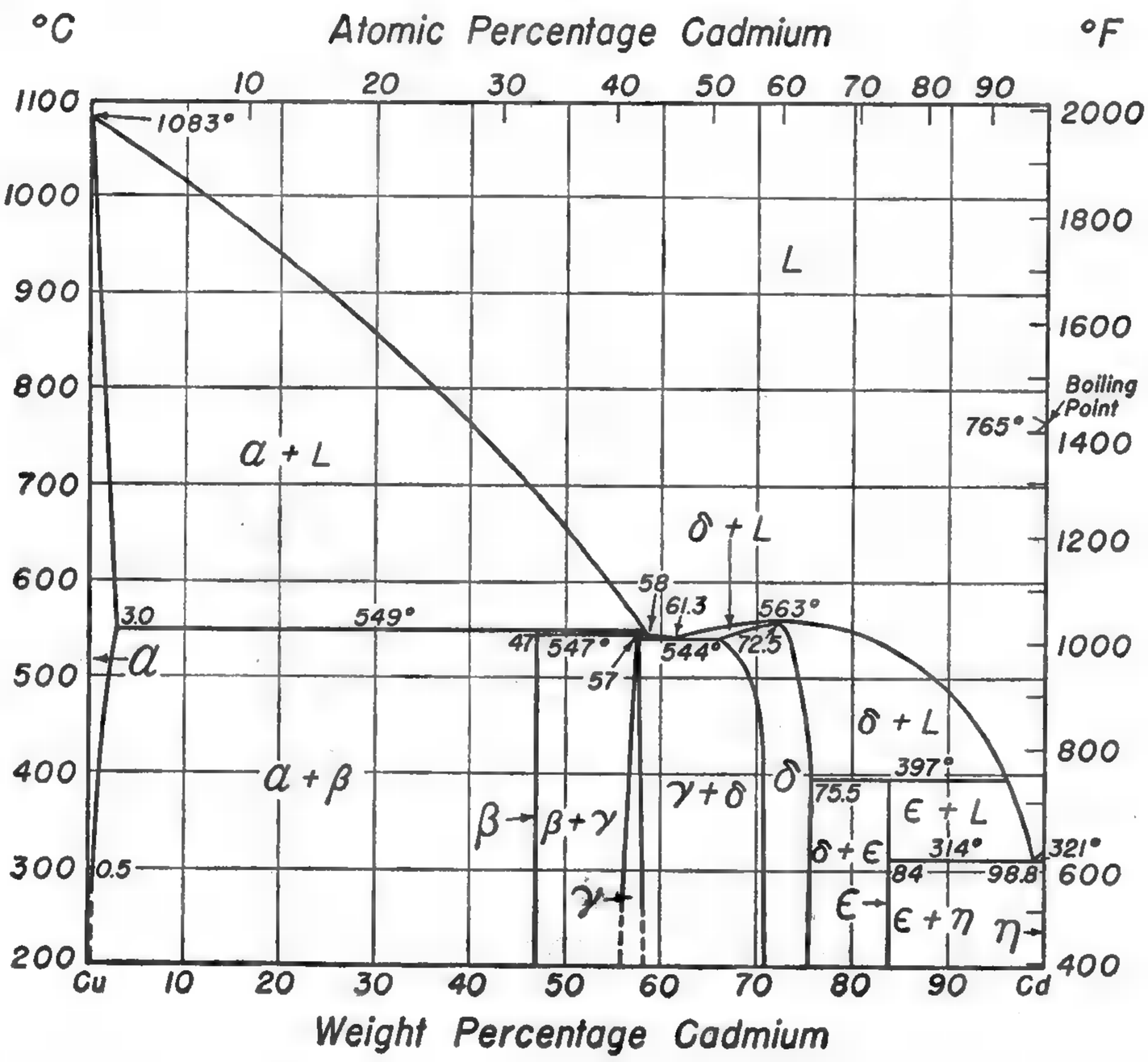
* By Taylor Lyman, Editor, Metals Handbook

Cd-Cu Cadmium-Copper

By Cyril Stanley Smith*

The liquidus is based on the works of Sahmen[1] and Jenkins and Hanson,[2] which are in excellent agreement. The γ phase (Cd_3Cu_4) does not form on solidification but appears only after prolonged annealing near 500 C. On solidification, even at a very slow rate, a metastable eutectic between δ and β forms at 540 C and 61.3% Cu. According to lattice parameter measurements[5] cadmium has a maximum solubility in copper of 3.0% at 549 C, decreasing to 0.5% at 300 C. The data could be reinterpreted to show appreciably greater maximum solubility. The solubility of copper in cadmium is between 0.005 and 0.10% at 270 C.[3]

The phases β and ϵ correspond exactly to Cu_2Cd and $CuCd_3$ respectively, and seem to have extremely narrow ranges of solid solubility. X-ray diffraction patterns[5] confirm this, though the crystal structures of these phases are not known. The δ phase is of gamma-brass structure,[4] cubic with 52 atoms (4 groups of Cu_5Cd_8) per unit cell; $a = 9.635$ kX.



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* Institute for the Study of Metals, University of Chicago, Chicago

Cd-Fe Cadmium-Iron†

Cadmium is insoluble in solid iron. Tammann and Oelsen[1] determined the solubility of iron in molten cadmium in the range 400 to 700 C to be 0.0002 to 0.0003%. According to Daniels[2] a compound, Cd_2Fe, exists. This high-melting compound is magnetic, and is less dense than cadmium.[2]

References

1 G. Tammann and W. Oelsen, Z anorg allgem Chem, 186, 257 (1930)
2 E. J. Daniels, J Inst Metals, 49, 178 (1932)

† By R. M. Parke, Kellex Corporation, Silver Spring, Md.

Cd-Hg Cadmium-Mercury‡

The only intermediate phase is tetragonal and extends from about 7 to 60% Cd. Near minus 10 C most compositions of this phase undergo a transition without a change in crystal structure. Two peritectic reactions exist: at minus 34 C (about 1 to 7% Cd) and at 188 C (about 50 to 65% Cd).

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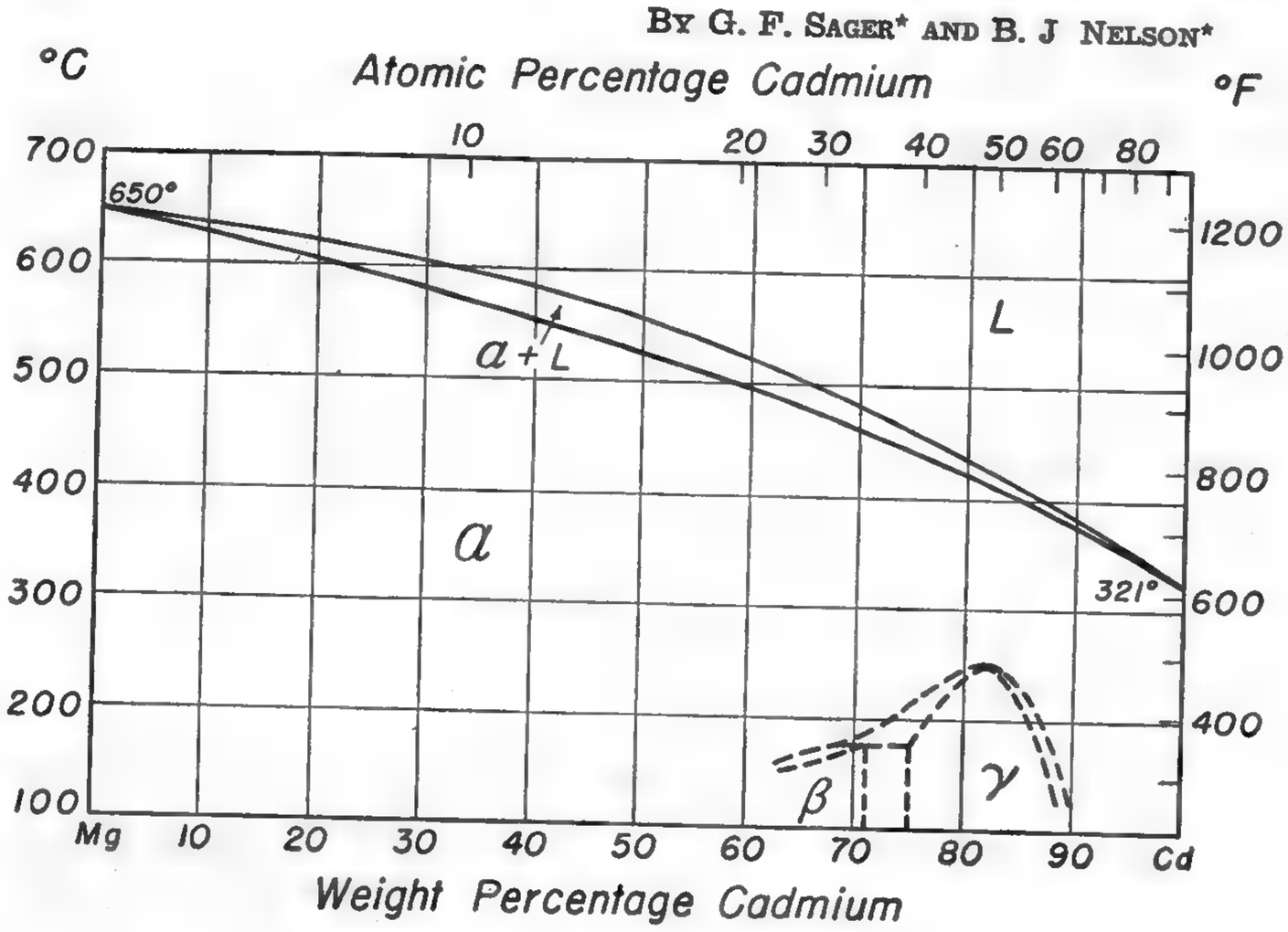
H. C. Bijl, Z physik Chem, 41, 641 (1902)

‡ By Taylor Lyman, Editor, Metals Handbook

Cd-Mg Cadmium-Magnesium

By G. F. Sager* and B. J Nelson*



Cadmium and magnesium form a complete series of solid solutions with superstructures occurring below 250 C, at compositions corresponding to the formulas Cd_3Mg, CdMg and $CdMg_3$. The superstructure based on Cd_3Mg exists below 100 C,[3,4] but the equilibrium relations of this structure with alpha and gamma are not established.

Cadmium lowers appreciably the boiling point of magnesium alloys, and has a small beneficial effect on mechanical properties.

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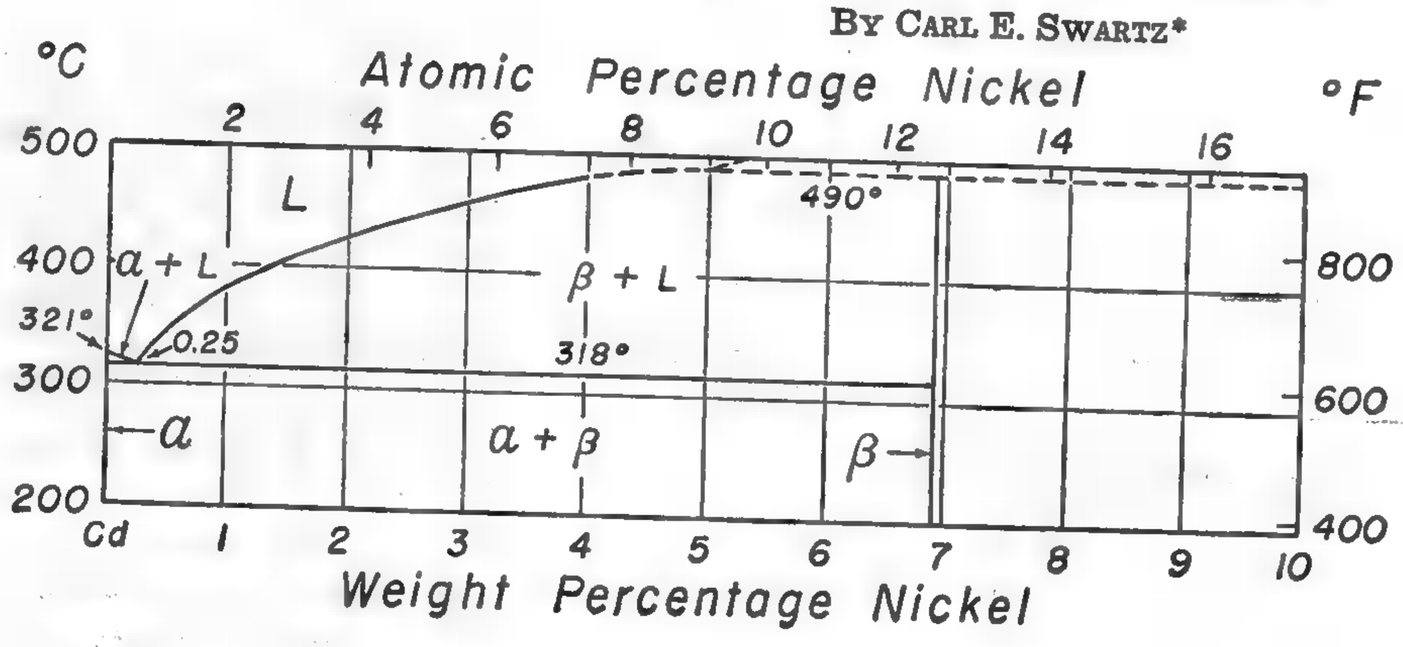
* Aluminum Research Laboratories, New Kensington, Pa.

Cd-Ni Cadmium-Nickel

By Carl E. Swartz*



The β phase in this system corresponds approximately to the composition $NiCd_7$.

The solubility of nickel in solid cadmium is low. Extension of the diagram beyond 8% Ni would necessitate working under pressures great enough to condense cadmium vapor at and above the high liquidus temperatures.

References

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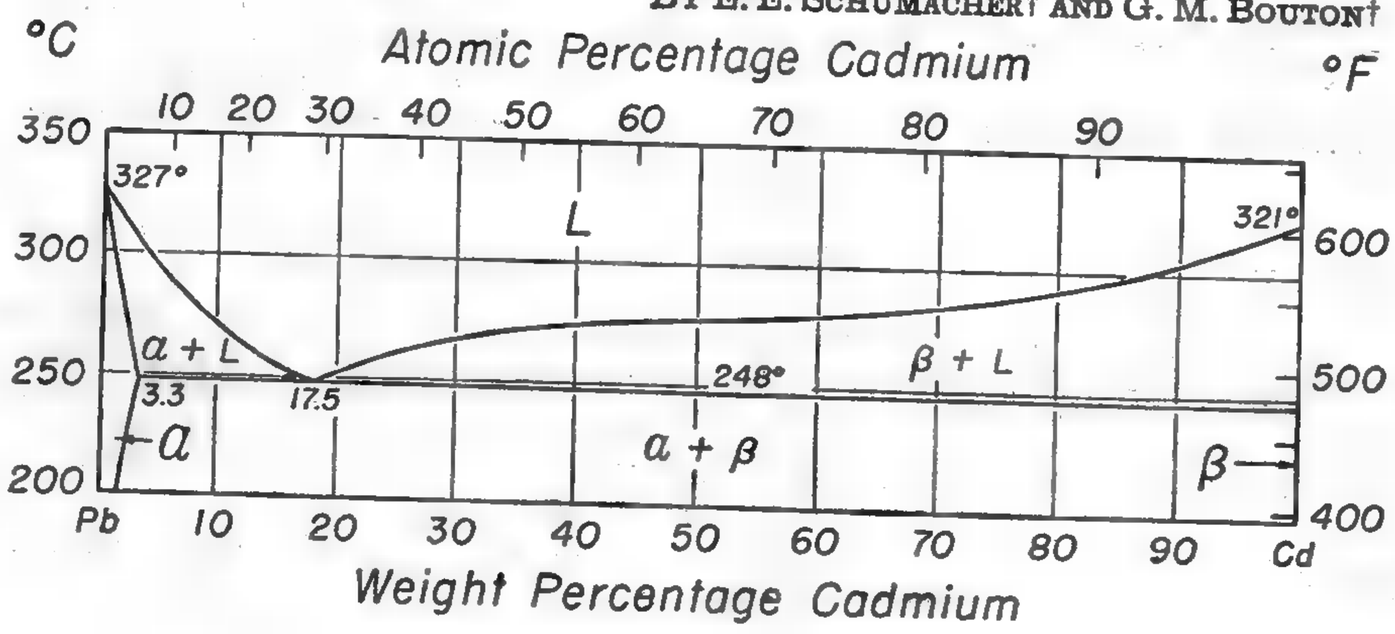
C. E. Swartz and A. J. Phillips, Trans AIME, 111, 333 (1934)

* Kellex Corporation, Silver Spring, Md.

Cd-Pb Cadmium-Lead

By E. E. Schumacher† and G. M. Bouton†



The lead-rich end of the system has been studied in considerable detail. There is some indication of solid solubility at the cadmium end of the system.

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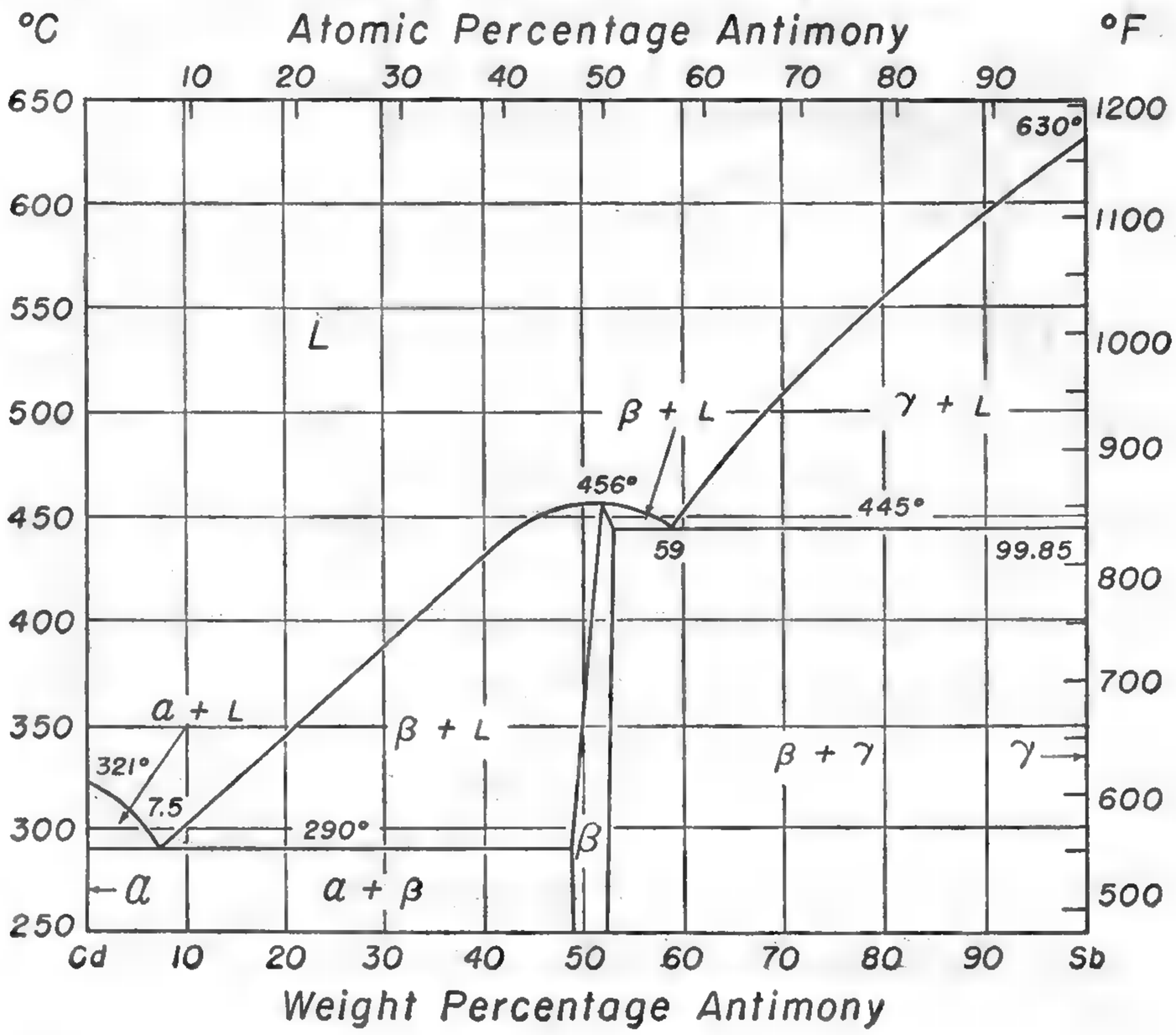
† Bell Telephone Laboratories, Inc., Murray Hill, N. J.

Cd-Sb Cadmium-Antimony

By Louis A. Carapella*



The phase designated here as β is usually referred to as CdSb. Under certain conditions of cooling, a metastable phase based on Cd_3Sb_2 forms instead of CdSb.[1,2,3] The metastable Cd_3Sb_2 phase (44% Sb) melts congruently at 420 C, and transforms eutectoidally at about 250 C.[1] In the metastable system, Cd_3Sb_2 forms a eutectic with cadmium at 8% Sb (285 C), and another eutectic with antimony at 54% Sb (395 C).[1]

The solubility of cadmium in antimony has been reported as 0.15% at 445 C.[1] Apparently the solubility of antimony in solid cadmium is slight.

The crystal structure of CdSb is orthorhombic;[4] Cd_3Sb_2 is monoclinic.[5]

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2 W. Treitschke, Z anorg Chem, 50, 217 (1906)
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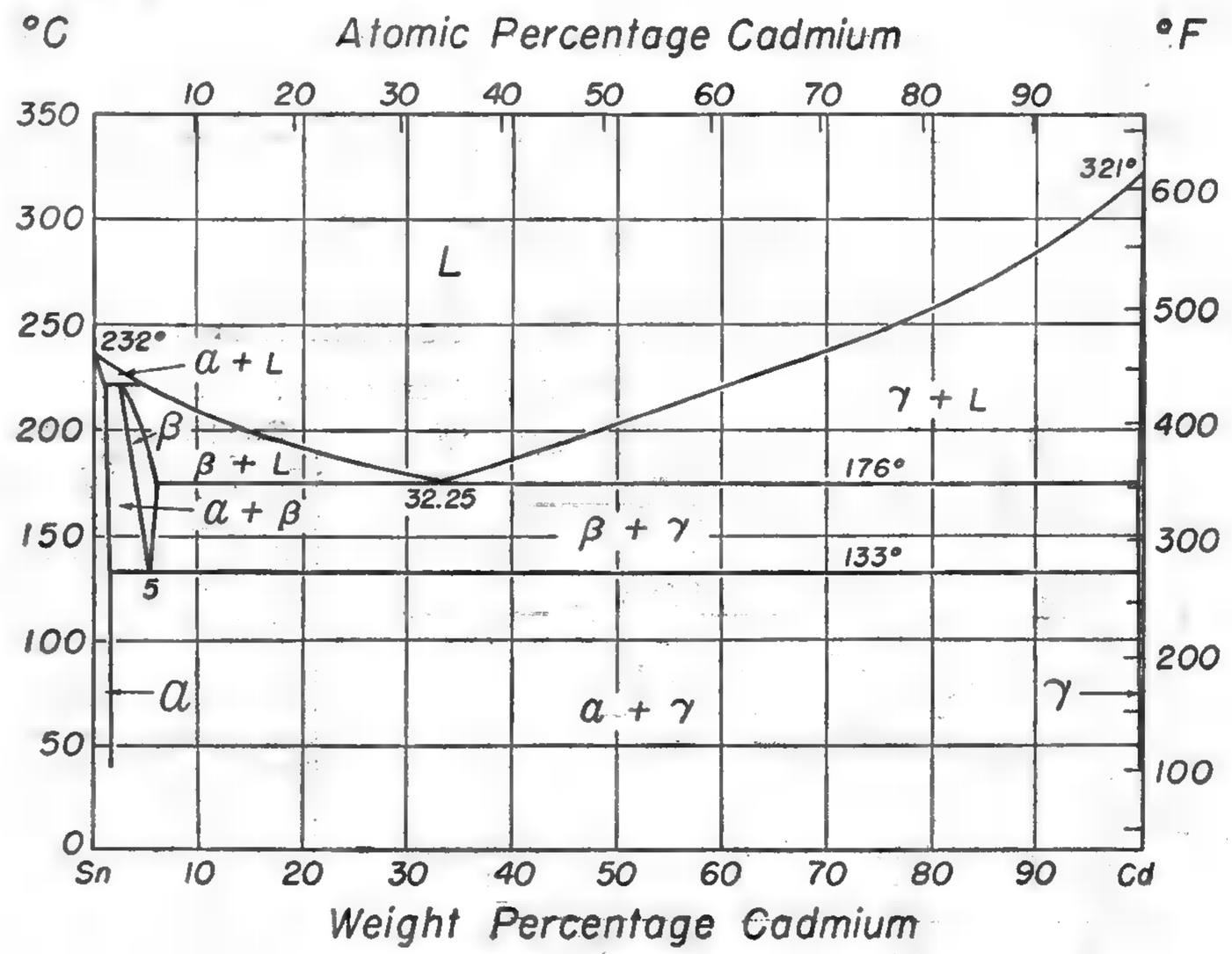
* Mellon Institute of Industrial Research, Pittsburgh

Cd-Sn Cadmium-Tin

By W. T. Pell-Walpole*



The peritectic reaction is readily suppressed by rapid cooling, but the β phase is then formed by direct deposition from the liquid below some (undetermined) temperature between 223 and 176 C.

The eutectoid decomposition of β occurs at 133 C under conditions of stable equilibrium. On cooling, the temperature of the eutectoid change is lowered to between 122 and 132 C; on heating, it is raised to between 135 and 140 C, depending on the rates of cooling or heating employed.

The sudden change in the solubility of tin in cadmium at 170 C causes a slight thermal arrest at this temperature in all alloys that contain the γ phase.

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2 D. Hanson and W. T. Pell-Walpole, J Inst Metals, 59, 281 (1936)
3 C. E. Homer and H. Plummer, J Inst Metals, 64, 189 (1939)
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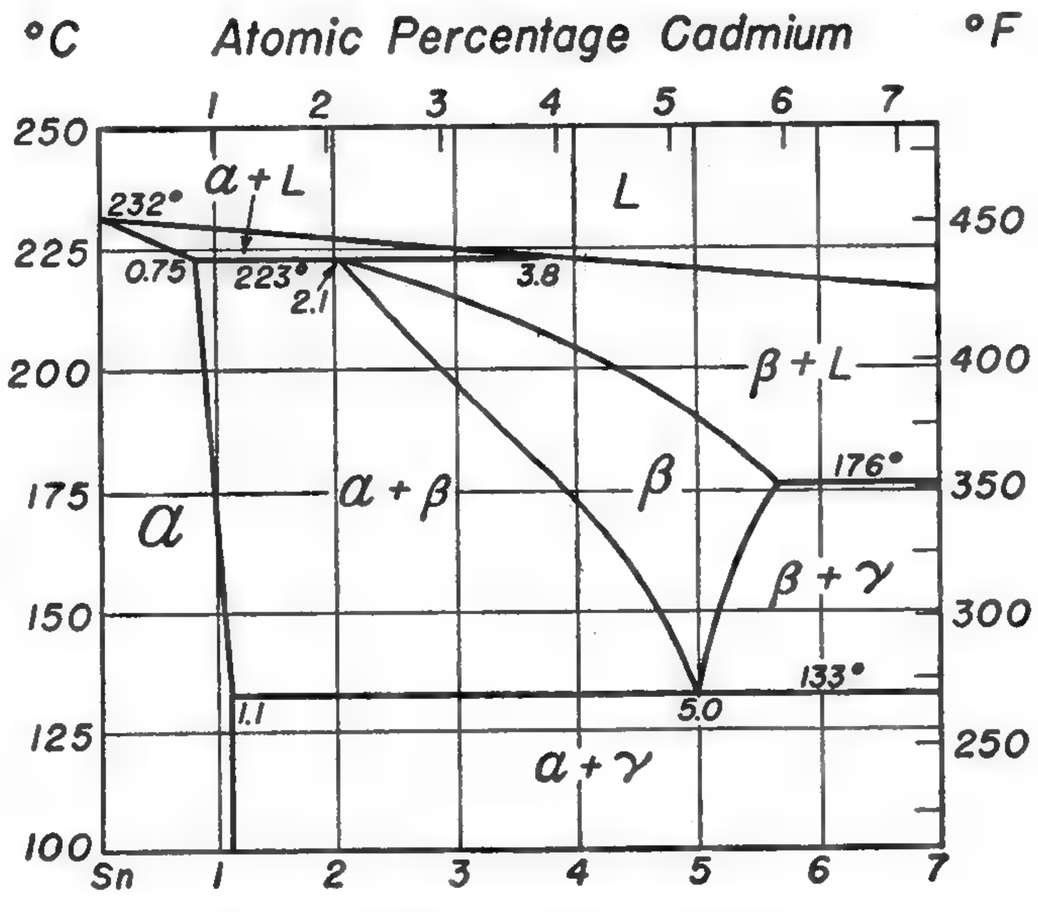
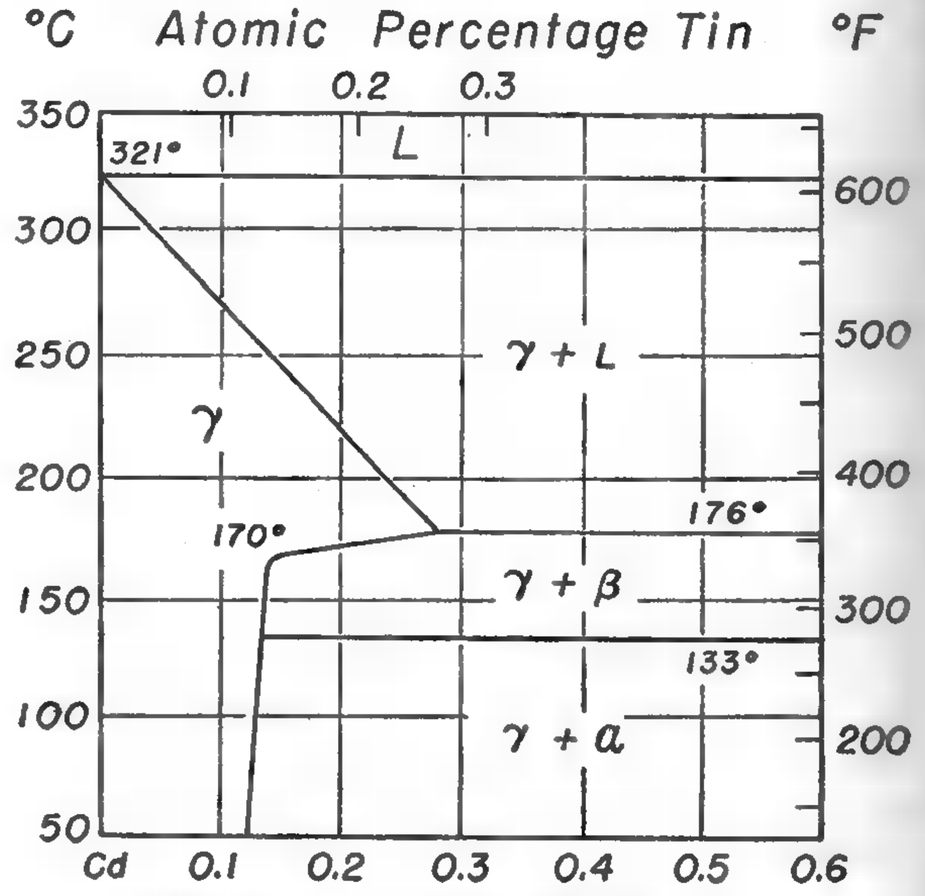
* Tin Research Institute, London, England

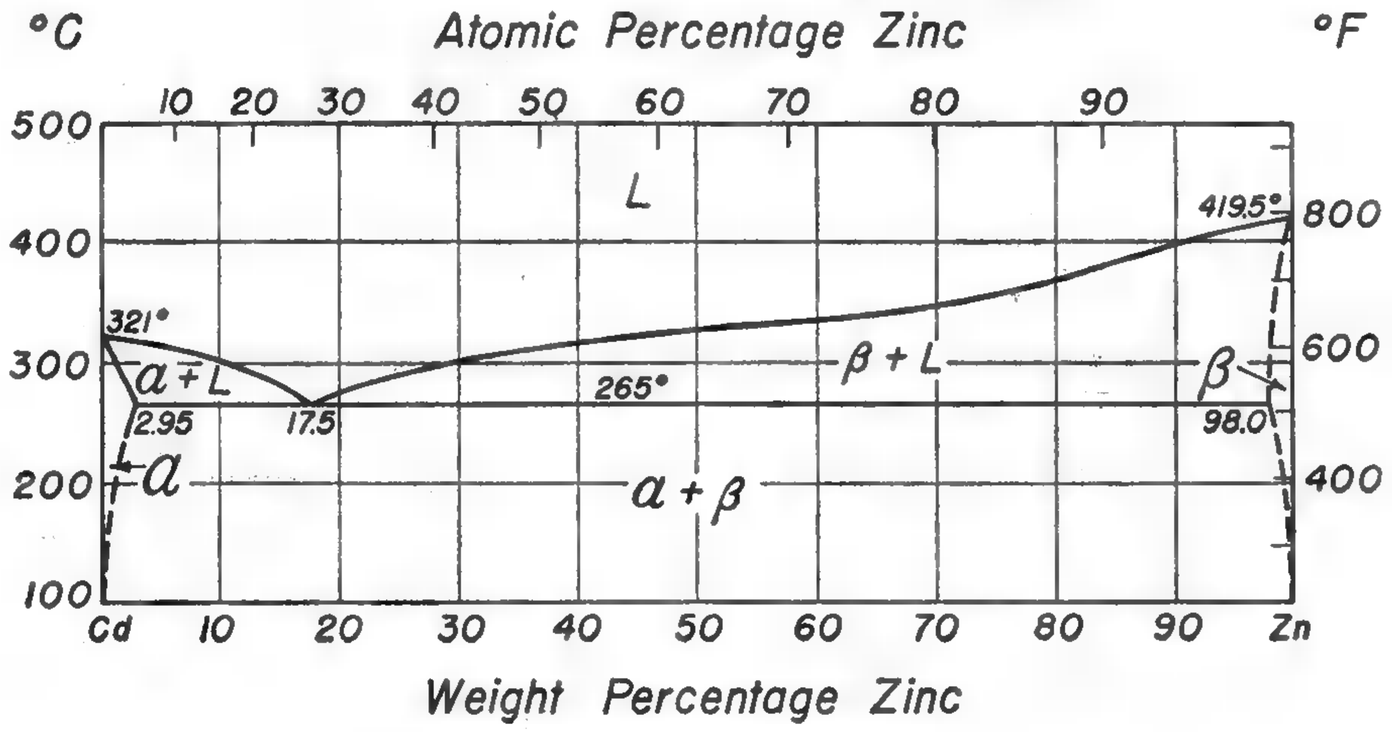
(For diagrams on a larger scale, see the next page.)





Cd-Zn Cadmium-Zinc

By E. A. Anderson*



The results of Jenkins and those of Stockdale indicate that the solubility of cadmium in zinc first increases and then decreases as the temperature is increased above 265 C.

There is need for a careful study of the solid solubilities on both sides of the diagram.

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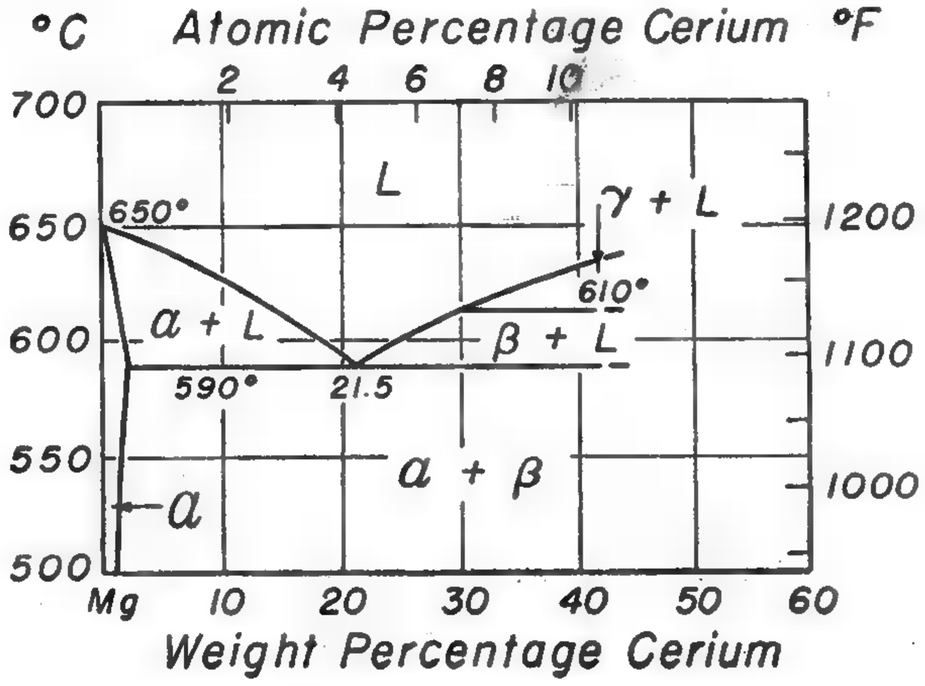
D. Stockdale, J Inst Metals, 44, 75 (1930)

* The New Jersey Zinc Company (of Pa.), Palmerton, Pa.

Ce-Mg Cerium-Magnesium

By G. F. Sager* and B. J Nelson*



The partial diagram is based on alloys made with cerium having a purity of 97.7%.[1] The results of other investigators have not been accepted because the purity of the cerium used was not reported, or because mischmetal was employed instead of cerium.

The solubility of cerium in magnesium is, as follows: 1.6% at 590 C, 1.0 at 550, 0.5 at 500, 0.15 at 337.

Cerium in magnesium alloys greatly increases the hardness and tensile strength of wrought alloys. Cerium-containing alloys retain a considerable part of their strength and hardness at temperatures up to 260 C. Cerium also gives exceptional creep resistance to magnesium alloys.[2] Magnesium-cerium alloys were used for supercharger impellers, cam-follower guides, and housings on a German aircraft engine during World War II.

References

1 J. L. Haughton and T. H. Schofield, J Inst Metals, 60, 339 (1937)
2 T. E. Leontis and J. P. Murphy, Trans AIME, 166, 295 (1946)

* Aluminum Research Laboratories, New Kensington, Pa.

Co-Cu Cobalt-Copper

By Cyril Stanley Smith*

Though Konstantinov[1] showed a two-liquid field extending from 32 to 72% Cu and Jitsuka[2] also found this, Sahmen[3] found no liquid segregation and his data are to be preferred. By analogy with the diagram for the copper-iron system, which also shows a nearly flat liquidus, it is expected that very small amounts of impurities will cause segregation into two liquids between 32 and 72% Cu.

The solubility of cobalt in copper has been established by both magnetic[5] and microscopic[4] examination. The solubility of copper in cobalt is placed at 10% as a result of Sahmen's thermal analysis data and his measurements of the temperature of the magnetic transformation of copper-cobalt alloys. Nothing is known concerning the effect of copper on the α-β transformation of cobalt at about 420 C.

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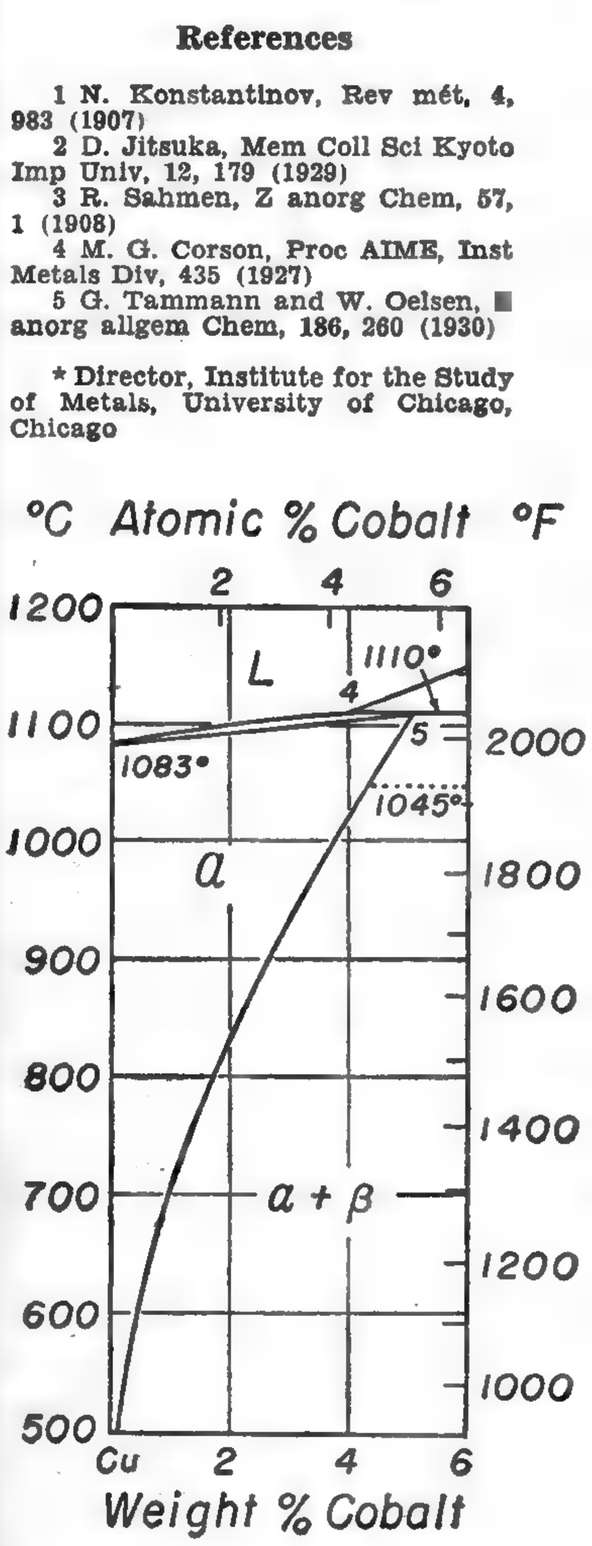
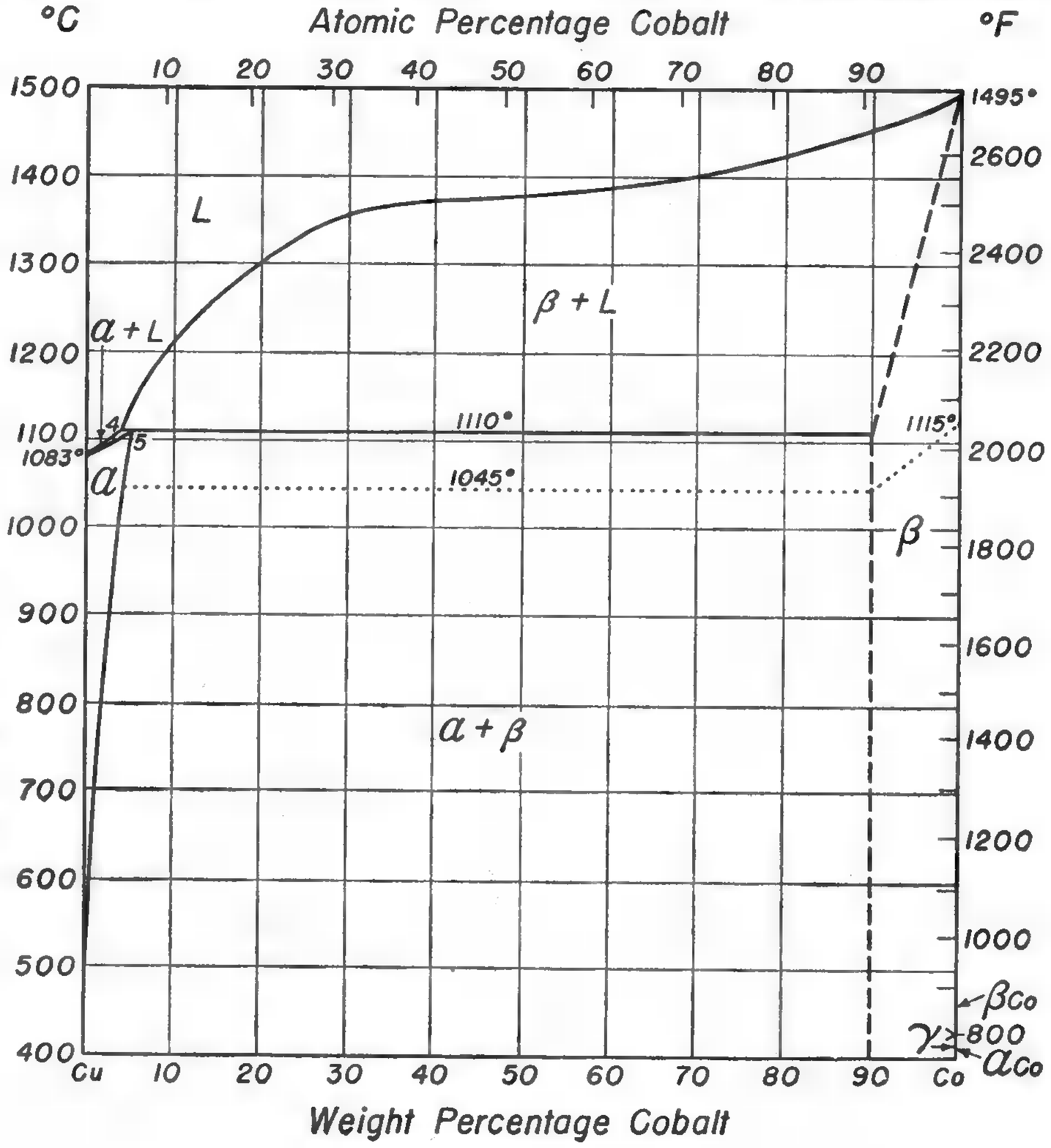
2 D. Jitsuka, Mem Coll Sci Kyoto Imp Univ, 12, 179 (1929)
3 R. Sahmen, Z anorg Chem, 57, 1 (1908)
4 M. G. Corson, Proc AIME, Inst Metals Div, 435 (1927)
5 G. Tammann and W. Oelsen, ■ anorg allgem Chem, 186, 260 (1930)

* Director, Institute for the Study of Metals, University of Chicago, Chicago





Co-Fe Cobalt-Iron

By W. C. Ellis* and E. S. Greiner*

There is good agreement among investigators concerning the location of the α-γ transformation except for the steeply descending portion in the region of 80% Co. The data used in constructing this portion of the diagram are from X-ray diffraction measurements.[14] The magnetic change[7] coincides with the γ boundary from about 13 to 73% Co. The α solid solutions in the region of equal atom ratios of iron and cobalt undergo ordering.

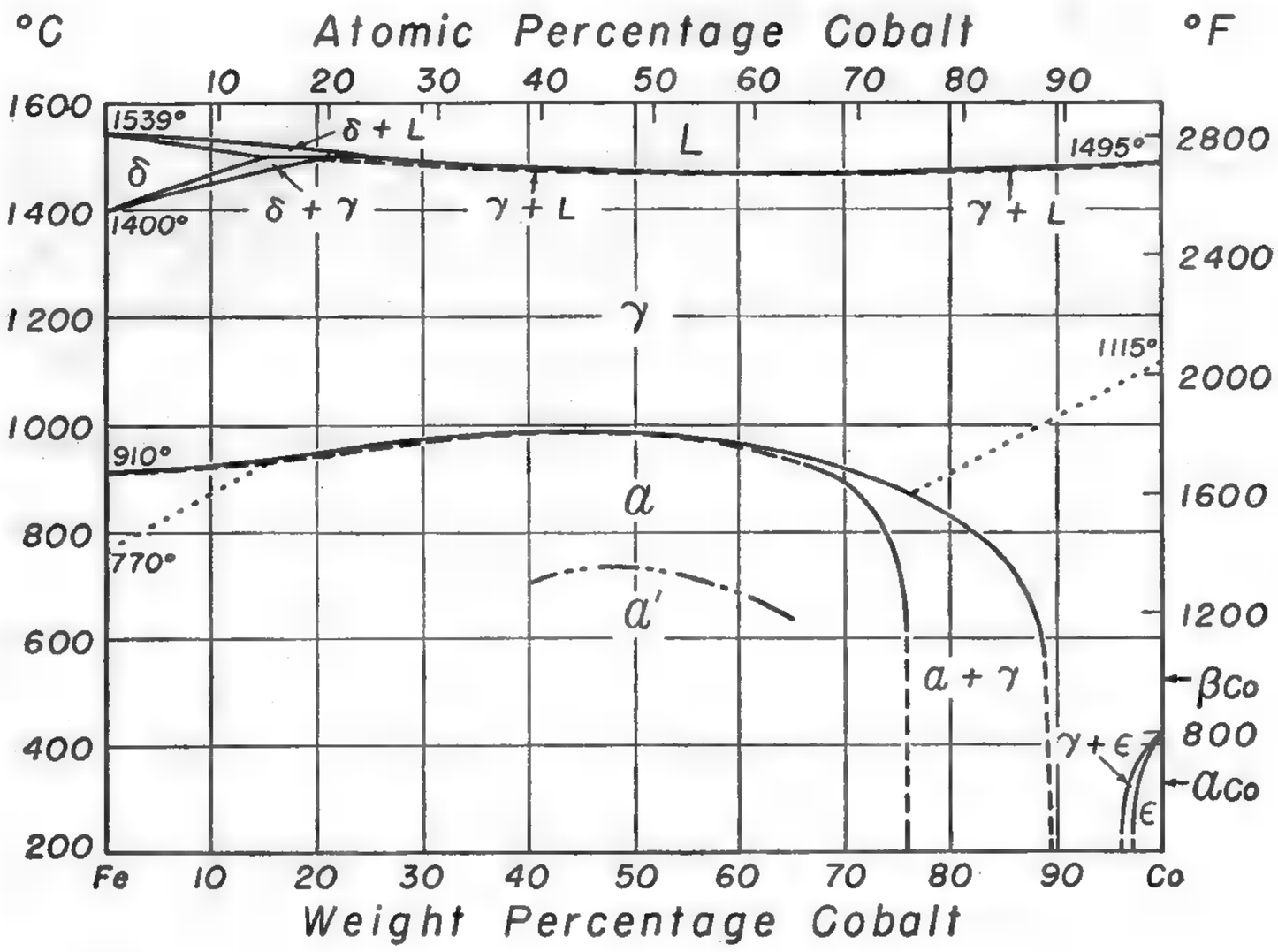
There is no general agreement on the temperature of the ϵ-γ transformation of cobalt, which has been located at 420 C.[3-8,12,15] The two phases often coexist below 420 C.

* Bell Telephone Laboratories, Inc., Murray Hill, N.J.

Crystal Structures and Lattice Parameters of Cobalt-Iron Alloys[14,16]

Phase	Percentage Cobalt	Description	Crystal Structure	Parameter, a, kX units at 25 C	Ratio, c/a
α	0	High-purity iron	Body-centered cubic	2.8607	....
α	76	Limit of α phase at 575 C	Body-centered cubic	2.8337	....
γ	89	Limit of γ phase at 575 C	Face-centered cubic	3.5484	....
γ	100	High-purity cobalt	Face-centered cubic	3.5368	....
ϵ	100	High-purity cobalt	Close-packed hexagonal	2.5020	1.6233

(Phase diagram and references are on the next page.)



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3 H. Masumoto, Science Repts Tôhoku Imp Univ, 15, 449 (1926)
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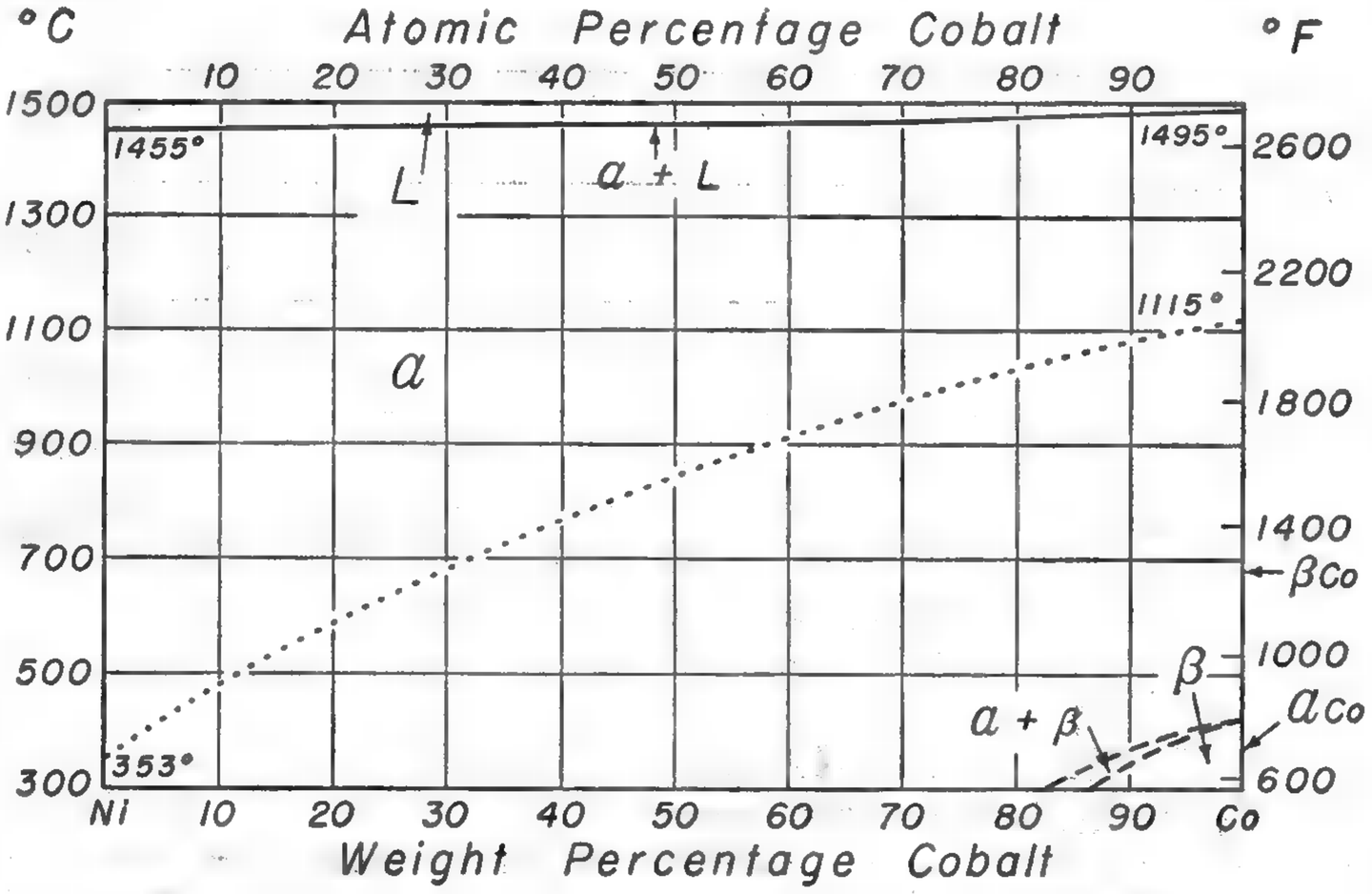
15 O. S. Edwards and H. Lipsoh, J Inst Metals, 69, 177 (1943)
16 E. S. Greiner, unpublished data (1947)

Co-Ni Cobalt-Nickel

By C. E. Lacy*



The liquidus and solidus are only about 5 degrees apart.

Temperatures of the α-β equilibrium are uncertain.

The lattice parameter of α is 3.5168 kX for pure nickel and 3.530 for the 70% Co alloy; hexagonal β has $a = 2.489$ kX ($c/a = 1.621$) at 80% Co, compared with 2.502 ($c/a = 1.6233$) for pure cobalt.

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7 F. D. Bennett, J. R. Doig and W. R. Ham, Phys Rev, 62, 295 (1942)

*Research Laboratory, General Electric Company, Richland, Wash.

Co-Pt Cobalt-Platinum

By R. I. Jaffee*

On freezing, cobalt-platinum alloys form a complete series of face-centered cubic solid solutions. The liquidus curve has a rather flat minimum at 1450 C and 50% Co. A face-centered tetragonal superstructure forms at the composition corresponding to PtCo (23% Co) during annealing below 800 C, as reported by Gebhardt and Köster[1] and by Hultgren and Jaffee.[2] The latter also found evidence of a body-centered cubic phase at this composition, in specimens annealed at 400 C; Jellinghaus[3] also reported that this phase was present in a cast 23% Co alloy. The ordered PtCo alloy has stronger permanent-magnet properties than any other known material.

*Battelle Memorial Institute, Columbus, Ohio

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3 W. Jellinghaus, Z tech Physik, 17, 33 (1936)
4 V. A. Nemilov, Z anorg allgem Chem, 213, 283 (1933)

Co-W Cobalt-Tungsten

By W. P. Sykes*

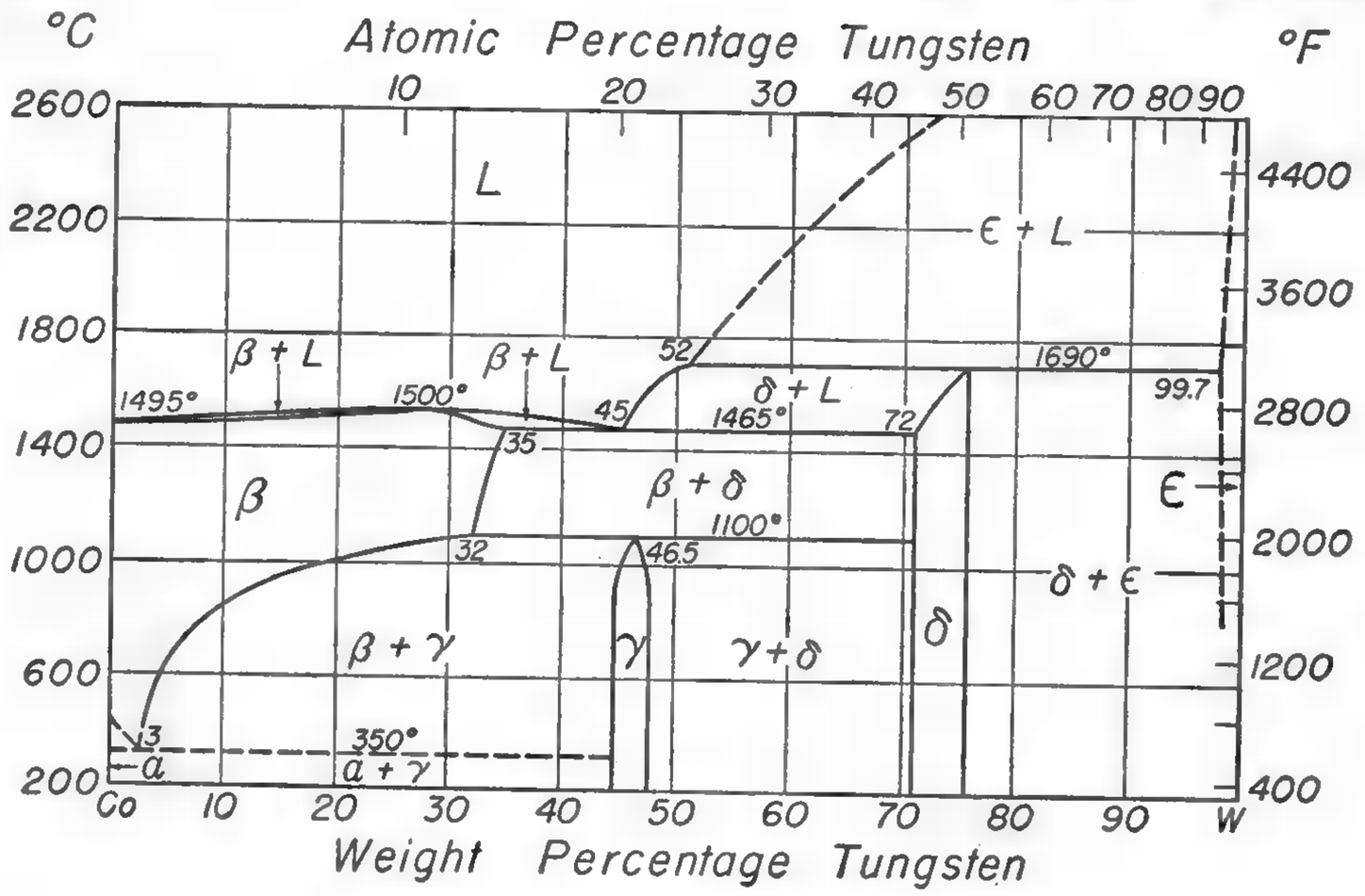
Because of the sluggish nature of the allotropic change in cobalt, which occurs between 400 and 500 C, exact data on the reaction $\beta \leftrightarrows \alpha + \gamma$ are lacking.

The γ phase appears to correspond to Co_7W_2 and the δ to CoW.[1,2,3] No data are available describing the crystal forms of these two intermediate phases.

* Lamp Department, General Electric Company, Cleveland

References

1 W. Köster and W. Tonn, Z Metallkunde, 24, 296 (1932)
2 W. P. Sykes, Trans ASST, 21, 385 (1933)
3 W. P. Sykes and H. F. Graff, Trans ASM, 23, 249 (1935)



Cr-Cu Chromium-Copper

By Cyril Stanley Smith*

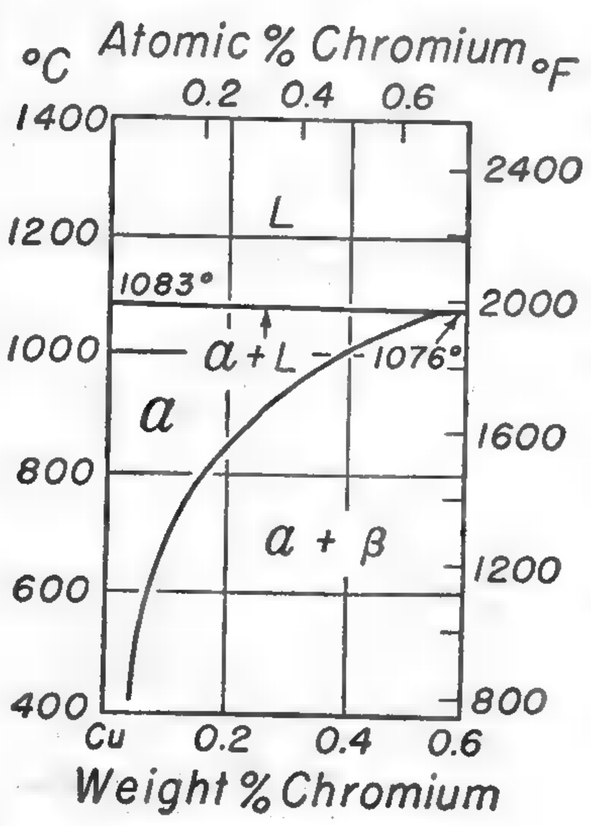
The liquidus and solidus shown are essentially those of Siedschlag,[2] but the liquidus has been modified to show the melting point of chromium at 1800 C instead of 1550 C, which was the melting point of the impure chromium that he used. Obviously, other parts of the diagram must also be affected by impurities. The extent of the two-liquid field is particularly uncertain.

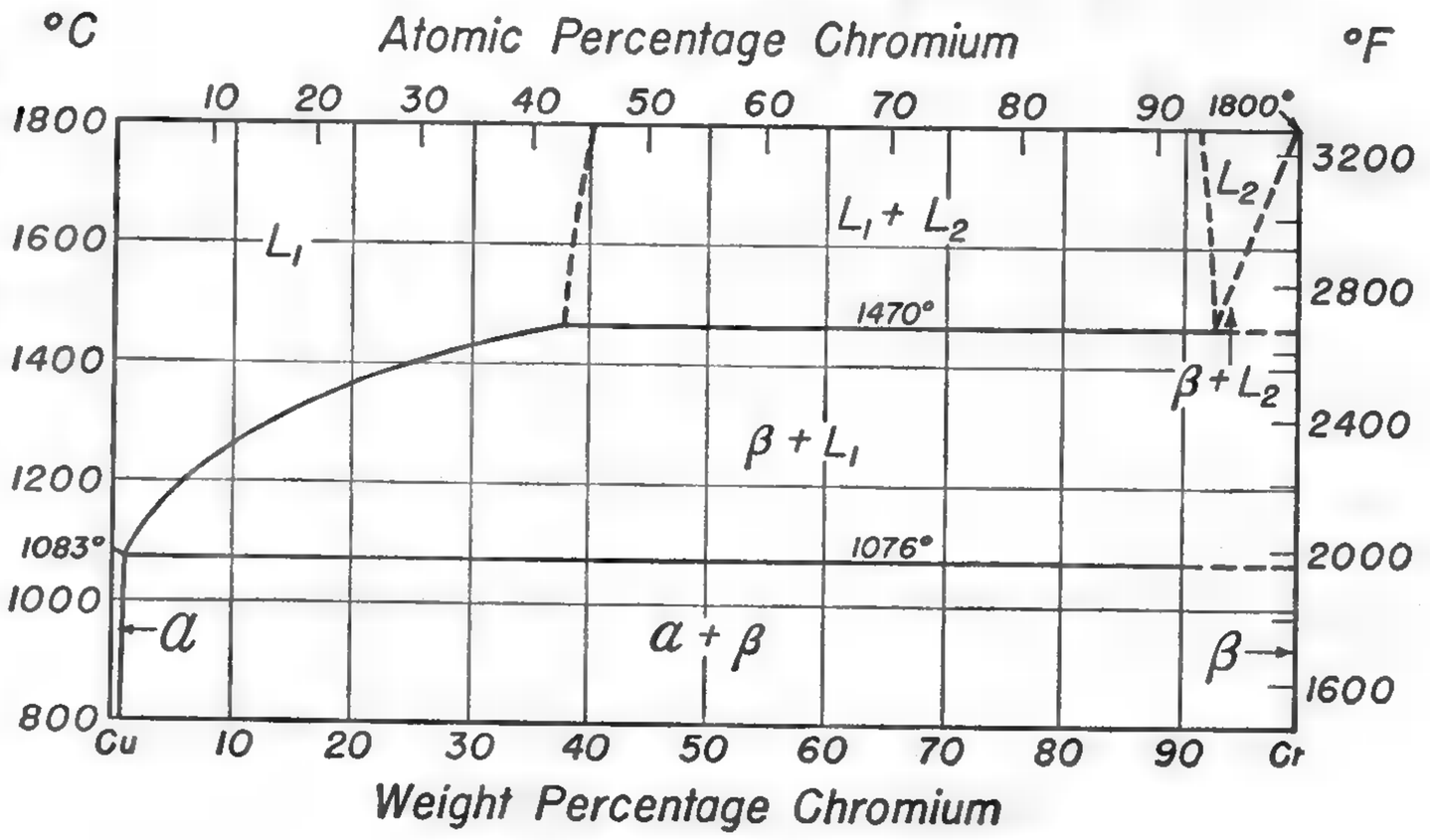
The values shown for the solubility of chromium in copper are those of Alexander[3] but his extrapolation to the eutectic temperature is not accepted. The values given by Corson[4] are somewhat higher than these—0.8 to 0.25% Cr at 1000 C and 500 C, respectively. The alloys must be quenched from about 1000 C if they are to be subsequently age hardened.

* Institute for the Study of Metals, University of Chicago, Chicago

References

1 G. Hindrichs, Z anorg Chem, 59, 414 (1908)
2 E. Siedschlag, Z anorg allgem Chem, 131, 173 (1923)
3 W. O. Alexander, J Inst Metals, 64, 93 (1939)
4 M. G. Corson, Proc AIME, Inst Metals Div, 435 (1927)





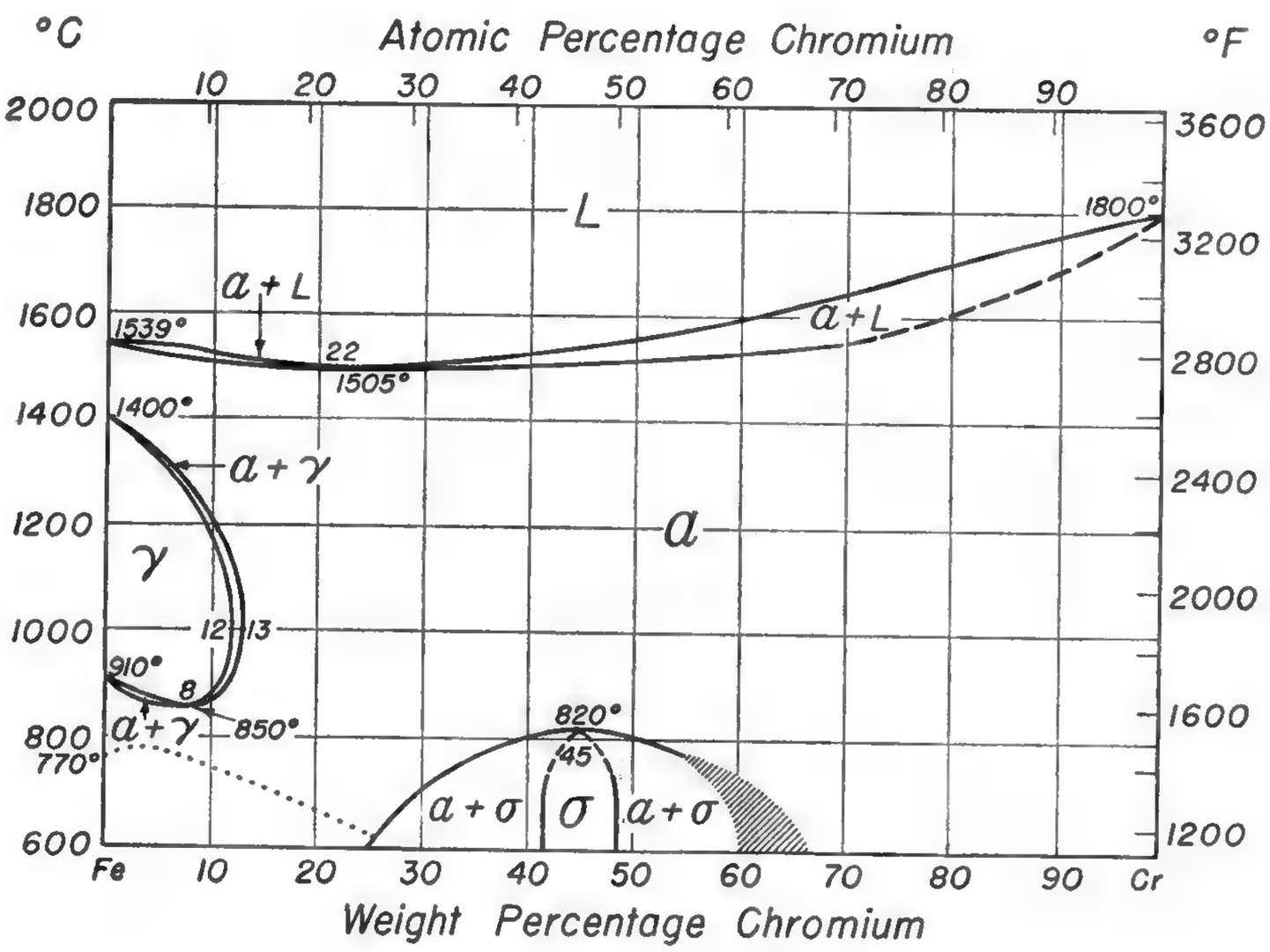
Cr-Fe Chromium-Iron

By E. C. Bain* and R. H. Aborn*

Sigma is a brittle nonmagnetic phase,[1] having the properties of an intermetallic compound approximating FeCr, but capable of dissolving a few per cent of either iron or chromium. Sigma forms from alpha at an extremely slow rate in pure alloys that have not been cold worked. The boundary between α and $\alpha + \sigma$ (from 60 to 67% Cr) is indicated as a shaded band because of uncertainty as to the exact location, owing to possible segregation in the alloys.[2]

The crystal structure of σ has not been determined with certainty but this phase appears to have a complex body-centered cubic structure.[3] The lines of the diffraction pattern are reported[3] to be not always identical, from which it has been suggested that two modifications can occur—one stable and the other a transitional structure.

The brittle phase σ is doubtless responsible for a marked embrittlement that occurs under certain conditions in the alloys with more than about 25% Cr.



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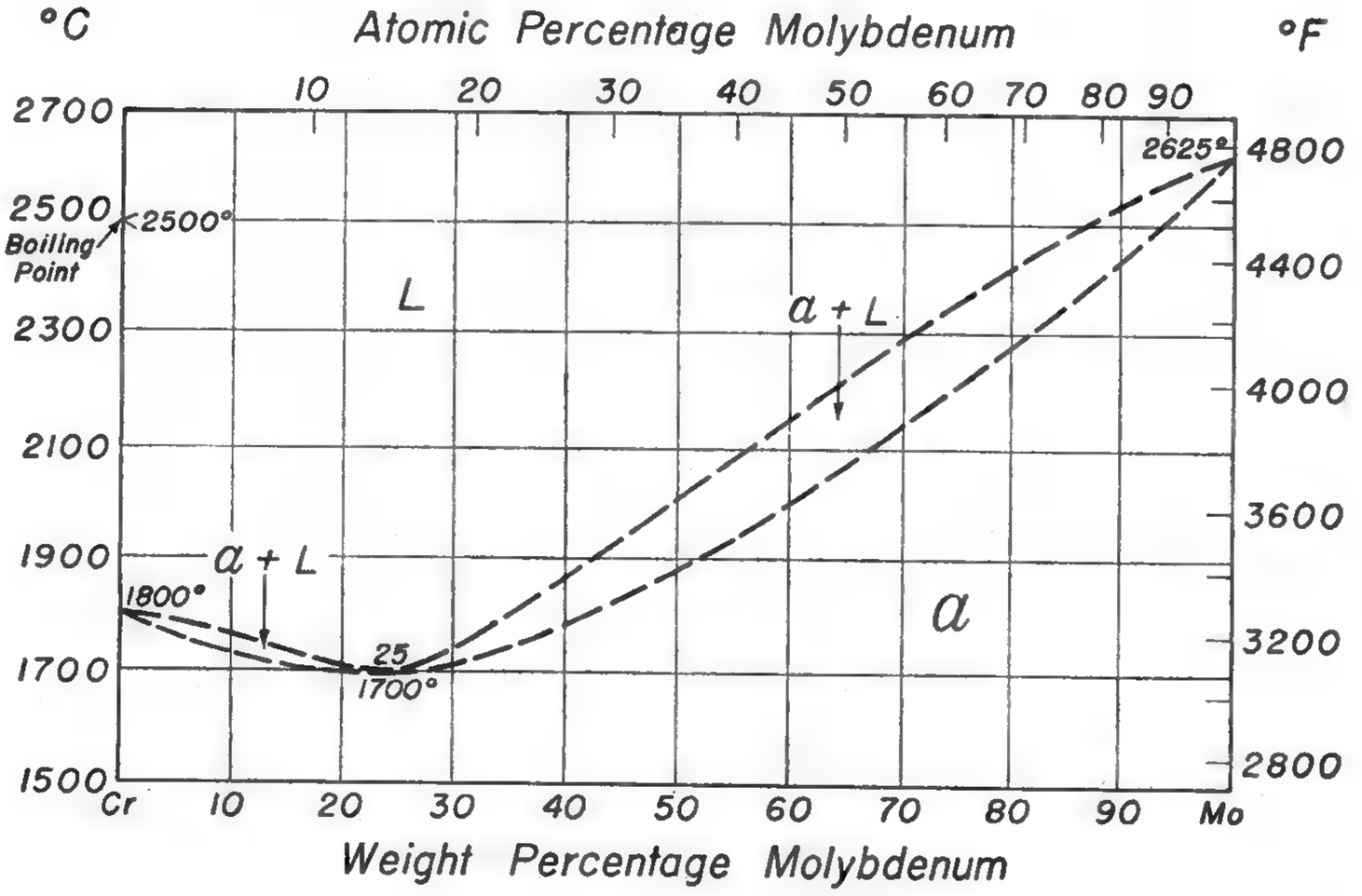
8 A. B. Kinzel and W. Crafts, "Alloys of Iron and Chromium, I, Low Chromium", Engineering Foundation, McGraw-Hill Book Co., New York, 1937, p 25

* Carnegie-Illinois Steel Corporation, Pittsburgh
* United States Steel Corporation, Research Laboratory, Kearny, N.J.

Cr-Mo Chromium-Molybdenum

By W. P. Sykes†



Published X-ray results[1] indicate that chromium and molybdenum are completely soluble in all proportions in the solid state. More recent unpublished data obtained by R. M. Parke and A. J. Herzig confirm the conclusion that there is only one solid phase in this system. The liquidus and solidus have not been determined accurately.

Reference

1 O. Kubaschewski and A. Schneider, Elektrochem, 48, 671 (1942)

Note Added in Proof. Since this diagram was drawn, experimental results have been published which confirm the extent of the solid solution field above 600 C, and confirm the temperature of minimum melting point. *See* W. Trzebiatowski, H. Ploszek and J. Lobzowski, X-Ray Analysis of Chromium-Molybdenum and Chromium-Tungsten Alloys, Analytical Chemistry, 19, 93 (1947).

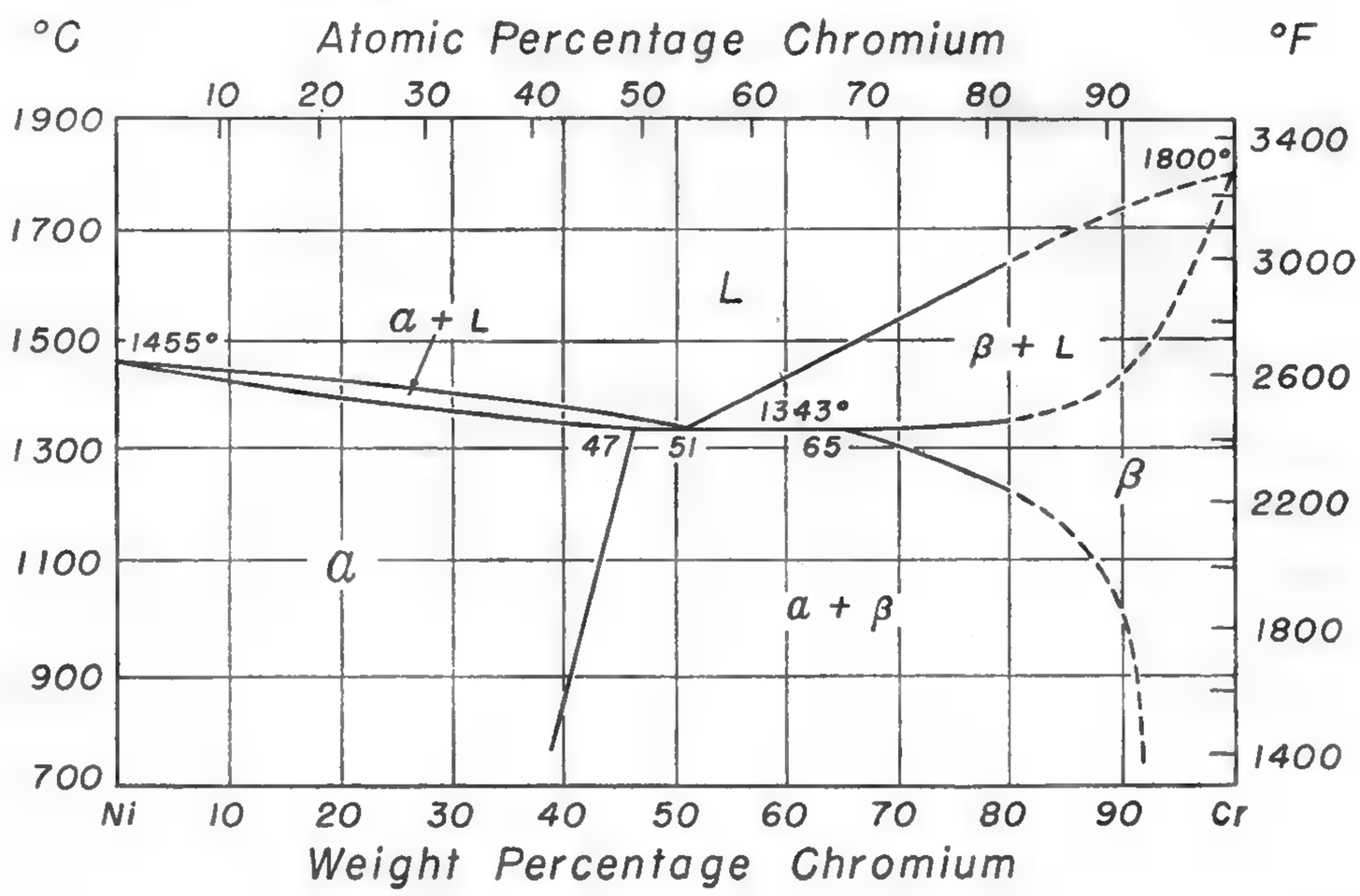
† Lamp Department, General Electric Company, Cleveland

Cr-Ni Chromium-Nickel

By E. M. Wise* and J. T. Eash*

The Curie temperature of nickel is lowered rapidly by the addition of chromium in solid solution. The results of Marian[1] are as follows:

Weight Percentage Chromium	Curie Temperature, deg Cent
0	353
1	310
2	270
3	225
4	170
5	115
6	60
7	10



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* The International Nickel Company, Inc., New York

* The International Nickel Company, Inc., Research Laboratory, Bayonne, N. J.

Cr-Pb Chromium-Lead

According to the results of Hindrichs [Z anorg allgem Chem, 59, 428 (1908)], the phase diagram for the chromium-lead system is similar to those for the copper-lead and chromium-copper systems. The chromium used in this investigation contained 1.20% Fe and 0.32% Si, and the melting point of this impure metal was 1550 C — 250 C lower than the melting point of pure chromium. Obviously other parts of the diagram must be affected by impurities. The monotectic point was reported as 1470 C and 28% Pb, and the monotectic horizontal was reported as extending to between 75 and 100% Pb. No effect of chromium on the melting point of lead was noted.

Cr-Si Chromium-Silicon

Kurnakov [Compt rend (Doklady) Acad Sci URSS, 34, 110 (1942)] investigated the entire system using alloys prepared from pure metals. Chromium dissolves about 7.5% Si. There are five intermediate phases. Cr_3Si (15.54% Si) melts at 1750 C, Cr_2Si (about 20% Si) at 1606 C, Cr_3Si_2 (about 25% Si) at 1550 C, CrSi (about 35% Si) at 1630 C, and $CrSi_2$ (about 53% Si) at 1500 C. There are five eutectics: α and Cr_3Si at 1515 C and 11.93% Si, Cr_3Si and Cr_2Si at 1593 C and 15.98% Si, Cr_2Si and CrSi [*sic*] at 1400 C and 28.1% Si, CrSi and $CrSi_2$ at 1445 C and 42.04% Si, and $CrSi_2$ and silicon at 1304 C and 76.1% Si. The preceding data are from an abstract [Met Abs, 10, 243 (1943)].

Cr-Pd Chromium-Palladium

The constitution of chromium-palladium alloys was investigated by Grube and Knabe [Z Elektrochem, 42, 793 (1936)], by means of thermal, microscopic, X-ray, hardness and electrical measurements. A face-centered cubic intermediate phase, Pd_2Cr_3, was reported, with melting point at 1398 C (42% Cr). There is a minimum in the liquidus curve of the palladium-rich solid solution at 1300 C and 38% Cr. Pd_2Cr_3 and the chromium solid solution form a eutectic at 1320 C and 59.5% Cr. The solubility of palladium in chromium is about 10% at the eutectic temperature. The phase diagram of Grube and Knabe shows no equilibrium between the palladium-rich solid solution and Pd_2Cr_3.

Cr-W Chromium-Tungsten

According to the results of Kubaschewski and Schneider [Z Elektrochem, 48, 671 (1942)], chromium and tungsten form a continuous series of solid solutions, with a minimum melting point at 30% W and 1720 C. Trzebiatowski, Ploszek and Lobzowski [Analytical Chemistry, 19, 93 (1947)] have confirmed the unlimited solid solubility at 1700 C, by means of X-ray measurements. However, they found a miscibility gap at lower temperatures, with solubilities as follow: at 1000 C, 16% W in chromium and 4.5% Cr in tungsten; at 1200 C, 21% W in chromium and 4.5% Cr in tungsten; at 1430 C, 65% W in chromium and 12% Cr in tungsten. The critical temperature was not determined.

Cr-Pt Chromium-Platinum

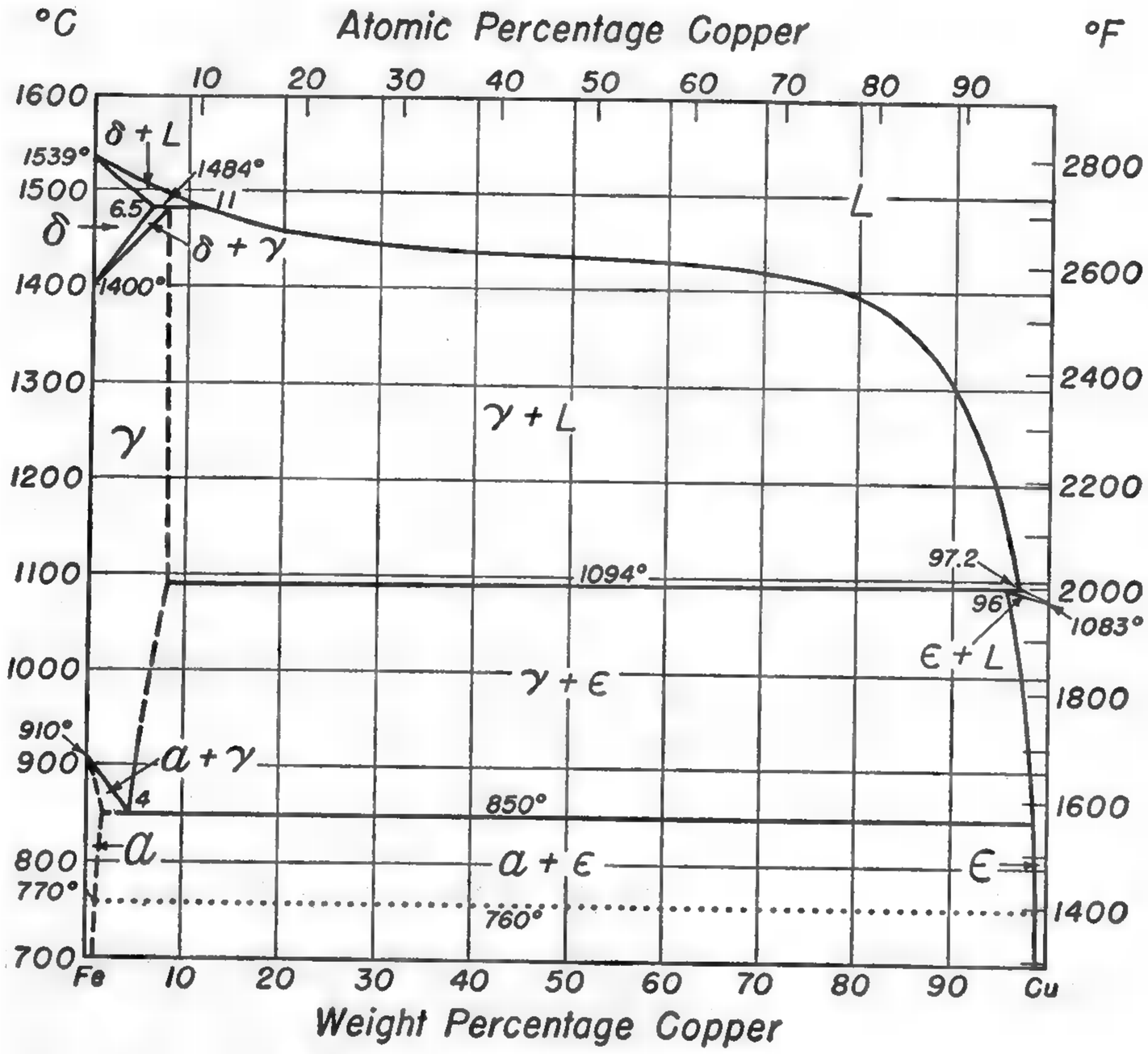
The liquidus descends from the melting point of platinum to about 1400 C at about 50% Cr. Compounds based on $PtCr_3$, PtCr and Pt_3Cr probably exist at low temperature. Ordered face-centered cubic alloys with about 6 to 17.5% Cr are ferromagnetic. (R. F. Vines, "Platinum Metals and Alloys")

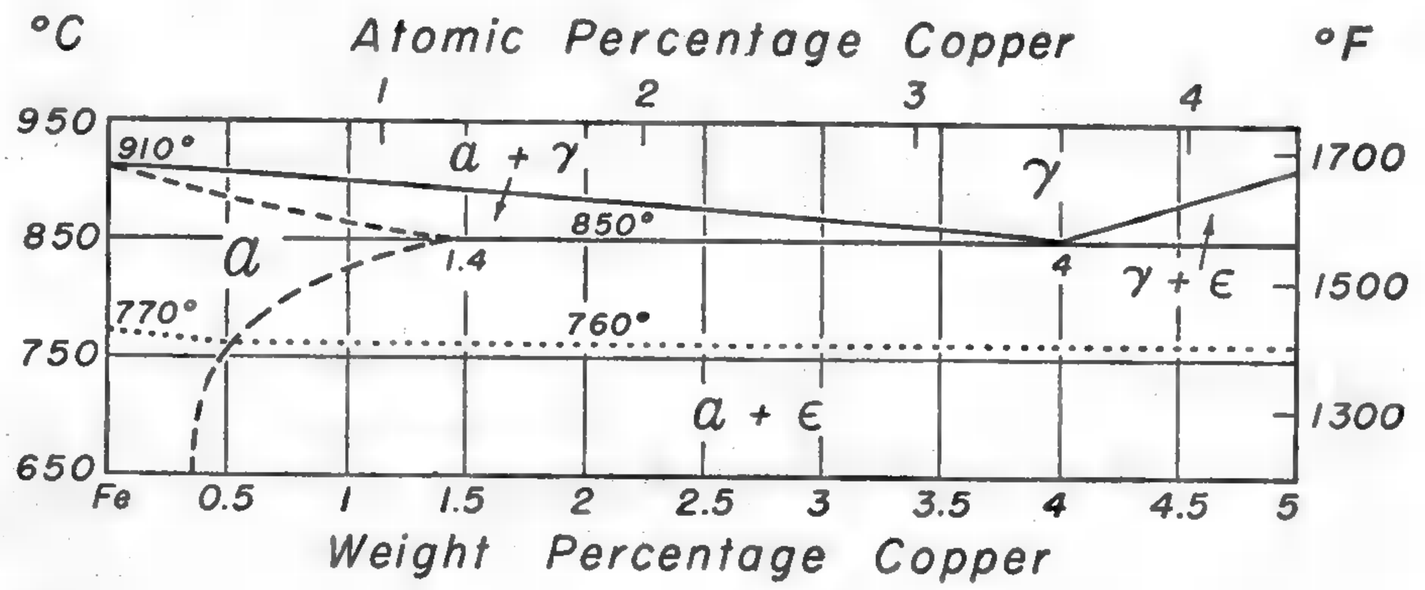
Cs-Fe Cesium-Iron

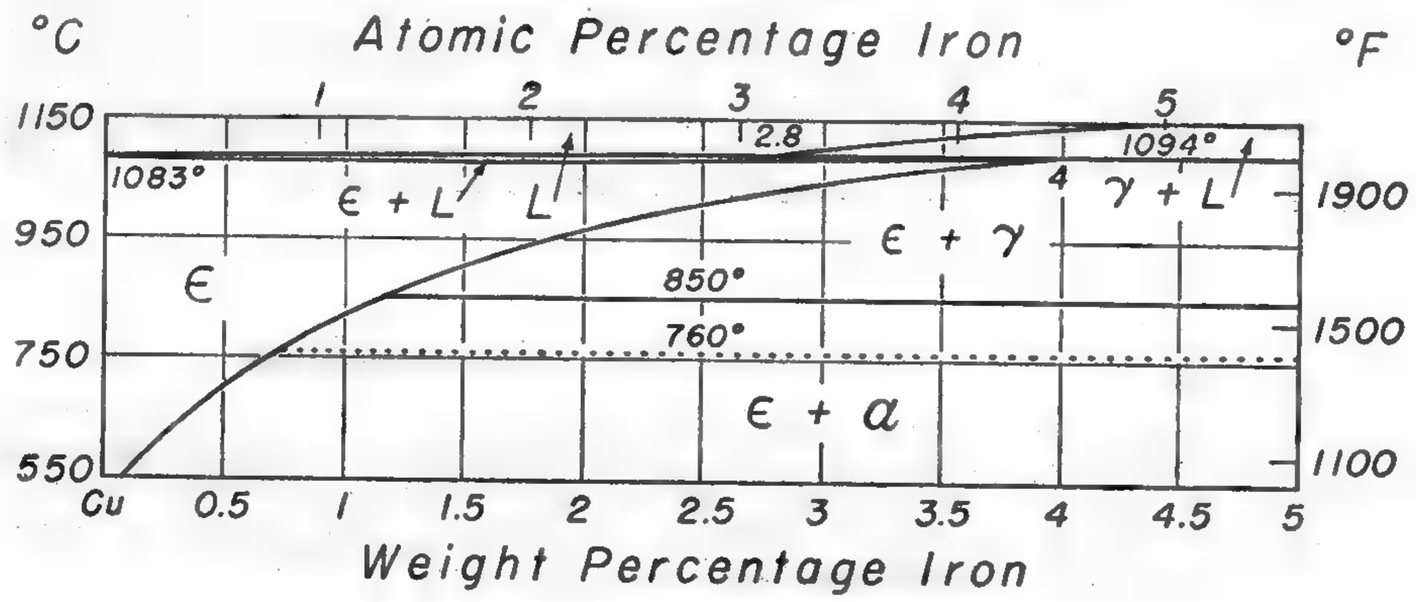
Iron is insoluble in liquid cesium. Cesium is insoluble in solid iron. Although the solubility of cesium in liquid iron is not known, the formation of iron-cesium alloys is considered improbable. (M. Hansen, "Der Aufbau der Zweistofflegierungen", J. Springer, Berlin, 1936)

Cu-Fe Copper-Iron

By B. N. Daniloff*







The boundaries separating the γ from the $\gamma + L$ and $\gamma + \epsilon$ fields have not been accurately determined. The maximum copper concentration of the γ solid solution has been variously reported to be from 8 to 10%[1,2,3,4] at 1484 C, and from 7.5 to 9%[1,2,3,4] at 1094 C. Experiments on sintered compacts of iron and copper showed that the solubility of copper in gamma iron between the peritectic and eutectoid temperatures may be considerably lower than indicated on the diagram, and that the copper solubility lines in gamma and alpha iron may form a nearly continuous curve.*

The solubility of copper in alpha iron at the eutectoid temperature is shown at 1.4% as determined by X-ray diffraction methods.[5] Earlier reports placed the solubility at 3.5% Cu.[6]

The line indicating the solubility of iron in copper has been fairly accurately established.[7,8] The iron-rich phase precipitated from ϵ solid solution remains in a nonmagnetic face-centered cubic form unless cold worked.[9,10,11]

X-Ray Data

Body-Centered Cubic Alpha[5]		Face-Centered Cubic Epsilon[8]	
Wt. % Copper	a, kX units	At. % Iron	a, kX units
0.25	2.8608	0.08	3.60762
0.31	2.8610	0.62	3.60793
0.44	2.8613	0.95	3.60813
0.75	2.8617	1.50	3.60848
		2.04	3.60880
		2.31	3.60896
		2.79	3.60926

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* San Francisco Naval Shipyard, San Francisco, Calif.

* Unpublished data, The New Jersey Zinc Company (of Pa.)

Cu-Ga Copper-Gallium

In connection with the theory of alloys, the copper-gallium system is of interest because of its place in the series of systems involving copper with the elements of the B groups (Zn, Ga, Ge, As; Cd, In, Sn, Sb). When plotted on a scale of atomic percentage, the liquidus, solidus and alpha solid solubility curves of the copper-gallium system are at larger copper contents than those of the copper-zinc system, and at smaller copper contents than those of the copper-germanium system.

Cu-Ge Copper-Germanium

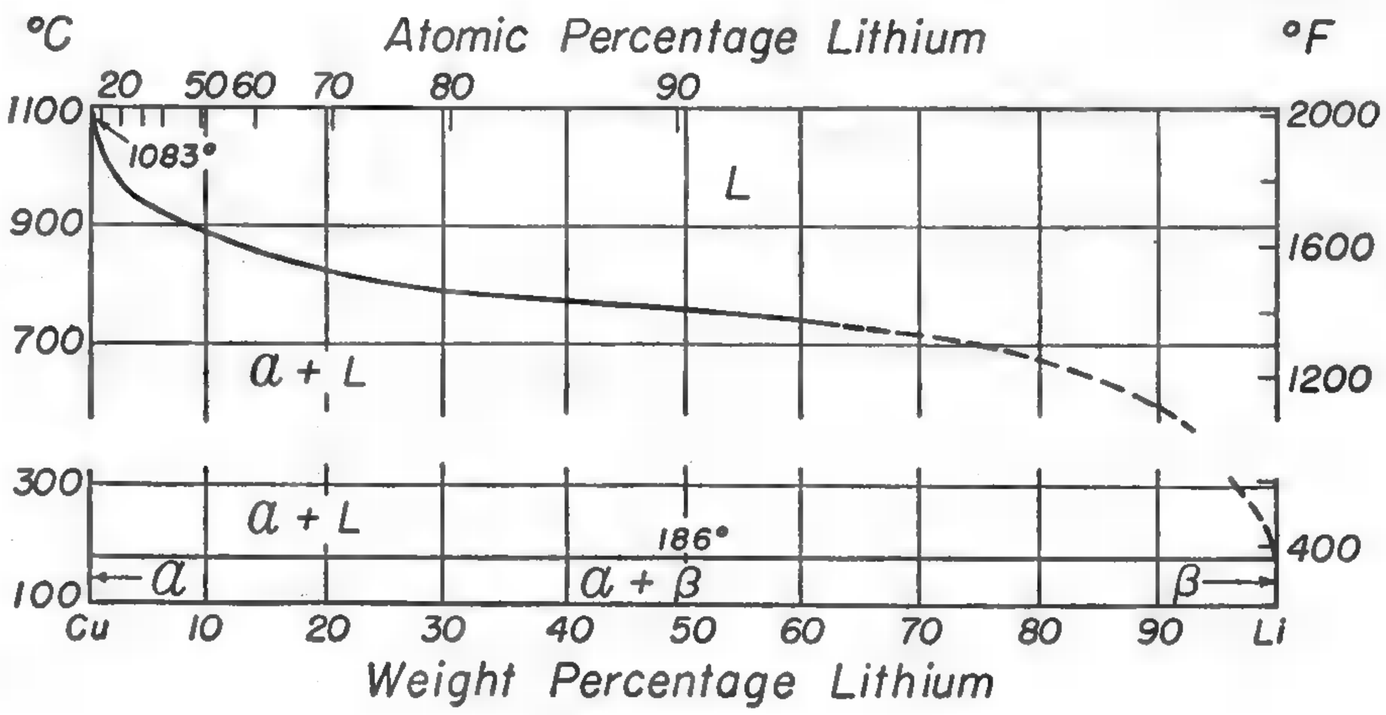
Like the copper-gallium system (*see* left-hand column), the copper-germanium alloys are of interest in building a theory of the structure of alloys. The liquidus, solidus and alpha solid solubility curves of copper-germanium alloys are at larger atomic percentages of copper than those of copper-gallium alloys, and at smaller copper contents than those of copper-arsenic alloys. The first intermediate phase in the copper-germanium system is hexagonal, and forms by peritectic reaction at 822.5 C.

Cu-Li Copper-Lithium

By A. C. Vaughan*

Thermal and X-ray methods were used for the investigation of copper-lithium alloys containing from 0.18 to 63.1% Li. No solid solubility of either metal in the other was detected.

The eutectic composition is very close to 100% Li; and the eutectic temperature, indicated here as 186 C, is apparently only slightly lower than the melting point of lithium.



Reference

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* American Smelting and Refining Company, Barber, N.J.

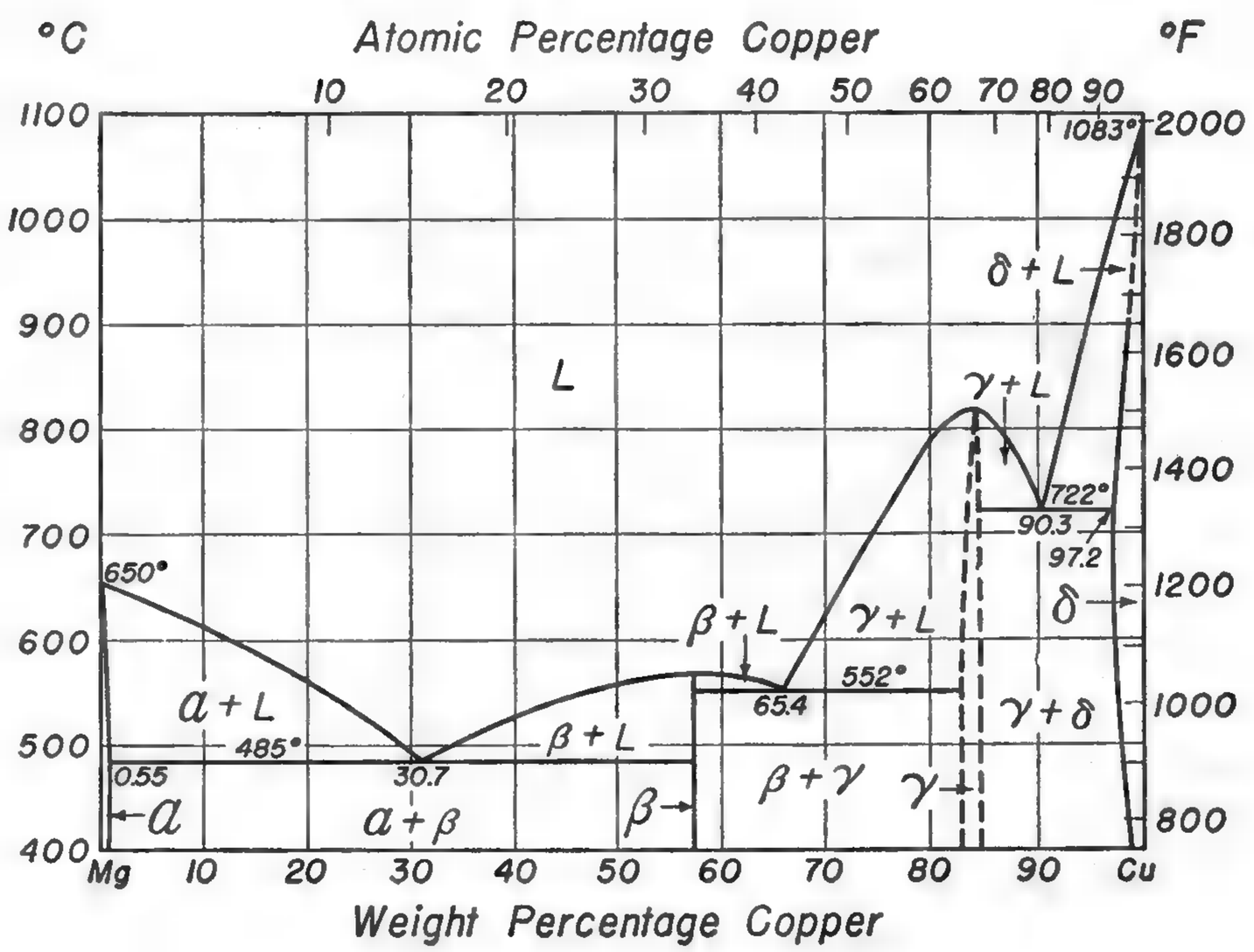
Cu-Mg Copper-Magnesium

By G. F. Sager* and B. J Nelson*

The solubility of magnesium in solid copper is, as follows: approximately 2.6% at 700 C, 2.5 at 600 C, 1.9 at 470 C, 1.2 at 400 C.

The solubility of copper in solid magnesium is 0.55% at 480 C, 0.30 at 400, 0.20 at 300.

The β phase is hexagonal with $a = 5.281$ kX, $c = 3.464$ kX;[2] γ is face-centered cubic with $a = 6.99$ kX.[7]



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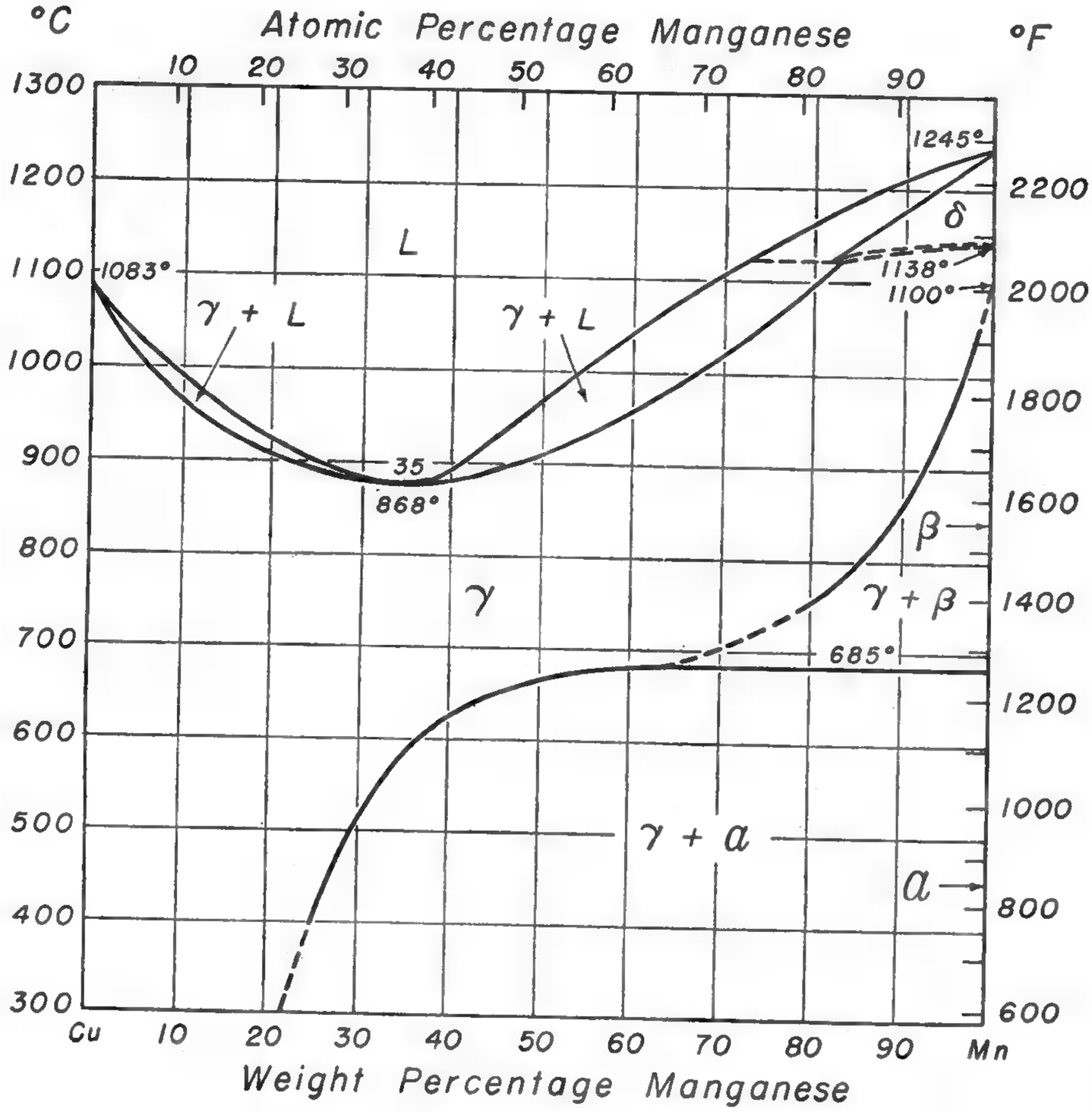
* Aluminum Research Laboratories, New Kensington, Pa.

Cu-Mn Copper-Manganese

By Blake M. Loring*



The phase diagram is based on the data of Persson,[1,2] Grube[3] and Dean,[4] except for the transformation temperatures of pure manganese, which were taken to be 685 C, 1100 C and 1138 C.

A reaction involving δ, γ and liquid has been established,[3,4] although the precise location of the phase boundaries is in doubt.

Gamma that contains less than 82% Mn is face-centered cubic. Gamma that contains from [illegible] to 100% Mn is tetragonal; the axial ratio of quenched alloys varies from 1.000 (at 82% Mn) to 0.937 (at 100% Mn).[2,3,4]

Neither alpha nor beta manganese dissolves an appreciable percentage of copper.

Studies of heat content[5] have essentially substantiated the form of the diagram in the temperature range from 25 to 850 C.

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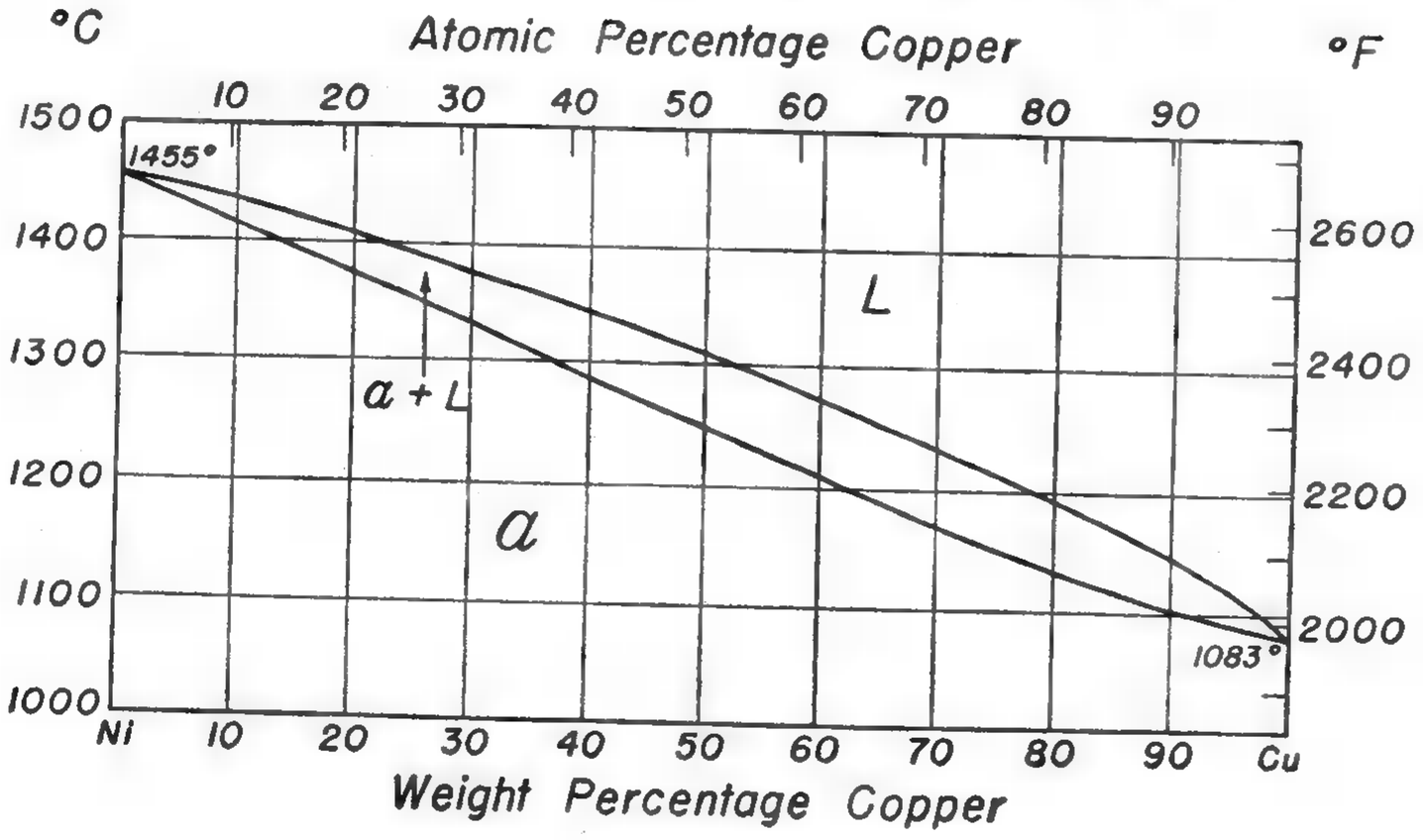
* Naval Research Laboratory, Washington, D.C.

Cu-Ni Copper-Nickel

By N. B. Pilling* and T. E. Kihlgren*



The alloys are face-centered cubic. The lattice parameter varies linearly with atomic concentration, from 3.60 kX for copper to 3.54 kX for nickel.

The Curie temperature varies linearly with weight percentage nickel, from 353 C for pure nickel to 25 C for the alloy containing 30% Cu. The magnetic change occurs near minus 170 C at 50% Ni.[3,4]

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* The International Nickel Company, Inc., Research Laboratory, Bayonne, N.J.

Cu-O Copper-Oxygen

By F. N. Rhines*

The β phase is Cu_2O; γ is CuO.

At some temperature above 1400 C, the liquid (L_2), approximating the composition of Cu_2O, probably decomposes, leaving liquid copper saturated with oxygen in equilibrium with the gas phase.

Of the several determinations of the solubility of oxygen in solid copper, the one by Phillips and Skinner,[4] giving the lowest values of all, has been selected for the construction of the phase diagram.

The pressure-temperature diagram is largely an approximation. The triple point of copper, point T, is estimated from the data collected by Randall, Nielson, and West;[6] the quadruple points, Q_1 and Q_2, are estimated from the data of Roberts and Smyth,[3] but if the data of Slade and Farrow[2] had been used, the point Q_2 would have fallen at a pressure of 10^{-3} atmospheres; there are no measurements available for locating Q_3 except the knowledge of the temperatures of the equilibriums CuO, Cu_2O, L_2, and G, CuO, L_2 at one atmosphere. Cuprous oxide, Cu_2O, is assumed to have a minimum melting point, M, at an unknown pressure. Such data as are available for the location of the G, Cu, Cu_2O equilibrium give pressures that appear impossibly low and have been disregarded.

* Department of Metallurgical Engineering, Carnegie Institute of Technology, Pittsburgh

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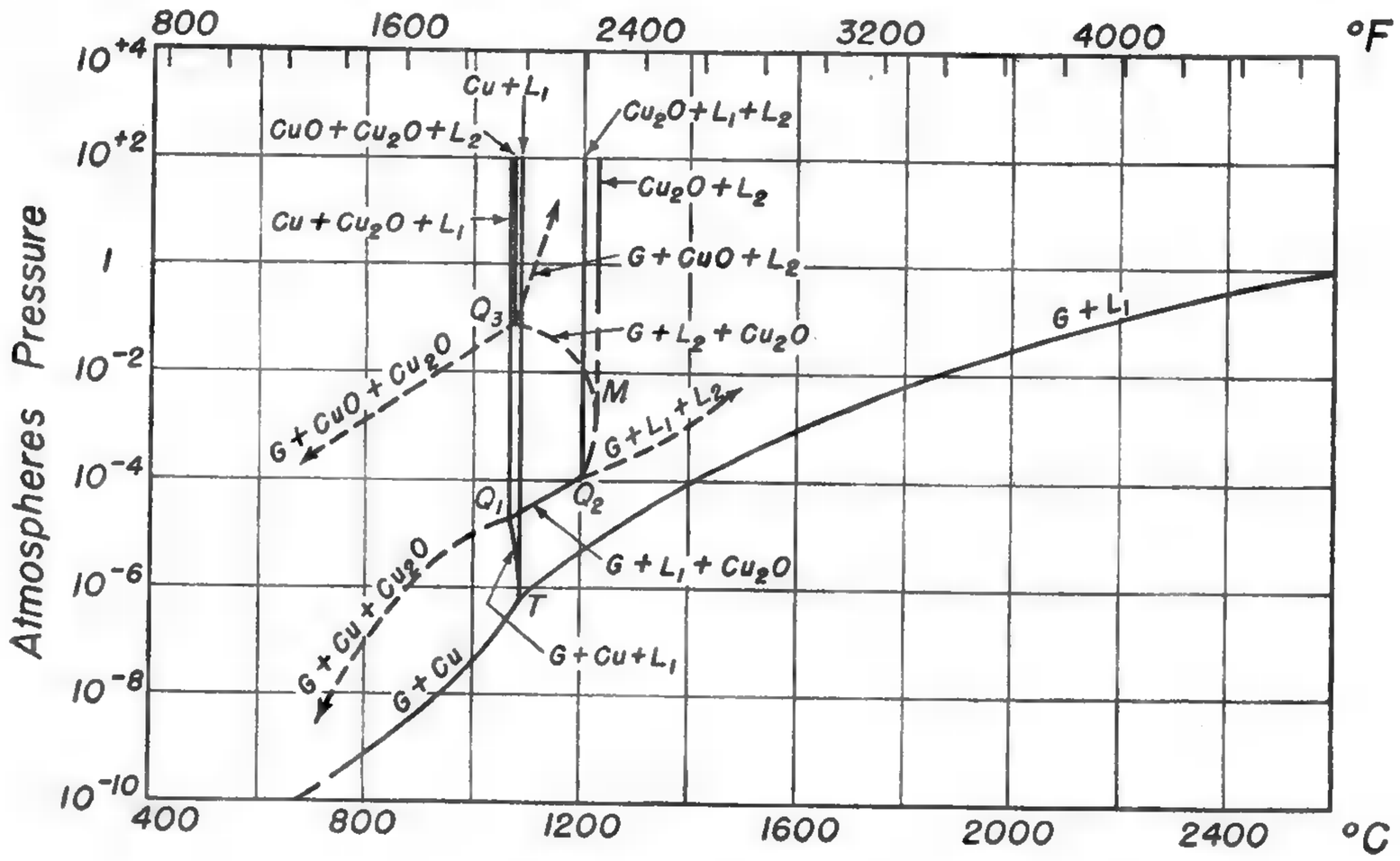
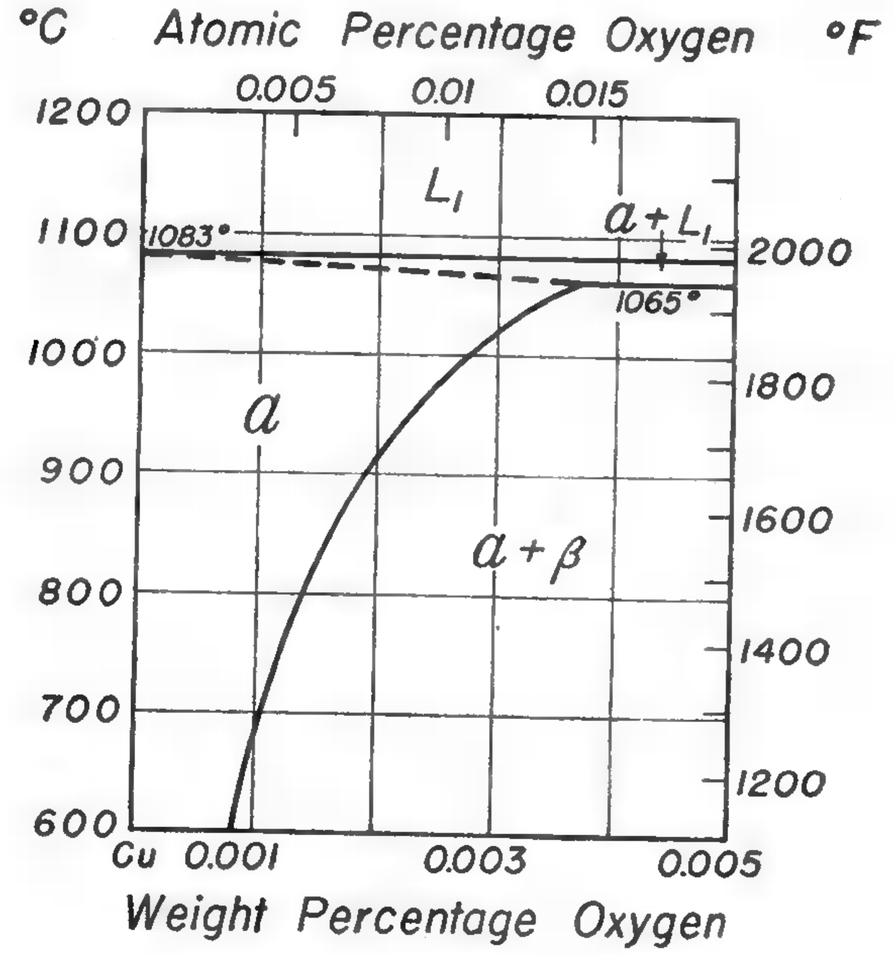
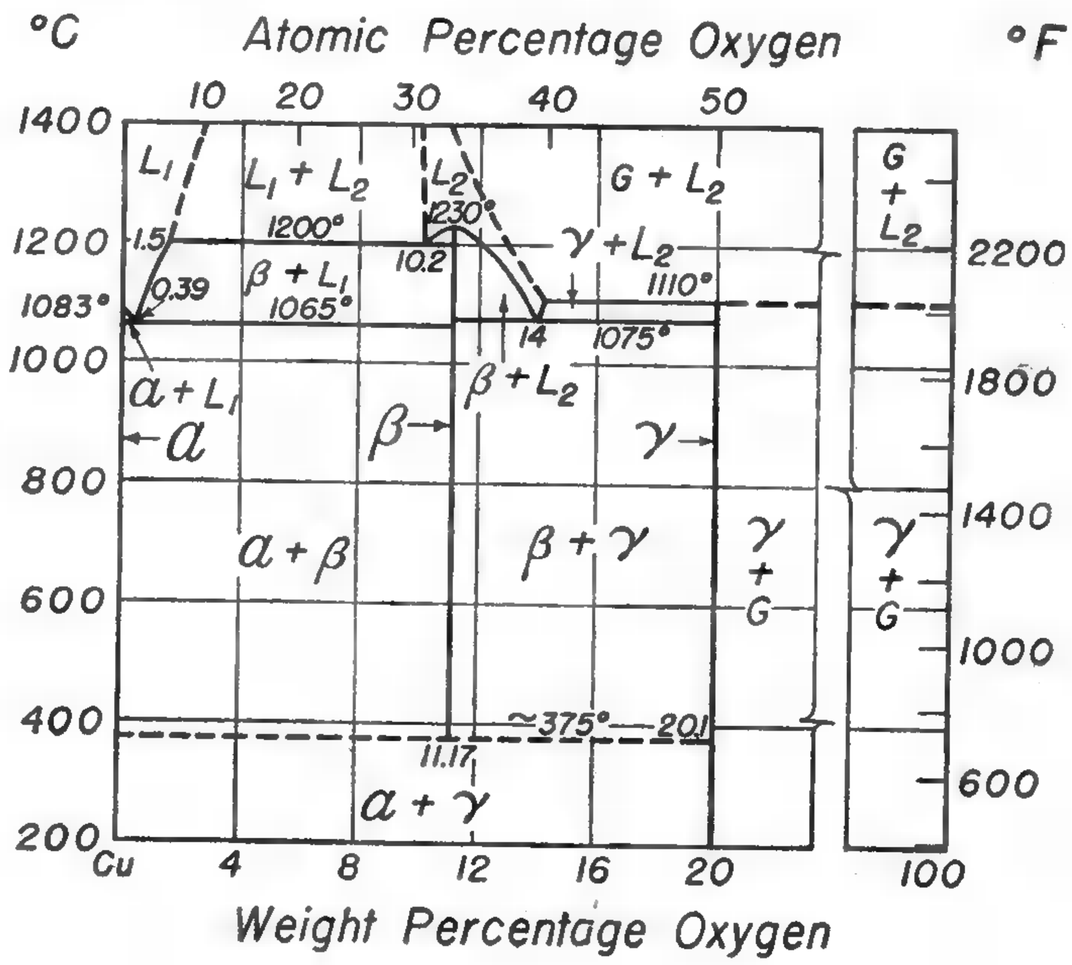
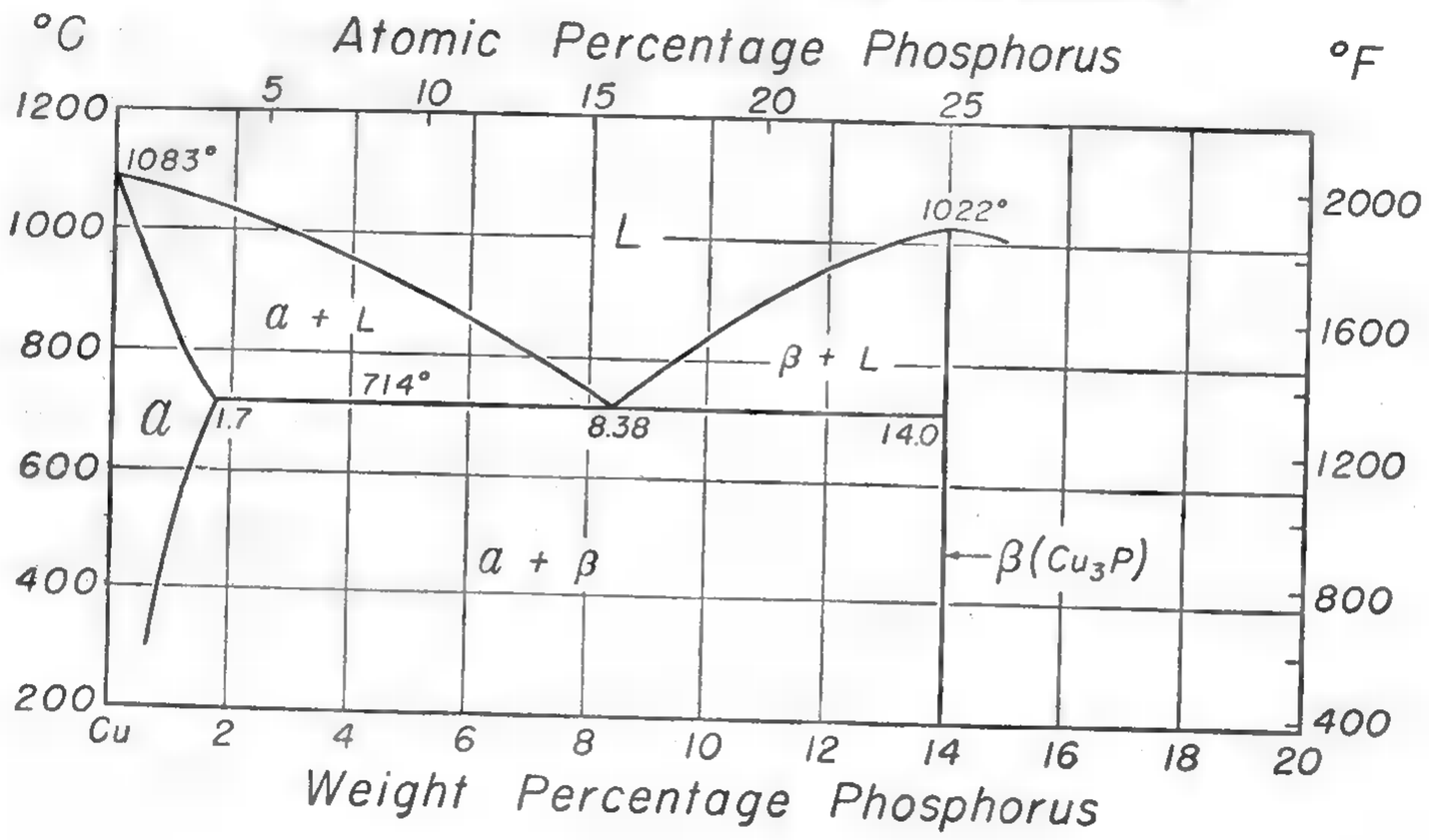






Cu-P Copper-Phosphorus

By H. L. Burghoff*



Alloys with more than 15% P are unstable at high temperatures and lose phosphorus. Alloys above 14% P consist of β (Cu_3P) plus a second compound, Cu_5P_2 or Cu_2P.

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* Chase Brass & Copper Co., Waterbury, Conn.

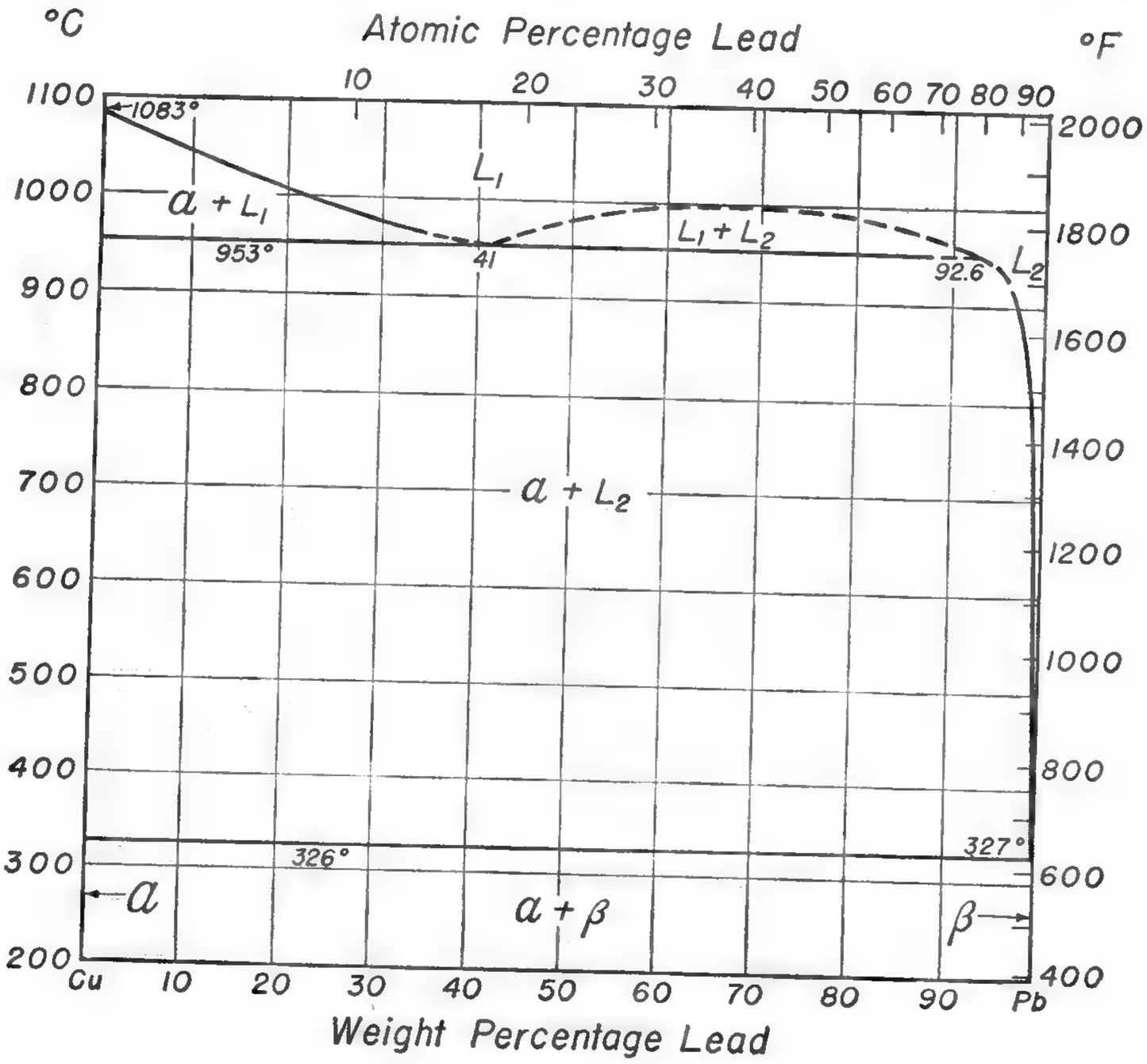
Cu-Pb Copper-Lead

By Paul A. Beck*

The position of the eutectic point, according to thermal analysis by Heycock and Neville,[1] and confirmed by industrial experience, is approximately at 0.06% Cu (326 C).

The solid solubility of copper in lead is less than 0.007% Cu as determined microscopically by Greenwood and Orr.[2] The solid solubility of lead in copper is probably of the order of 0.002 to 0.005% Pb.

The monotectic point is at about 41% Pb (953 C) in accordance with Heycock and Neville's liquidus curve for the copper-rich alloys[3] and with Briesemeister's data for the liquid miscibility gap.[4] The lead-rich end of the two-liquid field is probably about 92.6% Pb, where the liquidus curve of the lead-rich alloys, given by Bornemann and Wagenmann,[5] intersects the monotectic horizontal. The data of Friedrich and Waehlert[6] and of Briesemeister[4] indicate that the critical temperature (where the two-liquid field closes) is below 1025 C and probably close to 1000 C. This is confirmed by industrial experience with the casting at 1040 C of alloys that contain up to 45% Pb.†



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* University of Notre Dame, Notre Dame, Ind.

† Personal communication from A. F. Underwood

Cu-Pd Copper-Palladium

By E. M. Wise*

At temperatures above 600 C, only a face-centered cubic solid solution exists, but several transformations occur at lower temperatures.[2,3,4,5]

The β phase, in the region near PdCu, is of the ordered body-centered cubic type. The range of β (41 to 51% Cu) was determined by electrical resistivity measurements.[5] No evidence of any substantial hysteresis was found during the $\beta \rightarrow \alpha$ transformation in an alloy containing 60 atomic % Cu.[5]

An ordering transformation occurs, extending from about $PdCu_3$ some distance toward the copper side of the diagram. This has been considered analogous to the $AuCu_3$ transformation, which is of the ordered face-centered cubic type, but the work of Jones and Sykes[5] shows that in the area close to $PdCu_3$, designated α' in the diagram, very slowly cooled alloys (cooled to room temperature over a period of four months) develop a slight tetragonality; the axial ratio decreases to 0.986. This is confined to the α' region; the alloys containing from about 72 to 87% Cu (designated α'') become ordered but remain face-centered cubic.

The 40% Cu alloy is used for electrical contacts (*see* page 1128).

* The International Nickel Company, Inc., New York

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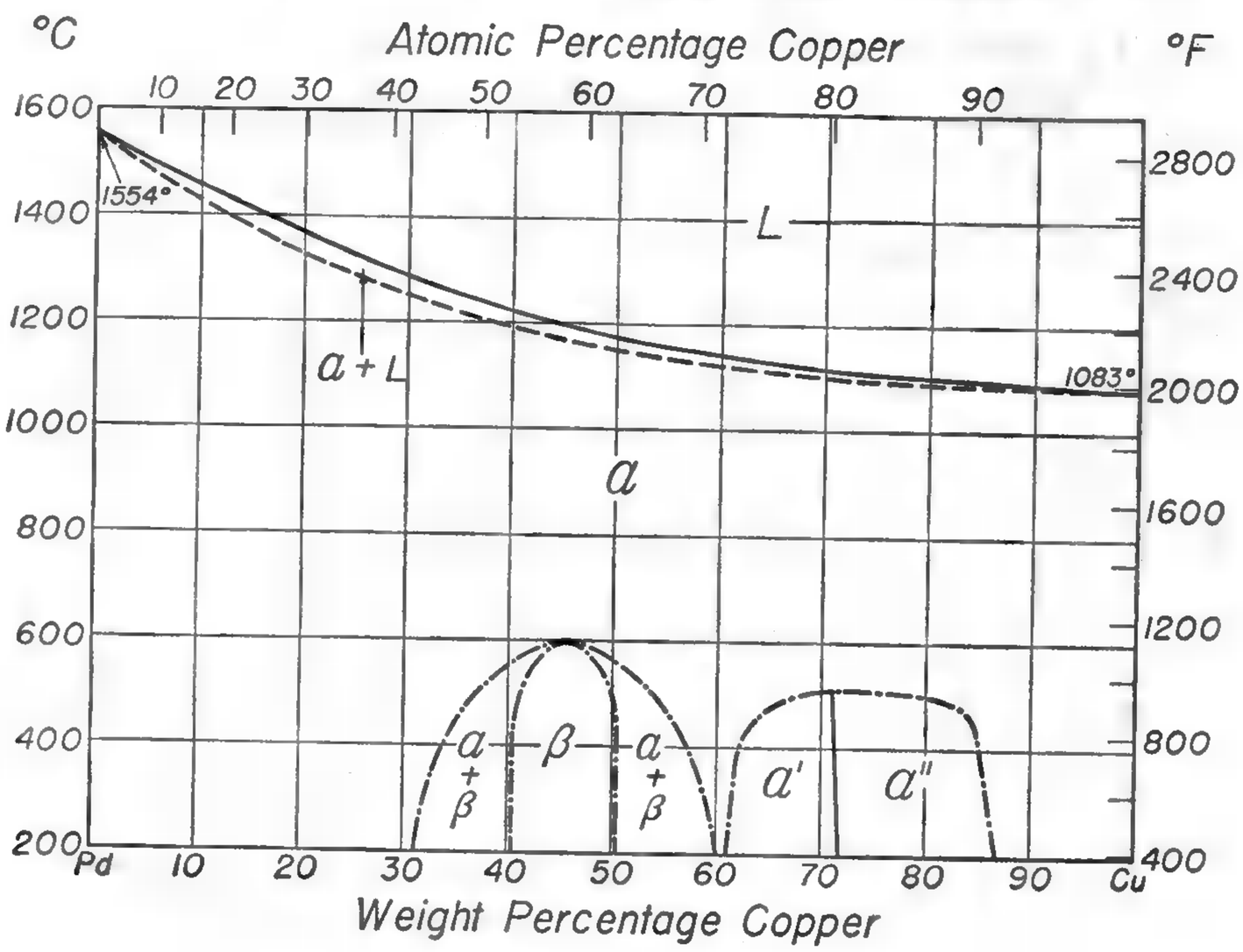
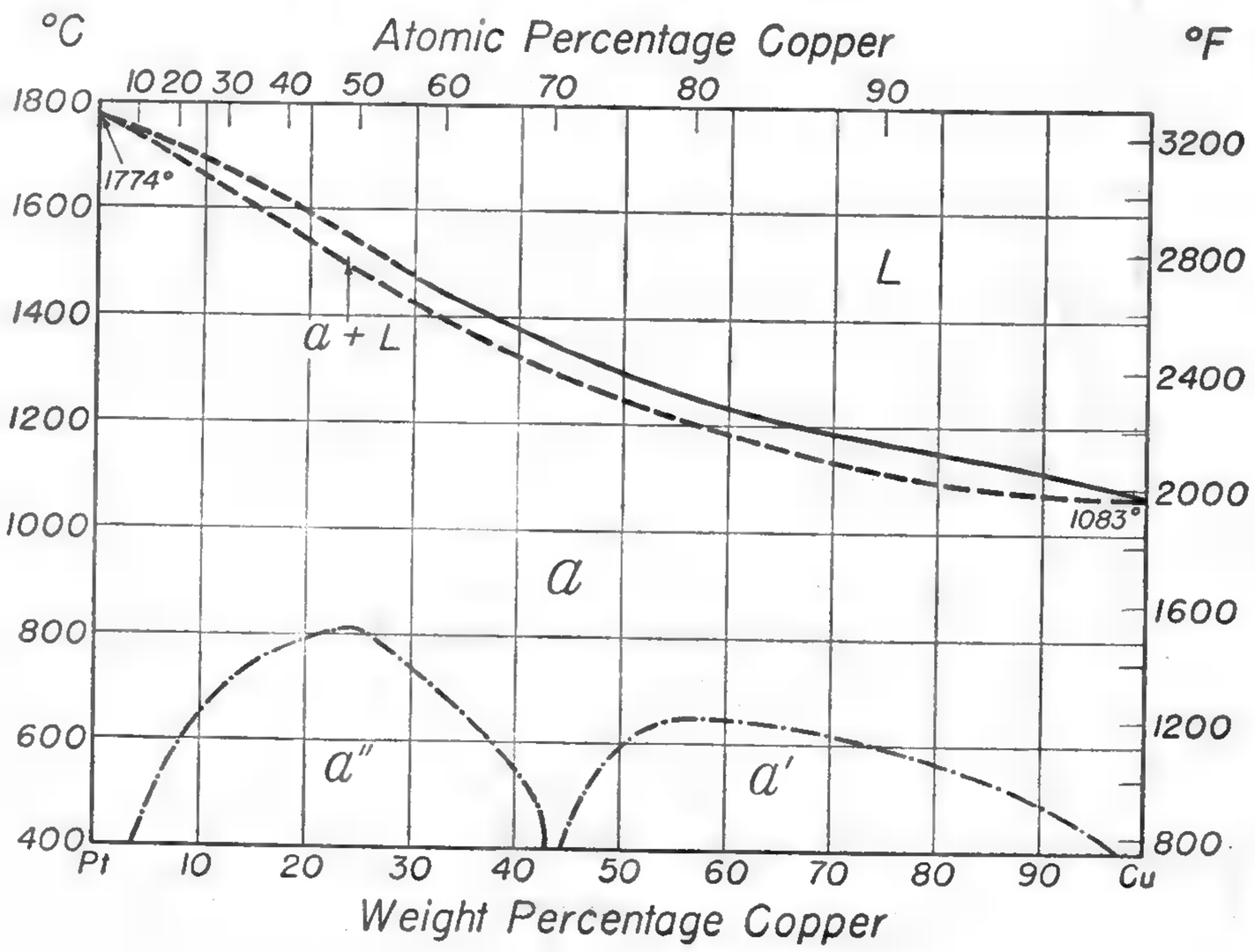


Cu-Pt Copper-Platinum

By E. M. Wise*

The liquidus was determined by Doerinckel.[1] CuPt, according to Linde,[4] has trigonal symmetry, and when the ratio of platinum to copper atoms exceeds unity, the excess platinum atoms assume an ordered arrangement. Another ordering reaction stems from $PtCu_3$, but these alloys remain face-centered cubic. For temperatures lower than 900 C, the diagram is drawn according to the results of Schneider and Esch.[6]



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* The International Nickel Company, Inc., New York

Cu-S Copper-Sulfur

By F. N. Rhines*

The β phase, (Cu_2S), found in nature as the mineral chalcocite, is normally orthorhombic; there is evidence of its transformation to a cubic form at about 100 C. Cupric sulfide, CuS (33.53% S), found in nature as the mineral covellite, appears only in the hexagonal form.

* Carnegie Institute of Technology, Pittsburgh

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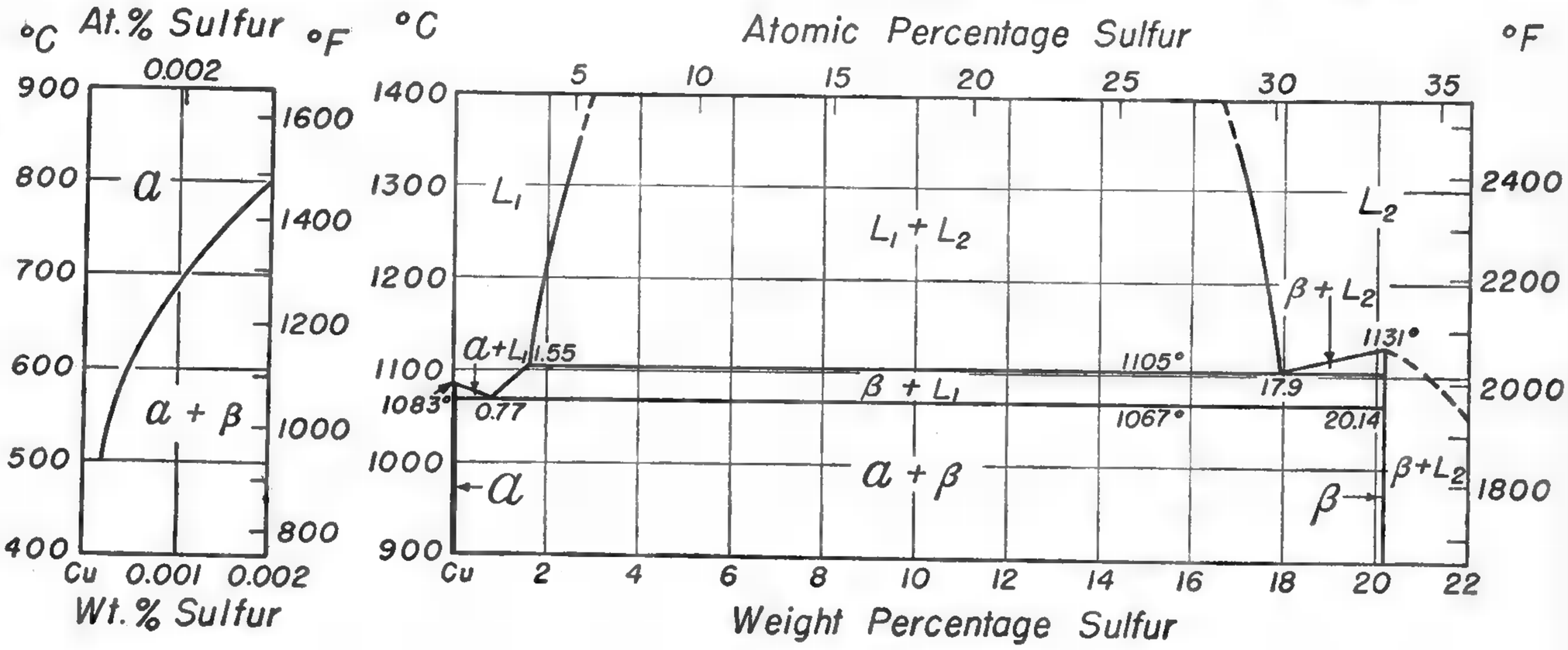
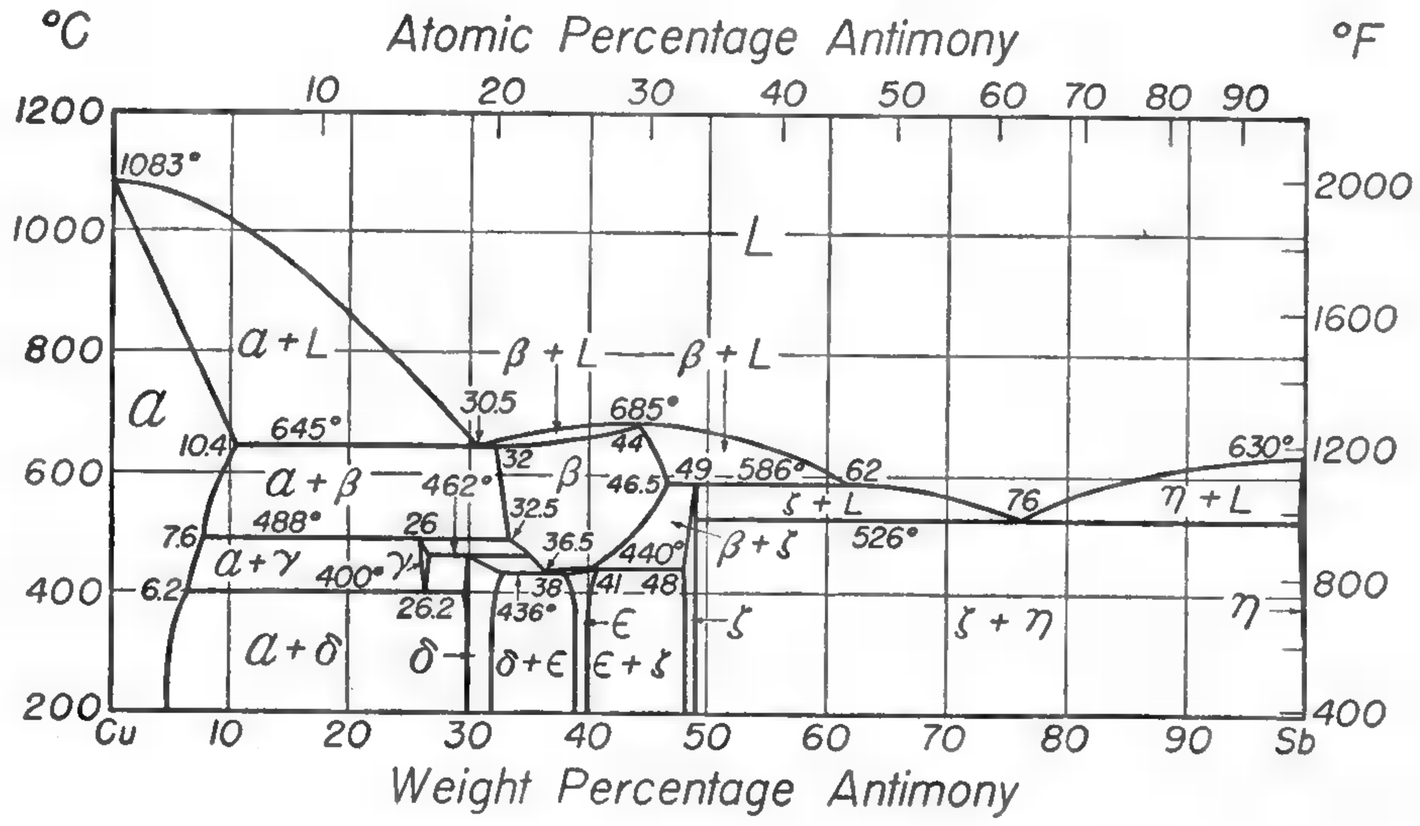


Cu-Sb Copper-Antimony

By H. L. Burghoff*



* Research Metallurgist, Chase Brass & Copper Co., Waterbury, Conn.

The diagram shown is that of Shibata and associates.

The solubility of copper in solid antimony is reported to be only about 0.2% at the eutectic temperature and even less at lower temperatures.

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Crystal Structures and Lattice Parameters of Copper-Antimony Alloys

Phase	Percentage Antimony	Crystal Structure	Atoms per Unit Cell	Lattice Parameter a, kX	Lattice Parameter c, kX	Lattice Parameter c/a	Specific Gravity
α	0 to 4.7	Face-centered cubic	4		Cu = 3.6079_2		8.92-8.542
					95.3% Cu = 3.6413		
γ	25.83	Orthorhombic	49	9.28_5	8.62_9	$b = 8.17_9$	8.909
δ	29.86	Hexagonal	12	10.836_0	8.611_2	0.794_7	8.878
ϵ	41.05	Hexagonal	15	5.494_7	8.686_3	1.580_9	8.617
β	43.29	Body-centered tetragonal	$2n$	9.01_4	8.57_4	0.951_2	~8.9
ζ	48.92	Simple tetragonal	12	5.62_1	6.07_4	1.081	8.446
η	100	Hexagonal	6	4.290_1	11.237_5	2.619_4	6.68

Cu-Se Copper-Selenium

By F. N. Rhines*

The β phase (Cu_2Se) transforms polymorphically at about 110 C; at room temperature the crystal structure has been identified as cubic, CaF_2 type. Cupric selenide, CuSe, (55.47% Se) melts peritectically at about 700 C.

* Carnegie Institute of Technology, Pittsburgh

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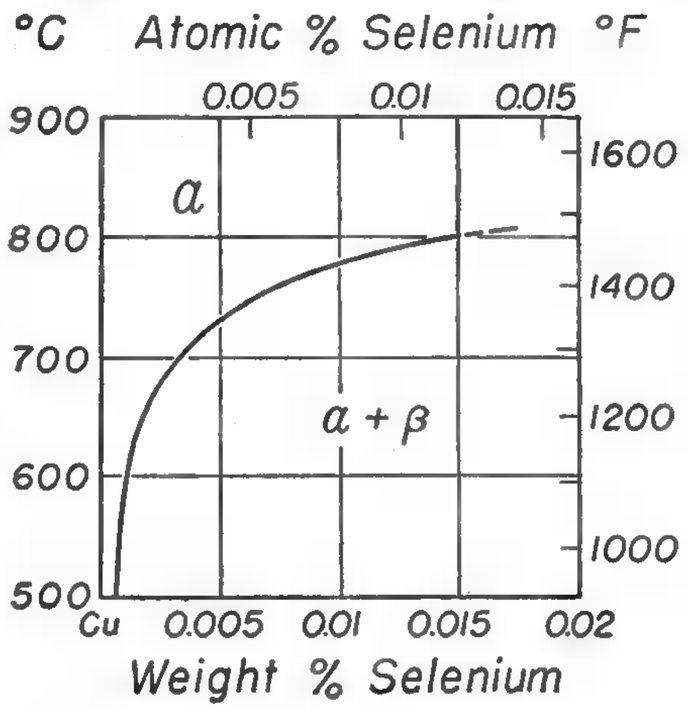

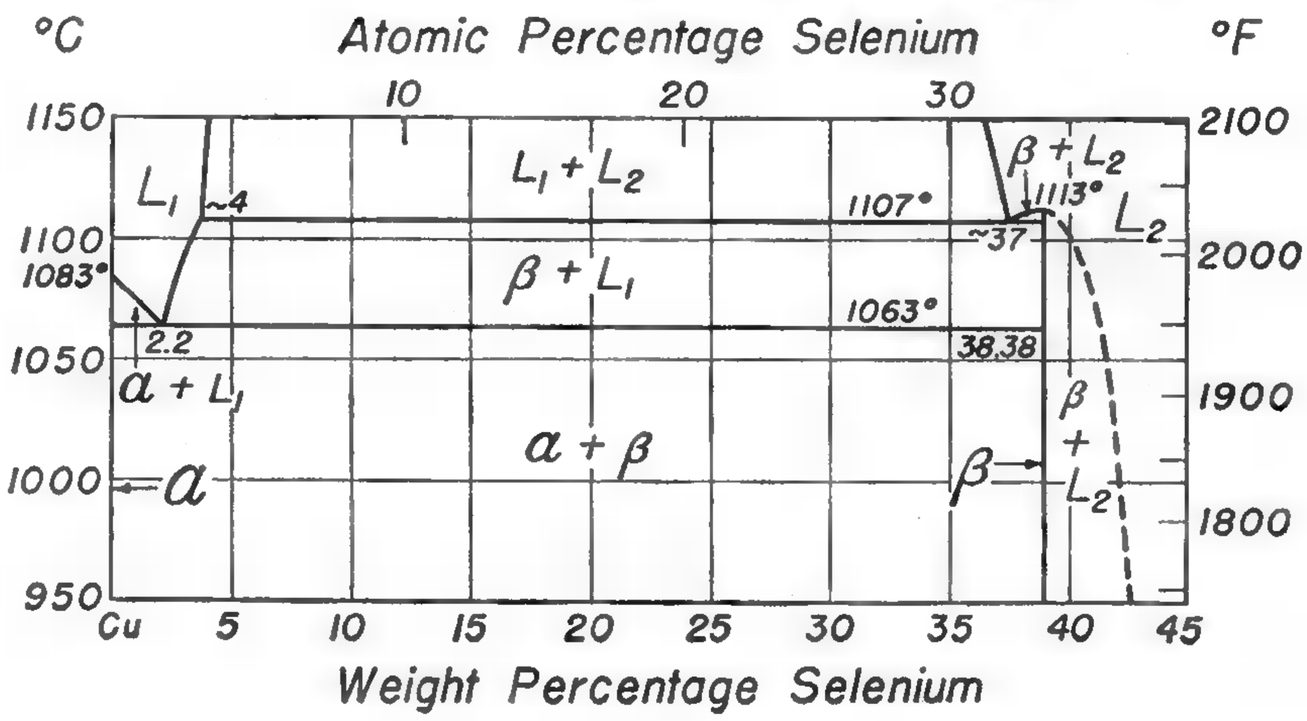

Cu-Si Copper-Silicon

By Cyril Stanley Smith*

The κ phase is very similar to α and alloys that contain both have the microstructural appearance of heavily twinned α, even after long annealing. The κ phase decomposes very slowly below 550 C unless cold worked.

There are no data concerning the solubility of copper in solid silicon, but it is presumed to be extremely small.

* Institute for the Study of Metals, University of Chicago, Chicago

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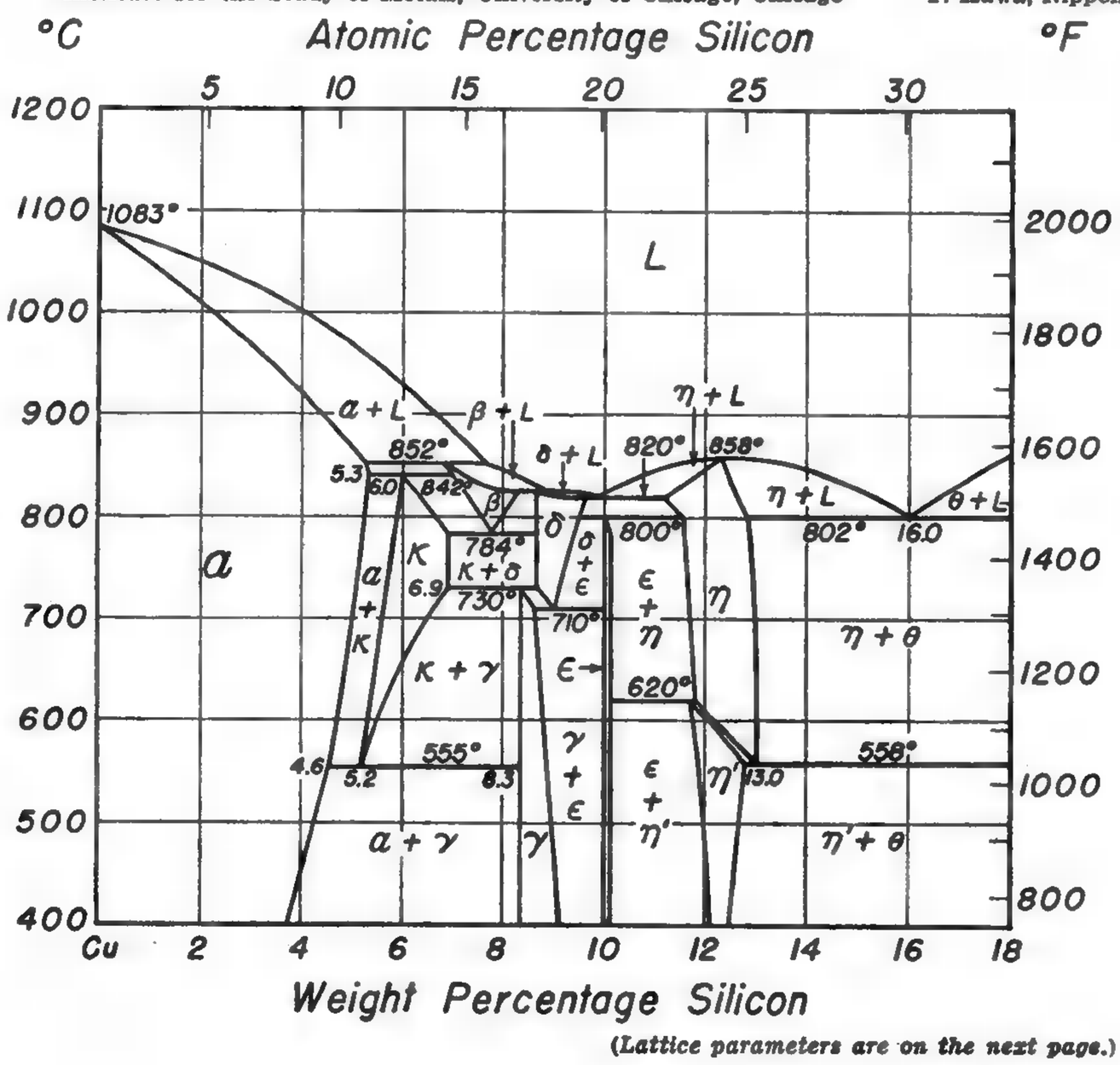
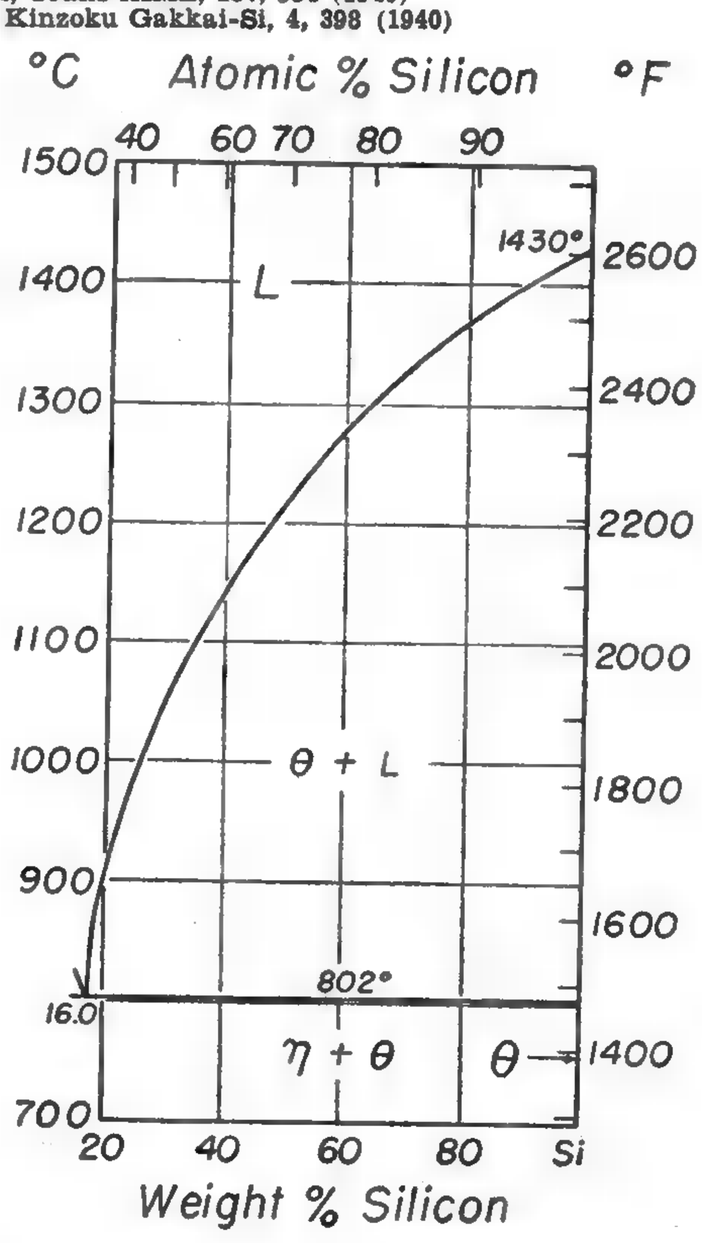




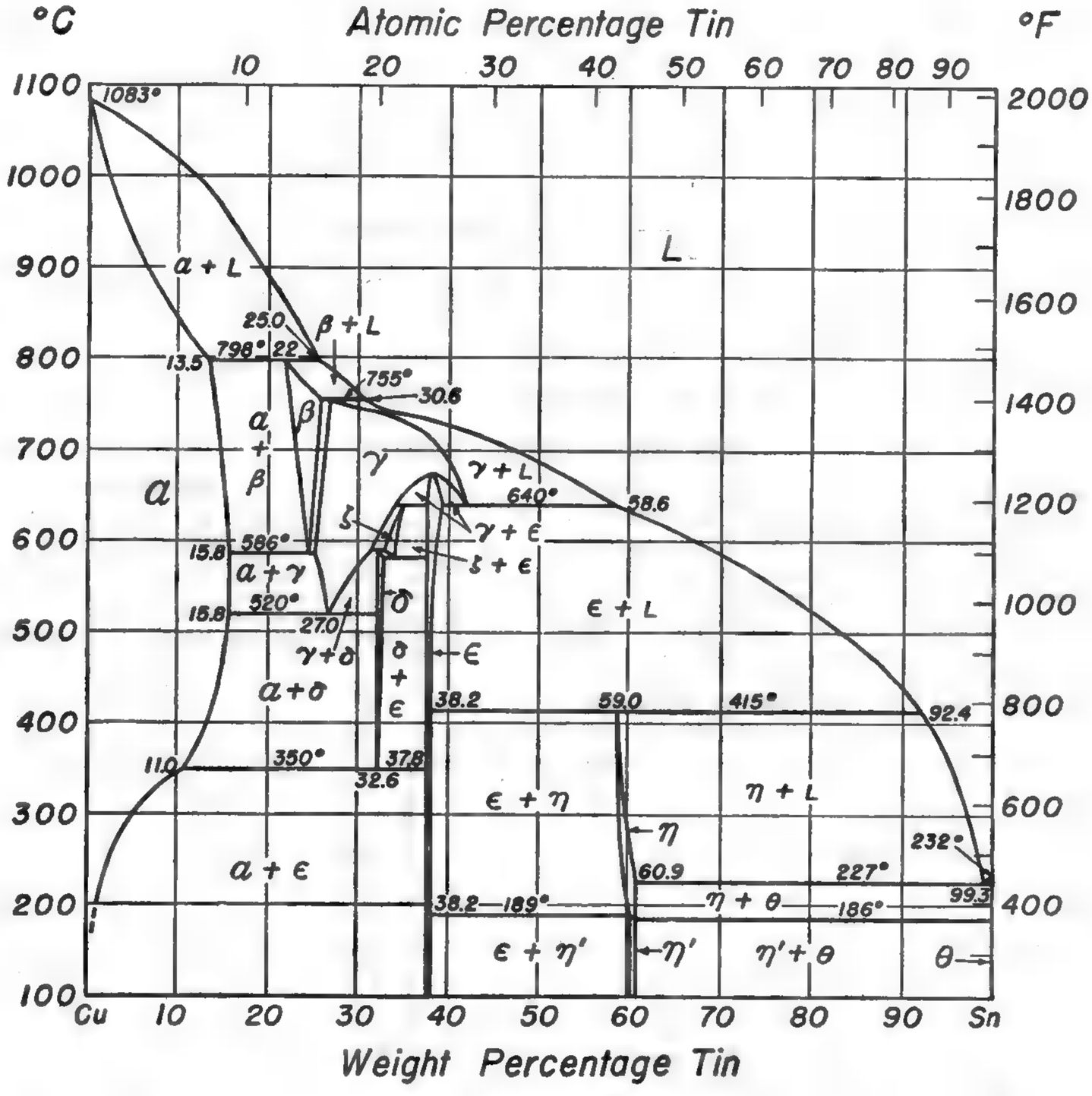
(Lattice parameters are on the next page.)

Crystal Structures and Lattice Parameters of Copper-Silicon Alloys

Phase	Crystal Structure	Lattice Parameter a, kX units
α (0% Si)	Face-centered cubic	3.608
α (5.5% Si)	Face-centered cubic	3.615
κ (5.2% Si)	Close-packed hexagonal ($c/a = 1.635$)	2.554
κ (6.9% Si)	Close-packed hexagonal ($c/a = 1.633$)	2.556
β	Body-centered cubic (?)	....
γ	Cubic (β-Mn type) (?)	6.21
δ	Cubic (γ-brass type) (?)	....
ϵ	Cubic (76 atoms per unit cell)	9.694
η	Hexagonal (?)	....

Cu-Sn Copper-Tin

By Cyril Stanley Smith*



The diagram is taken without change from Raynor,[1] who made a detailed critical study of the literature.

Though equilibrium is as shown in the diagram, in commercial operations the diminution of solubility of tin in the α phase below 520 C rarely occurs and, in all but alloys annealed for extremely long times after severe cold working, the solubility below 520 C can be considered as constant at 15.8%. Similarly, the decomposition of δ below 350 C occurs extremely slowly, and the $\alpha + \delta$ region, for most purposes, can be considered as extending vertically below the 520 C horizontal; that is, α 15.8% and δ 32.4%.

The β and γ fields have been the subject of much disagreement among investigators, for the phases do not differ much in crystal structure or in microstructure and are difficult to distinguish. Neither can be retained at room temperature by quenching the pure alloys, but a series of complex metastable transition structures form.

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The solubility of copper in tin is not greater than about 0.006% at the eutectic temperature.[6]

The crystal structures of the phases are, as follows: α, face-centered cubic; β and γ, both body-centered cubic (probably one is partially or completely ordered); ζ ($Cu_{20}Sn_6$), hexagonal with 26 atoms per unit cell; δ ($Cu_{31}Sn_8$), gamma-brass structure; ϵ (Cu_3Sn), orthorhombic; η' (Cu_6Sn_5), nickel arsenide structure, ordered.

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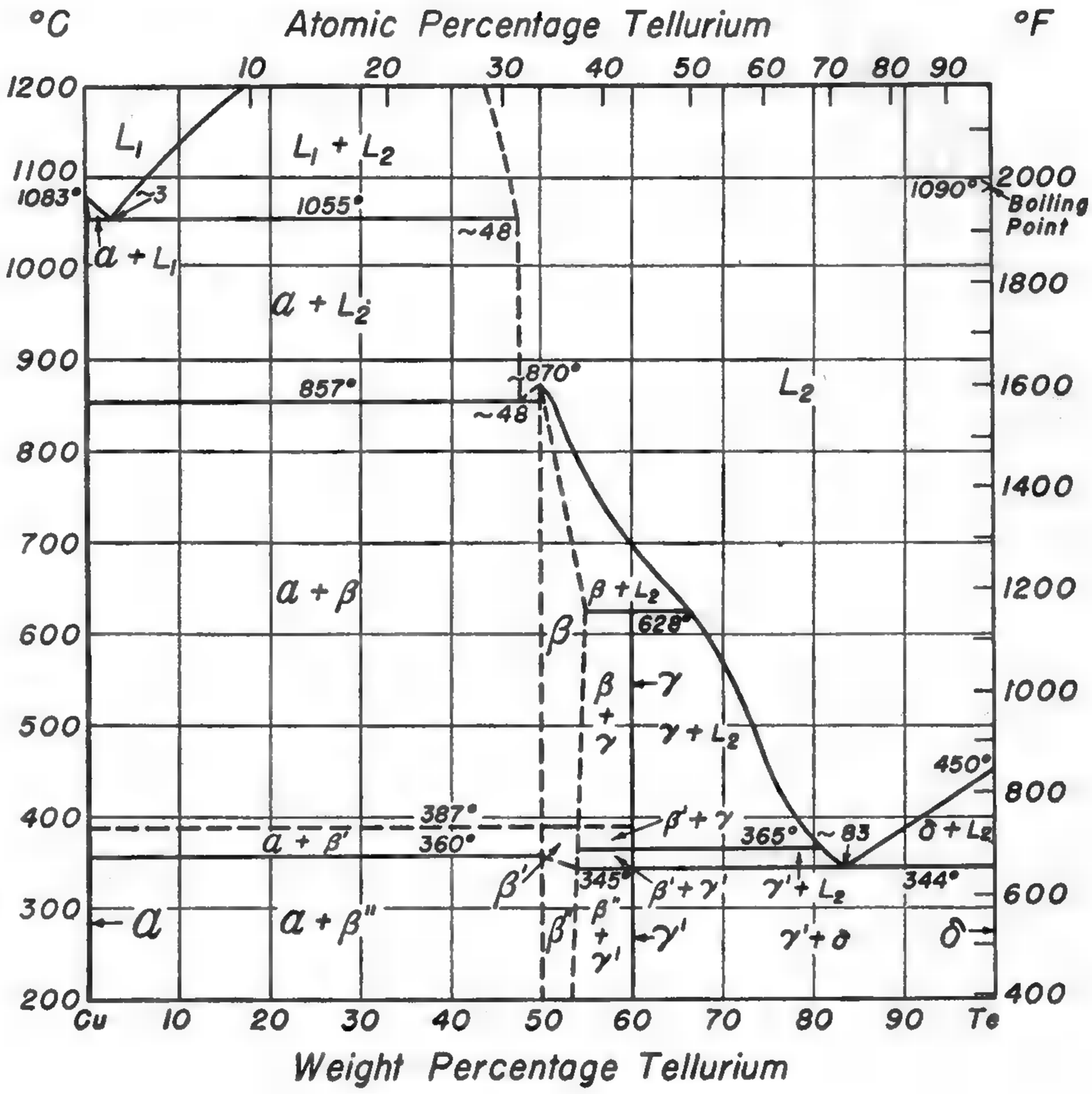
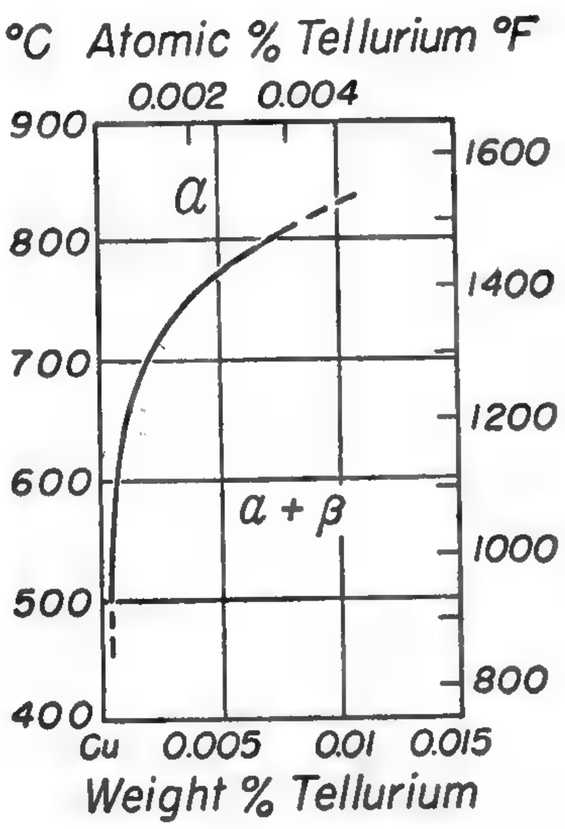
Cu-Te Copper-Tellurium

By F. N. Rhines*

It is not certain whether the β phase (Cu_2Te) melts congruently at 870 C, as indicated in the diagram, or undergoes peritectic reaction at 857 C. If the latter is correct, the β field should end at 857 C and the liquidus should be continued from the point at 870 C uninterrupted to the end of the monotectic reaction horizontal at 1055 C. There is uncertainty about the transformations in β and γ, since these transitions are based on thermal evidence alone.





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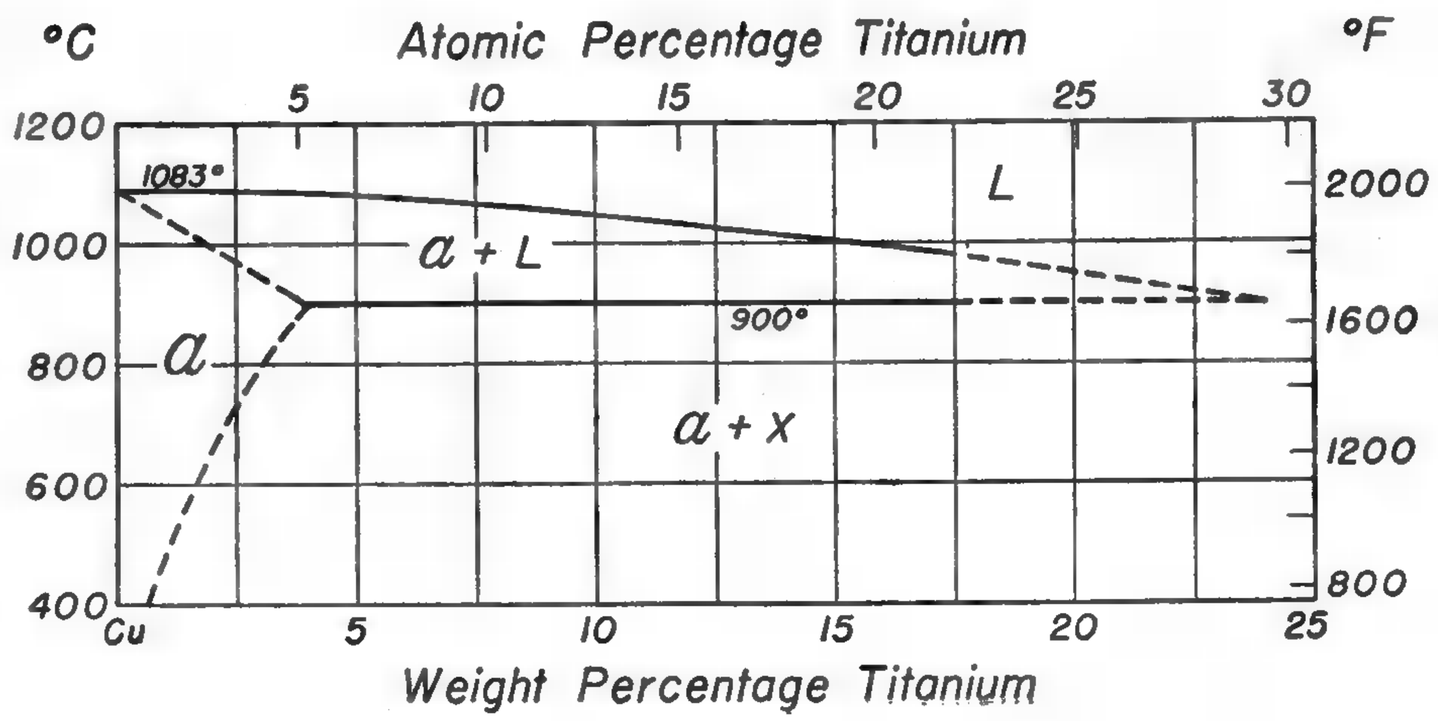
* Department of Metallurgical Engineering, Carnegie Institute of Technology, Pittsburgh

Cu-Ti Copper-Titanium

By H. L. Burghoff*

The diagram shown is based on the work of Kroll.[1] There appears to be a eutectic at about 24% Ti. The solubility of titanium in copper decreases from approximately 4% at the eutectic temperature (900 C) to less than 0.5% at 350 C. Alloys that contain 0.5% or more of titanium are age hardenable.

According to Hensel and Larsen,[2] the second solid phase may be either titanium or a titanium-copper compound.



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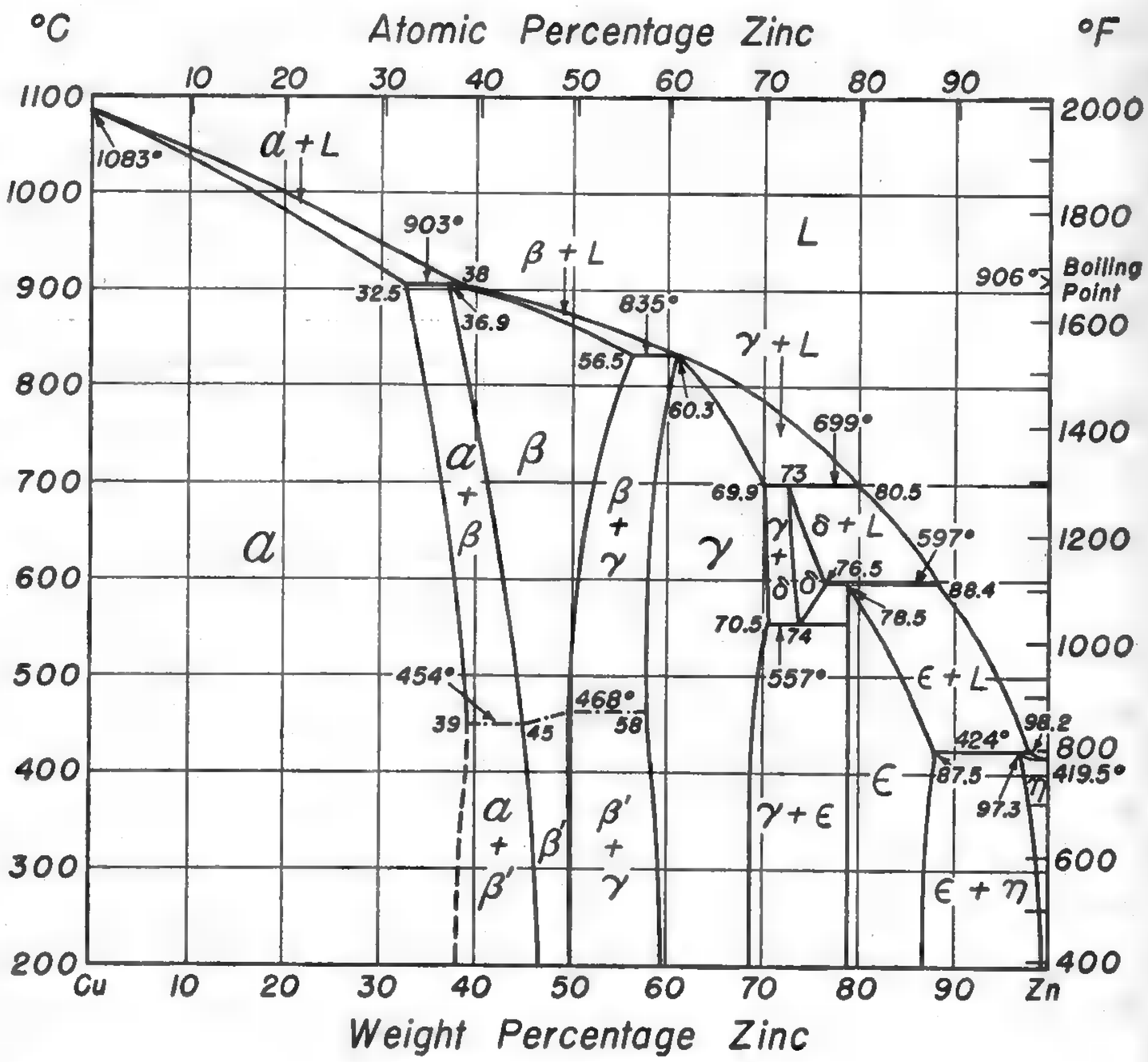
* Chase Brass & Copper Co., Waterbury, Conn.

Cu-Zn Copper-Zinc

By Arthur Phillips* and R. M. Brick*



In 1944, Raynor[1] published a completely annotated copper-zinc diagram. Raynor's diagram is in essential agreement with the diagram given here, with the exception of the lower end of the line showing the solubility of zinc in the α phase. In Raynor's diagram the solubility of zinc is shown to decrease from 39% at 454 C to 35% at 250 C. In the present diagram, the solubility line is drawn to show only a very slight decrease below 454 C.

The line traversing the $\alpha + \beta$, β, and $\beta + \gamma$ fields (454 and 468 C) indicates a progressive change of the β phase from a disordered to an ordered structure (or vice versa). On cooling to the temperature shown by the dot-dashed line, the body-centered cubic β with copper and zinc atoms randomly dispersed at lattice points becomes unstable and changes continuously to β'. β' has a body-centered cubic crystal structure identical with that of β, but with an ordered structure in which the copper atoms are segregated at the corners of the unit cubes and zinc atoms at their centers.[2,3] The ordering reaction is so rapid that it cannot be prevented or even retarded by quenching.

Various factors, including minute specific heat anomalies and the large effect of cold working on the electrical resistance, suggest that there may be some tendency to precipitation or ordering in the alpha solid solution.

An alloy containing about 62.5% Cu is of particular interest because, under equilibrium conditions, it has a completely β structure at 900 C and a uniform α structure below about 500 C. By a drastic quench from 900 C in an iced brine solution this alloy undergoes a diffusionless transformation resulting in a structure similar to the martensitic structure of steels. By the rapid quench, permitting no opportunity for time-consuming diffusion in the range 900 to 500 C, the retained beta transforms at about minus 14 C to a face-centered structure similar to alpha, but differing in that one edge is longer than the other two, thus forming a face-centered tetragonal structure. The high-temperature beta and the room-temperature alpha are of the same composition, and the change from body-centered cubic beta to face-centered cubic alpha requires only a slight change in crystal structure. If the dimensional readjustment is incomplete (because of lattice rigidity at low temperatures), the intermediate, unstable tetragonal lattice is found.[4] The diffusionless transformation of this brass is of no industrial importance, since the requirement of heating to within a few degrees of the melting point results in very coarse grains and the rapid quench required can be attained only in relatively thin specimens.

Some of the potential Widmanstätten structures in this system have been investigated. It has been found that α forming in β tends to grow as needles parallel to the [111] directions in the β structure. γ precipitating from β forms small polyhedra whose faces are parallel to the {110} planes of the matrix. ϵ precipitates from η with its {10.4} planes parallel to {10.4} planes of the η phase.

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* Professor of Metallurgy, University of Pennsylvania, Philadelphia

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Crystal Structures and Lattice Parameters of Copper-Zinc Alloys

Phase	Percentage Copper	Crystal Structure	Lattice Parameter, *a*, kX	Lattice Parameter, *c*, kX	Lattice Parameter, *c/a*
α	100	Face-centered cubic	3.608	....	....
α	62.5	Face-centered cubic	3.693	....	....
β	54.5	Body-centered cubic	2.942	....	....
β	50.0	Body-centered cubic	2.949	....	....
γ	41.5	Cubic, low symmetry	8.837	....	....
γ	32.5	Cubic, low symmetry	8.874	....	....
ϵ	saturated at 200 C	Close-packed hexagonal	2.762	4.308	1.560
η	2.6	Close-packed hexagonal	2.6732	4.8125	1.8012
η	0	Close-packed hexagonal	2.6590	4.9351	1.8560

Cu-Zr Copper-Zirconium

By H. L. Burghoff*

As would be expected, the variable solubility of zirconium in solid copper permits age hardening in copper-rich alloys.

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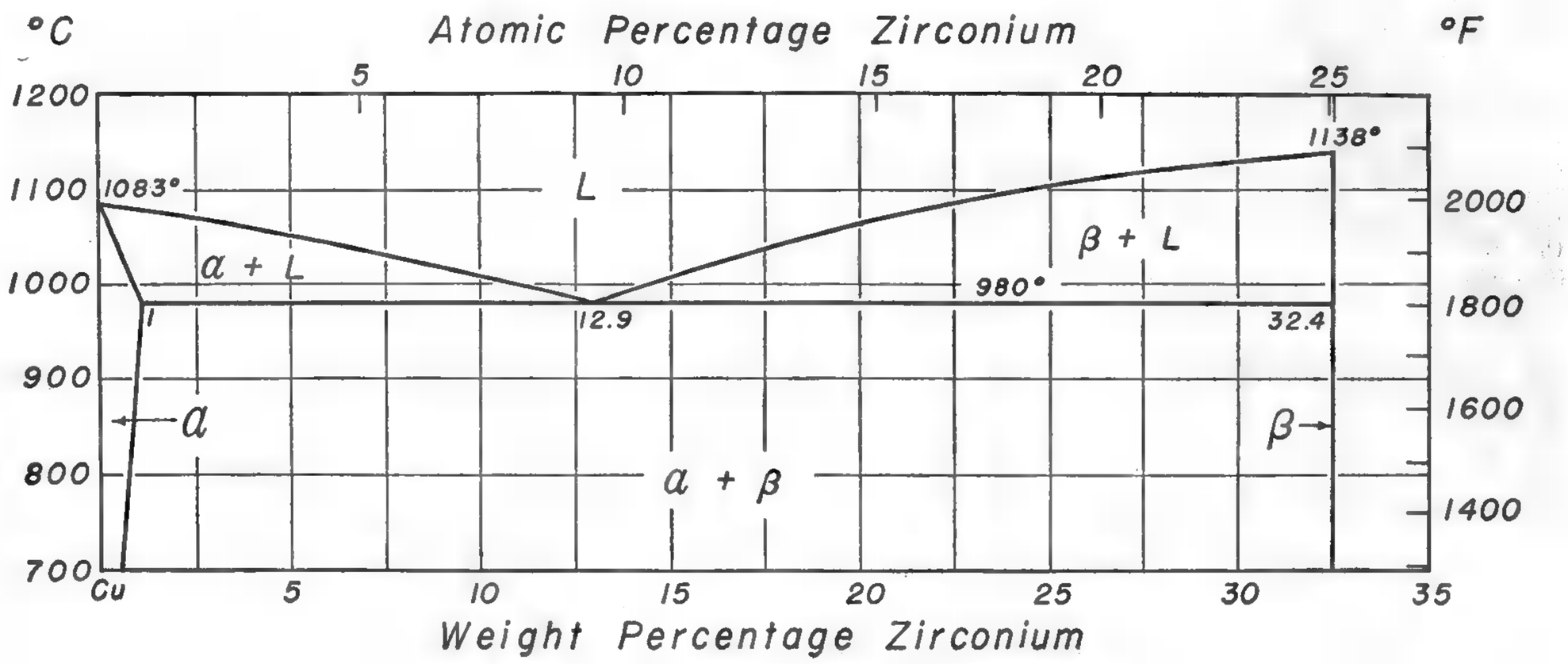


Fe-C Iron-Carbon

See "C-Fe Carbon-Iron", pages 1181 and 1182.

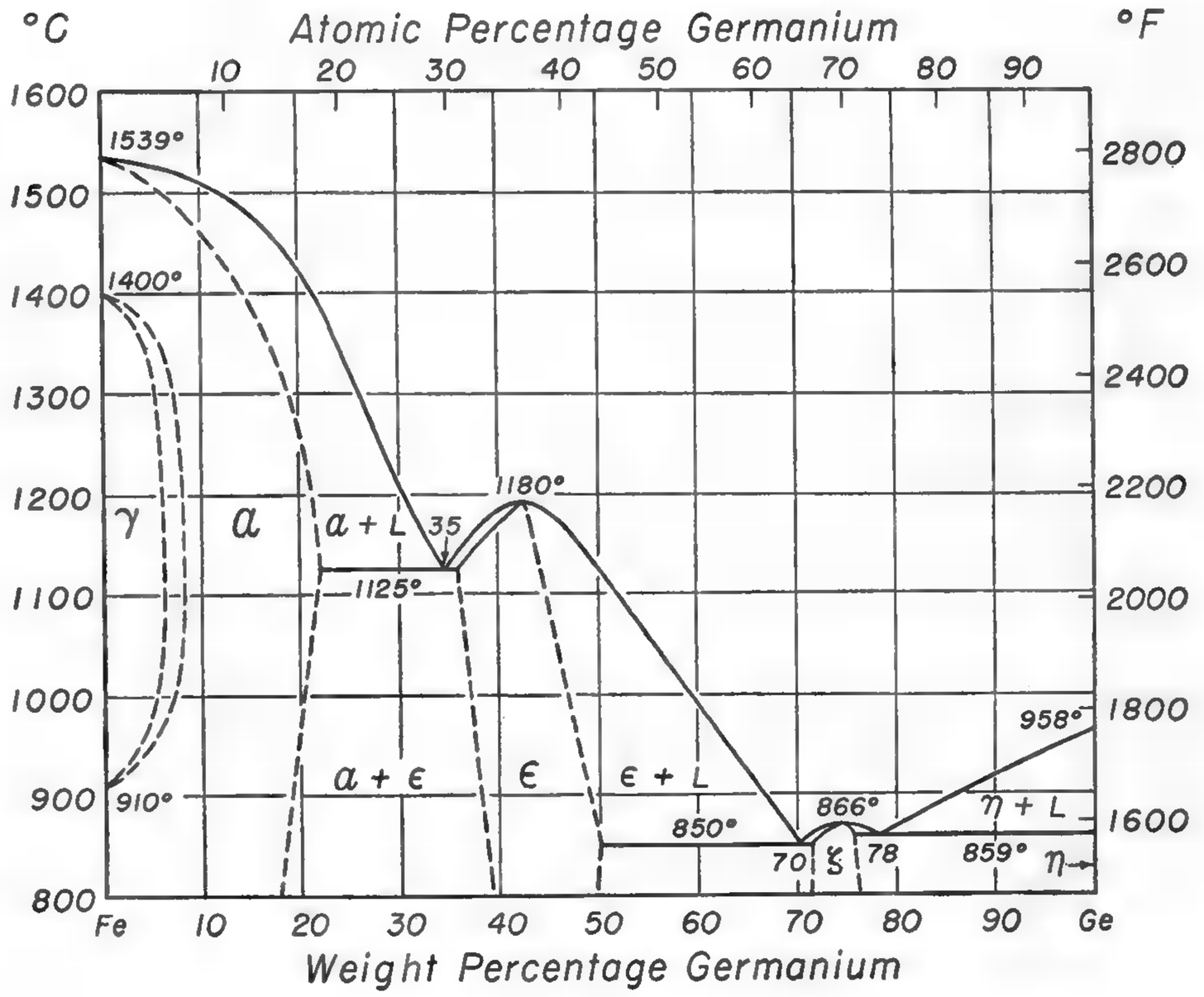
Fe-Ge Iron-Germanium

By R. M. Parke*

The composition limits of the $\alpha + \gamma$ field were not determined, but observations on alloys containing 0.5 and 1.5% Ge indicated a closed "gamma loop".[1]

The ϵ and ζ phases correspond approximately to the compositions Fe_2Ge and $FeGe_2$ respectively.[1] The ϵ phase (Fe_2Ge) is hexagonal (NiAs type), isomorphous with Fe_2Sn and Co_2Sn.[1] For an alloy corresponding to $Fe_{1.76}Ge$, the lattice parameters are $a = 4.031$ kX, $c = 5.022$ kX, $c/a = 1.275$.[2]

When alloys containing more than about 65% Ge are solidified rapidly by quenching the liquid, the formation of ζ is suppressed, and the alloys freeze metastably as a eutectic of ϵ and η. The eutectic point in the metastable system is at 830 C and 75% Ge.[1]



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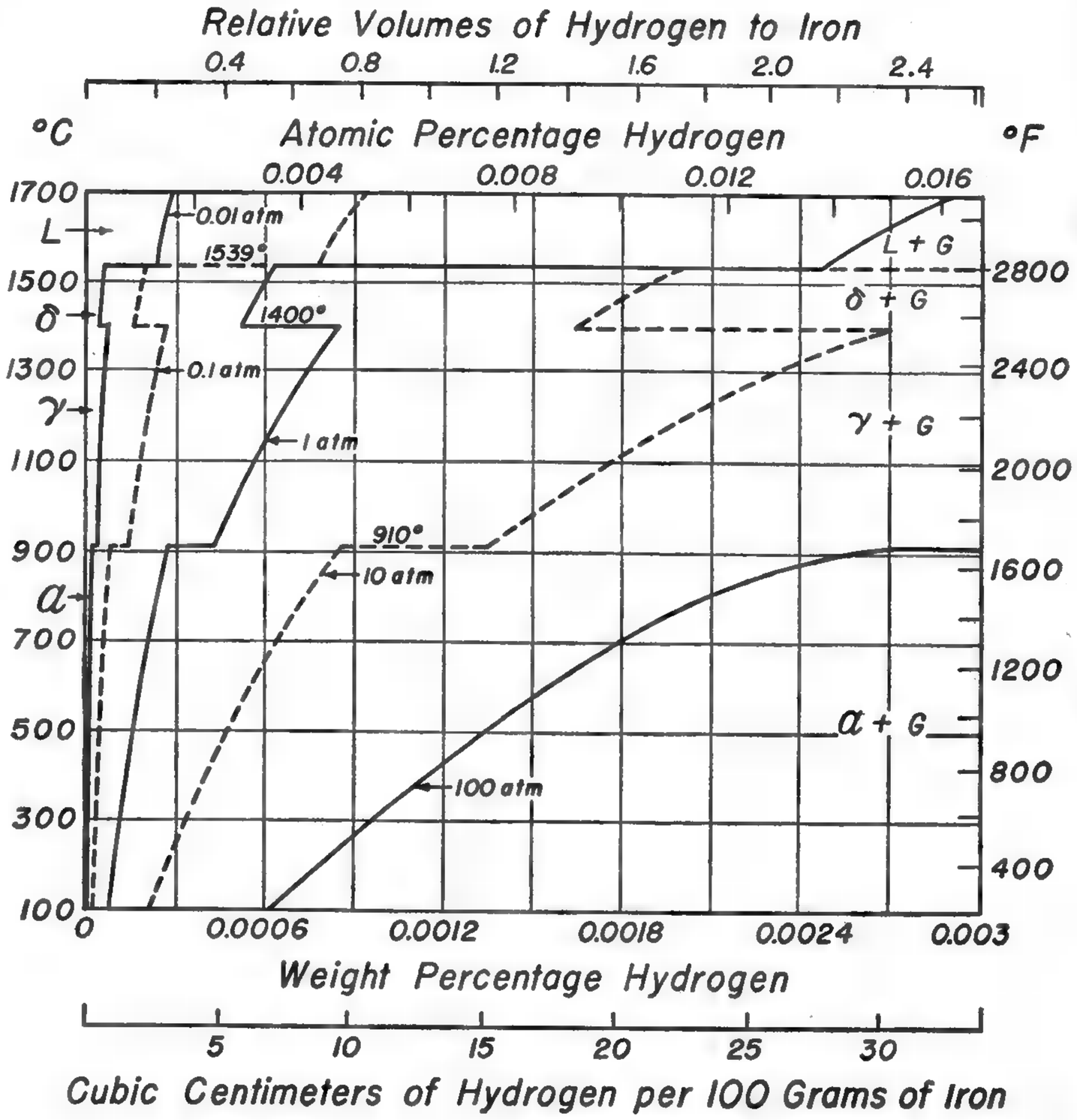
* Kellex Corporation, Silver Spring, Md.

Fe-H Iron-Hydrogen

By Carl A. Zapffe*



Constitutional study of the iron-hydrogen system began at least as early as 1862 when Meisinger[1] collected large quantities of H_2 from electrolytic iron; and 1863 when Deville and Troost[2] proved that a constitutional system existed by dissolving hydrogen in iron. Although numerous early investigators, such as Cailletet[3,4] and Graham[5] analyzed the hydrogen in iron, the work begun in 1907 by Sieverts and his colleagues[6-14] provided the first reliable data. Using a classic technique, Sieverts studied the absorption as the atmospheric pressure of H_2 varied up to 1.5 atm. His results established that the gas dissolves atomically and that the composition of the iron-hydrogen alloy varies with the square root of P_{H_2}:

$$[H] = K \cdot (P_{H_2})^{1/2}$$

Later quantitative work by Iwasé,[15,16] Martin,[17,18] and Luckemeyer-Hasse and Schenck,[19] (also related work by others[20,21]) essentially completed the iron-rich end of the system as shown in the diagram presented here.

Since iron-hydrogen alloys are pressure-sensitive, the system is only properly depicted in three dimensions. However, a solid model has not yet been proposed; and the isobaric sections in the accompanying diagram serve to show the measured absorption boundary at $P_{H_2} = 1$ atm and to indicate the probable boundaries at higher and at lower pressures as calculated from the quadratic relationship, assuming an unchanged activity coefficient. All values below about 400 C are similarly estimated, since their measurement has not yet been accomplished.

The solubility is known to increase sharply on passing from alpha to gamma, and seems reliably proved to decrease again abruptly on reverting to delta,[19] such that the boundary in delta ferrite becomes an extrapolation of the curve in alpha ferrite. On liquation, the solubility again increases sharply. No changes in transformation temperatures are indicated, because the single proved instance, discussed below, is too minor to register on the scale of the diagram.

No compounds are yet known for certain to exist. Atomized iron may combine with extremely large quantities of hydrogen, attaining stoichiometric Fe:H ratios of 1:1[21-25] and even 12:1;[26] but the highest recorded hydrogen content in bulk iron is only 0.45 atomic %.[27] Because of the common phenomenon of hydrogen embrittlement, an endothermic hydride has often been assumed to exist. Simons and Ham[28] describe diffusion in terms of hydride formation; and Andrew and his associates[29] observed a thin white constituent bounding hydrogen-caused cracks which they believe to be a hydrogen-rich phase. However, embrittlement occurs at such unlikely Fe:H ratios as 5000:1. In addition, it is known that at ordinary temperatures the gas resides largely within intragranular rifts[30] as an occluded phase under high pressure.[30] If a compound does exist, certainly its dissociation pressure is extremely high.

In 1899 Roberts-Austen[31] described several anomalous "hydrogen points" occurring in the ferrite range during the cooling of iron containing hydrogen. Ewing and Rosenhain[32] attempted to relate the point at 487 C to a surface phenomenon observed on iron heated in hydrogen; and Rawdon and others[33,34] and Jaquerod and Gagnebin[35] similarly discussed these points. An extensive series of investigations by Ham and his students[36-43] refined the definition of the phenomenon until Ham and Samans[44] in 1946, in a related research, demonstrated that at least six thermal points do exist in the ferrite range, probably representing subtle electronic changes not yet understood.

As for the effect of hydrogen on the allotropy of iron, Andrew[45] in 1911 reported finding no changes. Later, Esser and Cornelius[46,47] claimed that the doubling of A_3 and A_1 points noted by Harrington and Wood[48,49] was caused by hydrogen. Post, Lake, and Ham[50] then carefully measured the effect of hydrogen on A_3 in pure iron and found that the absorption from $P_{H_2} = 1$ atm caused a lowering of 4 °C which was proportional to the hydrogen content.

Wever and Pfarr[51,52] hydrogenized ferrite cathodically and, from X-ray diffraction patterns, computed an increase in the lattice parameter from 2.8609 to 2.8614 kX, a supposed expansion of 0.12% per 1 atomic % [H]. In view of the diffuseness of the patterns, the extremely low proportion of hydrogen atoms to iron atoms (one H atom in a cube 27 Fe atoms on an edge) and the planar-pressure theory of hydrogen embrittlement,[20,30] these results probably should not be regarded as decisive.

* Consulting Metallurgist, Baltimore

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Fe-He Iron-Helium

By R. M. Parke*

Helium does not diffuse through solid iron.[1,2] Evidently helium forms no solid solutions or compounds with iron.

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Fe-Hg Iron-Mercury

By R. M. Parke*

Most of the data on iron-mercury alloys pertain to solubilities, and agreement on this point is lacking. Tammann and Kollmann[1] give 1.15×10^{-17}% Fe at 170 C, and Palmäer[2] reported 0.00007% Fe between 20 and 211 C. Brill and Haag[3] found by X-ray examination that iron amalgams containing up to 25% Fe consist of a suspension of alpha iron in mercury. This fact may account for the conflicting reports of other investigators.

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Fe-Ir Iron-Iridium

By R. M. Parke*

The solubility of iridium in alpha iron is 15 atomic %.[1] Both the Curie point of iron and the $\alpha \rightleftarrows \gamma$ transformation are lowered by iridium.[2]

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Fe-K Iron-Potassium

By R. M. Parke*

Iron is not soluble in liquid potassium. Potassium is insoluble in solid iron, and although its solubility in liquid iron is not known, the formation of alloys is considered improbable. (*See* M. Hansen, "Der Aufbau der Zweistofflegierungen", J. Springer, Berlin, 1936.)

* Kellex Corporation, Silver Spring, Md.

Fe-Kr Iron-Krypton

By R. M. Parke*

Electrolytic iron does not absorb krypton at 1200, 1400, or 1500 C;[1] therefore, it may be assumed that neither solid solutions nor compounds are formed in the iron-krypton system.

Reference

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Fe-Li Iron-Lithium

By R. M. Parke*

Iron is not dissolved by liquid lithium. Lithium is insoluble in solid iron, and although its solubility in liquid iron is not known, the formation of alloys is considered improbable.[1]

Reference

1 M. Hansen, "Der Aufbau der Zweistofflegierungen", J. Springer, Berlin, 1936

Fe-Mg Iron-Magnesium

By G. F. Sager* and B. J Nelson*

Magnesium is not soluble in solid iron.[1] The solubility of iron in magnesium at the melting point of magnesium is 0.026%.[2]

Iron has a very adverse effect on the resistance of magnesium to corrosion, causing deep pitting in saline environments (*see* Fig. 7 on page 997). Iron can be removed from liquid magnesium alloys by precipitation with an excess of manganese or zirconium. This process is discussed under Refining, Settling and Sludging, in the article on page 973. Wrought magnesium alloys that contain 0.005% Fe, or less, are available commercially and have better resistance to corrosion than do magnesium alloys of normal iron content.

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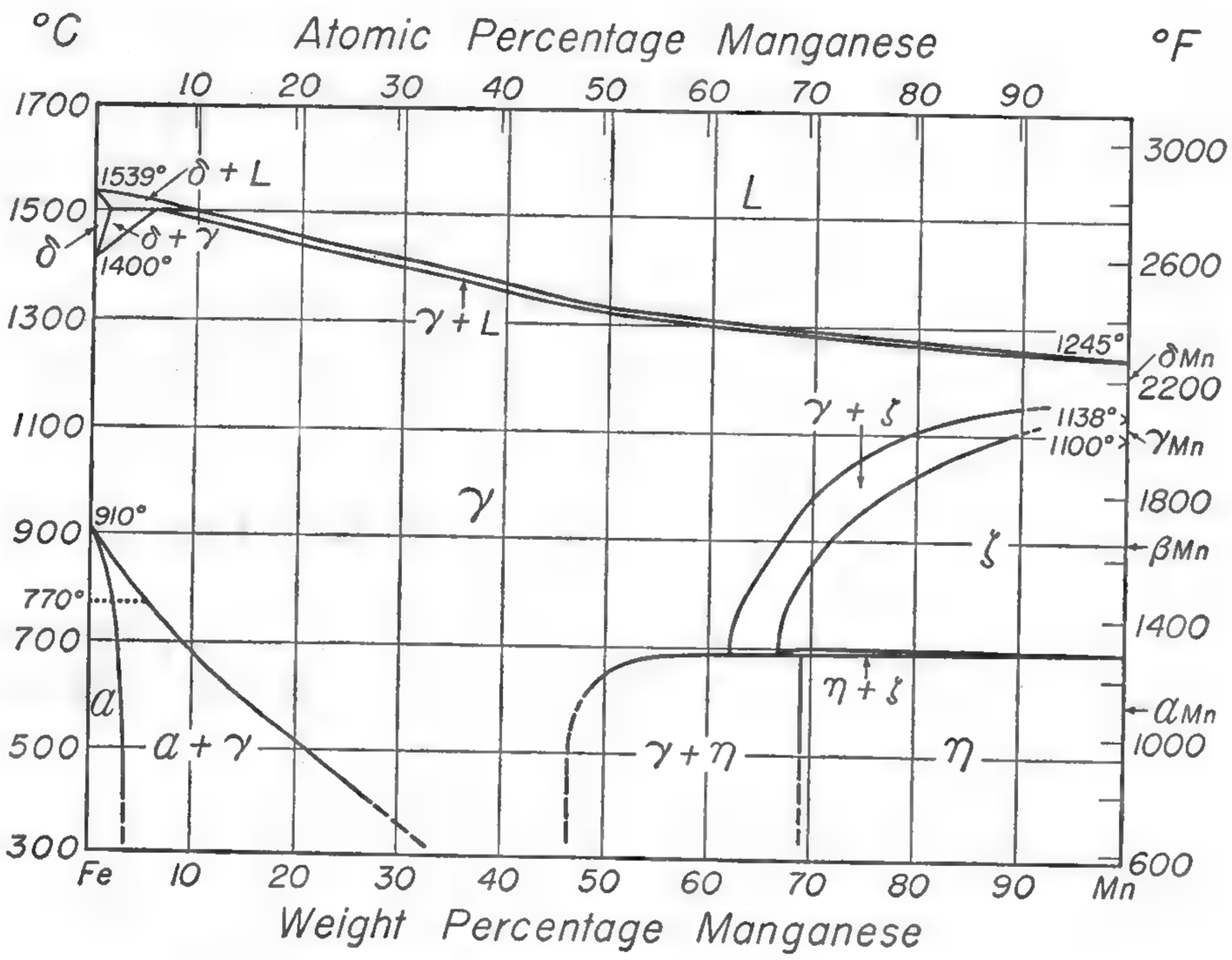
* Aluminum Research Laboratories, New Kensington, Pa.

Fe-Mn Iron-Manganese

By F. T. McGuire* and A. R. Troiano*

The manganese-rich portion of the diagram[1,2] has been drawn to indicate four allotropic forms of manganese.[3,4,5] There are no experimental data for iron-manganese alloys containing more than 95% Mn, and the diagram has been left blank between 1100 and 1245 C, from 95 to 100% Mn.

The γ phase containing up to 15% Mn transforms to supersaturated α by a martensite reaction during cooling; γ containing approximately 13 to 25% Mn transforms to close-packed hexagonal ϵ, also by a martensite reaction.[6] Neither ϵ nor supersaturated α is an equilibrium phase; therefore, they are not shown on the phase diagram. Transformation temperatures for the martensite reactions in iron-manganese alloys are shown in Fig. 1 of the article "Manganese in Steel", on page 465 of this Handbook. For a discussion of the characteristics of martensite transformations in general, see the article on page 263.



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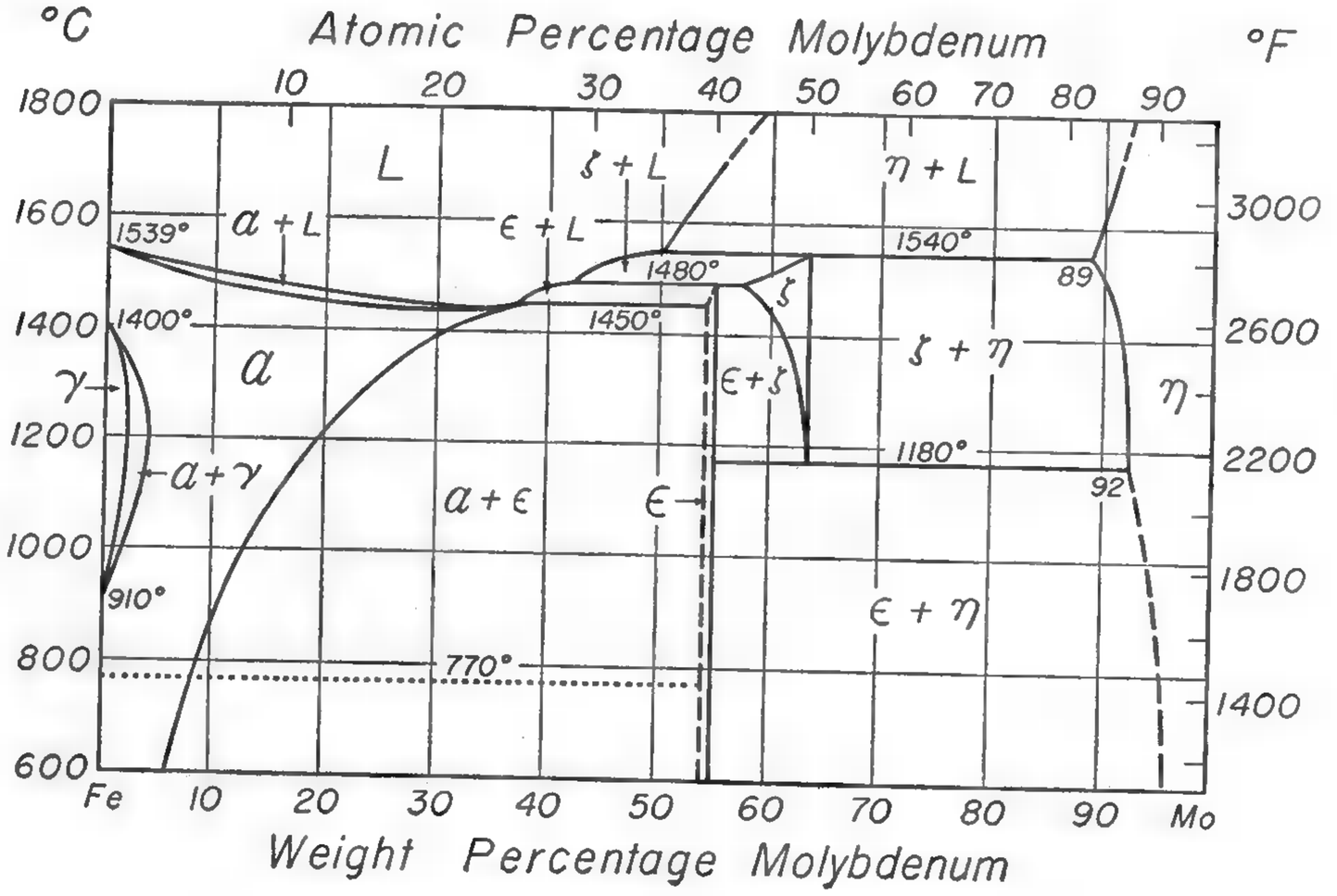
* University of Notre Dame, Notre Dame, Ind.

Fe-Mo Iron-Molybdenum

By W. P. Sykes†

When the molybdenum content exceeds about 3%, γ is completely replaced by α.[1,2] The ϵ phase, of very narrow homogeneity range, has a limiting composition represented by the formula Fe_3Mo_2[1,2,3] or by Fe_7Mo_6[4] while that of ζ appears to be represented by FeMo.[2] The η phase[5] is a substitutional solid solution of iron in molybdenum. The ϵ phase is hexagonal with $c/a = 5.404$.



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† Lamp Department, General Electric Company, Cleveland

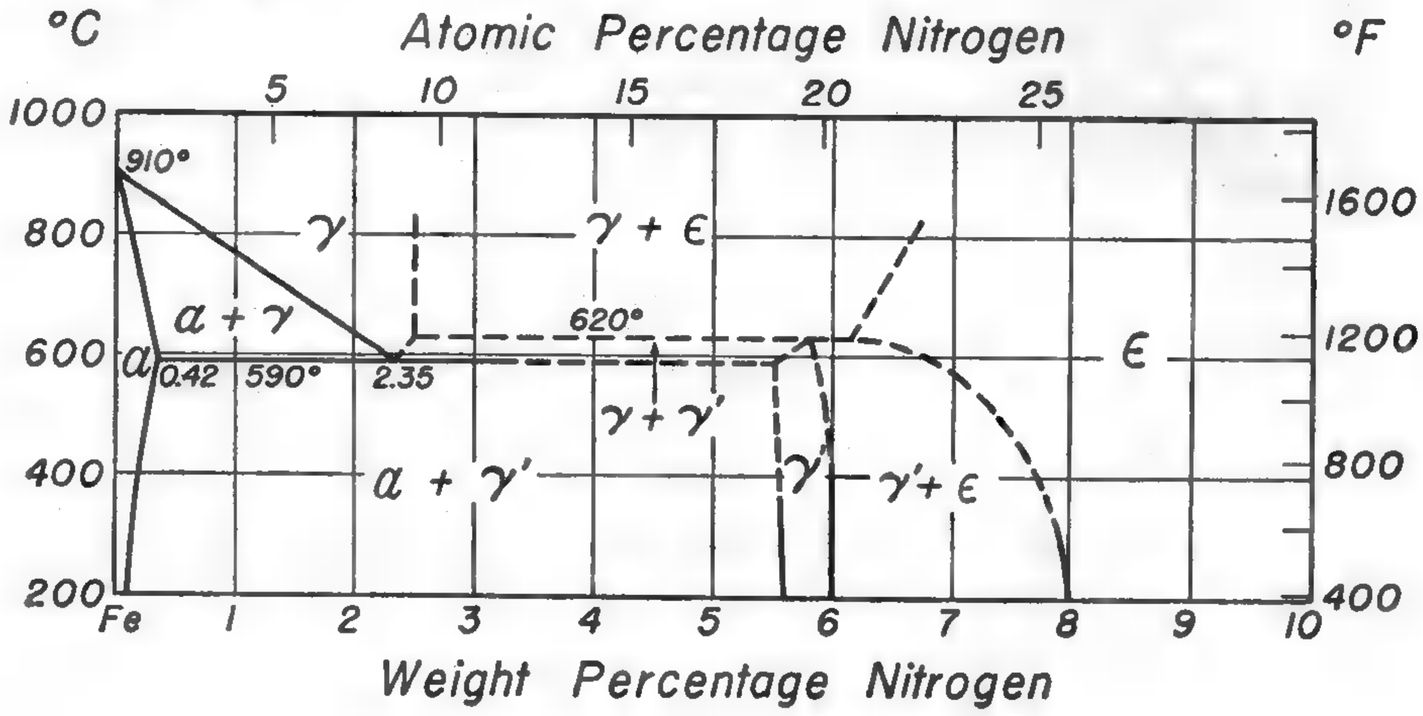
Fe-N Iron-Nitrogen

By J. T. Norton*

The diagram shown does not represent the iron-nitrogen system in equilibrium at atmospheric pressure but rather shows the phases that are in equilibrium with nitrogen at the very high pressures corresponding to the dissociation of ammonia.

The γ' phase (Fe_4N) is cubic with $a = 3.789$ kX. The ϵ phase containing 8% N is hexagonal with $a = 2.695$ kX, $c = 4.362$ kX.

* Massachusetts Institute of Technology, Cambridge, Mass.



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Fe-Ni Iron-Nickel

By George Sachs†

Because of the sluggishness of structural changes at low temperatures, the accurate phase boundaries below approximately 600 C have not yet been established. However, recent X-ray[1,5,7,9,14] and magnetic[11,15,16] investigations agree regarding the general extension of the $\alpha + \gamma$ field, down to a temperature of 350 C.

Considering the structure and properties at room temperature, under conditions of commercial treatments, the alloys can be grouped in six ranges of composition:

1 Alloys that contain up to 6% Ni are ferritic. With increasing nickel content, the alloys become increasingly subject to air hardening on slow cooling.[14]
2 Between 6 and 25% Ni, the alloys are martensitic after fast cooling; after slow cooling or reheating, they decompose into

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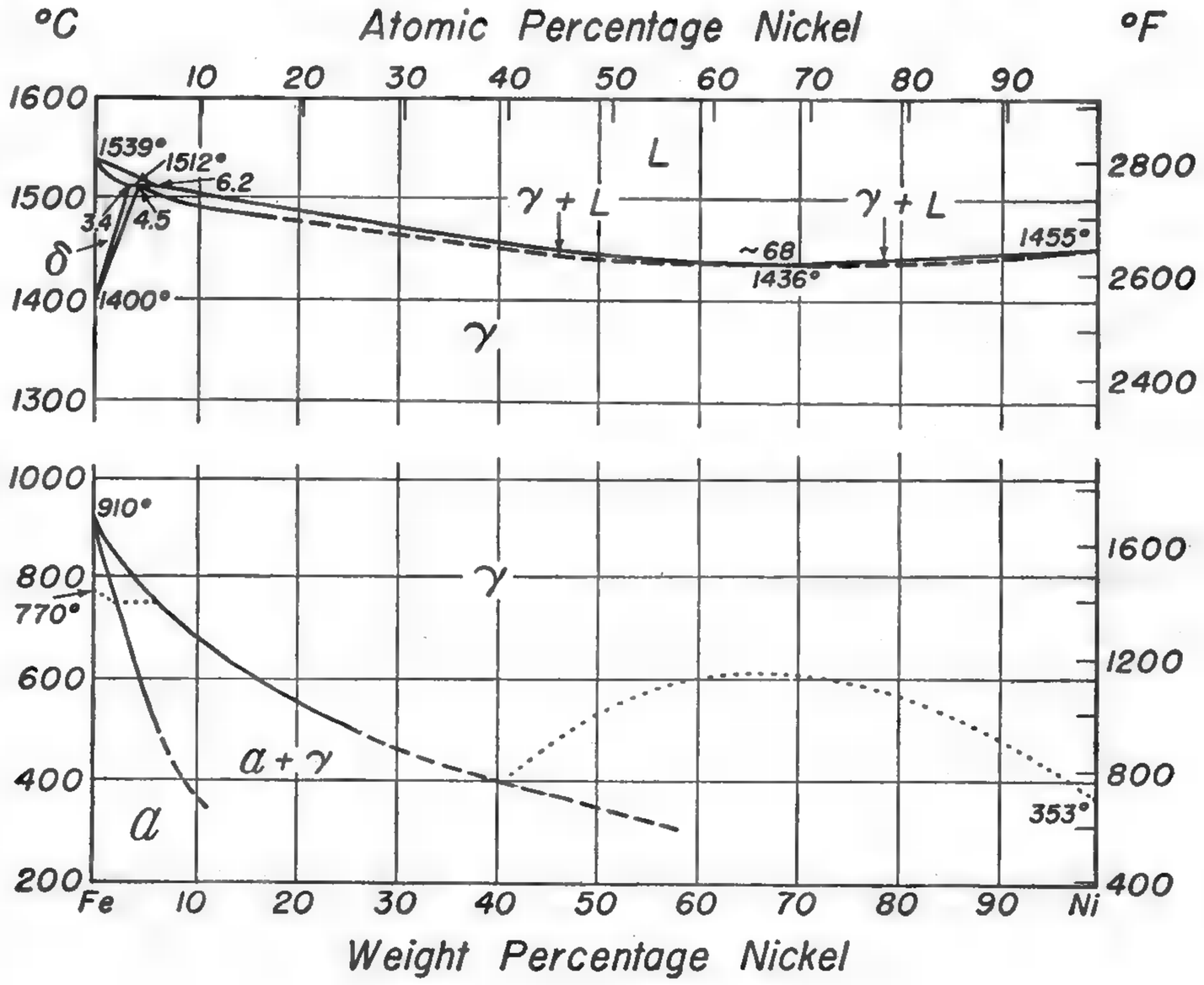

$\alpha + \gamma$. The structure varies from the martensitic to the Widmanstätten type observed in meteorites.[2,10,12]

3 Between 25 and 30% Ni, the alloys may consist either of a mixture of α and γ, or of pure γ, after fast cooling.[9] They decompose into $\alpha + \gamma$ on reheating to 350 to 450 C. Cold working at room temperature may transform them completely into α.[14]

4 Between 30 and 45% Ni, the structure of the alloys appears to be γ, after either rapid or slow cooling.[9] However, the lattice parameters are slightly affected by the rate of cooling and reheating, indicating some decomposition of an unknown nature.[13] Long-time heating at a temperature of 350 C causes a definite decomposition into $\alpha + \gamma$. These observations may also explain the maximum value of lattice parameter at 38 to 39% Ni,[3,4,13] and the low expansion of the alloys in this range (invar).

5 Alloys with more than 50% Ni are, for all practical purposes, γ or austenitic, and possess the characteristics of nickel-base solid solutions. The existence of $\alpha + \gamma$ in the lower-nickel part of this range, at temperatures below 400 C, has no practical significance.

6 Alloys near 76% Ni assume a superstructure, $FeNi_3$, on slow cooling.[4,8] This transition is probably related to the unique magnetic properties of the 78% Ni alloy (permalloy).

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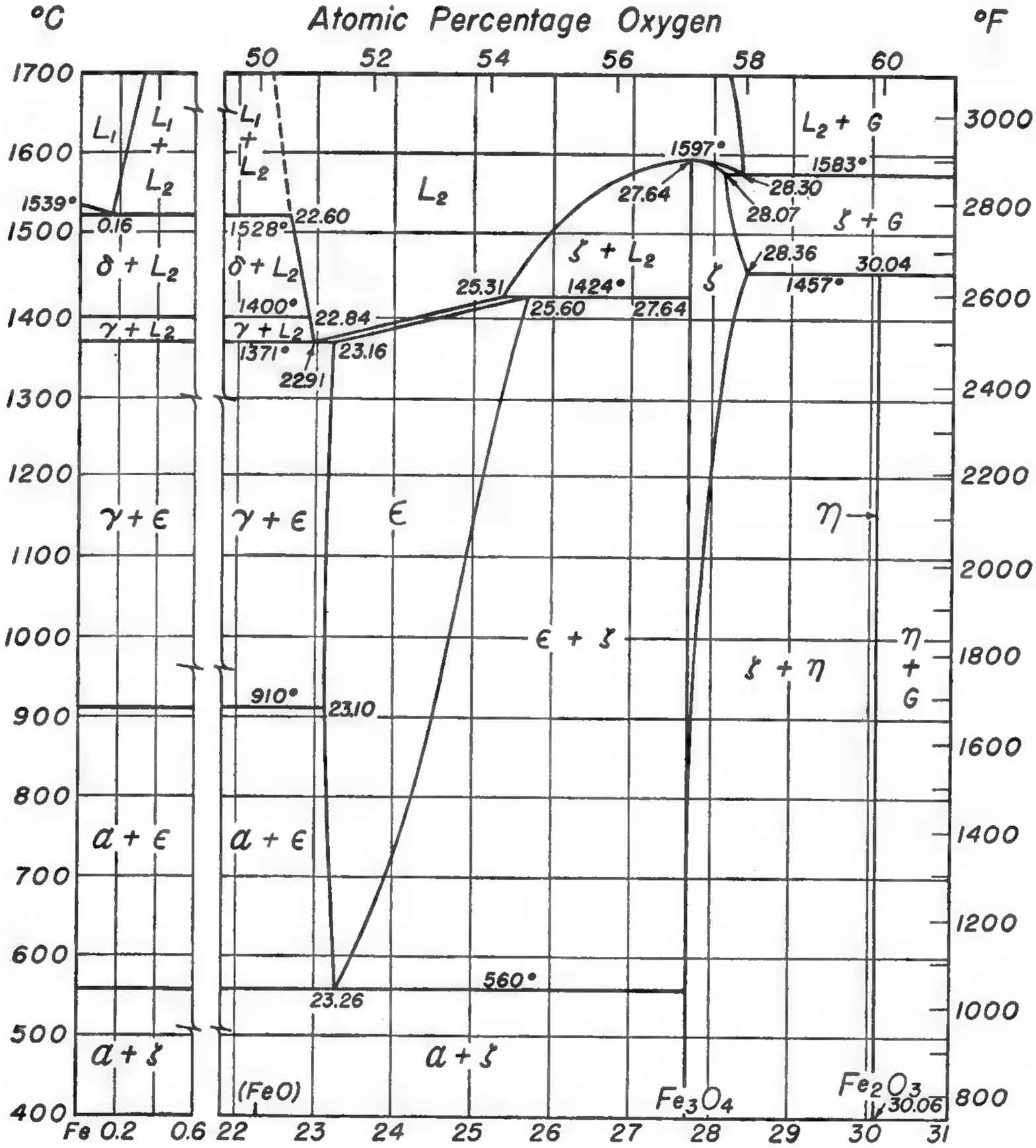
Fe-O Iron-Oxygen

By L. S. Darken* and R. W. Gurry*



The common names of the ϵ, ζ, and η phases are, respectively, wüstite, magnetite, and hematite.

The solubility of oxygen in molten iron is now fairly well established.[8,9,10] However, there is still a great discrepancy in the results of various investigations as to the solubility of oxygen in solid iron. The careful work of Dünwald and Wagner[11] indicates that the solubility is less than 0.01% between 800 and 1000 C; this is among the lowest of recorded values. Since nearly all experimental

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errors are likely to lead to an overestimate of this quantity it seems safe to conclude from the more reliable determinations[10,11] that the solubility is less than 0.10% at temperatures up to 1000 C and is probably less than 0.05%. The relative solubility of oxygen in α, γ, and δ iron is uncertain and hence it is not known whether oxygen raises or lowers the transformation temperatures. In view of these uncertainties, the diagram is drawn as though the solid solubility of oxygen in solid iron were very small.

On the decomposition of wüstite, magnetite usually separates out before iron,[7] thus leaving a wüstite considerably richer in iron; by this process it may be possible to form metastable wüstite containing considerably less oxygen than shown for the stable field in the diagram. It is difficult if not impossible to cool a high-oxygen wüstite to room temperature without the separation of magnetite.

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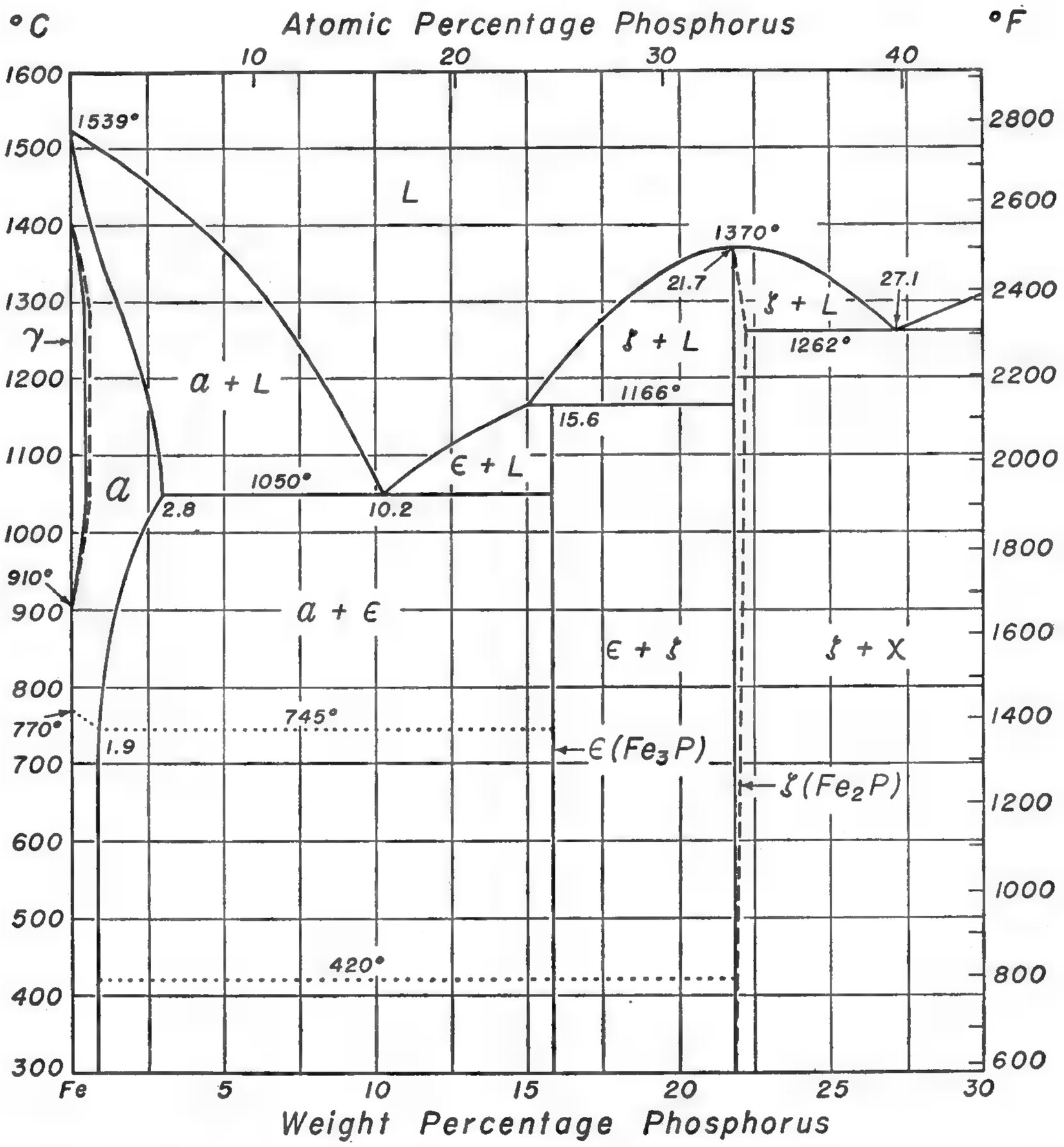
Fe-P Iron-Phosphorus

By C. H. Lorig*



Alloys containing more than 30% P have not been investigated. Constituent X is of unknown composition.

The line at 420 C represents the magnetic change in ϵ. This change is similar to the A_0 transformation in Fe_3C.

The boundaries of the $\alpha + \gamma$ region are doubtful.

The ϵ phase is tetragonal with $a = 9.09$ kX, $c = 4.45$ kX;[5] ζ (Fe_2P) is hexagonal with $a = 5.85$ kX, $c = 3.45$ kX.[3,6]

* Battelle Memorial Institute, Columbus, Ohio

References

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Fe-Pb Iron-Lead

By R. M. Parke*

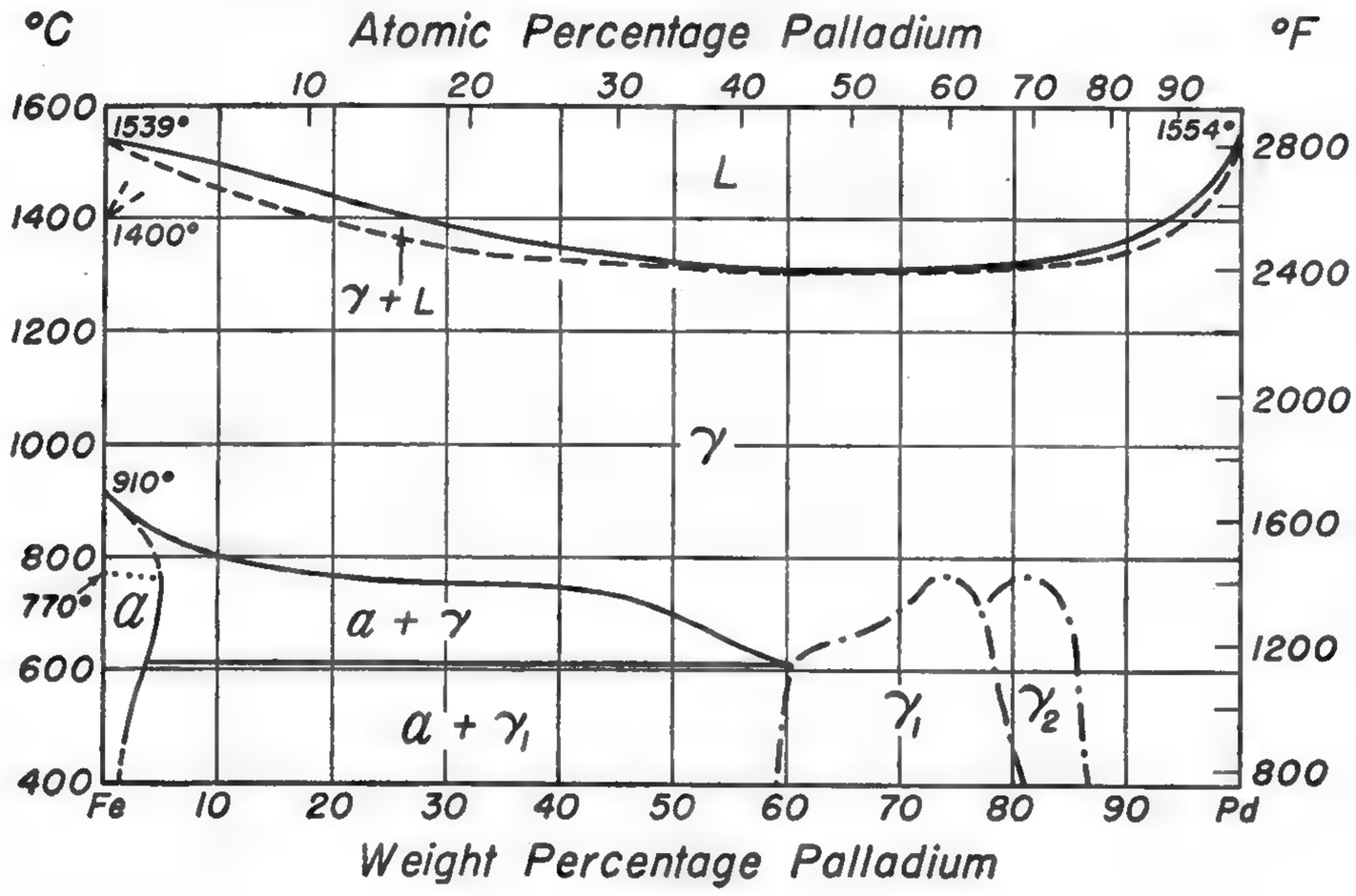
Liquid iron and liquid lead are virtually insoluble. The two metals are also mutually insoluble in the solid state.[1]

Reference

1 E. Isaac and G. Tammann, Z anorg Chem, 55, 58 (1907)

Fe-Pd Iron-Palladium

By R. M. Parke*



Palladium forms a complete series of solid solutions with gamma iron. There are two superlattices, corresponding to the formulas FePd and $FePd_3$. FePd is tetragonal, isomorphous with AuCu; and $FePd_3$ is cubic, isomorphous with $AuCu_3$.[1] An unstable intermediate phase, similar to martensite, formed by quenching gamma iron containing 5 to 20 atomic % Pd has been described by Hultgren and Zapffe.[1,2]

References

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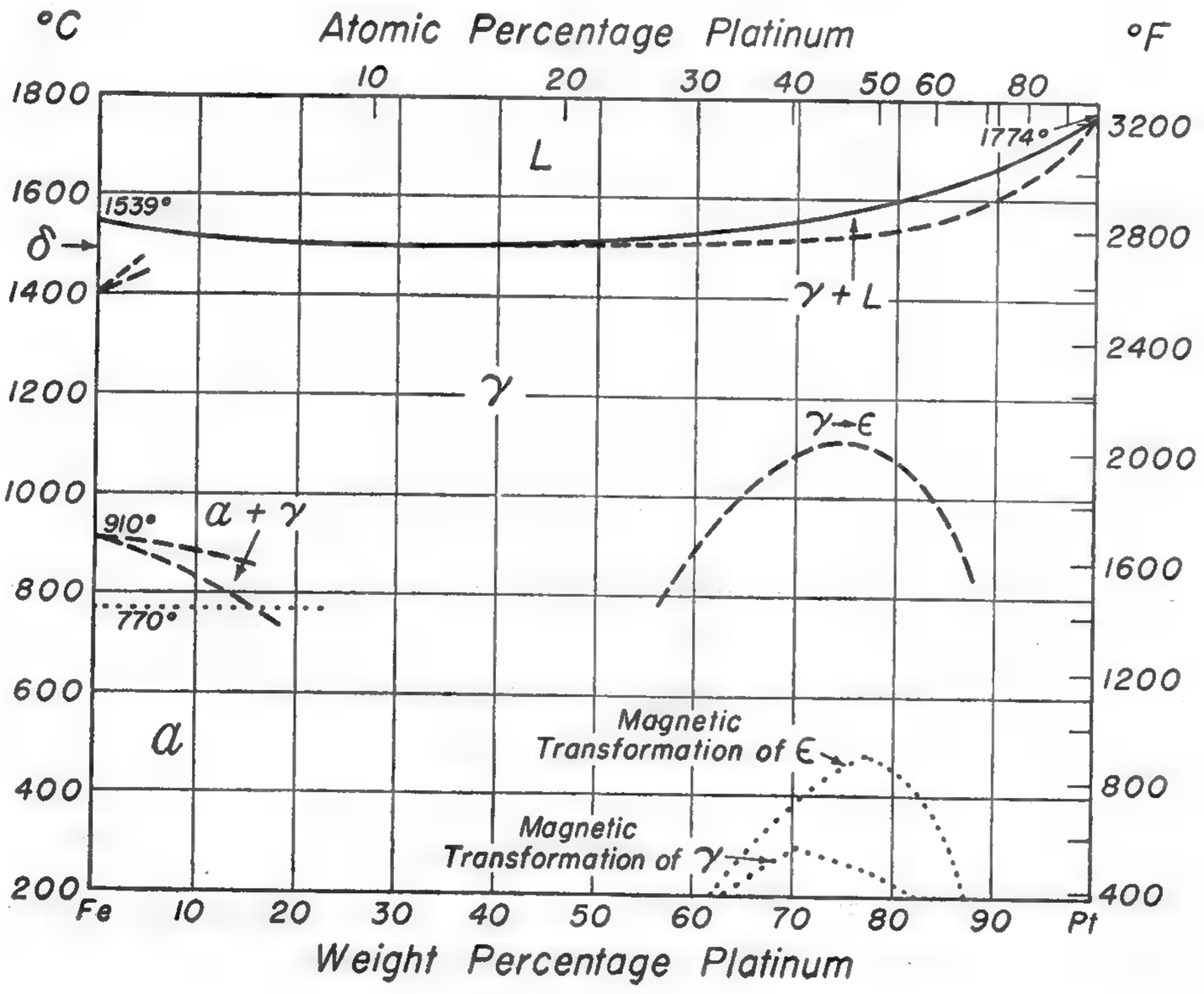
Fe-Pt Iron-Platinum

By R. M. Parke*



The alloys of approximately equiatomic composition (FePt, ε) undergo a transformation[4] near 1100 C, in which some γ is converted, on cooling, to a disordered body-centered cubic structure having a lattice parameter close to that of alpha iron. The change is not suppressed by quenching.

The gamma-alpha transformation occurs with considerable hysteresis. For example, the transformation temperatures during heating and cooling a 40% Pt alloy are about 700 and 400 C respectively.

According to Kussmann,[5] the alloys containing between 50 and 60% Pt have a negative coefficient of thermal expansion.

References

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* Kellex Corporation, Silver Spring, Md.

Fe-Rb Iron-Rubidium

By R. M. Parke*

Iron is insoluble in liquid rubidium. Rubidium is insoluble in solid iron, and although its solubility in liquid iron is not known, the formation of alloys is improbable.[1]

Reference

1 M. Hansen, "Der Aufbau der Zweistofflegierungen", J. Springer, Berlin, 1936

Fe-Rh Iron-Rhodium

By R. M. Parke*

The solubility of rhodium in alpha iron is greater than 60 atomic %.[1] Rhodium lowers the Curie temperature of iron and the $\alpha \rightleftarrows \gamma$ transformation temperature.

References

1 M. Fallot, Bull soc franç phys (J phys radium) No. 409, 120 (1937)
2 M. Fallot, Ann phys, 10, 291 (1938)

* Kellex Corporation, Silver Spring, Md.

Fe-Rn Iron-Radon

By R. M. Parke*

Electrolytic iron does not absorb radon at 1200, 1400, or 1500 C;[1] therefore, it may be assumed that neither solid solutions nor compounds are formed in this system.

Reference

1 A. Sieverts and E. Bergner, Ber, 45, 2576 (1912)

Fe-Ru Iron-Ruthenium

By R. M. Parke*

The solubility of ruthenium in alpha iron is about 13%.[1] The Curie temperature of iron and the $\alpha \rightleftarrows \gamma$ transformation temperature are lowered by ruthenium.

References

1 M. Fallot, Bull soc franç phys (J phys radium) No. 409, 120 (1937)
2 M. Fallot, Ann phys, 10, 291 (1938)

* Kellex Corporation, Silver Spring, Md.

Fe-S Iron-Sulfur

By John Chipman*

The compounds of iron and sulfur are given the nominal formulas FeS and FeS_2. The latter is capable of existence in two allotropic forms: pyrite, which is cubic, and marcasite, which is rhombic. Pyrite (ζ in the diagram) is the more stable of these two forms.

The mineral pyrrhotite (ϵ in the diagram) varies in composition from FeS to approximately $FeS_{1.2}$ at elevated temperatures and to about $FeS_{1.1}$ at room temperature. The structure is that characteristic of NiAs and a superlattice occurs in the low-sulfur region. Alloys in the sulfur-rich region of the solid solution are ferromagnetic and the crystal structure is described as deficient in iron atoms. Several allotropic forms have been described, having the same structure but differing in lattice dimensions. Transformations occur at 138 and 325 C.

A continuous series of liquid solutions can be formed extending from pure iron to a composition higher in sulfur than FeS. The compound FeS melts over a temperature range of about 100 C. The highest melting composition in the pyrrhotite field is at 38.5% S, which corresponds to a formula $FeS_{1.09}$ or $Fe_{12}S_{13}$.

The transformation temperatures of iron are not appreciably affected by sulfur. The solubility of sulfur in solid iron has not been determined with accuracy but has been variously estimated from 0.01 to 1.5%. The most dependable value appears to be approximately 0.025% in gamma iron at 940 C, decreasing with increased temperature. In alpha iron, the solubility is probably smaller.

FeS_2 (pyrite) decomposes, on heating, into pyrrhotite and sulfur vapor; the pressure of the vapor reaches atmospheric at 693 C. The region above this temperature and beyond 41% S has not been investigated.

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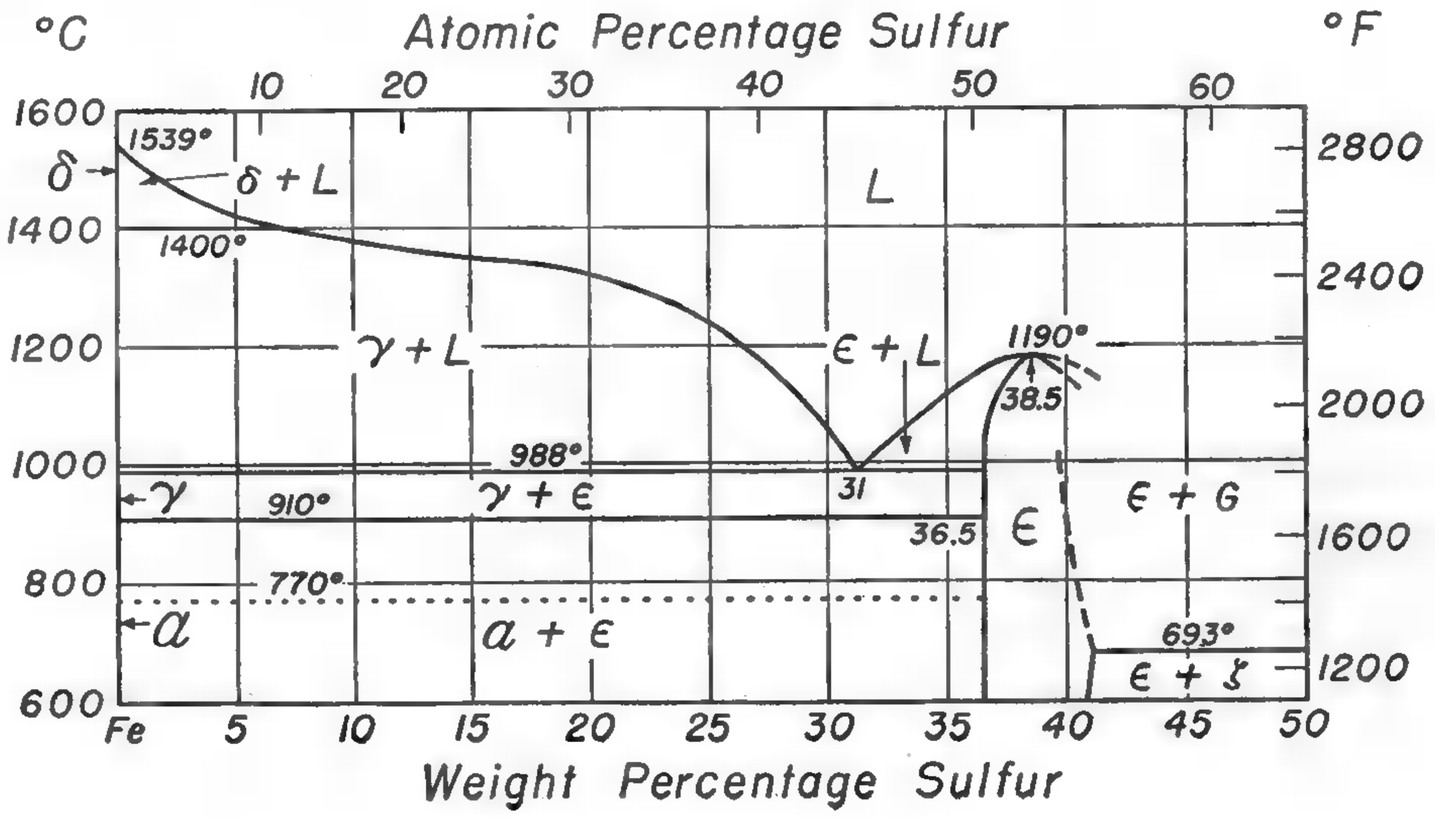
* Massachusetts Institute of Technology, Cambridge, Mass.



Fe-Sb Iron-Antimony

By R. M. Parke*

The iron-antimony diagram has been tentatively constructed from the data of references 1 to 4.

The η phase ($FeSb_2$) has a rhombic crystal structure, probably structurally analogous to that of natural marcasite (FeS_2).[3] The unit cell contains two $FeSb_2$ groups.

The transformation from ϵ to ϵ' at 620 C is doubtful.[5]

* Kellex Corporation, Silver Spring, Md.

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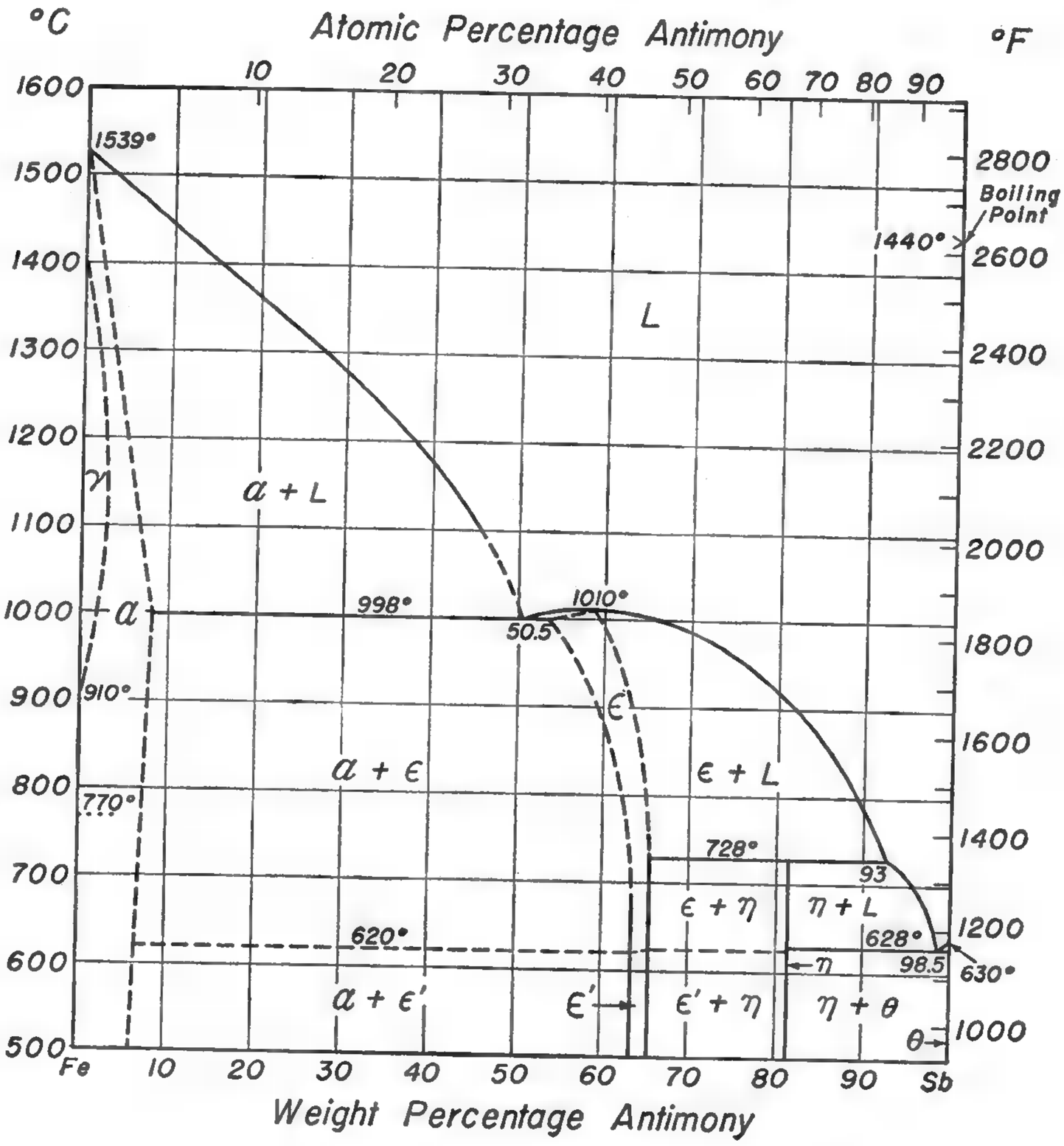

Fe-Se Iron-Selenium

By R. M. Parke*

The compound FeSe occurs in two forms. The α modification is stable below 300 to 600 C; above this temperature range the β form is stable. α FeSe has a PbO (tetragonal) structure, $a = 3.765$ kX, $c = 5.518$. The β phase has the hexagonal NiAs structure, $a = 3.607$ kX, $c = 5.844$ kX. The β phase can dissolve up to 57.5% Se.[1]

* Kellex Corporation, Silver Spring, Md.

Tengner[2] identified the compound $FeSe_2$, having an orthorhombic structure, with $a = 3.575$ kX, $b = 4.791$ kX, $c = 5.715$ kX.

References

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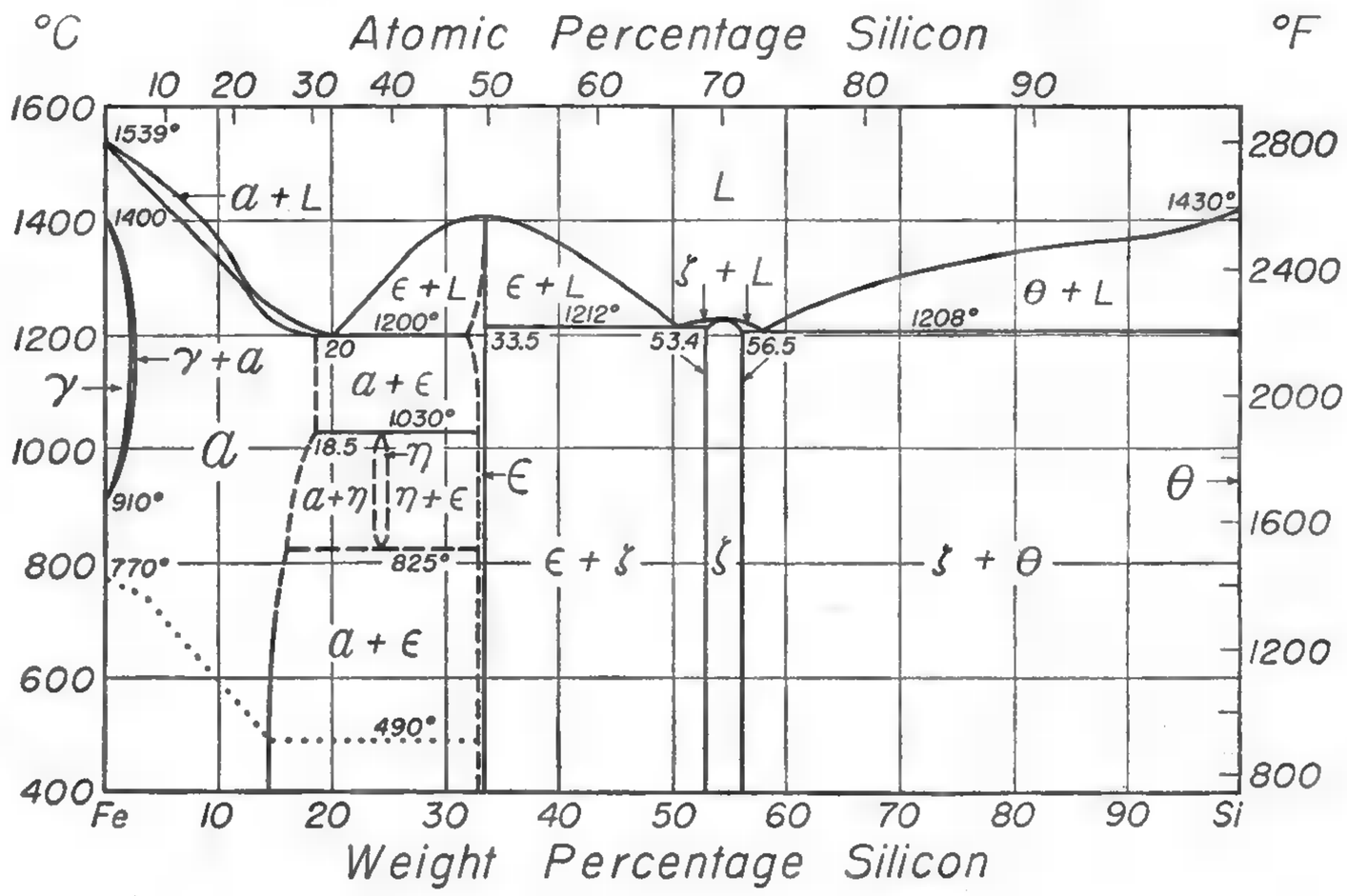
Fe-Si Iron-Silicon

By R. L. Rickett*

Ordering appears in α-phase alloys at about 7% Si; the superstructure has a parameter twice that of alpha iron. The solubility limit of silicon in iron between 1030 and 1200 C is given as 18.5% by Haughton and Becker[2] and 20.4% by Greiner and Jette,[3] whereas Farquhar, Lipson and Weill[4] report two phases of similar crystal structure in this range, one containing 18.5% and the other about 20.5% Si.

Greiner and Jette[3] have shown that although η is unstable above 1030 C or below about 825 C, the rate at which it transforms to $\alpha + \epsilon$ may be extremely slow.



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T. Murakami, Science Repts Tôhoku Imp Univ, 10, 79 (1921)

* United States Steel Corporation, Research Laboratory, Kearny, N.J.

Crystal Structures and Lattice Parameters of Iron-Silicon Alloys

Phase	Percentage Silicon	Crystal Structure	Lattice Parameter, a, kX	Lattice Parameter, c, kX	Reference
α	0.0	Body-centered cubic	2.8604	....	4, 5
α	2.38	Body-centered cubic	2.8580	....	5
α	5.16	Body-centered cubic	2.8535	....	5
α	10.76	Body-centered cubic	2.8327	....	4
α	15.70	Body-centered cubic	2.8164	....	4
α	18.25	Body-centered cubic	2.8092	....	4
η (Fe_3Si_2 or Fe_5Si_3)	25.[a]	Hexagonal	6.727	4.705	4
ϵ (FeSi)	33.5[b]	Cubic	4.47–4.48	....	6
ζ ($FeSi_2$ or Fe_2Si_5)	53.5–56.5	Tetragonal	2.687	5.127	6
Si	100	Cubic	5.419	....	6

(a) Approximate and probably variable (b) Probably slightly variable

Fe-Sn Iron-Tin

By O. E. Romig*

The complete constitution of the iron-tin alloys has not yet been definitely established. The diagram shown has been drawn to represent the present state of knowledge based mainly on the work of Edwards and Preece,[1] with modifications and additions by Ehret and Westgren,[2] Jones and Hoare,[3] Wever and Reinecken,[4] and recent work by Ehret and Gurinsky.[5] For the history of development, the reader may consult references 6 and 7. Below 496 C, from 10 to 100% Sn, the diagram seems well established.

It is likely that if more than 1.9% Sn is present the γ phase is not stable. With a given tin content, the positions of the transition points vary with carbon content, even when

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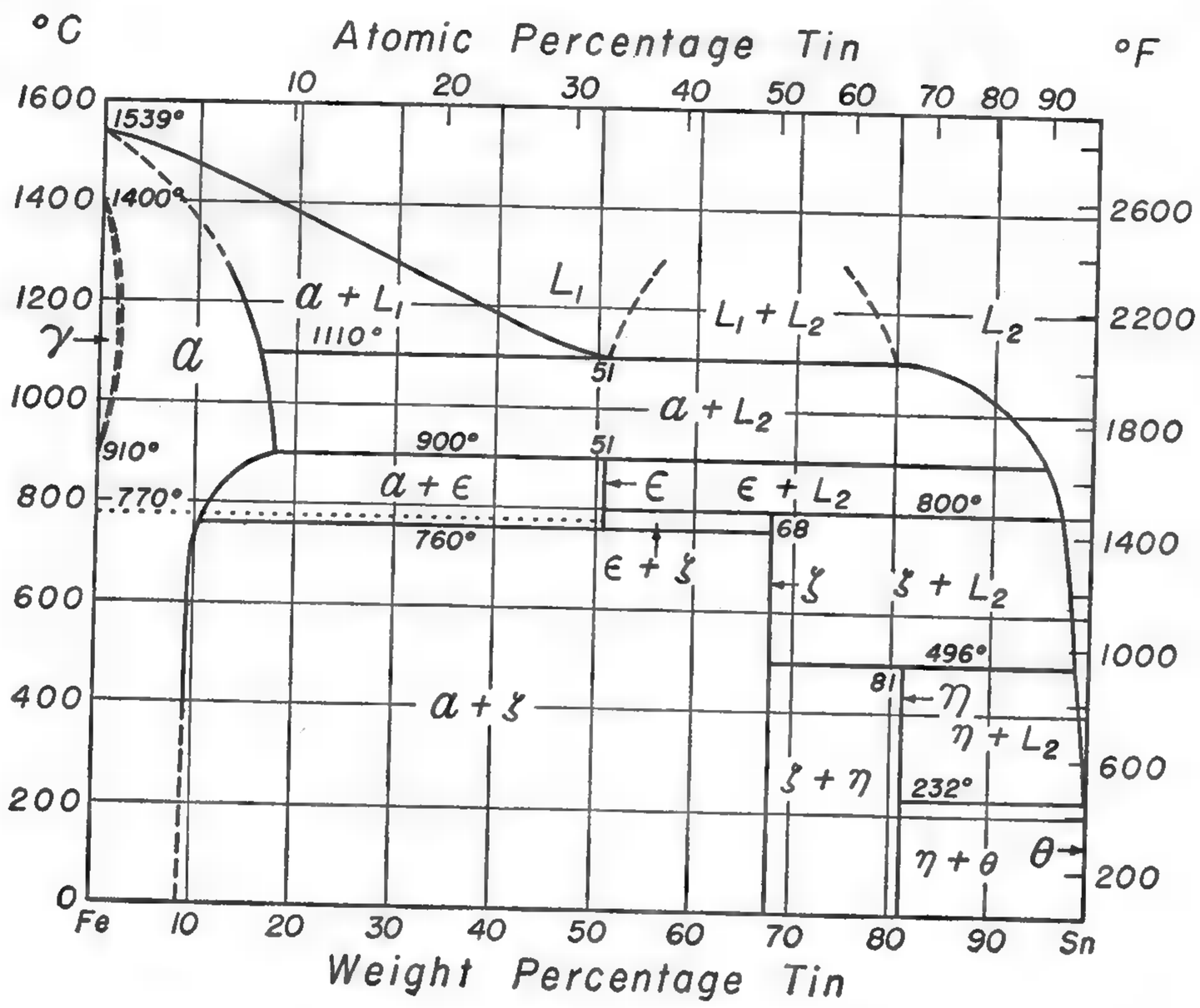
Crystal Structures and Lattice Parameters of Iron-Tin Alloys

Phase	Crystal Structure	Lattice Parameter, a, kX	Lattice Parameter, c, kX	c/a	Reference
η ($FeSn_2$)	Hexagonal	5.317	9.236	1.737	2, 5
η ($FeSn_2$)	Tetragonal	6.520	5.312	....	8
ζ (FeSn)	Hexagonal	5.292	4.440	0.839	2
ζ (FeSn)[a]	Hexagonal	5.228	4.442	0.840	5
ϵ (Fe_2Sn)	Hexagonal	5.449	4.353	0.799	2
ϵ (Fe_2Sn)[a]	Hexagonal	5.449	4.347	0.798	5
(Fe_3Sn_2)[b]	Hexagonal	21.32	4.381	0.205	5
(Fe_3Sn)[c]	Hexagonal	5.447	4.352	....	8

(a) Preferred lattice constants. For $FeSn_2$ no basis for preference is definitely known.
(b) See Ehret and Gurinsky[5] for temperature and composition limits where this compound may be found and for X-ray data.
(c) See Isaac and Tammann,[9] also Wever and Reinecken,[4] for possible temperature and composition limits and Nial[8] for X-ray data.



carbon is present in very small amounts. Thus it would be expected that the position of the transformation points in steel containing small percentages of tin might vary considerably. The magnetic change of iron at 770 C, as indicated by the dotted line, is not appreciably affected by tin content.

References

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Fe-Sr Iron-Strontium

By R. M. Parke*

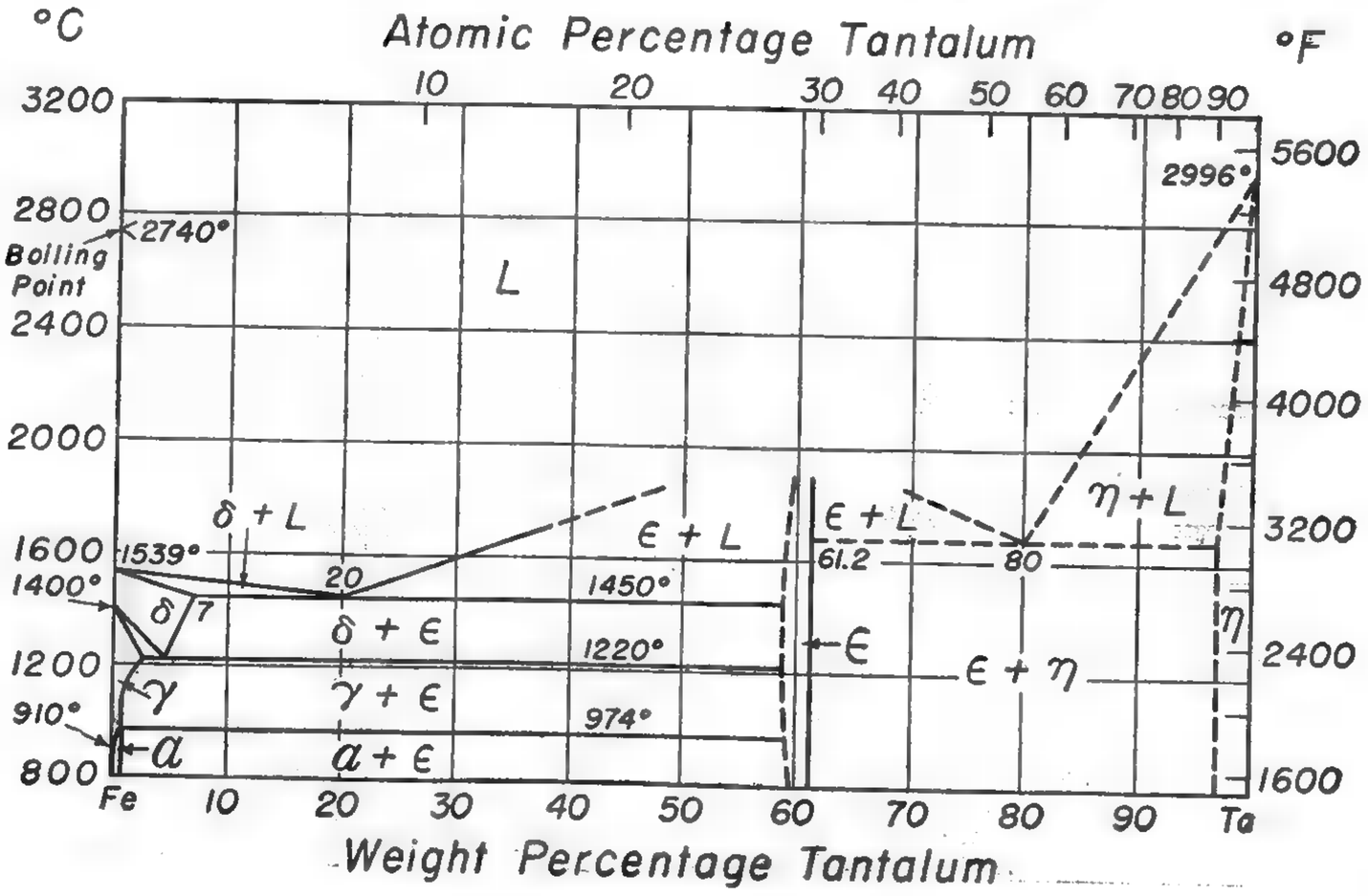
Iron is not dissolved by liquid strontium. Strontium is insoluble in solid iron, and although its solubility in liquid iron is not known, the formation of alloys is improbable.[1]

Reference

1 M. Hansen, "Der Aufbau der Zweistofflegierungen", J. Springer, Berlin, 1936

Fe-Ta Iron-Tantalum

By R. M. Parke*



Jellinghaus[1] and Nemilov and Voronov[2] claimed the existence of the compound FeTa, but Genders and Harrison[3] were unable to discover such a phase. The diagram of Genders and Harrison is presented here since their work appears reliable and they seem to have carried out the most complete investigation of this system.

Gamma iron dissolves about 3% Ta at 1220 C.

References

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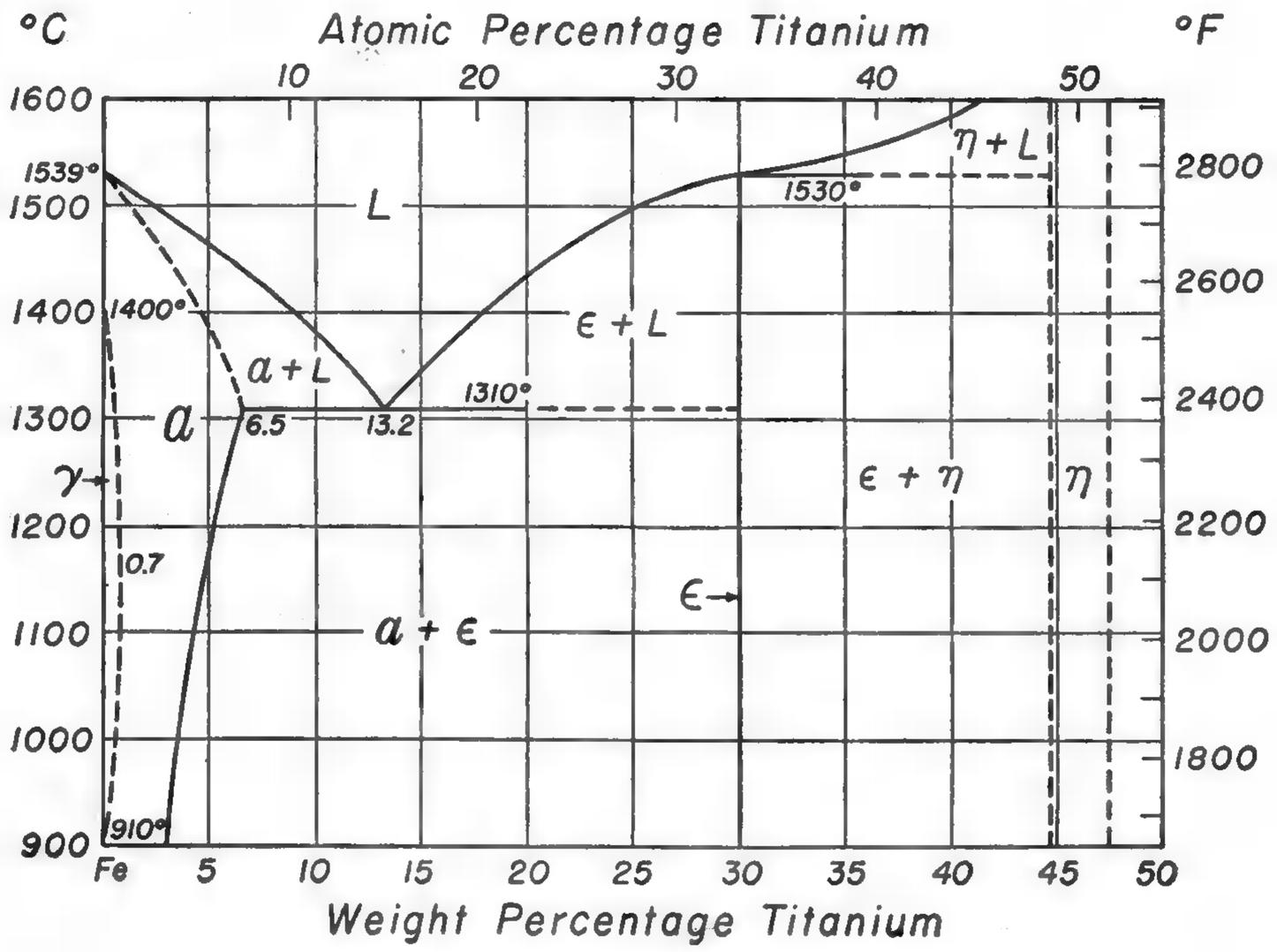
* Kellex Corporation, Silver Spring, Md.

Fe-Ti Iron-Titanium

By G. F. Comstock* and J. C. Southard*

The intermetallic compound nearest the iron end of this system has usually been considered to be Fe_3Ti, according to Tofaute and Büttinghaus,[1] although its identification as Fe_2Ti by Witte and Wallbaum[2] is now believed to be correct. There is also a slight disagreement regarding the extent of solid solubility at the eutectic temperature; this was reported as 6.9% by Vogel and Ergang,[3] and 6.3% by Tofaute and Büttinghaus.[1] The latter found the eutectic temperature to be 1350 C, while Vogel and Ergang[3] found it at 1298 C. The intermediate value of 1310 C, which is indicated, was proposed by Witte and Wallbaum.[2] The η phase (FeTi) was suggested by Wallbaum,[4] who found that this phase melted above 1600 C. Wallbaum also suggested the existence of $FeTi_2$, and indicated that the higher-titanium part of the system is solid at least up to 1550 C.

Hume-Rothery and Christian[5] indicate a maximum at 1600 C in the liquidus for a phase based on Fe_2Ti (30% Ti).



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* Titanium Alloy Manufacturing Company, Niagara Falls, N. Y.
* Solar Aircraft Company, San Diego, Calif.

Fe-V Iron-Vanadium

By Jerome Strauss†

The gamma phase may extend to a vanadium content as great as 2.5%.[2,3,4,6] The crystal structure of the ϵ phase (FeV) is complex and has not been determined. Wever and Jellinghaus[3] have described this phase.

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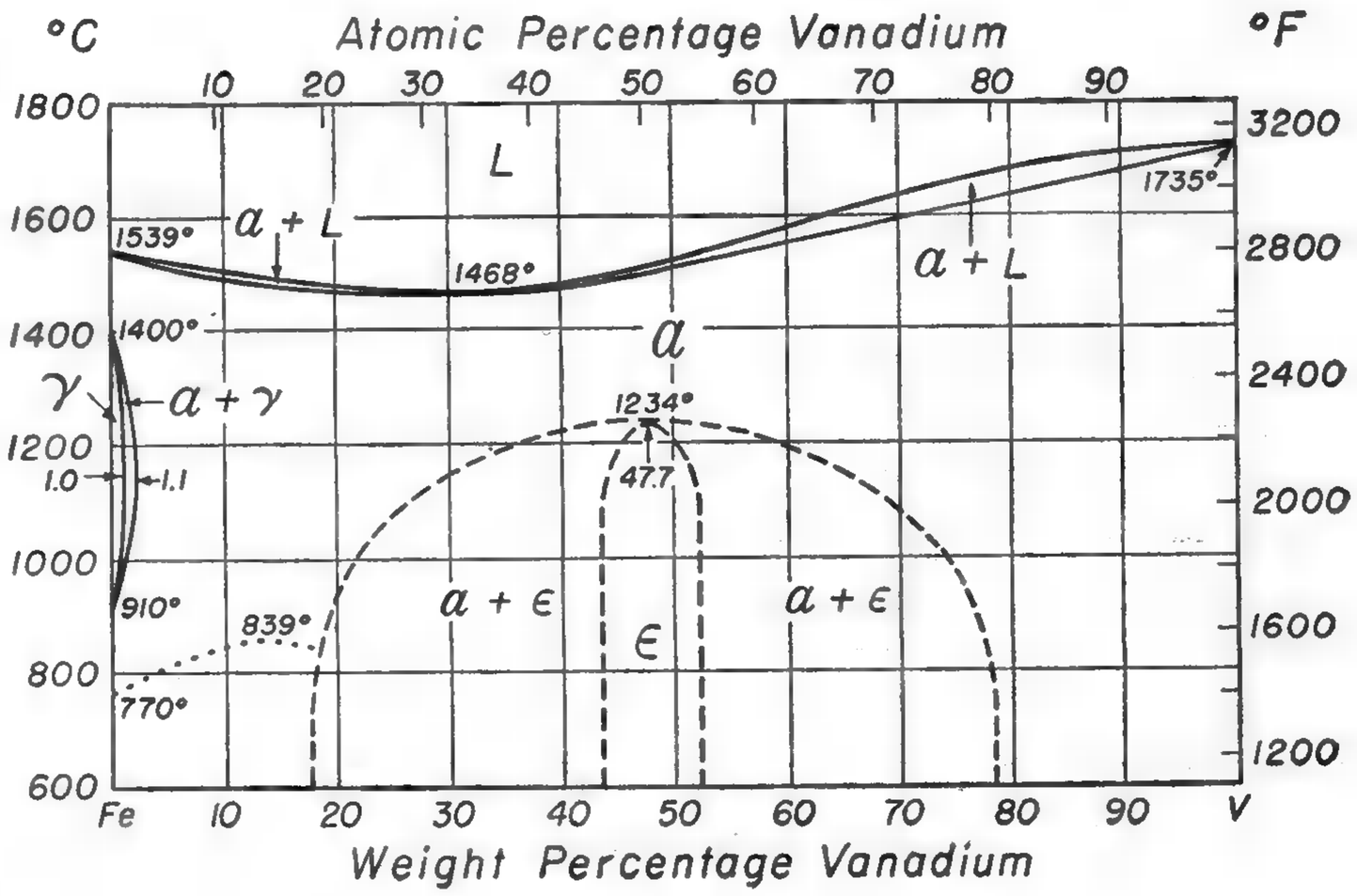
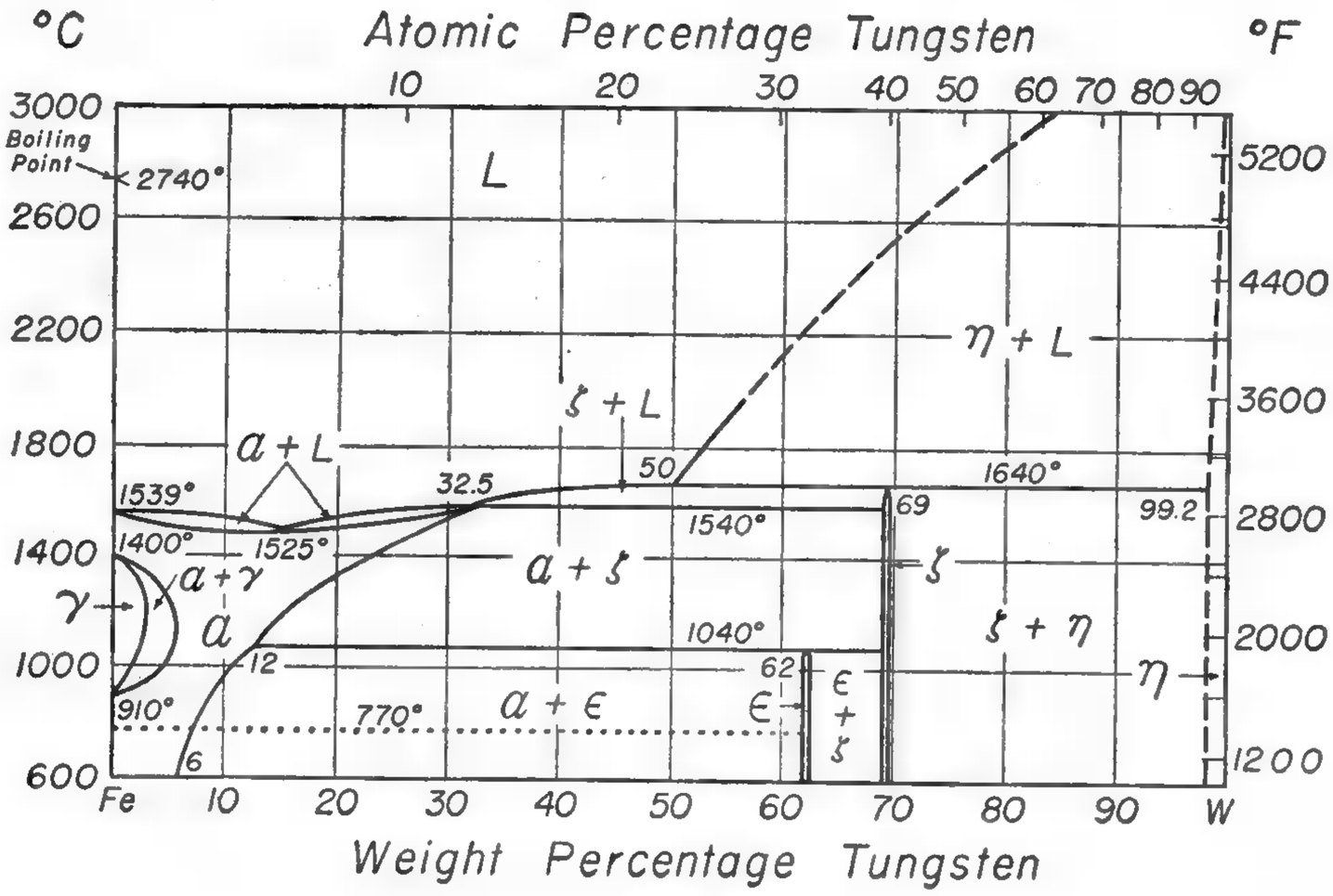
† Vice President and Technical Director, Vanadium Corporation of America, New York



Fe-W Iron-Tungsten

By W. P. Sykes*



Solid tungsten dissolves about 0.8% Fe at 1600 C.[1,7]

Certain $a + \epsilon$ alloys can be precipitation hardened.

The ϵ phase is hexagonal with $a = 4.727$ kX, $c = 7.704$ kX, $c/a = 1.630$. ζ is also hexagonal with $a = 4.731$ kX, $c = 25.76$ kX, $c/a = 5.440$.

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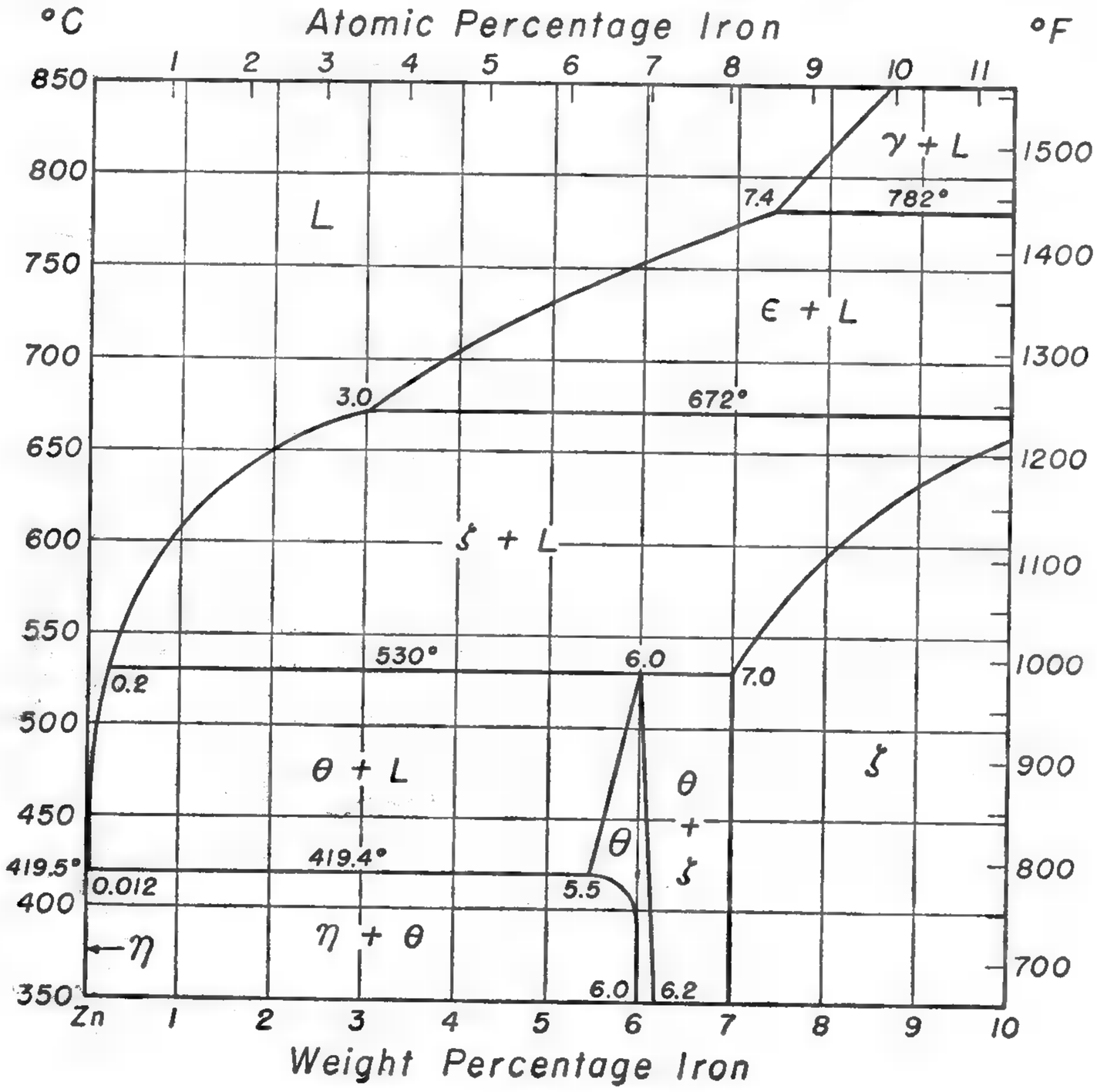
* Lamp Department, General Electric Company, Cleveland

Fe-Zn Iron-Zinc

By E. A. Anderson*



The solid solubility of iron in zinc at 150 and 400 C lies between 0.0009 and 0.0028%. The work of Jones[3] and Svechnikov and Gridnev[4] indicates the existence of a gamma loop instead of the $a + \gamma$ region shown on the diagram by dotted lines. Further work in this region is needed.

Since zinc boils at 906 C, all portions of the diagram above this temperature must represent conditions at higher than atmospheric pressure.

The preparation of homogeneous and nonporous zinc-iron alloys is difficult when the iron content is more than a few per cent. By a unique method of preparing alloys containing from 4 to 20% Fe, Schramm[5,6] prevented the usual expansion and excessive porosity, and produced alloys suitable for microscopic examination. Alloys containing from 20 to 100% Fe were prepared by annealing highly compressed powder mixtures of iron with a zinc-iron alloy containing 15% Fe. The need for high temperature, and consequent high pressure in order to prevent volatilization of zinc, was avoided in this way.

The peritectic reaction at 530 C involves considerably

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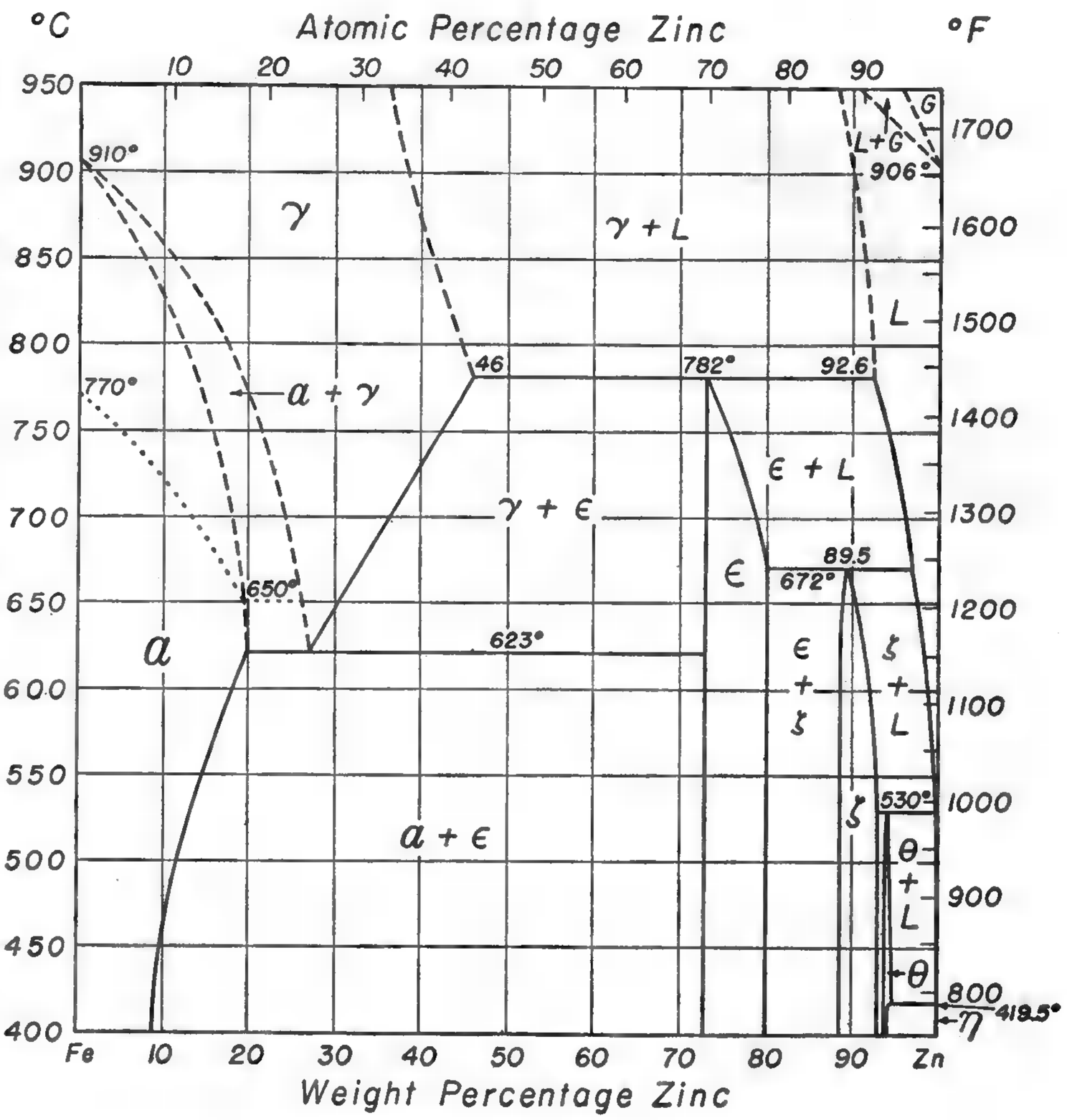
more solid than liquid, is sluggish, and may often be suppressed almost completely during cooling from the liquid state.

Rapid attack of iron by molten zinc near 500 C may be associated with the formation of the θ phase.

The crystal structures of the phases are as follows:

Phase	Crystal Structure
α	Body-centered cubic
γ	Face-centered cubic
ϵ	Cubic, with 52 atoms per unit cell
ζ	Hexagonal
θ	Similar to ζ
η	Close-packed hexagonal



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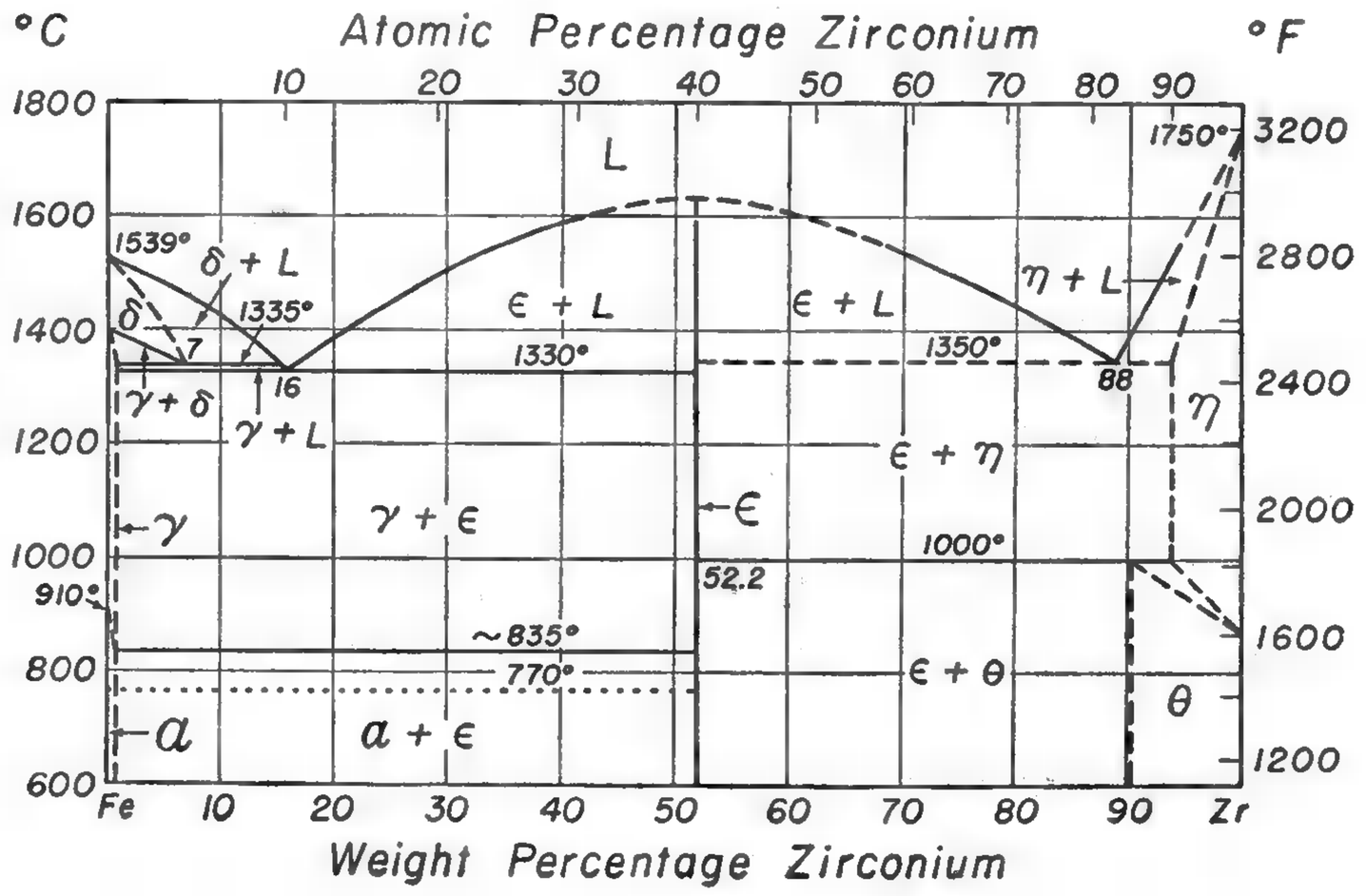
Fe-Zr Iron-Zirconium

BY R. M. PARKE*

The diagram is that of Vogel and Tonn,[2] modified to show the melting points of iron and zirconium as 1539 and 1750 C respectively. The ϵ phase is shown corresponding to Fe_3Zr_2. Wallbaum[2] reported different intermediate phases, including one forming by peritectic reaction.

Allibone and Sykes[1] made a preliminary study of alloys containing up to 30% Zr. The Brinell hardness number of the eutectic alloy in the as-cast condition was given as 290.



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* Kellex Corporation, Silver Spring, Md.

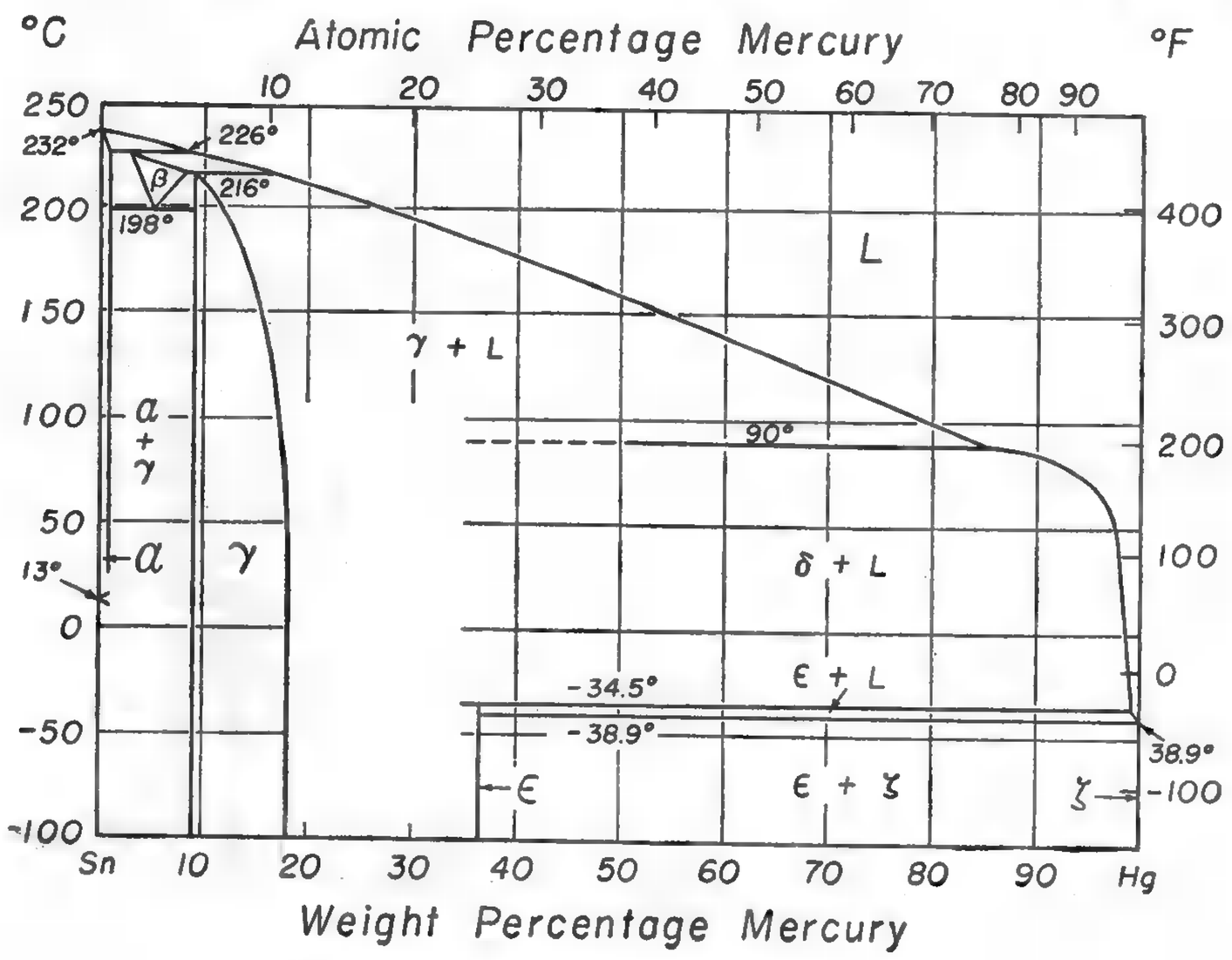
Hg-Sn Mercury-Tin

By Louis A. Carapella*

There is excellent agreement concerning the position of the liquidus curve.[1-6] However, the nature of the system below the liquidus temperatures has been reported with considerable variance, chiefly because of the difficulty of establishing equilibrium conditions at the relatively low temperatures where transformations involving solid phases occur. The latest contributions to the diagram, consistent with many early findings, are those of Prytherch and Gayler.

The β phase decomposes by a eutectoid reaction at 198 C. The eutectoid composition is about 5% Hg.

There is evidence for the formation of a δ phase — not shown in the diagram — which probably forms by peritectic reaction at 90 C. The structure of the silver-mercury-tin system indicates also that this phase exists.[6] Since the equilibrium relations between the δ phase and γ, ϵ and liquid are not known, the portion of the phase diagram between 20 and 35% Hg, and below 100 C, has been left blank in the adjoining cut.



The ϵ phase ($HgSn_3$) apparently has a very narrow range of homogeneity. No solubility of tin in solid mercury has been reported. The effect of mercury on the allotropic transformation of tin is unknown.

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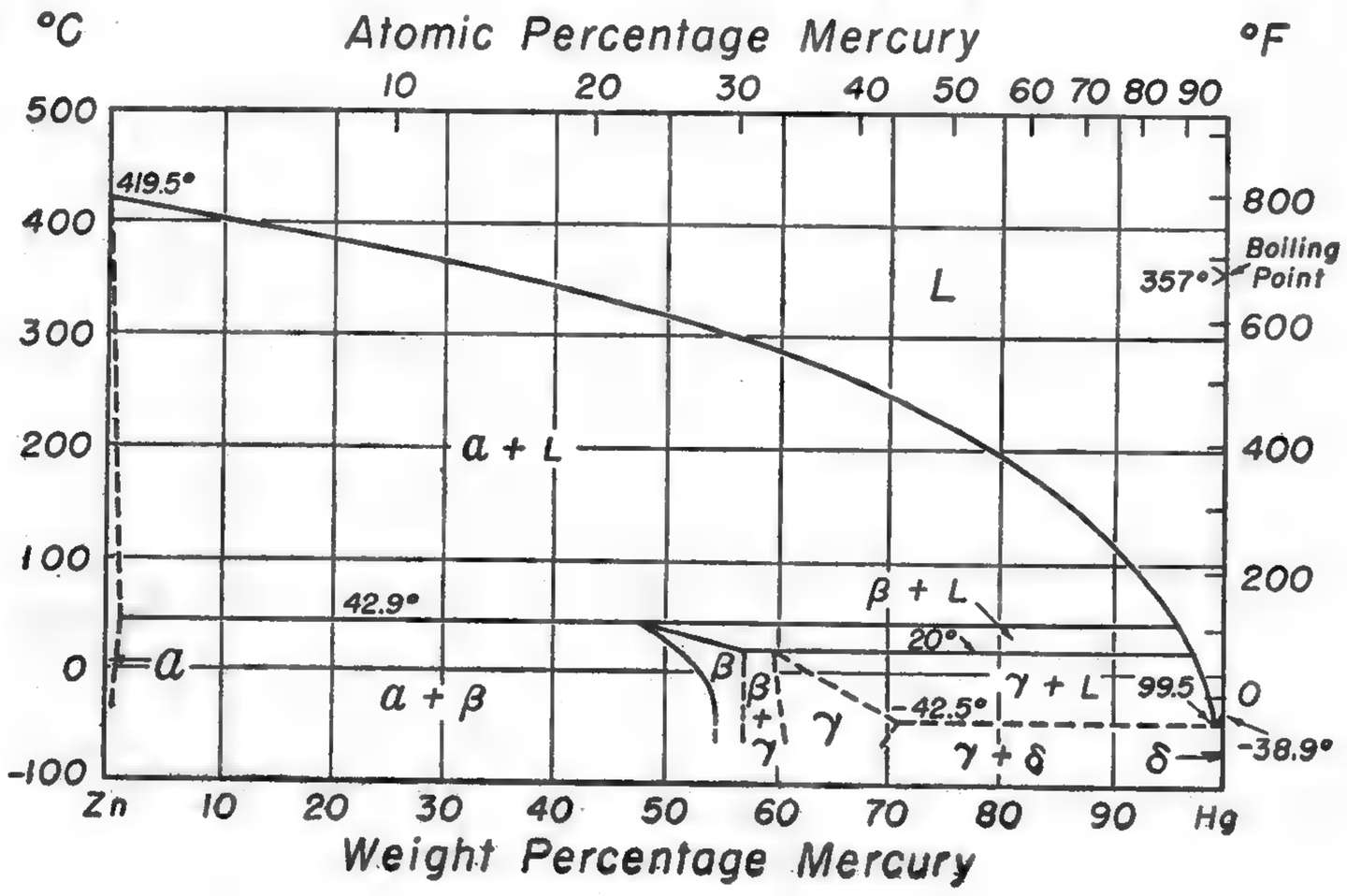
* Mellon Institute of Industrial Research, Pittsburgh

Hg-Zn Mercury-Zinc

By E. A. Anderson*



The solubility of mercury in solid zinc has not been established accurately but is probably less than 1% at room temperature. No data are available concerning the solubility of zinc in solid mercury.

According to von Simson,[4] the β phase is hexagonal with an axial ratio of 2.01. Apparently the crystal structure of the γ phase, stable only below room temperature, has not been determined.

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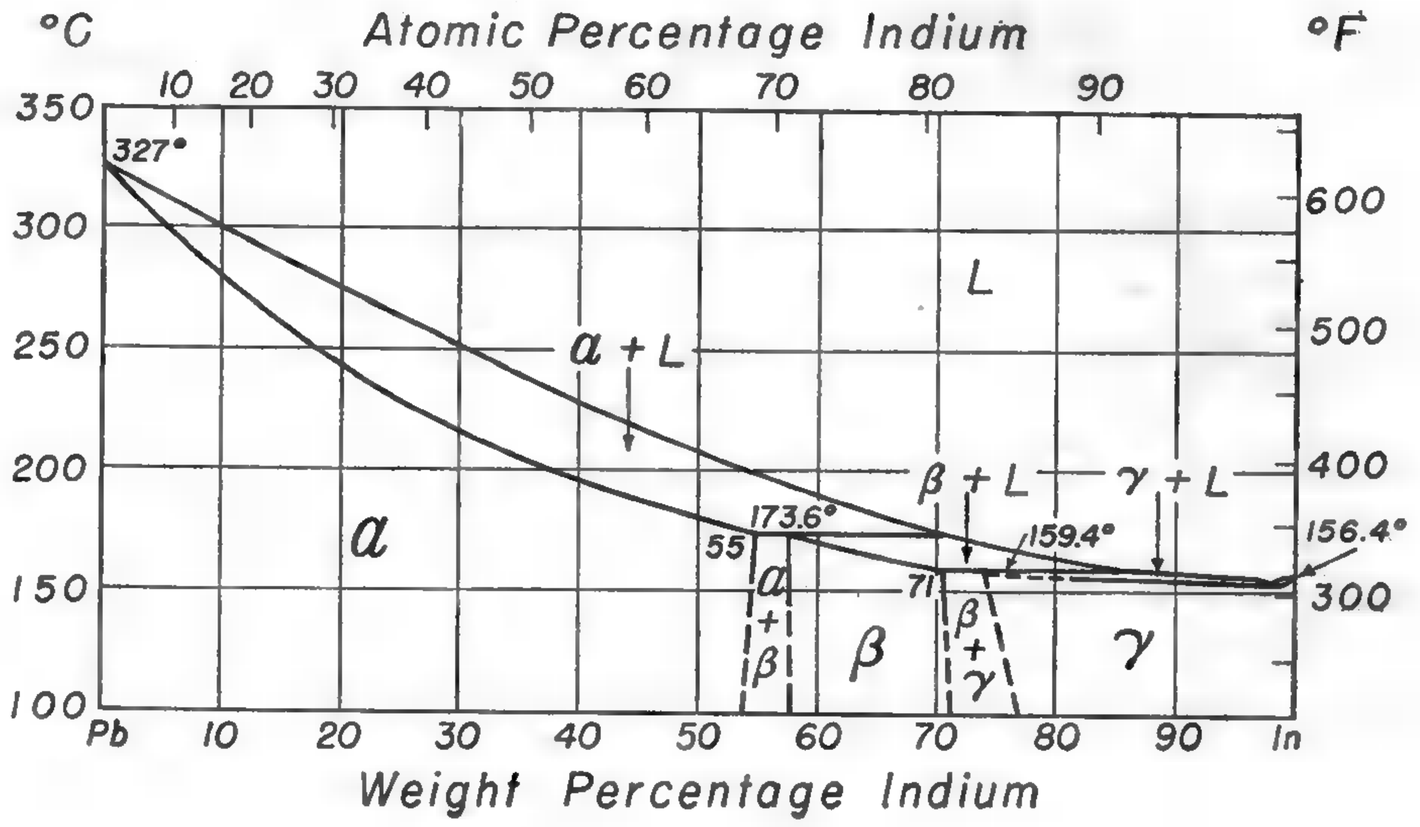
* Research Division, Technical Department, The New Jersey Zinc Company (of Pa.), Palmerton, Pa.

In-Pb Indium-Lead

By H. M. Davis*

The liquidus and solidus are based on unpublished research by H. M. Davis and G. H. Rowe.*

Homogeneous liquid solutions are attained slowly unless the liquid is agitated and held near the melting point of lead.



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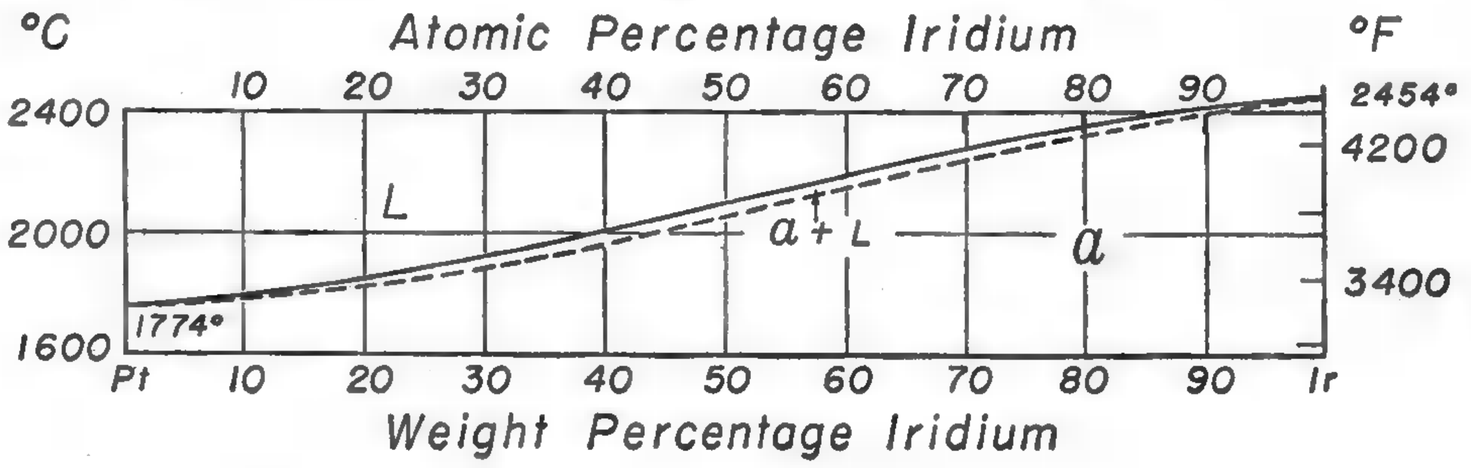
* Associate Professor of Metallurgy, The Pennsylvania State College, State College, Pa.

* Editor's Note. In the original work, the melting point of indium was determined as 157.3 C, but it is shown on the diagram here as 156.4 C, which is the value employed elsewhere in this Handbook.

Ir-Pt Iridium-Platinum

By E. M. Wise†

The liquidus is based on the results of Feussner and Müller,[1] adjusted to conform with more recent determinations of the melting point of iridium. The solidus probably is close to the liquidus throughout. There is some evidence of a sluggish transformation at intermediate temperatures in platinum-rich alloys. (*See also* page 1124.)



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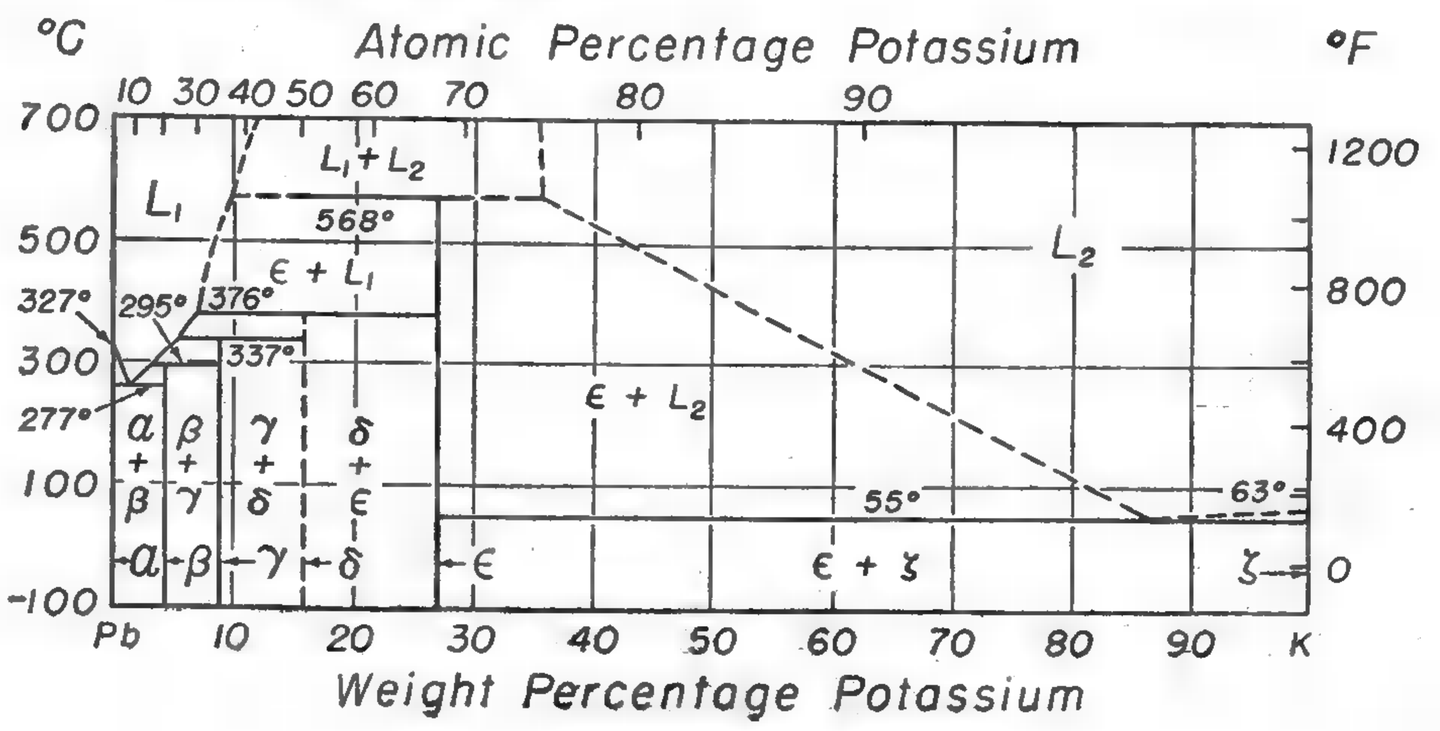
† The International Nickel Company, Inc., New York.

K-Pb Potassium-Lead

By James A. Collins‡

The phases designated here as a, β, γ and δ correspond approximately to the compositions KPb_4, KPb_2, KPb and K_2Pb respectively.

The composition of the a-β eutectic is about 1.9% K.



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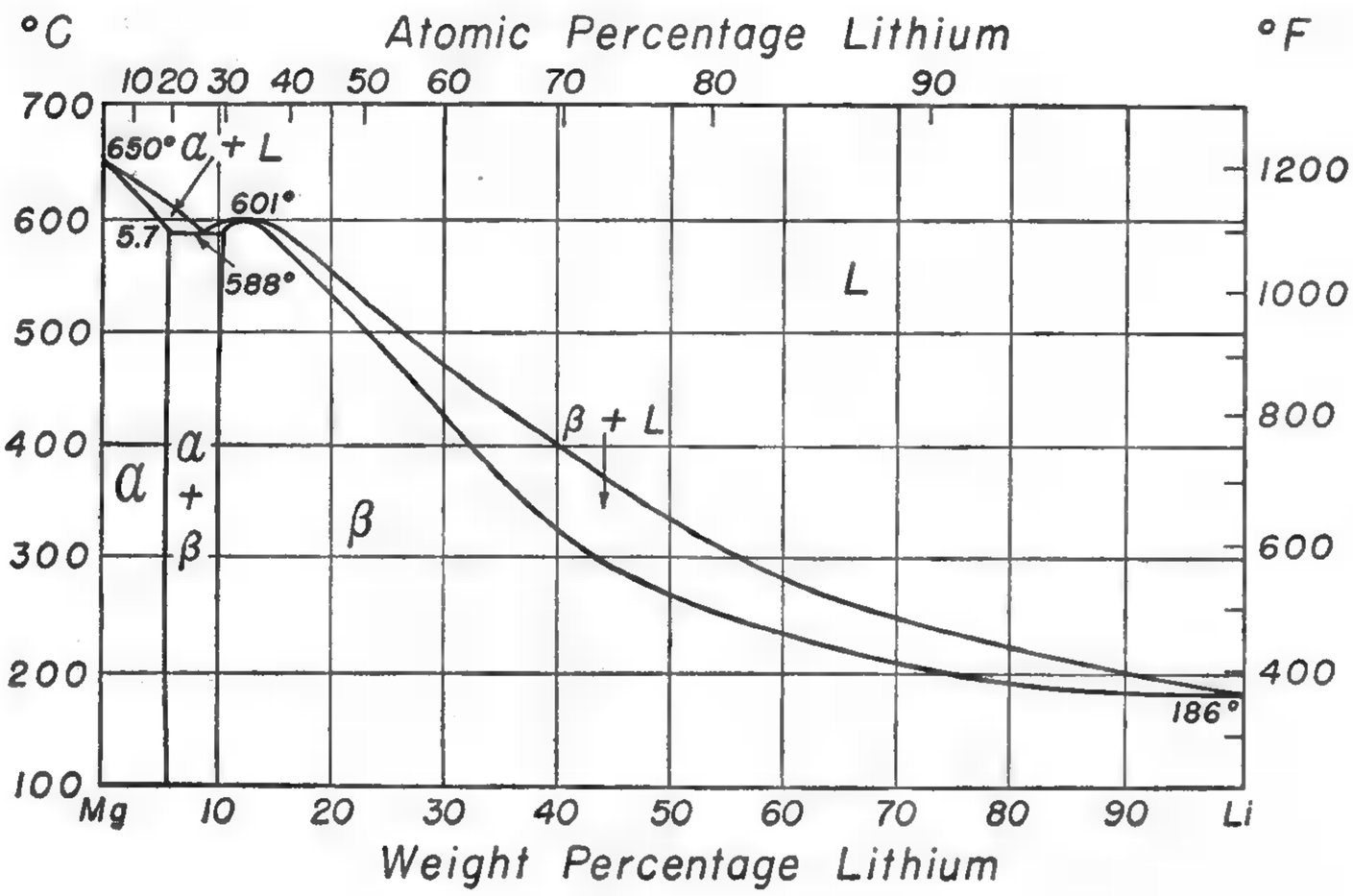
‡ E. I. du Pont de Nemours & Company, Inc., Engineering Department, Experimental Station, Wilmington, Del.

Li-Mg Lithium-Magnesium

By G. F. Sager* and B. J Nelson*

The work of Henry and Cordiano[4] indicates a peritectic reaction between the magnesium-rich solid solution and the melt to form a lithium-rich solid solution, rather than the eutectic type of diagram shown. The slightly increasing solubility of lithium in solid magnesium with decreasing temperature[5] seems most probable although some investigators[2,4] found that the solubility decreased with decreasing temperature. There is some evidence[1,5] of a superstructure near the boundary between β and $\alpha + \beta$.

The β-phase alloys are ductile, and Hume-Rothery[5] has suggested the possibility of obtaining strong, body-centered cubic alloys, lighter than magnesium, in this range of composition.



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* Aluminum Research Laboratories, New Kensington, Pa.

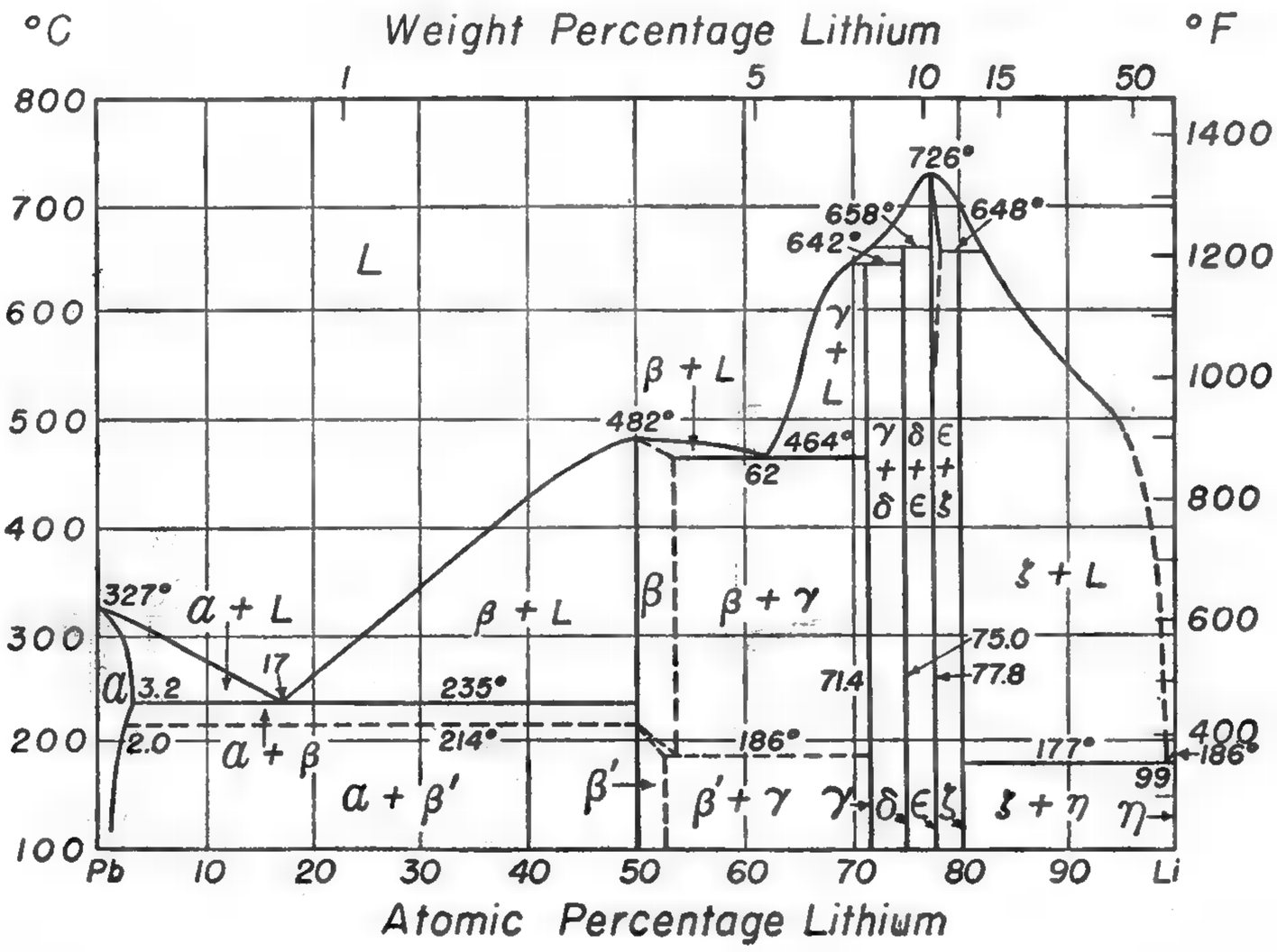
Li-Pb Lithium-Lead

By H. Osborg*

According to a recent investigation[3] only one compound ($Li_{10}Pb_3$) exists in the region occupied by δ, ϵ and ζ in the diagram shown here. However, insufficient data are available to warrant changing the diagram from the form in which it was presented by Hansen.[7] The γ, δ, ϵ and ζ phases are the compounds Li_5Pb_2, Li_3Pb, Li_7Pb_2, and Li_4Pb, respectively.

The β-β' transition is an order-disorder change.[4]

It has been reported[3] that the crystal structure of $Li_{10}Pb_3$ is of the same type as that of Cu_9Al_4; with a unit cell containing four $Li_{10}Pb_3$ groups (52 atoms) and having a lattice parameter of 10.082 kX.



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* Consultant, Port Washington, N.Y.

Mg-Mn Magnesium-Manganese

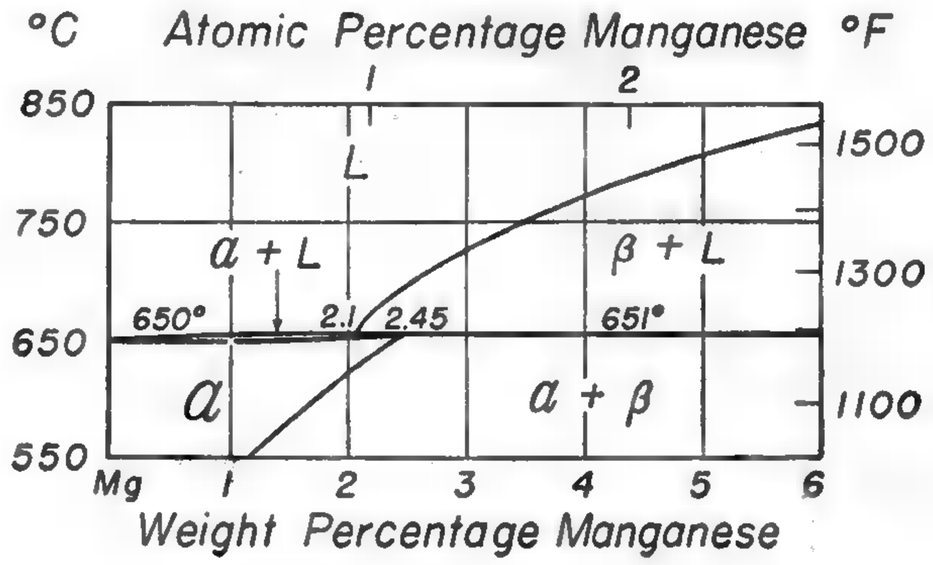
By G. F. Sager* and B. J Nelson*

The β phase in equilibrium with magnesium-rich solid and liquid solutions is alpha manganese.[2]

The most reliable solubility values are, as follows:[2,3]

Temperature, deg Cent	651	670	700	765	850
% Mn in liquid Mg[3]	2.1	2.3	2.6	3.9	6.6
Temperature deg Cent	651	620	540	455	
% Mn in solid Mg[2]	2.45	2.06	1.00	0.25	

The Mg – 1.5% Mn alloy is used commercially in both cast and wrought forms. Manganese (0.1 to 1%) is a secondary component in all other commonly used magnesium alloys.



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* Aluminum Research Laboratories, New Kensington, Pa.

Mg-Ni Magnesium-Nickel

By A. M. Hall*

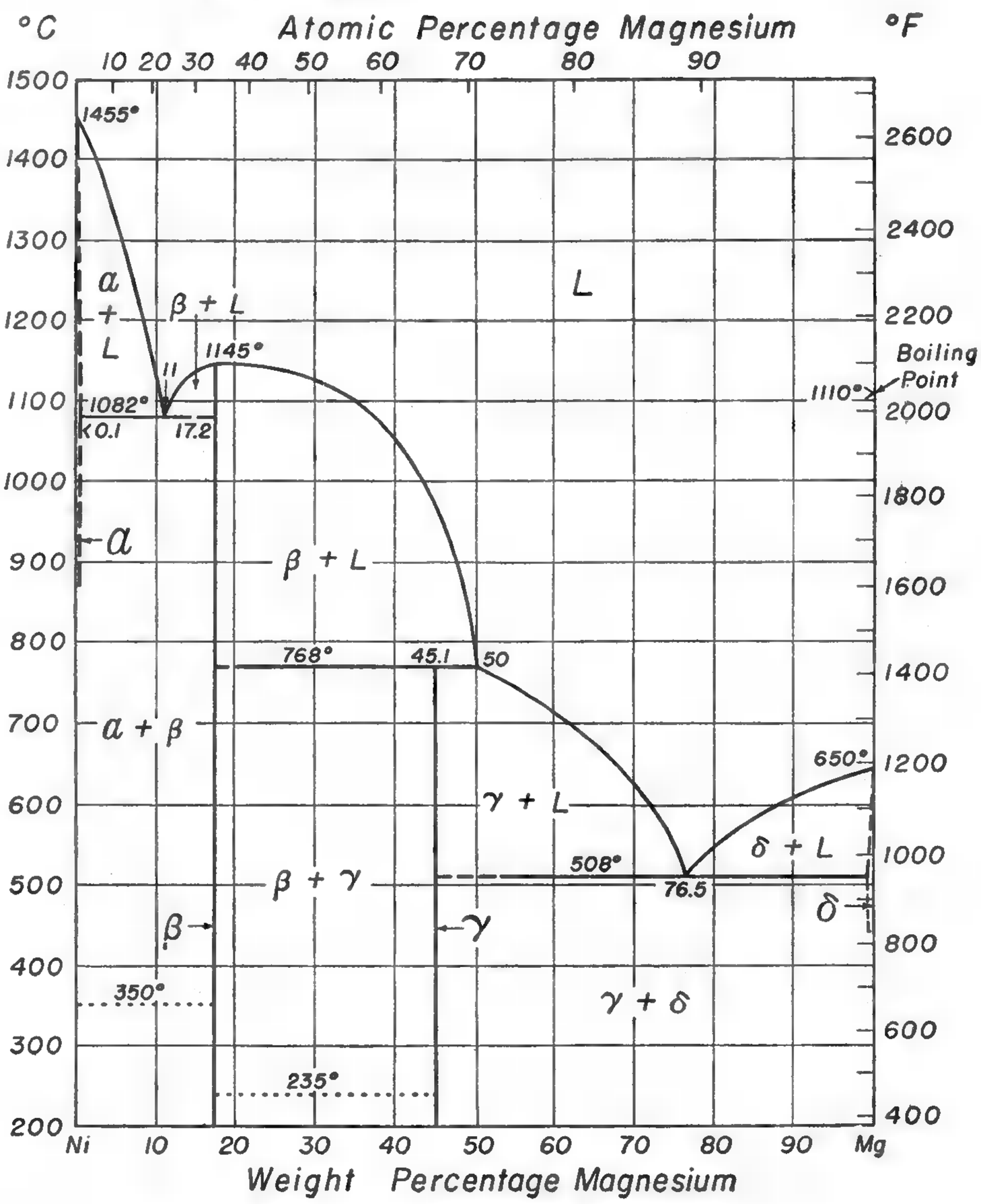
The presence of a two-liquid field has been suggested between 16 and 28% Mg with a lower boundary at 1145 C; however, there is considerable question about the existence of such an area. The phenomenon is probably related to the formation of the β phase (Ni_2Mg) at 1145 C.

The solubility of magnesium in solid nickel is considered to be less than 0.10% at 1100 C.[5] The solubility of nickel in solid magnesium is less than 0.10% at 500 C.[3]

The β phase is hexagonal with $a = 4.81$ kX and $c/a = 1.65$.[6]

Greatest commercial interest is in age-hardenable high-nickel alloys containing small additions of magnesium.

Nickel, like iron, has an extremely adverse effect on the resistance of magnesium alloys to corrosion in saline environments (*see* the article on page 994 in this Handbook). For specialized applications, the control of the nickel and iron contents of magnesium alloys offers a means for obtaining an alloy with a controlled rate of corrosion.



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* Battelle Memorial Institute, Columbus, Ohio

Mg-Pb Magnesium-Lead

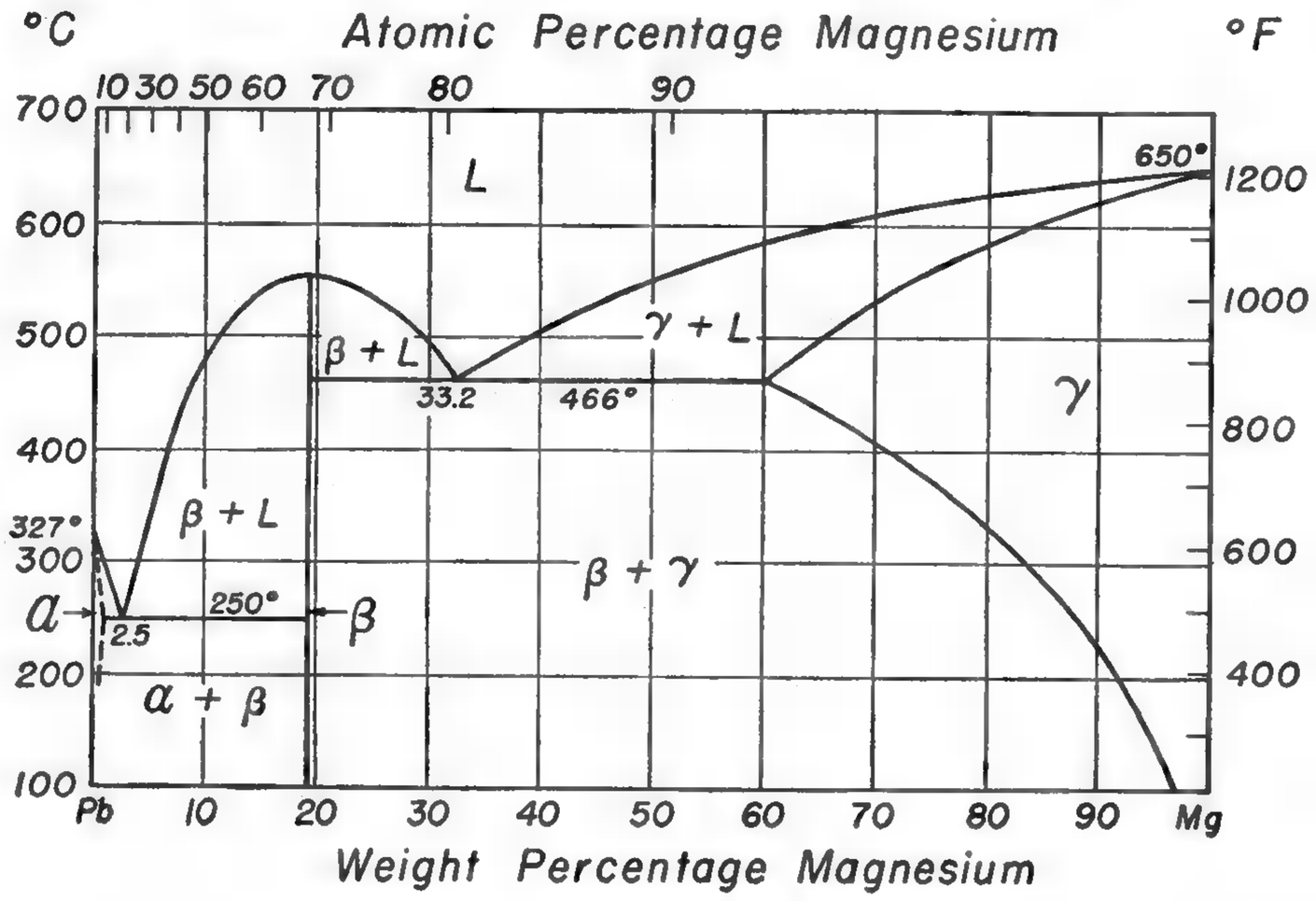
By A. A. Smith, Jr.*

The diagram is based largely on references 1 to 4.

The solubility of magnesium in solid lead decreases from 0.7% at 245 C to 0.2% at 20 C.[7] Vosskühler[3] reported the solubility of lead in solid magnesium to be about 27% greater than shown here.[4]

The β phase (Mg_2Pb) is face-centered cubic (CaF_2 type) with $a = 6.75$ kX.[5,6]

Even as little as 1% Mg in lead produces an alloy that is unstable in moist air.[8]



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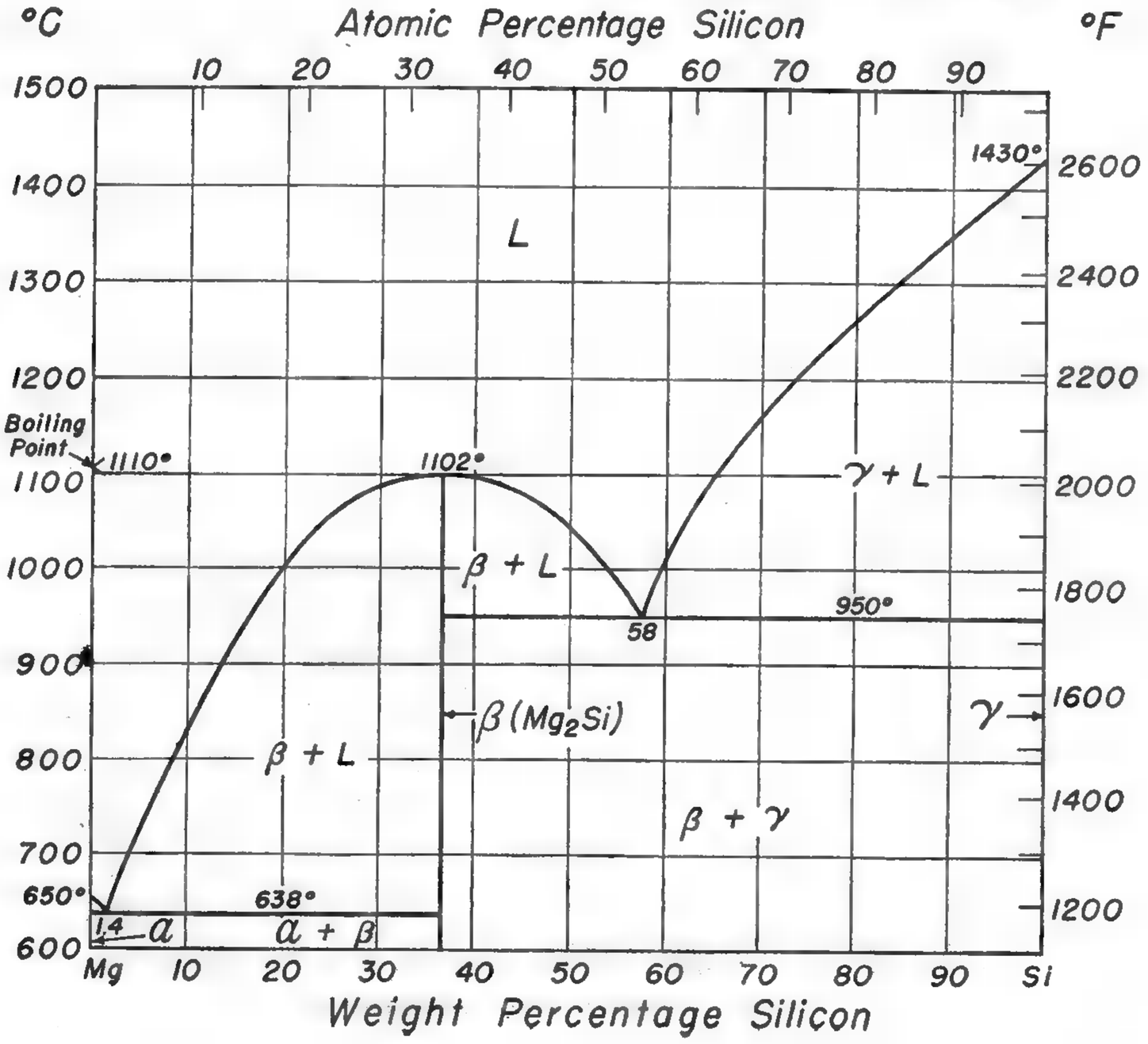
* American Smelting and Refining Company, Barber, N.J.

Mg-Si Magnesium-Silicon

By G. F. Sager* and B. J Nelson*



The solubility of silicon in solid magnesium is of the order of 0.003 atomic % at 600 C.

No range of solubility has been detected for the β phase (Mg_2Si).

The β phase (Mg_2Si) is face-centered cubic (CaF_2 type) with a lattice parameter of 6.391 kX.[5]

The boiling point of magnesium and the melting point of Mg_2Si are at nearly the same temperature. During the distillation of magnesium that contains silicon, the residue consists mainly of Mg_2Si crystals.

Silicon increases the hardness of magnesium alloys; the tensile strength reaches a maximum at about 1% Si.

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* Aluminum Research Laboratories, New Kensington, Pa.

Mg-Sn Magnesium-Tin

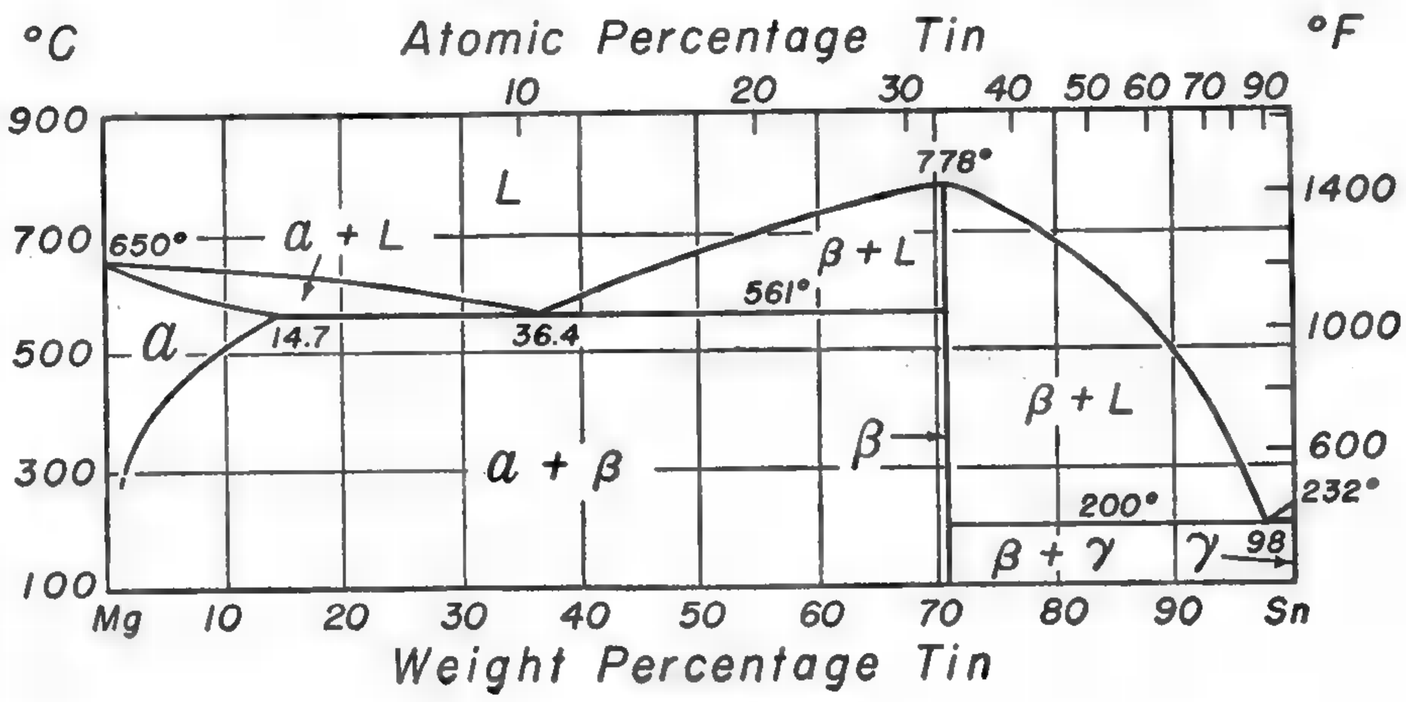
By G. F. Sager* and B. J Nelson*

The β phase is the compound Mg_2Sn; no range of solid solubility of magnesium or tin in this compound has been detected. The solubility of tin in solid magnesium, from unpublished results of L. A. Willey,* is as follows:

deg Cent	560	525	500	475	422	325	300	250
% Sn	14.7	11.75	9.95	8.10	5.25	1.90	1.40	0.98

The β phase (Mg_2Sn) is face-centered cubic (calcium fluoride type) with a lattice parameter of 6.76 kX.

A quaternary magnesium-base alloy containing 5% Sn is used commercially in making hammer forgings.



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* Aluminum Research Laboratories, New Kensington, Pa.

Mg-Zn Magnesium-Zinc

By J. B. Hess*

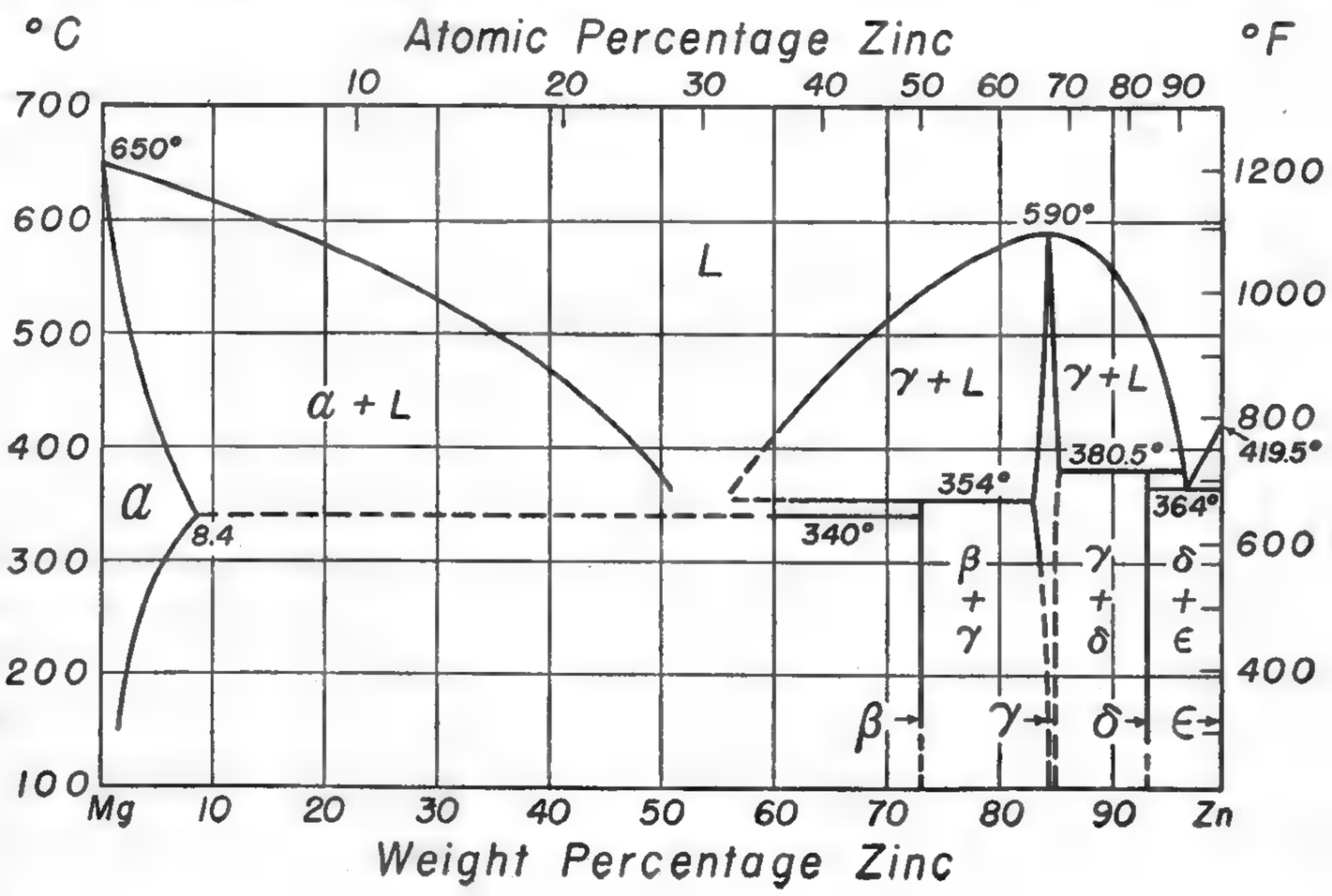
The solubility of zinc in solid magnesium is as follows:[3]

deg Cent	340	300	250	200	150
% Zn	8.4	6.0	3.3	2.0	1.7

The solubility of magnesium in zinc has been reported to be approximately 0.11% at 364 C[1,2] and less than 0.002% at room temperature.[4]

At least three intermetallic phases have been identified. The β phase (MgZn) is hexagonal, with $a = 5.33$ kX, $c = 8.58$ kX.[13,14] The γ phase ($MgZn_2$) is also hexagonal, with $a = 5.15$ kX, $c = 8.48$ kX.[11] The δ phase (Mg_2Zn_{11}?) is probably cubic.[4,13,14,15] Solid solubility in these compounds has been both reported and denied.

Early work on the magnesium-rich alloys indicated the phase diagram to be of the simple eutectic type, and consequently this part of the diagram has received limited study subsequently. However, there is now ample metallographic,[4,7,10,†] thermal,[7,10] X-ray,[9,†] and other[5,6,8] evidence to establish the existence of an additional phase, in the neighborhood of 50 to 54% Zn, which undergoes eutectoid decomposition at lower temperature. The data are still not sufficient to permit a revision of the diagram in this region. The reported evidences of polymorphic transformations in β and γ are probably misinterpreted effects of this eutectoid.



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* Magnesium Laboratory, The Dow Chemical Company, Midland, Mich.

† Unpublished results, Magnesium Laboratory, The Dow Chemical Company.

Mg-Zr Magnesium-Zirconium

By G. F. Sager* and B. J Nelson*

The evidence for this system is too fragmentary to allow the construction of a diagram. Siebel[1] reports a peritectic system analogous to the magnesium-manganese system, with the liquidus meeting the peritectic temperature at 0.26% Zr, near the melting point of magnesium, and rising steeply with increase of zirconium content until 1000 C is reached, at which point it curves away toward horizontal.

Vosskühler[2] states that the solubility of zirconium in magnesium is 0.8% at 500 C and less than 0.1% at 400 C. Nowotny, Wormnes, and Mohrnheim[3] report the solubility of zirconium as 0.8% at 700 C and 0.3% at 300 C.

* Aluminum Research Laboratories, New Kensington, Pa.

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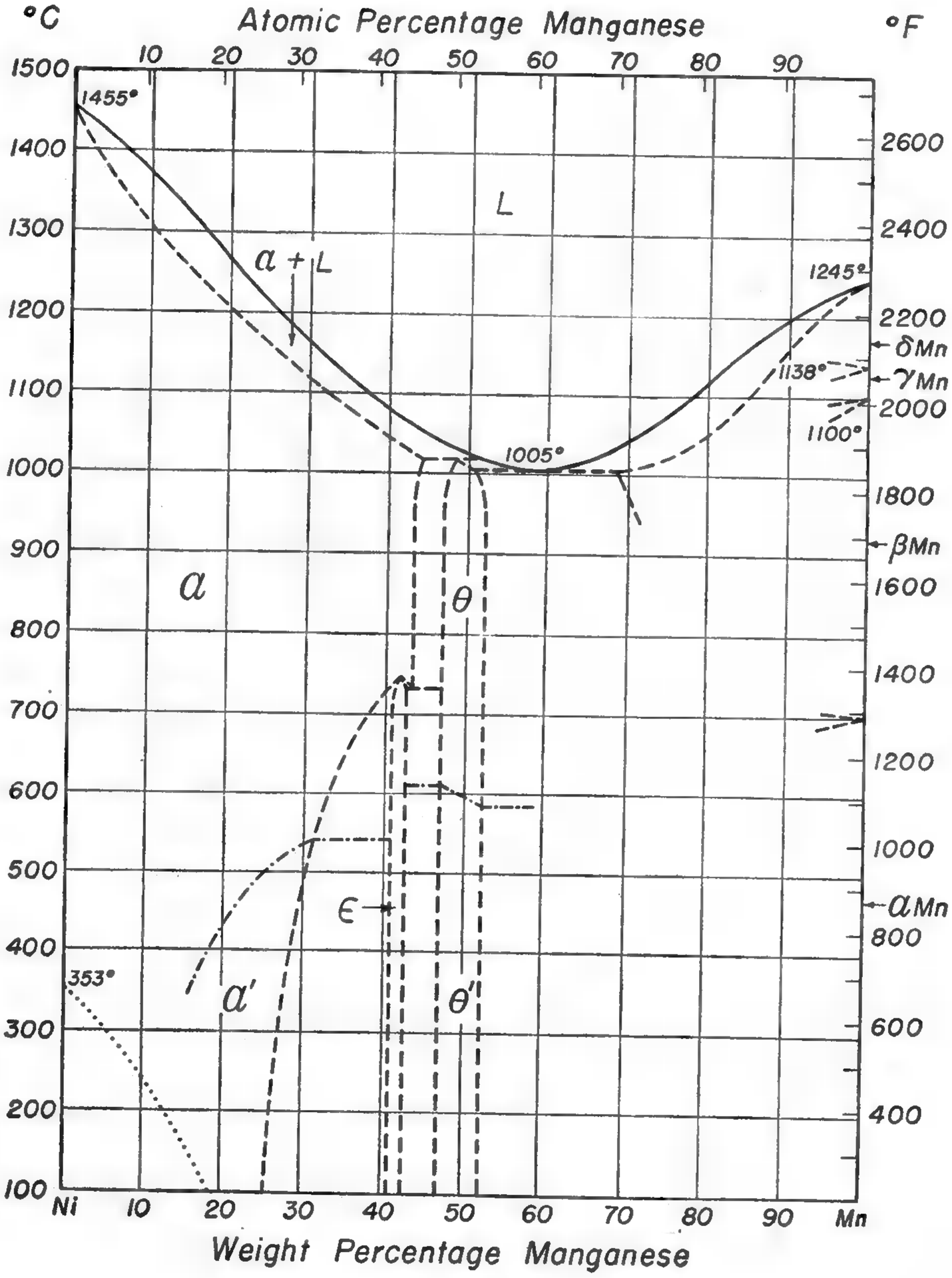
Mn-Ni Manganese-Nickel

By C. E. Lacy*



The equilibrium relationships shown for the region between 25 and 60% Mn are only approximate. They are based mainly on information given by Dourdine[2] and are supported in part by the data of other workers.[3,4] Valentiner and Becker[6] confirmed the θ phase, found an additional phase at 70% Mn, but failed to confirm the ϵ phase. Little is known about the diagram in the region from 50 to 100% Mn. Study of the manganese-nickel system is complicated by the fact that the alloys apparently freeze metastably.

It has been definitely established[3,6,7] that the magnetic transformation occurring in alloys containing from 15 to 40% Mn is associated with the formation of a $MnNi_3$ superstructure of the $AuCu_3$ type. The $MnNi_3$ superstructure is ferromagnetic. The θ phase may also form a superlattice.[6]

The transformation temperatures of pure manganese are based on the work of Potter and Lukens.[9]

The ϵ phase containing approximately 42% Mn is face-centered cubic; θ (48% Mn) is face-centered tetragonal.

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* Research Laboratory, General Electric Company, Richland, Wash.

Mn-Pd Manganese-Palladium

The rather complicated phase diagram, based on the works of several German investigators, is included in "The Platinum Metals and Their Alloys", by R. F. Vines, 1941. The liquidus and solidus temperatures of the palladium-rich alloys have an unusual sinuous form. The liquidus curve descends from the melting point of palladium (1554 C) to a minimum at 1350 C and 21.3% Mn, rises to a maximum at 1515 C and 34% Mn, and then descends to the eutectic point at 1147 C and 57.5% Mn.

Mn-Pt Manganese-Platinum

The platinum-rich alloys were studied by Nemilov, Vidusova and Pivovarova [Izvest Akad Nauk SSSR (Chim), 743 (1937)]. The liquidus curve reaches a minimum at about 45% Mn. Heat effects were obtained at 22% Mn (PtMn) and 956 C, and at 53% Mn ($PtMn_4$) and 980 C. Another intermediate phase is indicated at 8.5% Mn (Pt_2Mn) from measurements of hardness and temperature coefficient of electrical resistivity. Alloys containing up to 5% Mn are ductile enough to be drawn into wire.

Mn-Zn Manganese-Zinc

By E. A. Anderson*

The diagram is essentially that of Schramm.[1] Information is lacking regarding alloys that contain more than 50% Mn.

On the basis of unpublished data Rodda* places the solubility of manganese in solid zinc at 0.45% at the eutectic temperature, decreasing to less than 0.02% at 200 C.

* Research Division, Technical Department, The New Jersey Zinc Company (of Pa.), Palmerton, Pa.

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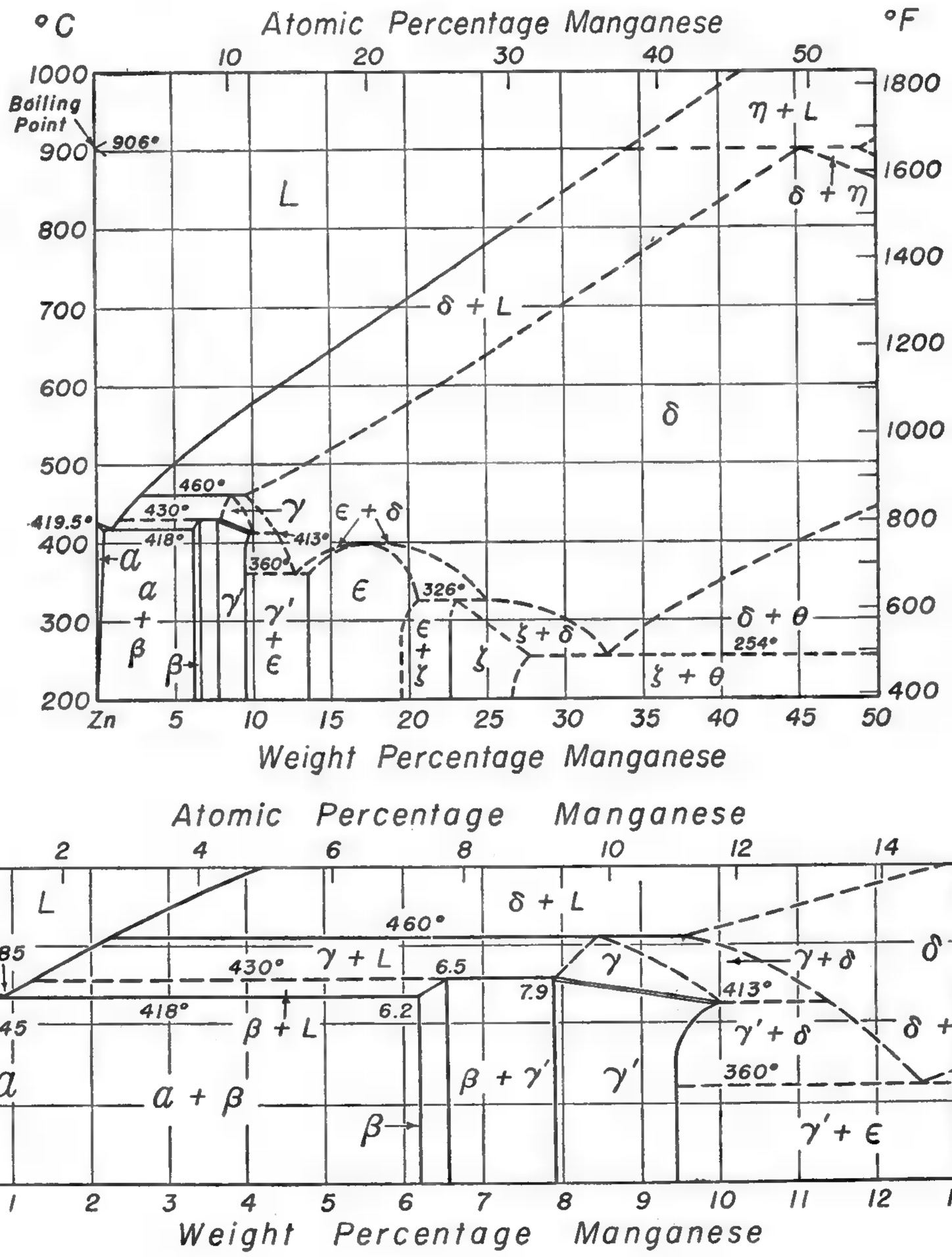
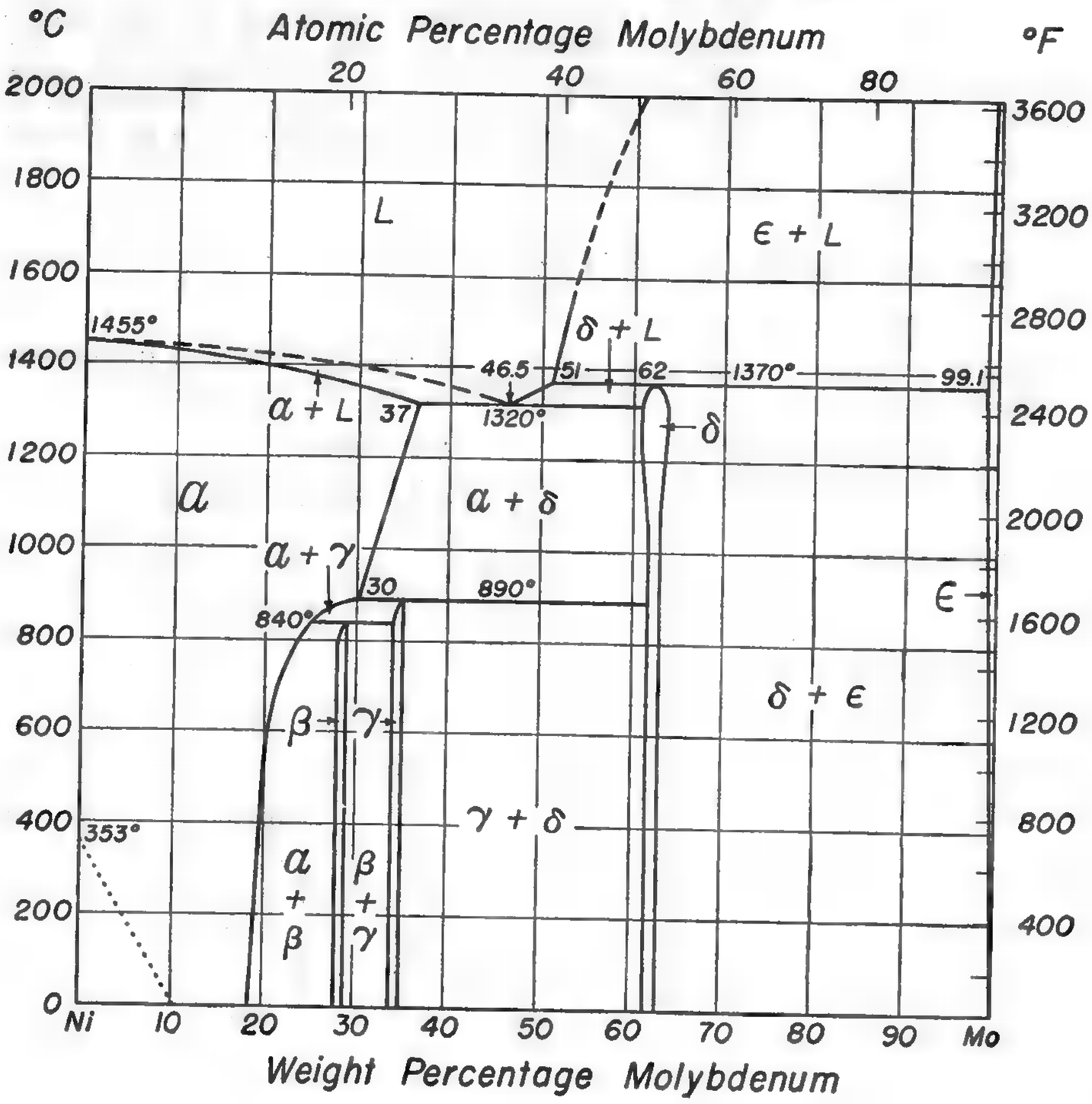


Mo-Ni Molybdenum-Nickel

By R. M. Parke*



The β, γ and δ phases are based on the compositions Ni_4Mo, Ni_3Mo and NiMo respectively.

The γ phase[1] is close-packed hexagonal with an axial ratio (c/a) of about 1.65. The β phase[2] is face-centered tetragonal with axial ratio 0.98.

Ellinger[1] investigated the age hardening of alloys in the range from 21 to 35% Mo. These alloys are in two groups: (1) those that harden by precipitation of β from supersaturated α, and (2) those that harden as a result of decomposition of α into β plus γ. Alloys that contain about 30% Mo do not over-age during 500 hr at 800 C.

Ellinger found that alloys containing about 30% Mo were not in equilibrium after prolonged annealing at 800 C; three phases (β, γ and δ) were present even after 1200 hr at 800 C. After these alloys had been cold worked, annealing at 800 C caused recrystallization and the structure consisted entirely of β plus γ.

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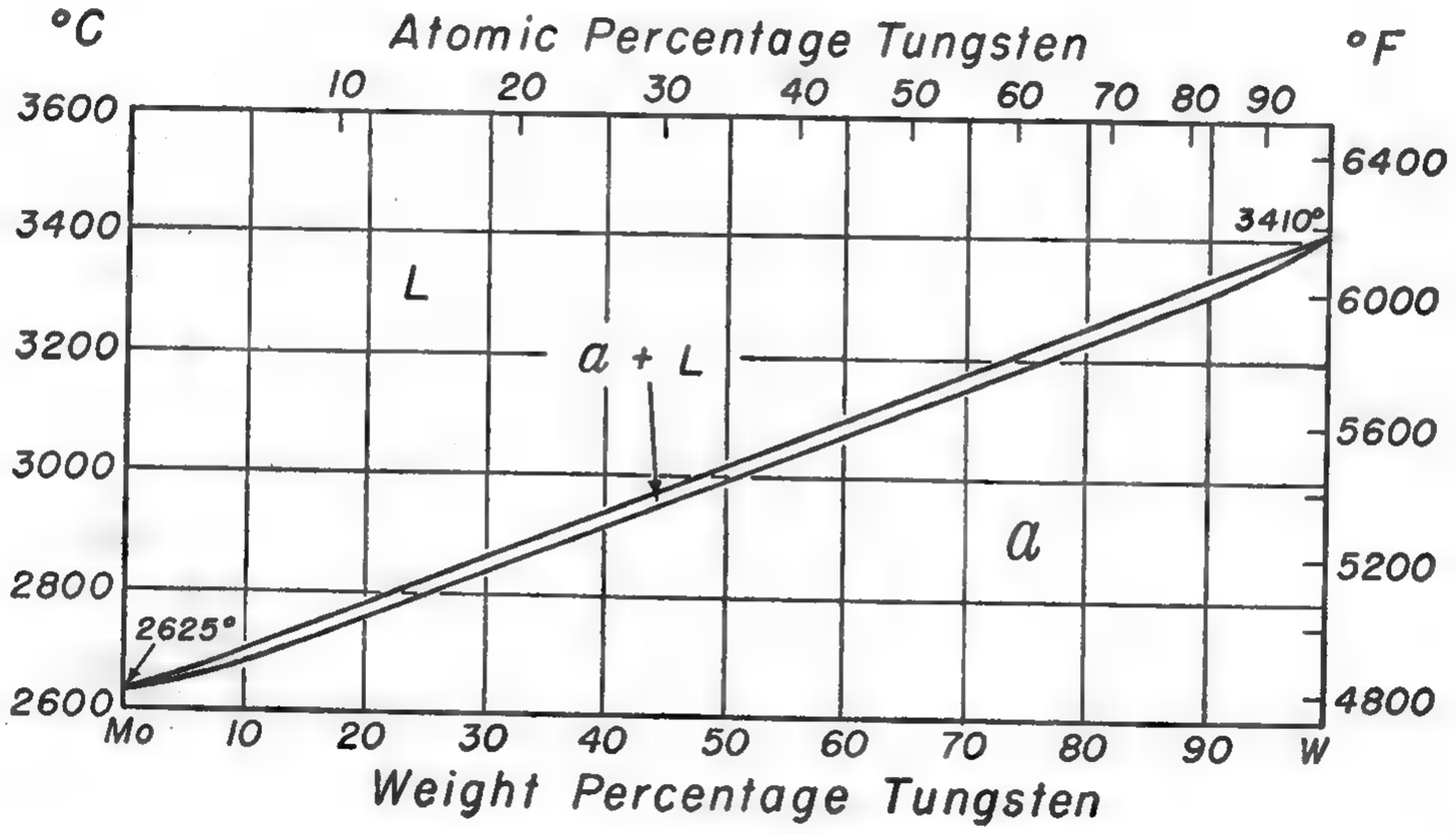
* Kellex Corporation, Silver Spring, Md.

Mo-W Molybdenum-Tungsten

By W. P. Sykes*



The course of the solidus and liquidus curves has been established both by the composition-fusion wattage method[1] and by direct observation of temperatures with an optical pyrometer.[2] Measurements of electrical resistivity,[3] studies of microstructures[1] and X-ray diffraction patterns[4] indicate that this system is an unbroken series of solid solutions.

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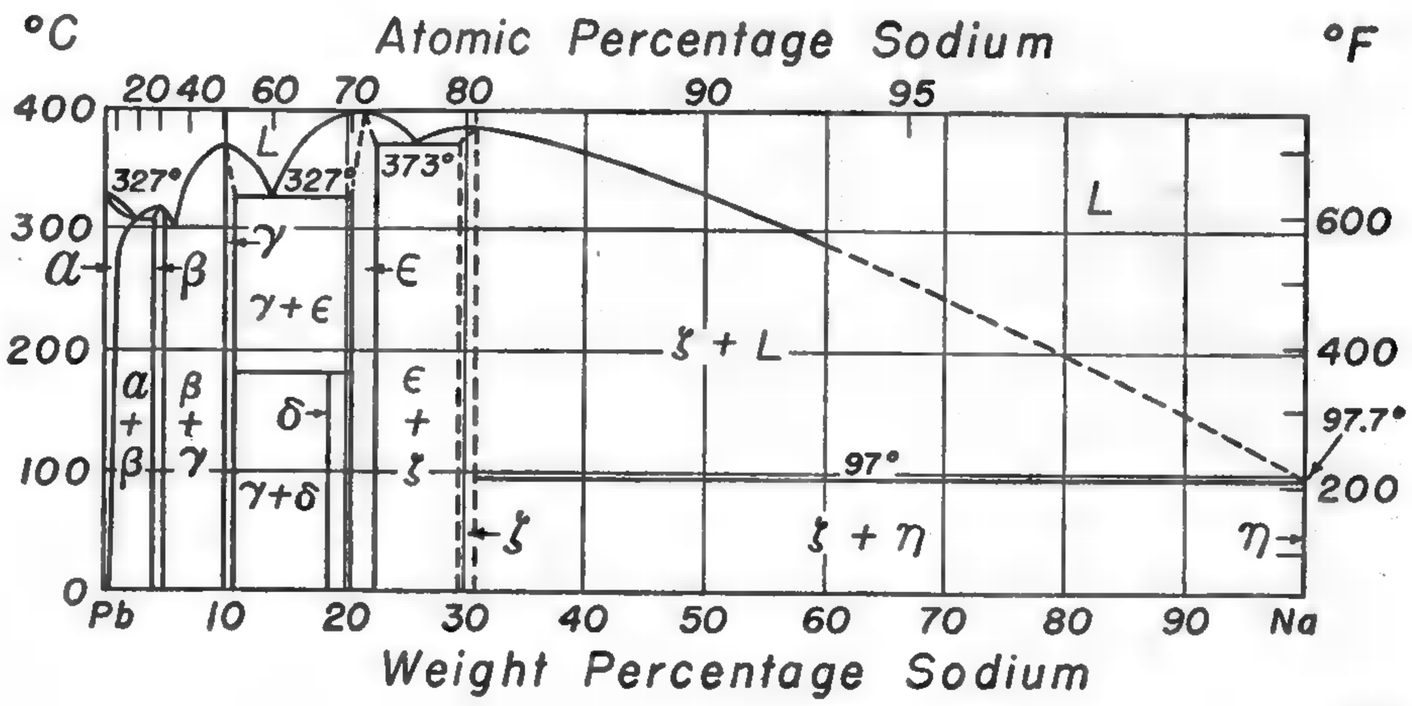
* Lamp Department, General Electric Company, Cleveland

Na-Pb Sodium-Lead

By James A. Collins*



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* E. I. du Pont de Nemours & Company, Inc., Wilmington, Del.

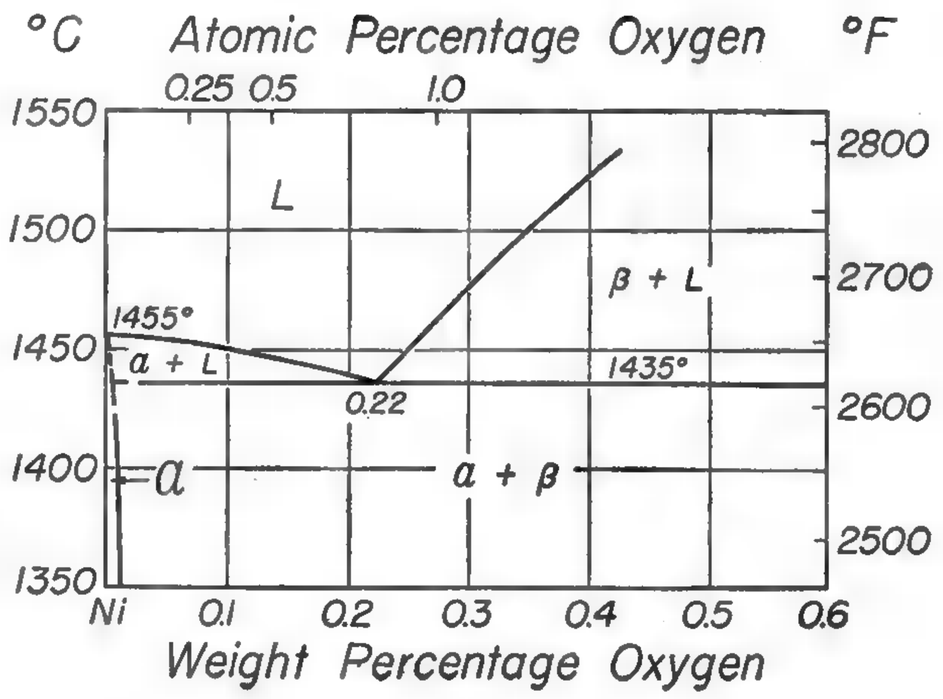
Ni-O Nickel-Oxygen

By E. N. Skinner*

Although the qualitative existence of a bi-liquidal region has been reported,[1] more recent evidence[2] has indicated complete liquid miscibility, at least up to 13.8% O (64.5% NiO). Therefore it seems likely that the liquidus extends in an unbroken flat curve to the melting point of NiO at 1990 C and 21.4% O.

The solubility of oxygen in solid nickel is exceptional; the amount dissolved increases with decreasing temperature:[3]

Temperature, °C	1200	1000	800	600
Solubility, % O	0.012	0.014	0.019	0.020



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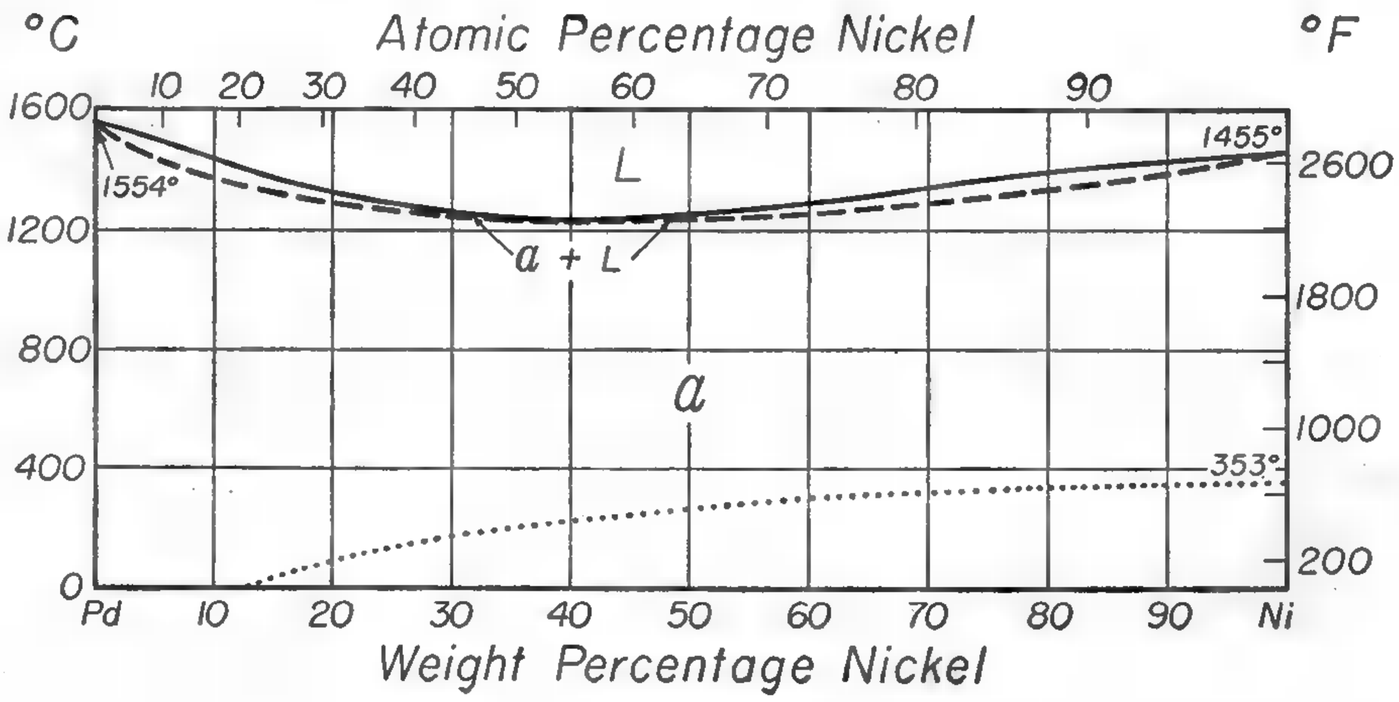
* The International Nickel Company, Inc., New York

Ni-Pd Nickel-Palladium

By E. M. Wise†

Except for the magnetic transition, there are no changes in the solid alloys during heating or cooling.



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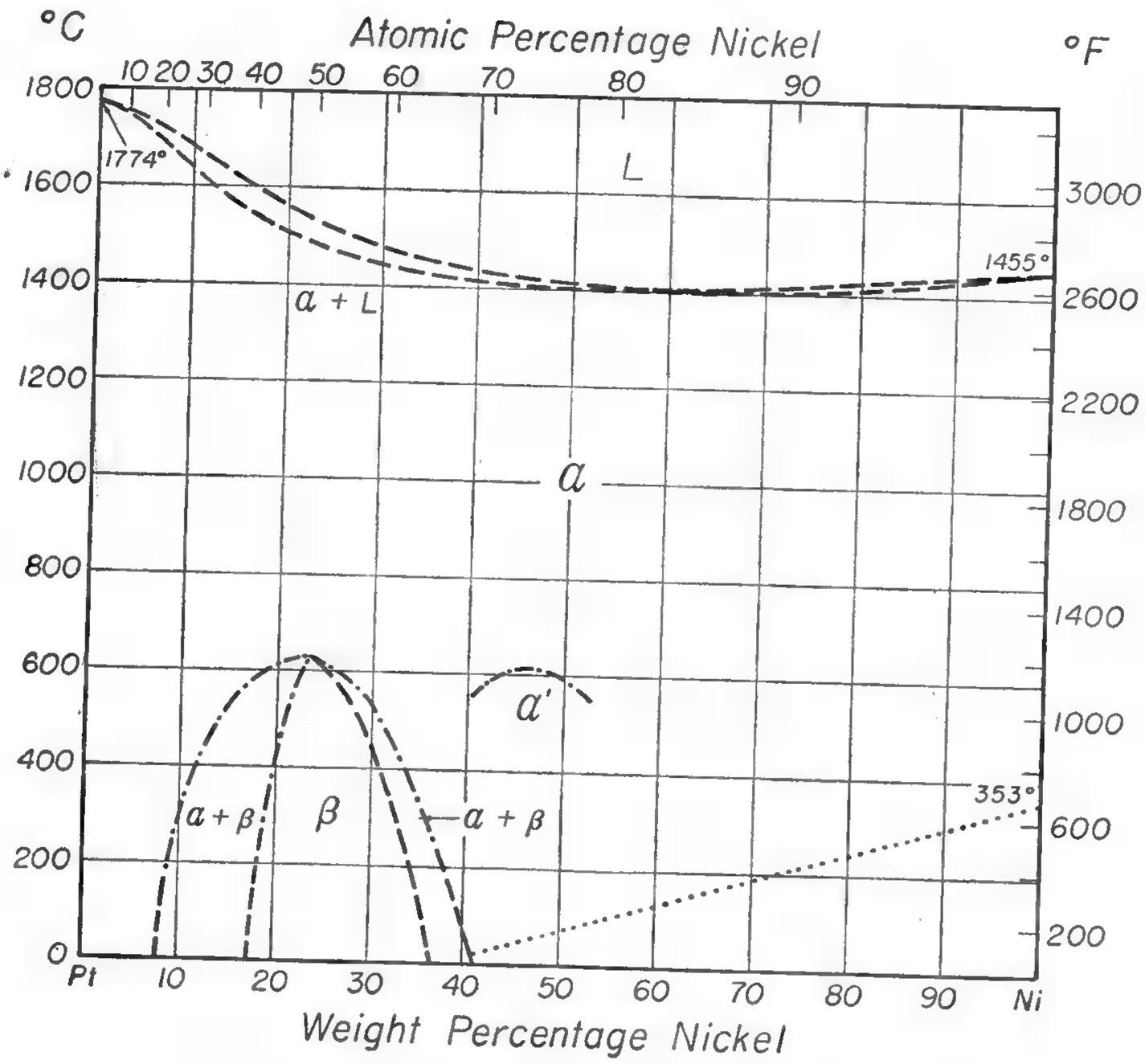
† The International Nickel Company, Inc., New York

Ni-Pt Nickel-Platinum

By E. M. Wise*



Although the variation in lattice parameter with composition is virtually linear for alloys quenched from 900 C, long holding at about 450 C results in the formation of a superstructure in the vicinity of $PtNi_3$, or 47.5% Pt,[2] and also results in a slight decrease in electrical resistivity, Curie temperature and in the saturation magnetization of alloys in this region.

The NiPt phase[3] has an ordered tetragonal structure and is a relatively good electrical conductor; it resembles the AuCu phase.

The Curie curve shown is essentially that of references 3 and 4, modified to conform to a Curie temperature of 353 C for pure nickel.

The alloys of industrial importance contain 5% or less of nickel (*see* page 1125).

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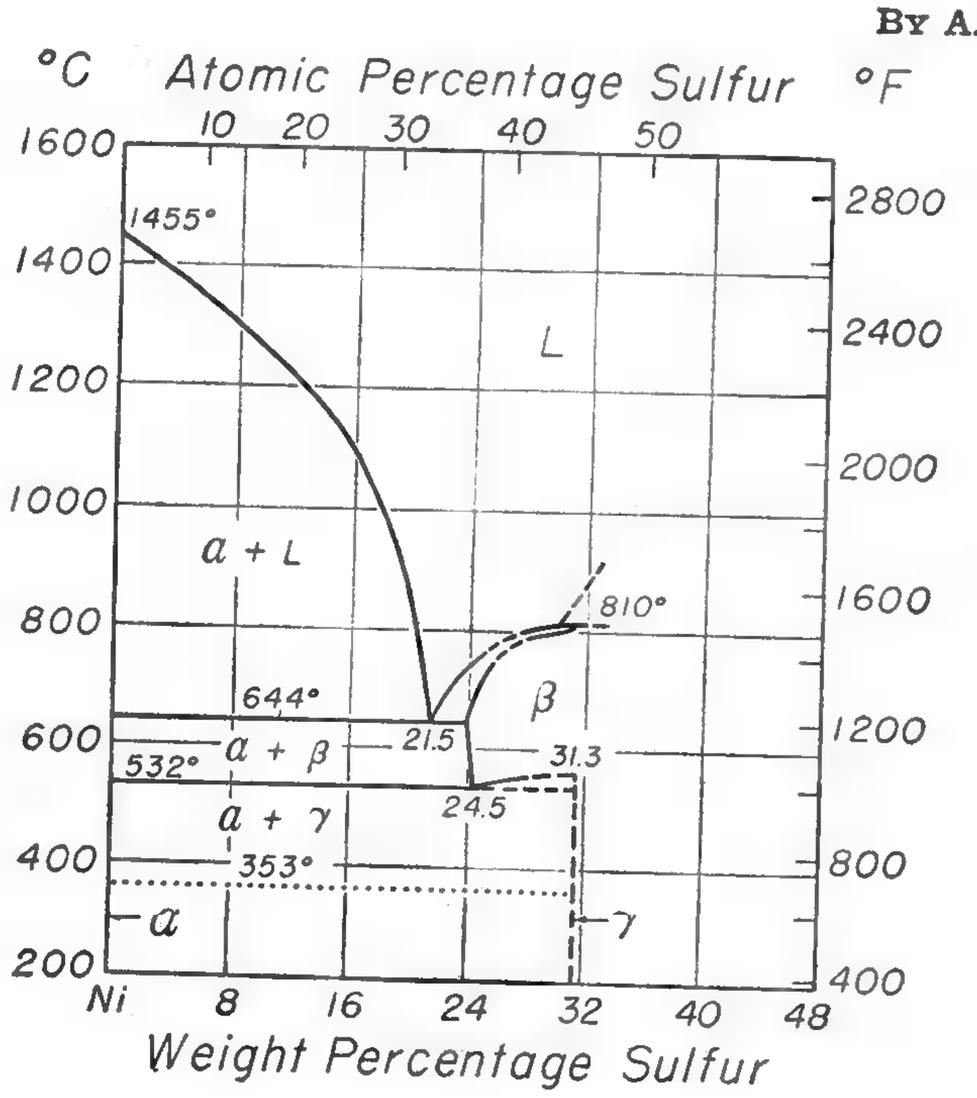
* The International Nickel Company, Inc., New York

Ni-S Nickel-Sulfur

By A. M. Hall*



The solubility of sulfur in solid nickel is probably of the order of 0.005%.[4]

Apparently β decomposes eutectoidally at 532 C into α and a second phase, which may be either γ (Ni_6S_5) or NiS. Conflicting observations[1,2,3] indicate the complexity of the diagram in this region. The experimental data available are insufficient to determine the nature of the system beyond about 28% S. It has been reported that at high sulfur contents, NiS and NiS_2 form a series of solid solutions.[8]

The β phase is cubic with a lattice parameter of 4.08 kX.[6] NiS has the NiAs type of structure, hexagonal, $c = 3.4$ kX, $c/a = 1.55$.[7,8] NiS_2 has the pyrite type of structure, cubic with $a = 5.7$ kX.[7,8]

Methods for the identification of nickel sulfide and other sulfides in nickel have been described.[9] See also Table I and Fig. 3 in the article "Metallography of Nickel and Nickel Alloys", page 1045.

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* Battelle Memorial Institute, Columbus, Ohio

Ni-Si Nickel-Silicon

By E. N. Skinner*

Several investigators[1,2] have proposed the eutectoidal decomposition of the beta phase into alpha and gamma at 1125 C. There is, however, good evidence that Ni_2Si exists at room temperature[3,4] for, although the ordering transformation of β_2 to β_1 at 1040 C takes place slowly with a negligible heat effect, the changes in volume and crystal structure are clearly defined.

Silicon additions depress the Curie temperature of commercially pure nickel (containing iron and cobalt), as follows:[5]

% Silicon	0	1	2	3	4	5	6
deg Cent	362	320	263	195	130	45	−45

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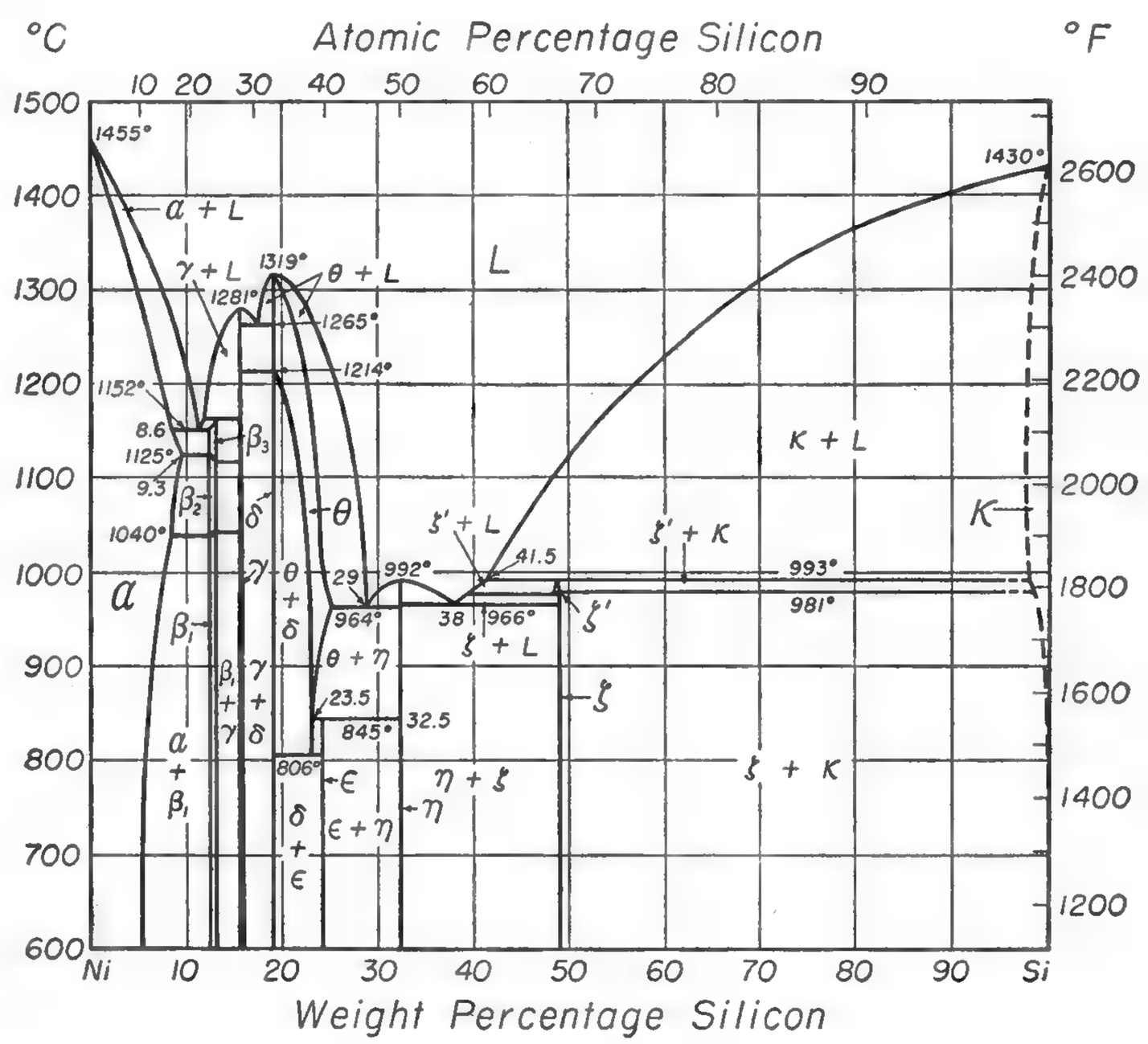

Crystal Structures and Lattice Parameters of Nickel-Silicon Alloys*

Phase	Percentage Silicon	Crystal Structure	Atoms per Unit Cell	Lattice Parameters: a, kX	b, kX	c, kX	c/a
a	Less than 5	Face-centered cubic(a)	4	3.516_9 to 3.510_0			
β_1 (Ni_2Si)	13.0	Face-centered cubic(b)	4	3.496_9			
γ (Ni_5Si_2)	16.0	Orthohexagonal	91	13.28_9	7.672_1	9.751_6	
					$a:b:c = 1.732:1:1.271$		
δ (Ni_2Si)	19.3	Orthorhombic	48	7.39_2	9.90_2	7.03_6	
					$a:b:c = 0.6465:1:0.7106$		
θ (Ni_2Si)	23.0	Hexagonal(c)	6	3.7970		3.892_8	1.290_7
ϵ (Ni_3Si_2)	24.3	Orthorhombic	45	6.605_4	7.627_2	9.574_0	
η (NiSi)	32.5	Tetragonal	40	7.653_8		8.451_4	1.104_4
ζ ($NiSi_2$)	49.0	Rhombohedral	54		8.881, $\alpha = 90° 23.6'$		
ζ' ($NiSi_2$)	49.0	The lines of Si and ζ appeared strongly in the specimen quenched in ice water from 1025 C.					

(a) Lattice constant decreases linearly. (b) Superstructure of the $AuCu_3$ type, Si atoms at corners. (c) The distribution of lines is the same at low and high temperatures.

* The International Nickel Company, Inc., New York

Ni-Sn Nickel-Tin

By H. P. Nielsen* and Bruce W. Gonser*

The transformation from β to β' is concluded to be a change from a disordered to an ordered structure.[4] The nature of the transformation at 600 C is not clear; a thermal effect and a change in crystal structure have been reported.[4]

There is some uncertainty concerning the existence of a eutectic near the melting point of tin. One report gives a eutectic at 0.18% Ni at substantially the melting point of tin;[8] another gives 0.13% Ni at 0.8 °C below the melting point of tin.[9] The solubility of nickel in solid tin is believed to be less than 0.005%.[8]

Between 2.0 and 19.8% Sn the lattice parameter of a changes from 3.5237 to 3.6084 kX.[7]

* University of Southern California, Los Angeles
* Battelle Memorial Institute, Columbus, Ohio

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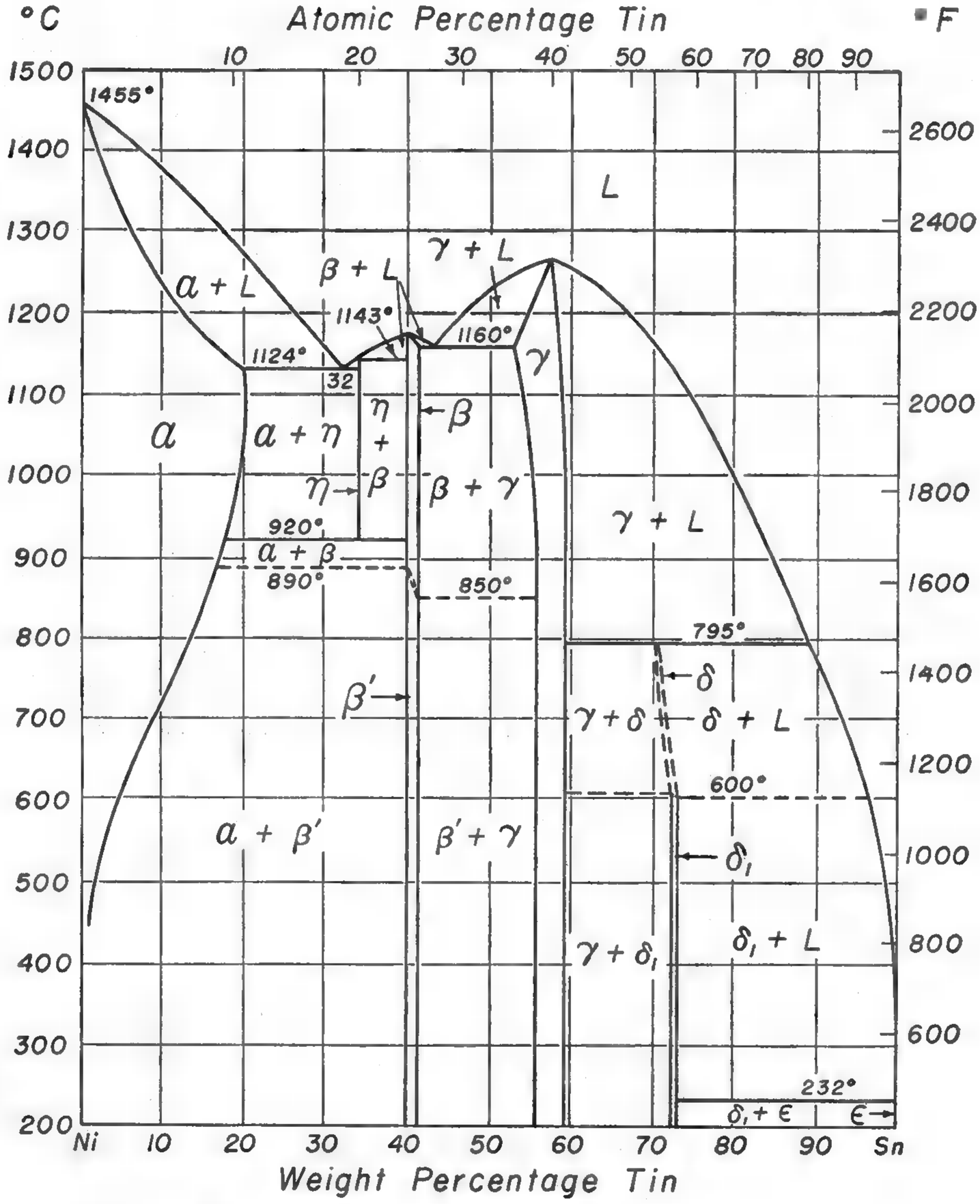

Crystal Structures and Lattice Parameters of Nickel-Tin Alloys

Phase	Crystal Structure	Atoms per Unit Cell	Lattice Parameters			Reference
			a, kX	c, kX	c/a	
η (Ni_4Sn)	Tetragonal	2	5.111	4.881	0.955	3
β' (Ni_3Sn)	Close-packed hexagonal with superlattice	..	5.282	....	0.801	4
δ_1 (Ni_3Sn_2)	Hexagonal, modified NiAs type	1	4.092	5.186	1.267	3

Ni-Ta Nickel-Tantalum

By R. W. Yancey* and W. H. Lenz*

A polymorphic transformation in the β phase (Ni_3Ta) has been reported at about 1350 C.[3]

According to unpublished results of W. H. Lenz and W. M. Shafer,* between 95 and 100% Ta and below 1600 C the alloys consist of the tantalum-rich solid solution containing less than 0.5% Ni, and an intermediate phase—probably a compound.

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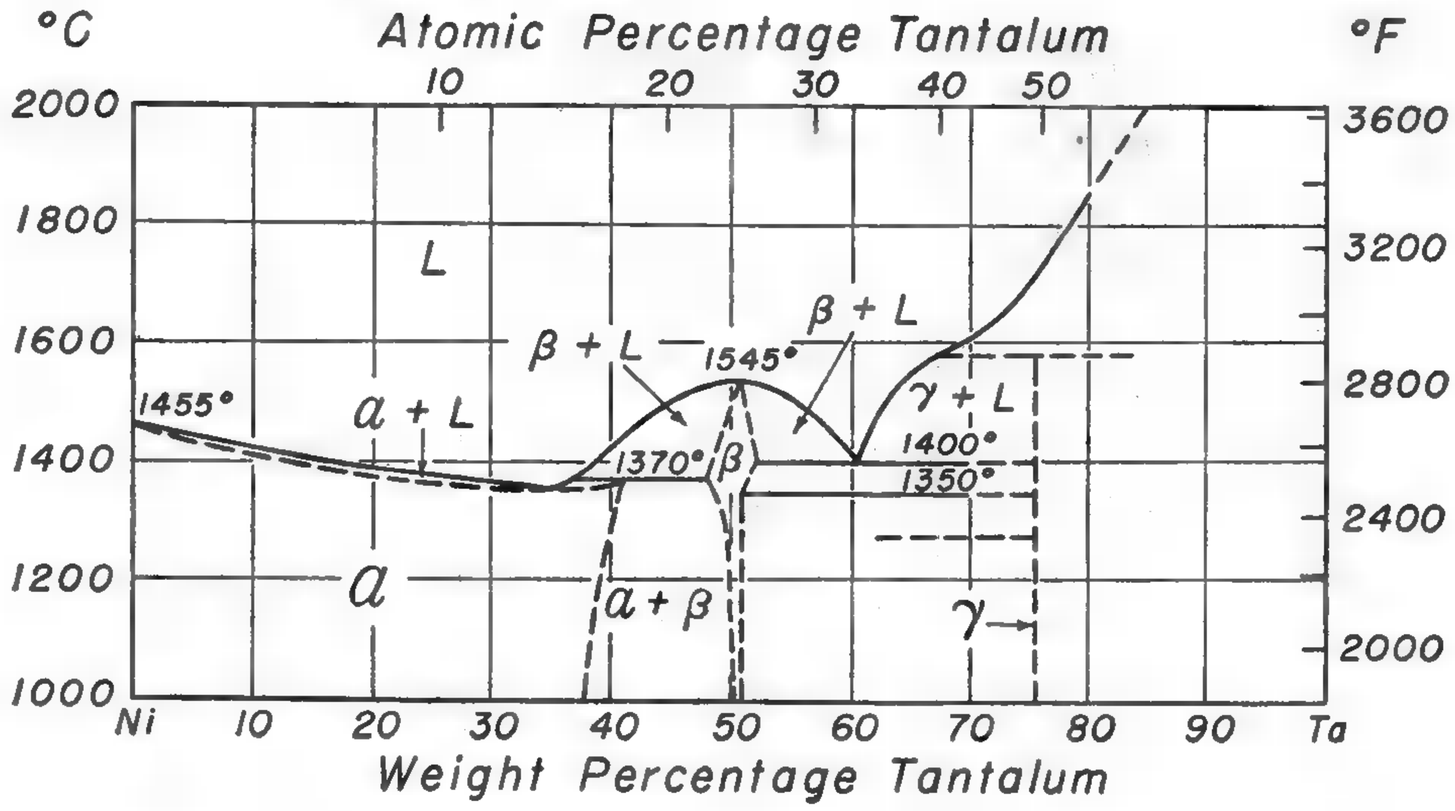
* Fansteel Metallurgical Corporation, North Chicago, Ill.



Ni-Ti Nickel-Titanium

By E. N. Skinner*

The peritectic formation of γ (NiTi) has been established,[1] but the temperature and composition limits have not.

A titanium-rich phase, δ ($NiTi_2$), exists at 62% Ti. This phase, not shown in the diagram, melts without decomposition and forms a eutectic with the titanium solid solution.

With 8% Ti dissolved in high-purity nickel, the Curie temperature is lowered to about 25 C.

The β phase (Ni_3Ti) is hexagonal with $a = 5.096$ kX and $c/a = 1.630$;[3] γ has the CsCl structure (body-centered cubic);[4] δ is face-centered cubic with 96 atoms per unit cell.

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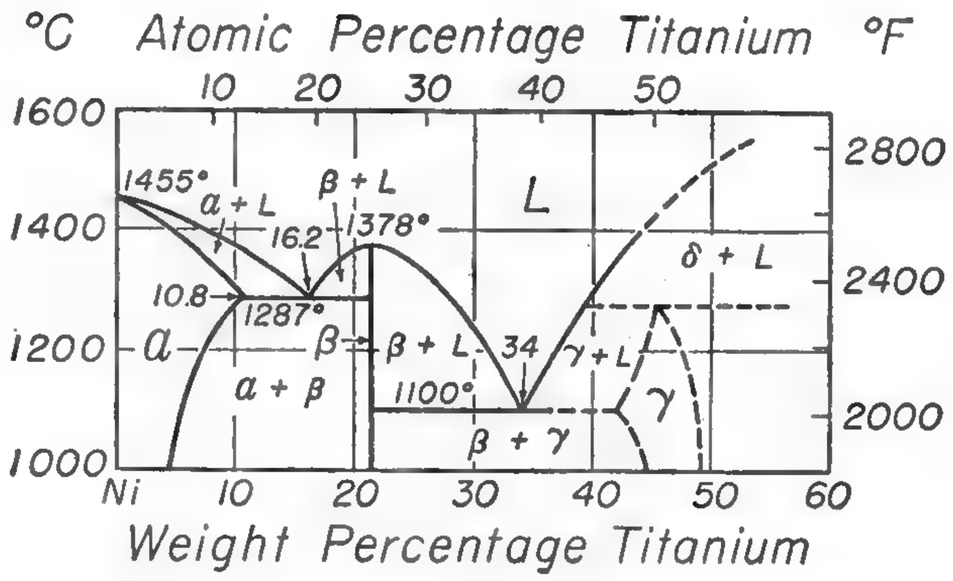


Ni-W Nickel-Tungsten

By W. P. Sykes†

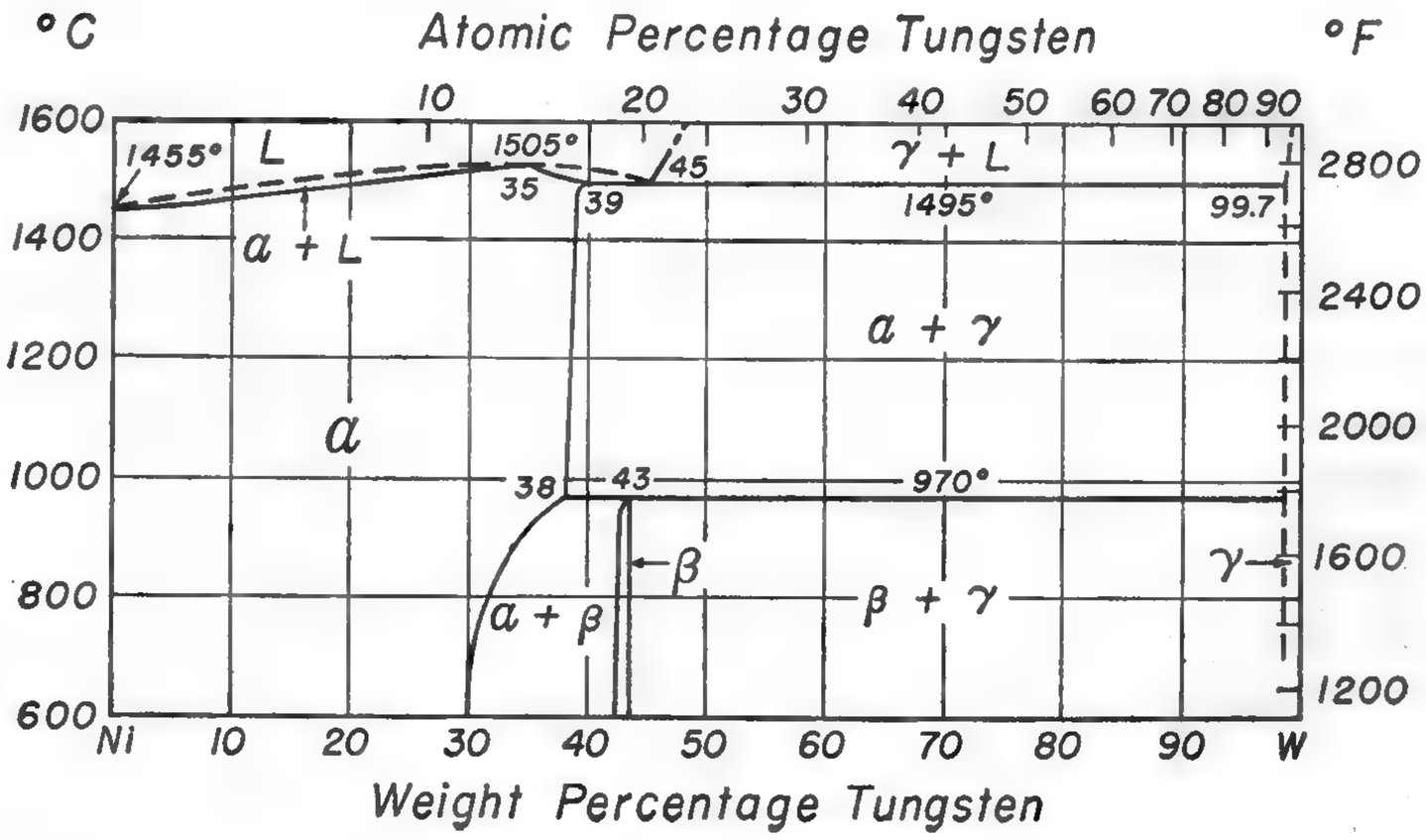
The one intermediate phase, β, forms very slowly at temperatures just below 970 C and crystallizes with a face-centered cubic structure, the dimensions of which are nearly identical with those of the saturated alpha solid solution.[1]

Alloys that contain from 32 to 45% W can be precipitation hardened. A hardness of 490 Brinell is developed in an alloy containing 45% W, aged at 900 C for 100 hours, after solution treatment at 1200 C. Overaging occurs very slowly at 900 C.

Reference

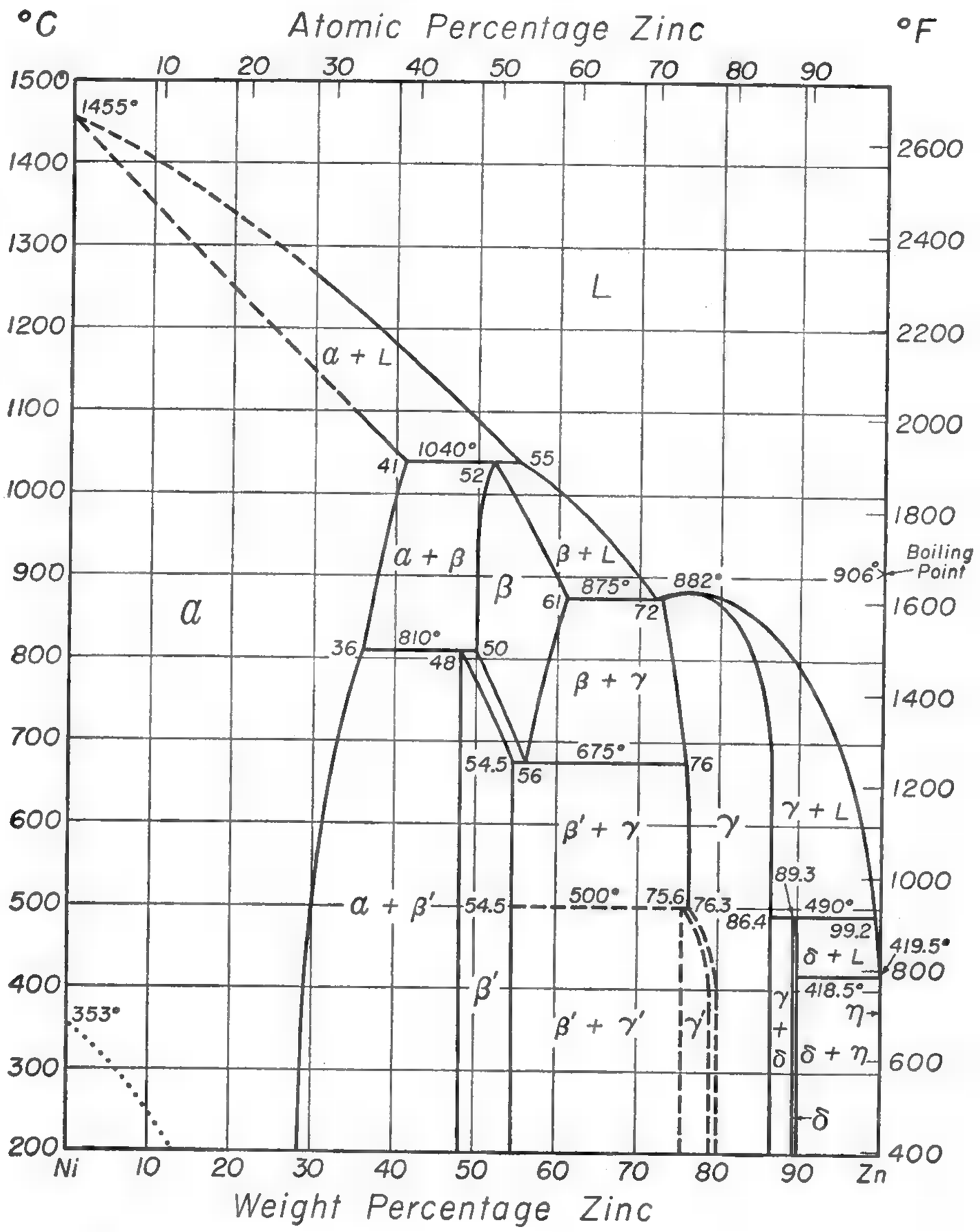
1 F. H. Ellinger and W. P. Sykes, Trans ASM, 28, 619 (1940)

† Lamp Department, General Electric Company, Cleveland



Ni-Zn Nickel-Zinc

By C. E. Lacy*



The nickel contents of the phases at the eutectic temperature, 418.5 C, are: δ, 10.0%; liquid, 0.25%; η, 0.04%.

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* Research Laboratory, General Electric Company, Richland, Wash.

Crystal Structures and Lattice Parameters of Nickel-Zinc Alloys

Phase	Percentage Zinc	Crystal Structure	Lattice Parameters	
			a, kX	c/a
α	0	Face-centered cubic	3.5168	.....
a	28	Face-centered cubic	3.576	.....
β	..	Body-centered cubic	2.908	.....
β'	52	Tetragonal	2.7460	1.1559
γ	84	Complex cubic	8.9077	.....
δ	89.5	Hexagonal	8.855	1.649
η	100	Close-packed hexagonal	2.6597	1.8561

P-Sn Phosphorus-Tin

By H. P. Nielsen* and R. I. Jaffee*

Vivian[1] found that alloys containing more than 8.5% P could not be made in an open crucible, but had to be made in sealed glass tubes. Consequently, not only were they in contact with phosphorus vapor, but they were subject to a varying and undetermined pressure. A true equilibrium diagram at atmospheric pressure would probably show a gas phase in equilibrium with either solid or liquid throughout the range where the diagram is drawn with dashed lines.

* University of Southern California, Los Angeles
* Battelle Memorial Institute, Columbus, Ohio

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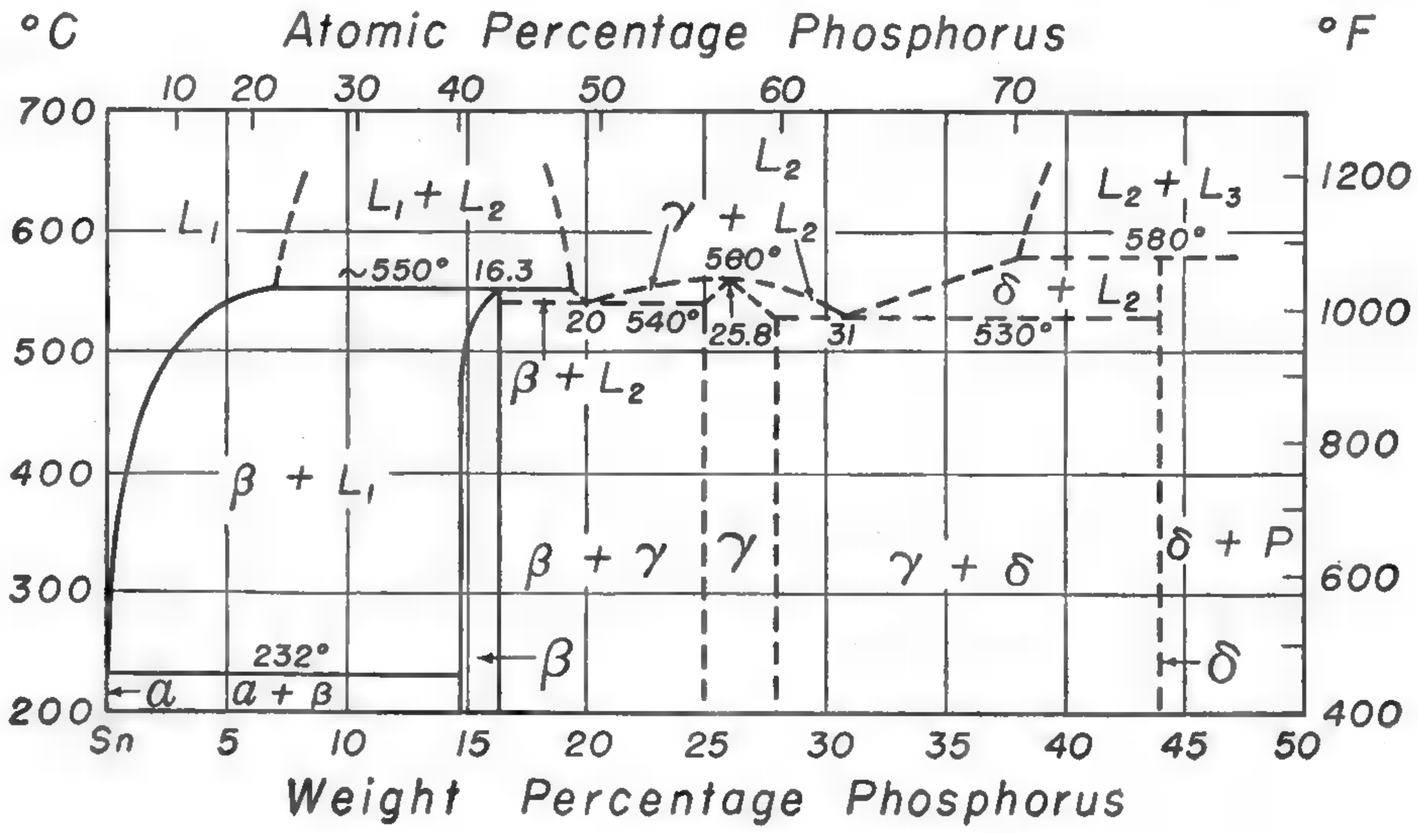
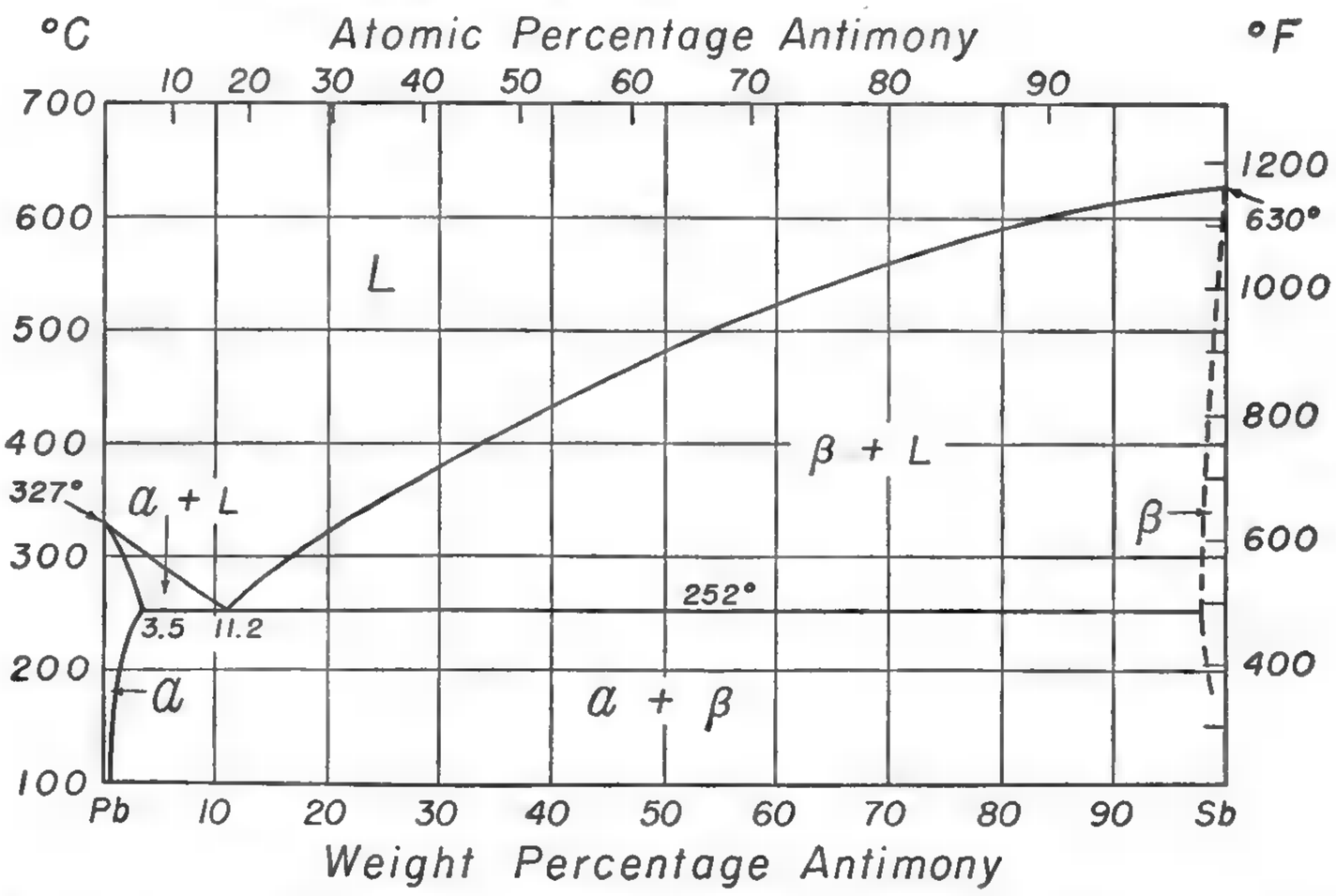


Pb-Sb Lead-Antimony

By E. E. Schumacher† and G. M. Bouton†



The lead-rich end of the system has been reviewed critically in recent years. Alloys containing about 1% Sb are very slow in reaching equilibrium conditions at ordinary, atmospheric temperatures. The properties and structure may change for many years. During solidification the alloys containing eutectic have strong supercooling tendencies. This has been responsible for reports of lower eutectic temperature than the one now accepted (252 C).

† Bell Telephone Laboratories, Murray Hill, N.J.

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Pb-Sn Lead-Tin

By G. O. Hiers*

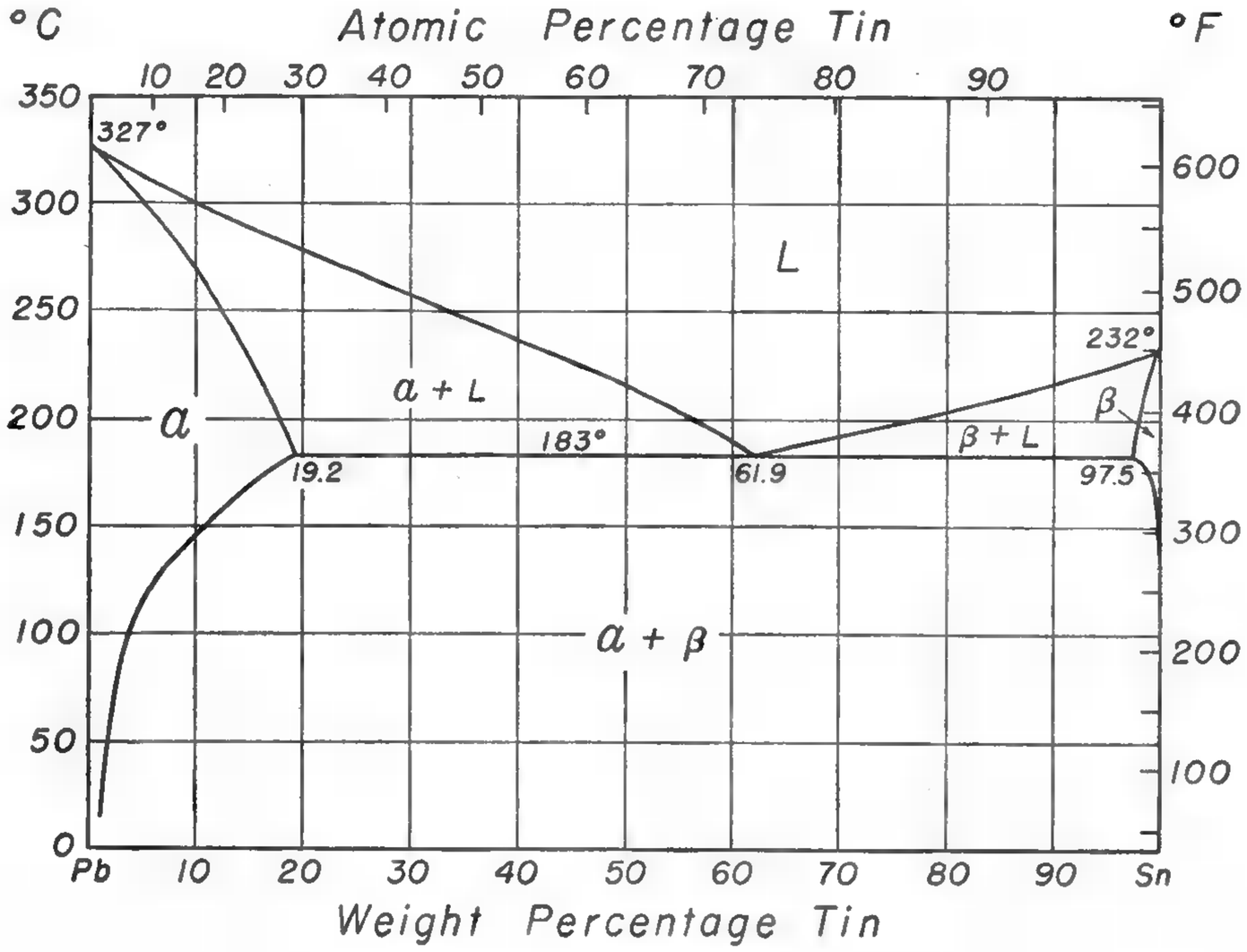
The diagram shown is taken without change from that given by Raynor.[14]

Alloys containing 18 to 62% Sn exhibit a slight exothermic point in the vicinity of 145 to 155 C in cooling curves determined with great sensitivity. This is attributed to accumulated supersaturation and a sudden precipitation consistent with the atomic mobility of the alloy.

Eutectiferous alloys in general exhibit instability in solid solution zones in finished products. From an engineering viewpoint detectable eutectic in actual soldered joints, where solders contain 10 to 19.2% Sn, justifies the consideration of 183 C as the solidus or zero mechanical strength point.

By X-ray methods, a solid solution of 0 to 3.6% Sn in Pb has been shown, corresponding to the face-centered cubic structure of lead and varying in size from 4.942 to 4.931 kX.

The solid solubility of tin in lead at 50 C is 2%.



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* Metallurgist, National Lead Company, Research Laboratories, Brooklyn

Pb-Te Lead-Tellurium

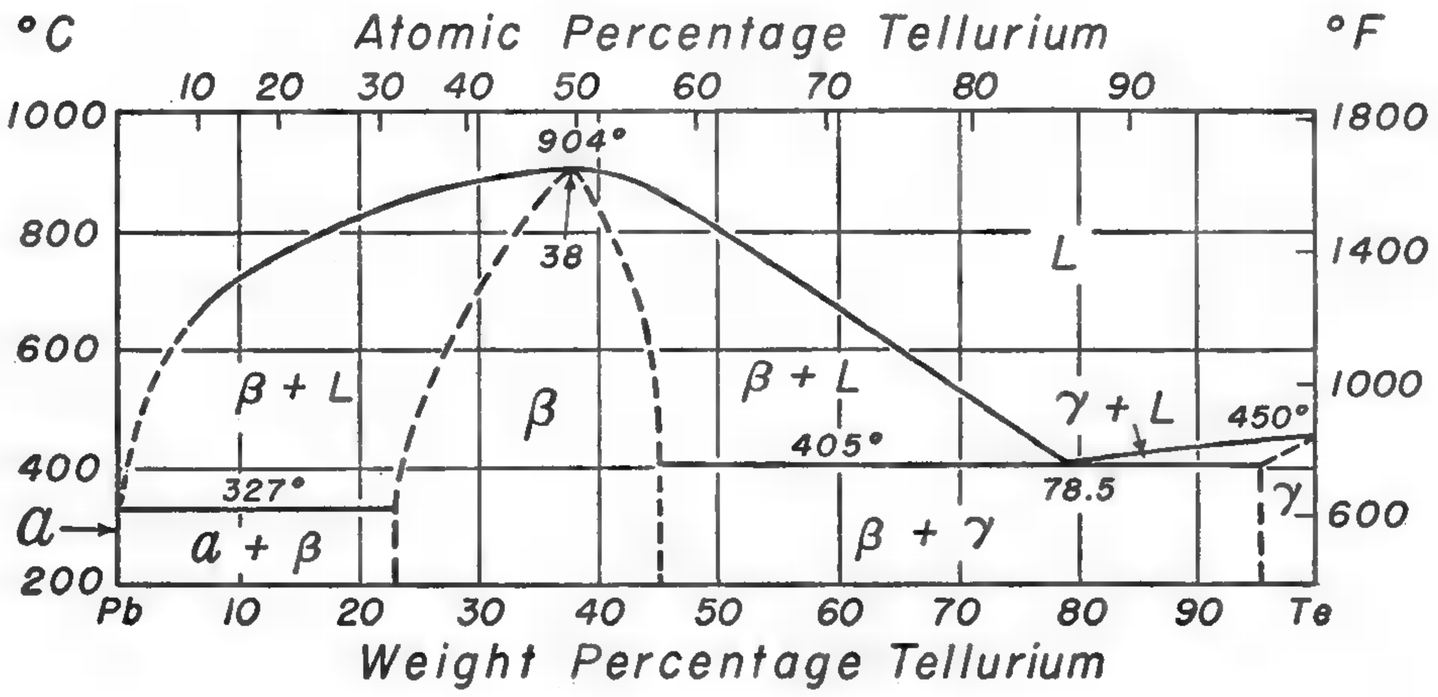
By G. O. Hiers*

The general nature of the system has been well established. Further detailed data and X-ray crystallographic data are needed.

Because of the commercial importance of a lead alloy containing tellurium in an amount less than 0.1%, the following points were determined by means of both mechanical strength and microstructure of pertinent alloys: eutectic between the α and β phases, 0.025% Te; eutectic temperature, 0.7 C below the melting point of lead; solubility of tellurium in solid lead at 300 C, 0.004% Te.

The reference article by Greenwood and Worner includes micrographs of cast alloys containing 0.02, 0.03 and 0.05% Te.

For a summary of the properties of lead-tellurium alloys, the reader may refer to the book "Blei und Bleilegierungen", by Wilhelm Hofmann, J. Springer, Berlin, 1941, pages 52 to 55. (Republished by J. W. Edwards, Ann Arbor, Mich., 1944)



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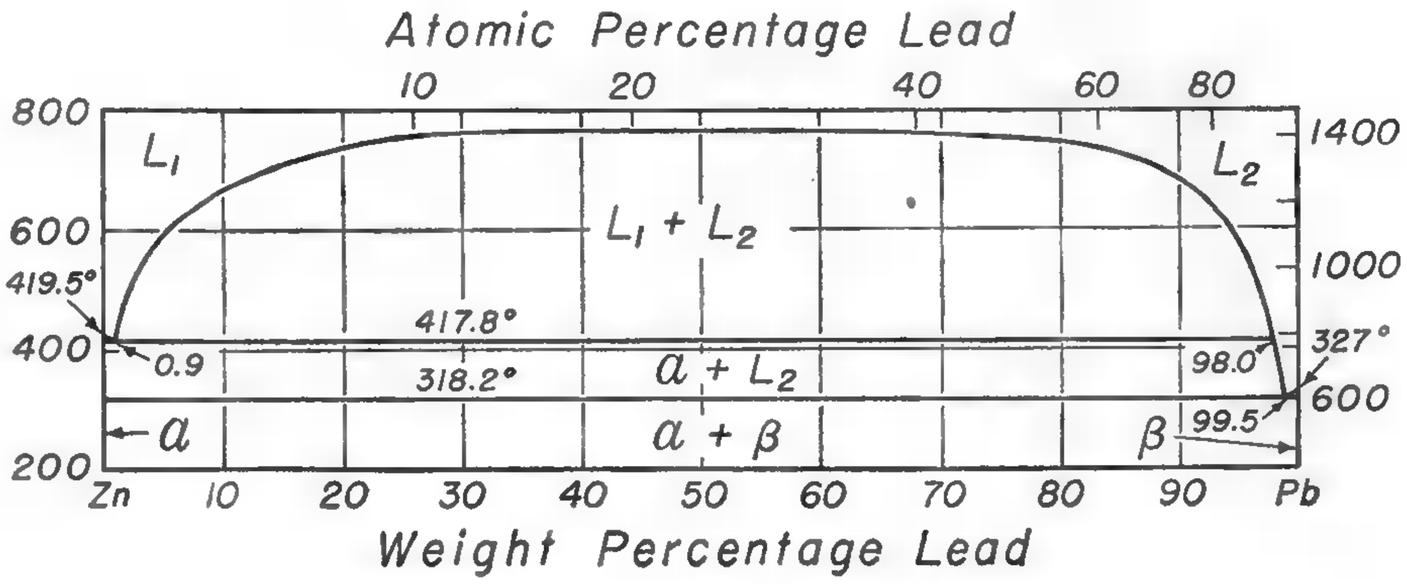
* Metallurgist, National Lead Company, Research Laboratories, Brooklyn

Pb-Zn Lead-Zinc

By E. A. Anderson*

Solid lead dissolves about 0.05% Zn at 318 C. Rodda[1] states that the solid solubility of lead in zinc definitely is less than 0.0019% and may be less than 0.0002%.

Waring and Springer* extrapolated the data of Waring, Anderson, Springer, and Wilcox[2] to the monotectic temperature by plotting $1/T$ against the logarithm of the mol fraction of lead in the liquid phase. The results alter slightly the interpolated values originally published by Waring and associates. The monotectic concentration, 0.9% Pb, shown in the diagram is that selected by Waring and Springer.*



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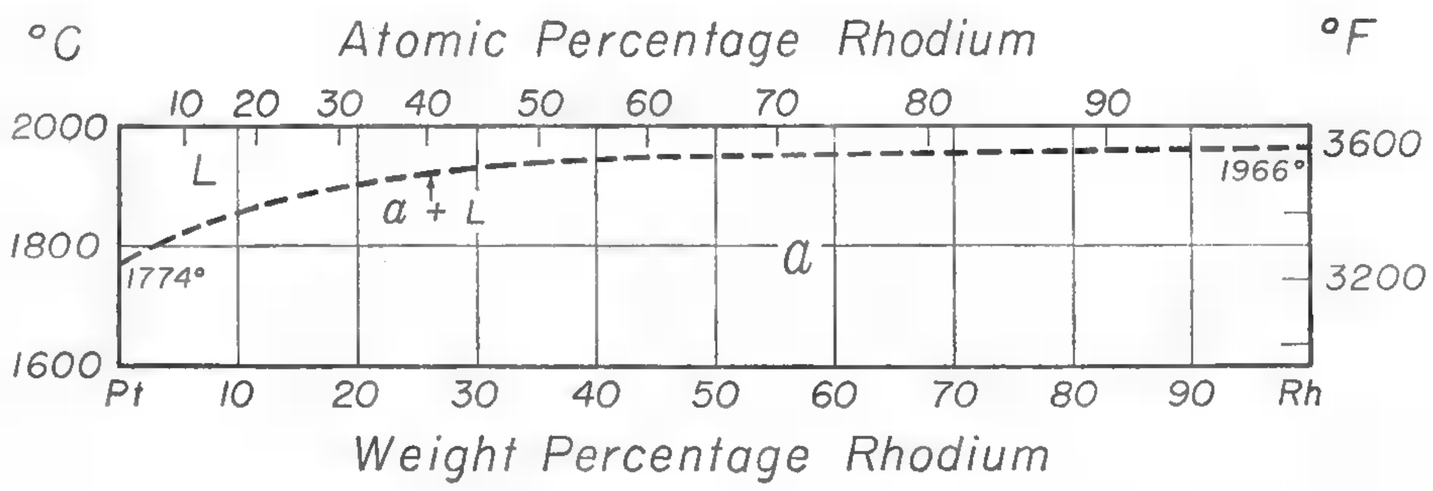
* The New Jersey Zinc Company (of Pa.), Palmerton, Pa.

* Unpublished data, The New Jersey Zinc Company (of Pa.)

Pt-Rh Platinum-Rhodium

By E. M. Wise*

The solidus is so close to the liquidus that it can scarcely be distinguished.



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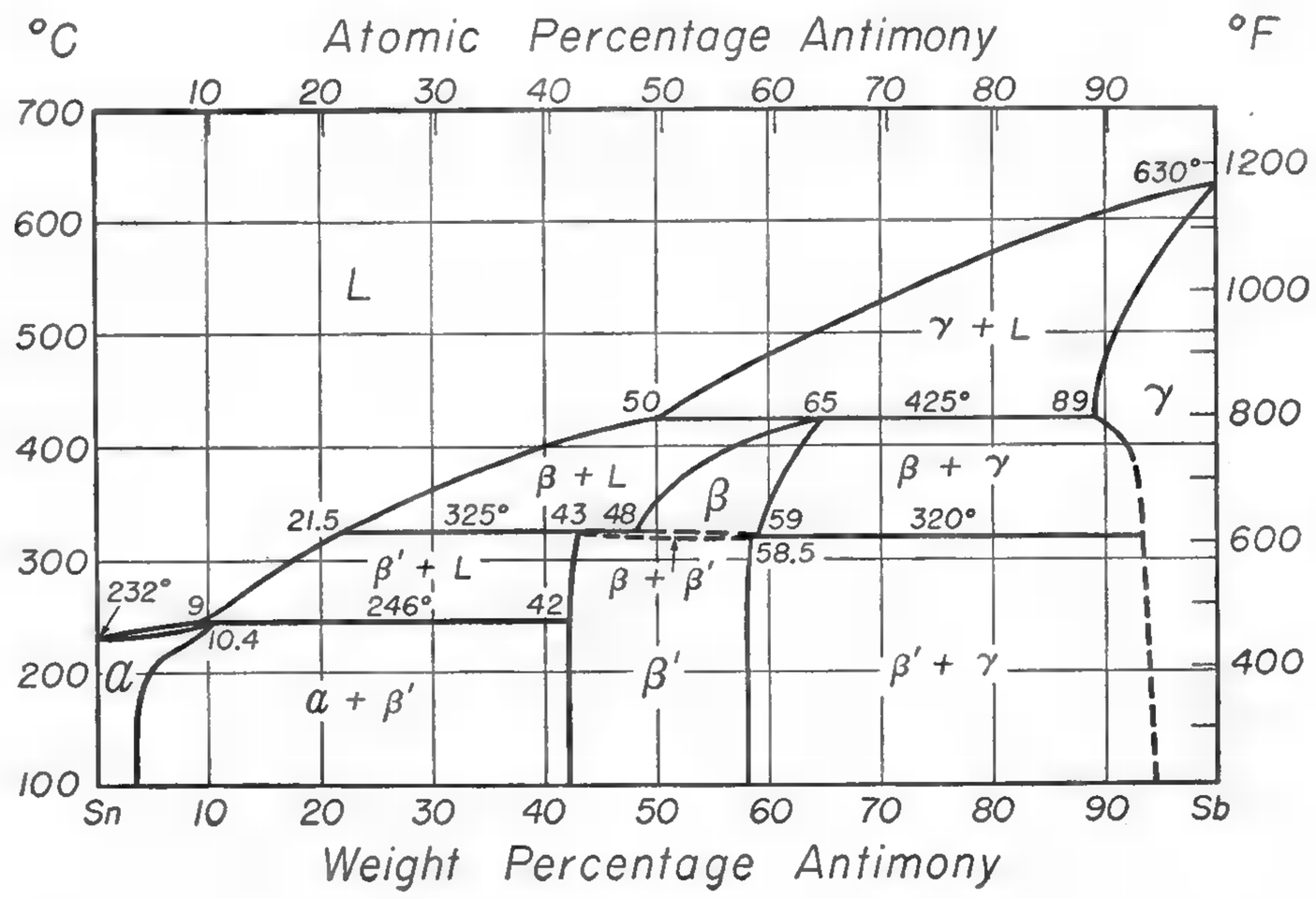
* The International Nickel Company, Inc., New York

Sb-Sn Antimony-Tin

By R. I. Jaffee† and B. W. Gonser†

Iwasé, Aoki, and Osawa[2] could find no evidence of the two-phase $\beta + \beta'$ region, nor could they find X-ray evidence for the existence of β in quenched specimens.

Williams,[3] using alloys annealed for 16 hours at 360 C, found a range of homogeneity for SbSn of only 47.5 to 50% Sb. For alloys cast under normal conditions, the transformation at 325 C may probably be ignored and the range of homogeneity of SbSn may be taken as quite small.



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† Battelle Memorial Institute, Columbus, Ohio

Sn-Te Tin-Tellurium

By John L. Everhart*

Hansen's diagram[1] has been modified by a change in the melting point of tellurium to 450 C.[2]

Hanson and Pell-Walpole[3] report the solubility of tellurium in solid tin as 0.12% at 230 C, decreasing to 0.07% at 20 C. Jenckel and Roth[4] state that the solubility is about 0.025% at 200 C.

The diagram for the high-tin alloys with 0 to 3% Te is from unpublished results of W. T. Pell-Walpole. No data on the solubility of tin in solid tellurium have been found.

The β phase (SnTe) is cubic (NaCl type) with a lattice parameter of 6.28 kX.[5]

* Battelle Memorial Institute, Columbus, Ohio

References

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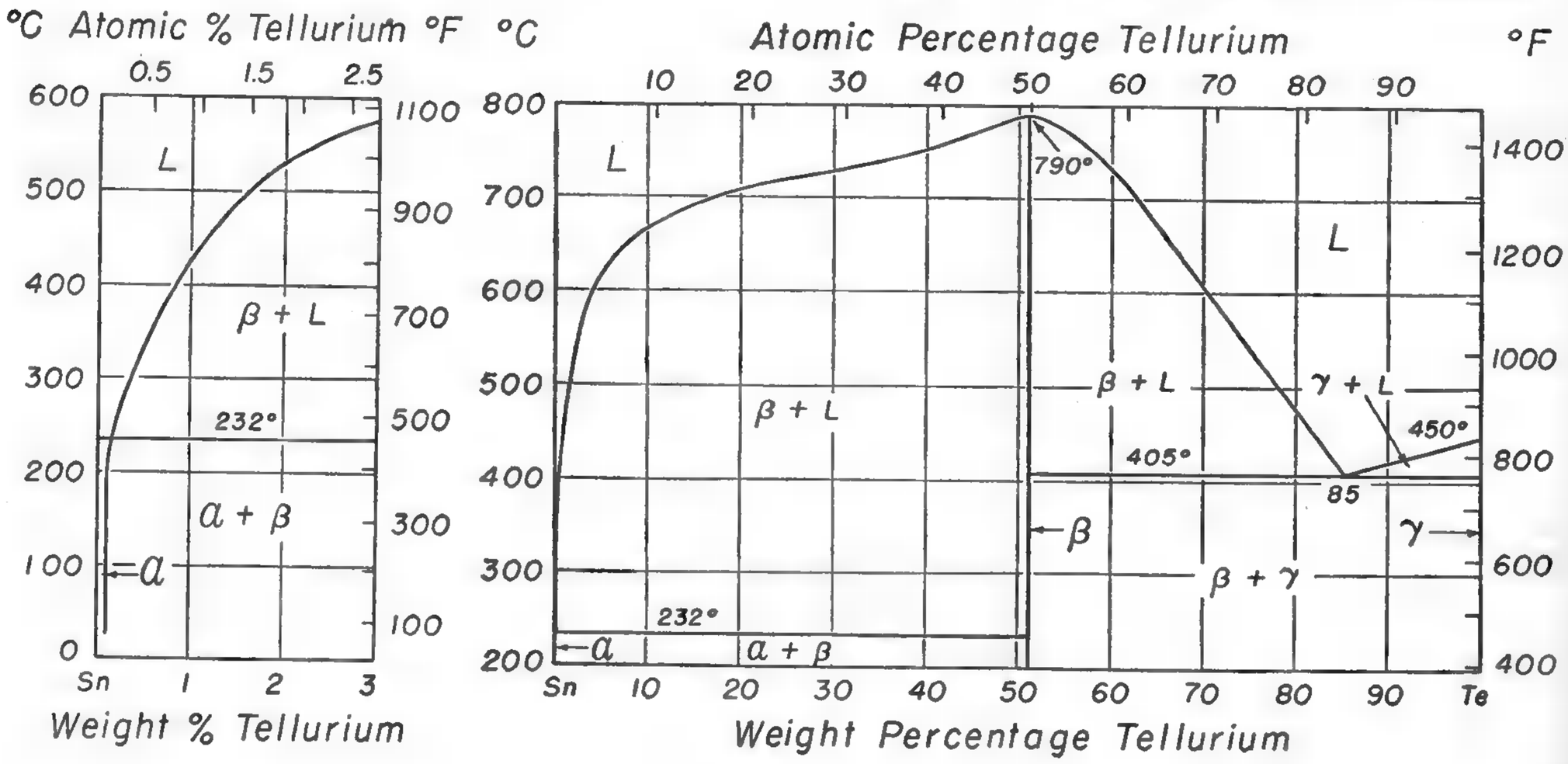
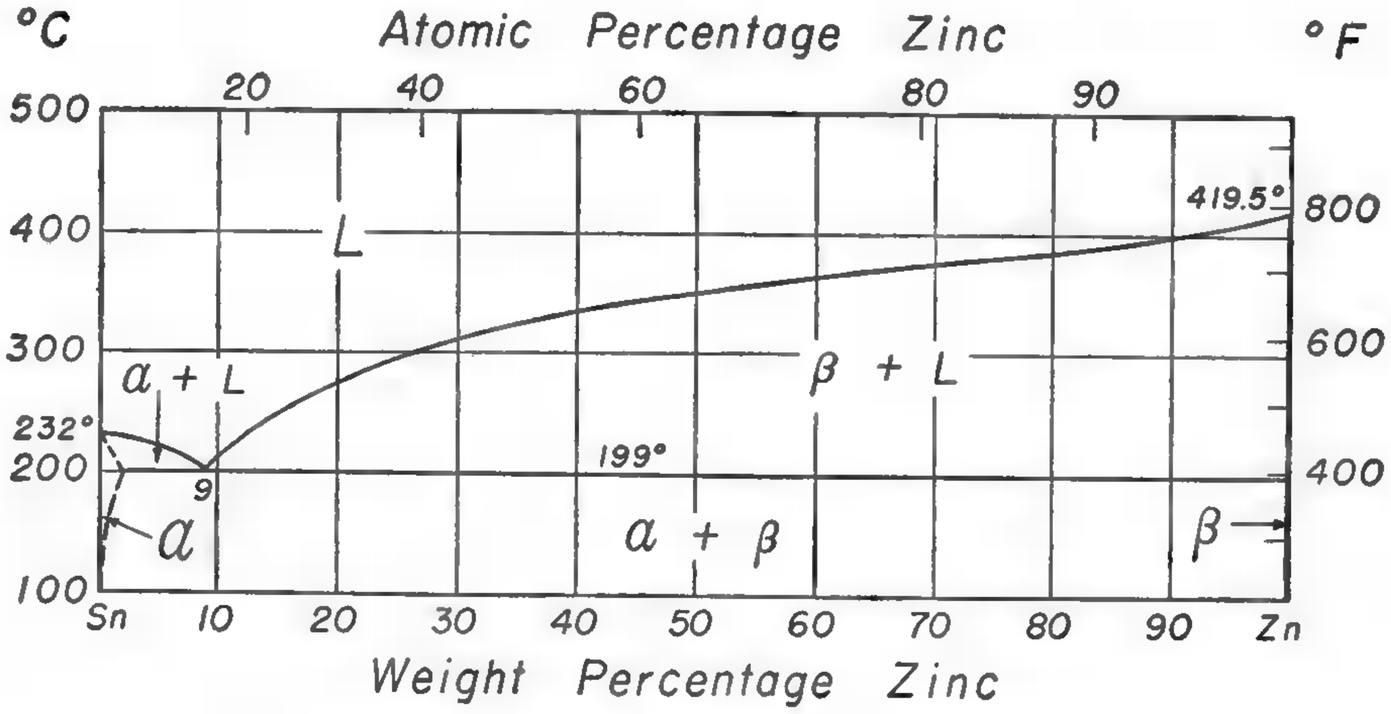


Sn-Zn Tin-Zinc

By E. A. Anderson*



Peirce[1] places the solubility of tin in solid zinc below 0.05%. It is probable from known effects of tin on the hot shortness of zinc that the actual solubility is much less than 0.05%.

The solid solubility of zinc in tin has not been established clearly. Saldau[2] places the limit between 0.5 and 1.5% at 185 C. There is reason to doubt this work because of Saldau's observation of polymorphic changes in his tin. Blondel and Laffitte[3] claim a solid solubility of 2.5%.

* Research Division, Technical Department, The New Jersey Zinc Company (of Pa.), Palmerton, Pa.

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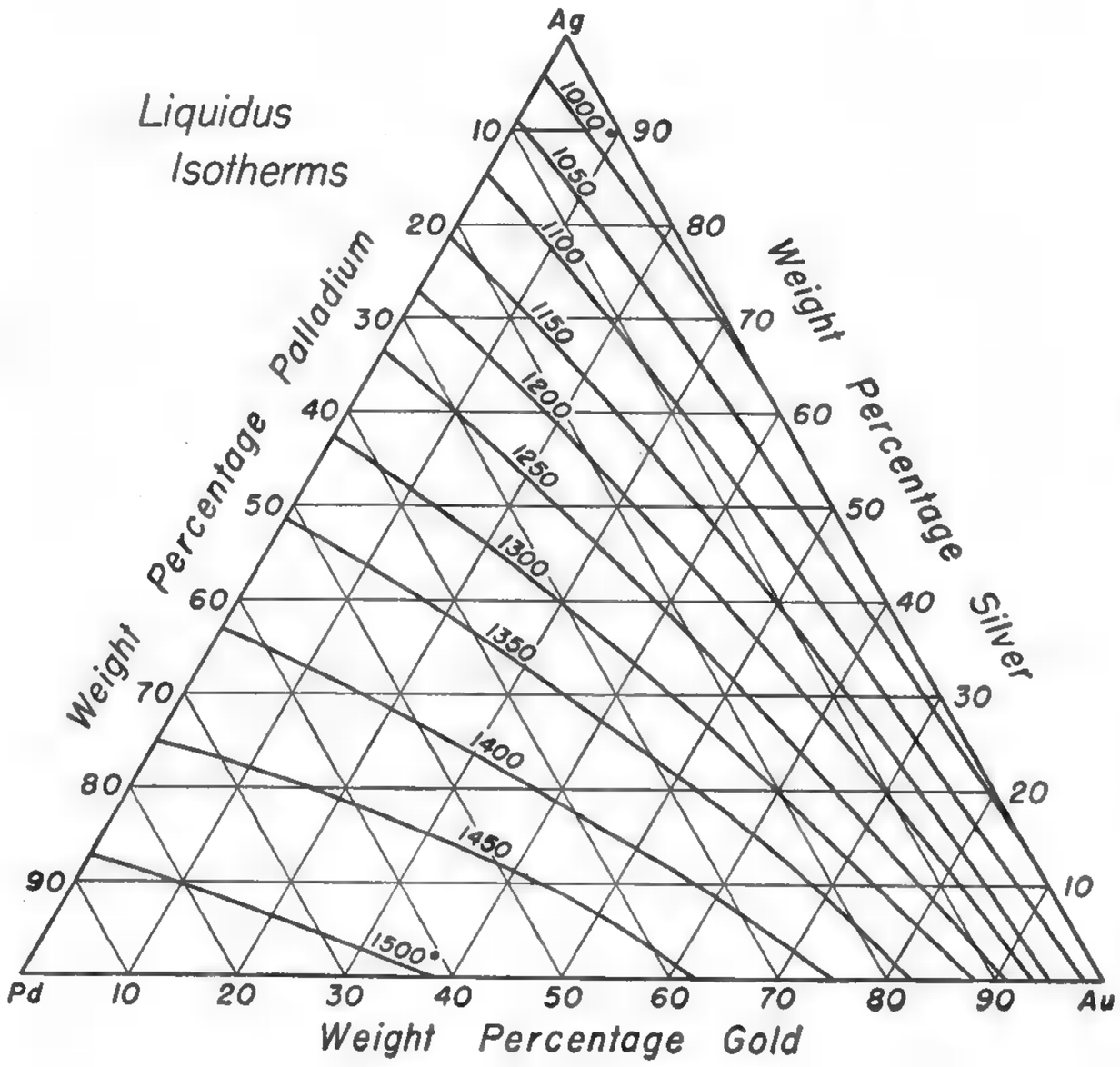
CONSTITUTION OF TERNARY ALLOYS

Ag-Au-Pd Silver-Gold-Palladium

By E. M. Wise*



Throughout the system, the melting range is narrow. The solid ternary alloys are probably free from transformations, as are all the binary alloys of these metals with one another.

Gold-palladium alloys that contain 15 to 20% Pd are essentially white, and are tarnish-proof. The gold-silver alloys that contain about 50% Ag also are white, but will tarnish. The ternary alloys extending from these points to the palladium corner are white. These alloys, however, should not be confused with the Au-Ni-Cu-Zn alloys ("white gold"), which are much harder and more difficult to fabricate than the Ag-Au-Pd alloys.

The resistance of the alloys to tarnishing increases with the sum of the percentages of gold plus palladium, but palladium is somewhat more effective than gold. The resistance to tarnishing becomes very good at 50 to 60% Pd or at about 70% Au.

The addition of copper to Ag-Au-Pd alloys provides metals that are responsive to age hardening and are the basis for many of the cast and wrought high-strength dental materials. Certain Ag-Au-Pd alloys have been used also as high-melting solders for joining palladium or platinum.

The Vickers hardness of annealed Ag-Au-Pd alloys is plotted on the ternary concentration plane on page 1129. The maximum hardness of the ternary alloys in the annealed condition is between 90 and 100 Vickers.

* The International Nickel Company, Inc., New York

Ag-Cu-Pd Silver-Copper-Palladium

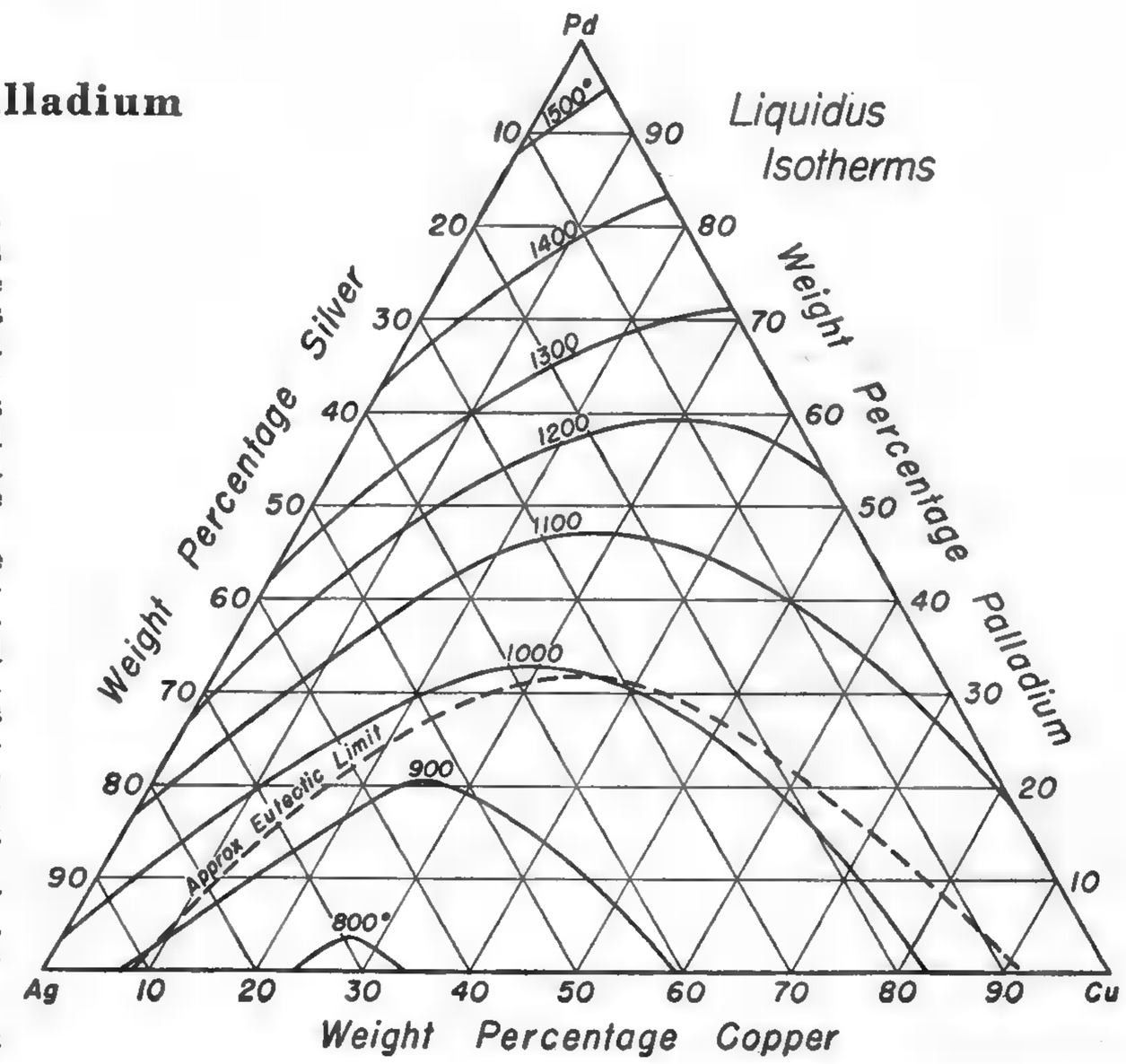
By E. M. Wise*

Palladium increases the mutual solid solubility of silver and copper. The first additions of palladium increase the temperature of the silver-copper eutectic; with further additions the eutectic reaction is eliminated. At high temperatures most of the alloys are single-phase solid solutions; at lower temperatures there are ordered phases based on PdCu and $PdCu_3$. In the low-palladium alloys, silver-rich and copper-rich terminal solid solutions are the stable phases below the solidus.

These low-temperature phases and the changes in solubility of the terminal solid solutions make age hardening possible. The maximum Vickers hardness of aged alloys is plotted on the ternary concentration plane in Fig. 1 on page 1128 in this Handbook. Hardness values higher than 450 Vickers or about Rockwell C 49 are attainable in alloys with approximately 30% Cu, 30% Ag, 40% Pd. This hardness is unusually high for an alloy that is readily workable in the quenched condition.

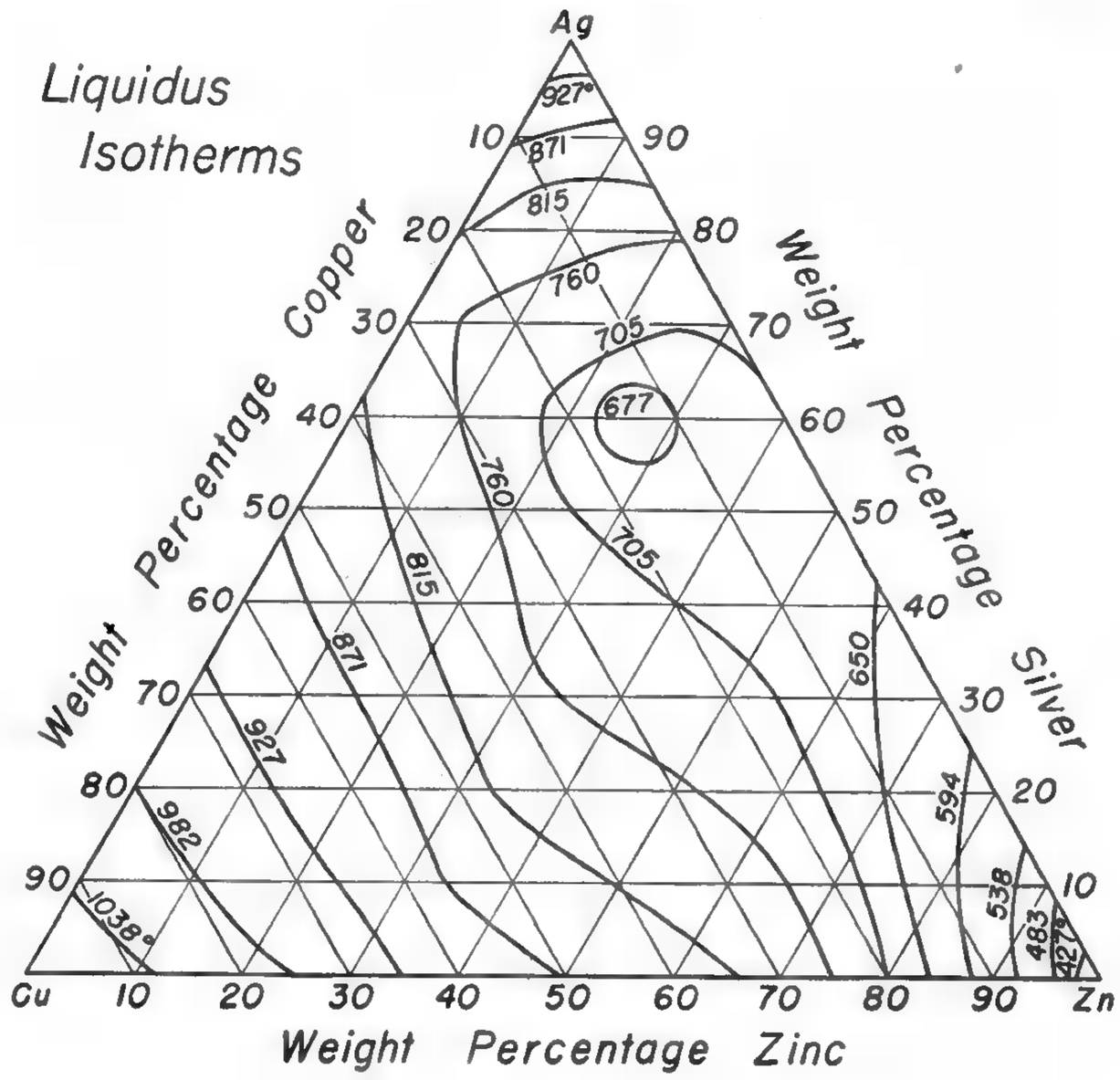
Alloys of this type containing 45% Pd, or slightly more, and modifications containing a little gold are used in dentistry and for electrical contacts subjected to sliding wear.

* The International Nickel Company, Inc., New York



Ag-Cu-Zn Silver-Copper-Zinc

By Robert H. Leach*



The liquidus diagram shown is based on cooling curves made in the research laboratory of Handy & Harman.

Alloys containing less than 15 to 30% Zn are eutectiferous, like the binary silver-copper alloys. Alloys with more than 15 to 30% Zn contain intermediate phases that derive from the corresponding phases in the copper-zinc and silver-zinc systems.

Addition of zinc to silver-copper alloys decreases the eutectic temperature and increases the silver-copper ratio of the eutectic. The silver-copper eutectic absorbs about 24% Zn. The approximate position of the terminus of the pseudobinary, ternary eutectic is indicated by the circular isotherm labeled 677° on the diagram. Copper-rich alloys absorb more zinc and silver-rich alloys less zinc than the eutectic.

Zinc broadens the melting ranges of the copper-rich and silver-rich alloys, since it lowers the eutectic solidus more than the primary liquidus surfaces.

The basic, intermediate copper-zinc and silver-zinc phases have similar structures and seem to alloy isomorphously.

Quaternary alloys with varying percentages of cadmium or tin, as well as silver, copper and zinc, have lower liquidus temperatures than the ternary alloys, and are used commercially as silver brazing alloys. For additional information, see the articles on pages 78 and 1113 in this Handbook.

* Vice President, Handy & Harman, Bridgeport, Conn.

Ag-Pd-Pt Silver-Palladium-Platinum

By R. F. Vines*

The addition of palladium to silver-platinum alloys decreases the difference in temperature between the liquidus and solidus. The approximate composition limits for coexisting solid solutions are shown as a dashed line on the diagram. This line refers to temperatures of about 500 to 800 C.

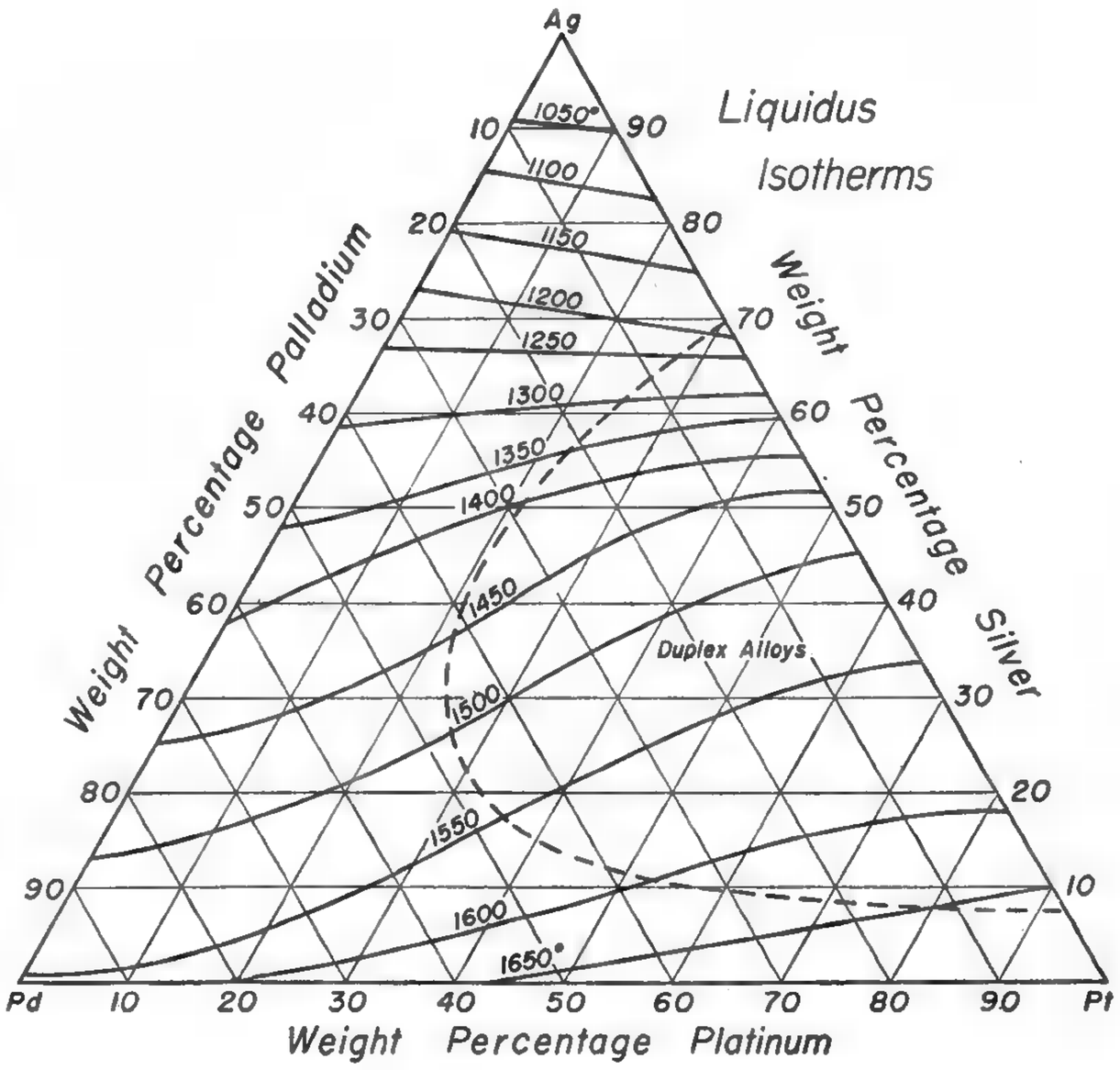
The wide separation between the liquidus and solidus temperatures of the silver-platinum alloys and the transformations that occur in the binary alloys generally have limited the interest to alloys containing a few per cent of platinum. The addition of palladium, which forms simple solid solutions with both platinum and silver, avoids both difficulties and gives rise to a wide field of readily fabricated single-phase alloys.

Some of the ternary alloys can be age hardened appreciably, but the solid solution alloys are of most interest. If higher hardness is desired, supplementary hardeners may be added — for example, a few per cent of nickel.

Alloys that contain about 25% Pt, 25% Ag, 50% Pd offer a good base for high-melting, corrosion-resistant dental alloys. These alloys, like those lower in platinum and palladium, can be hardened further by small additions of certain other metals.

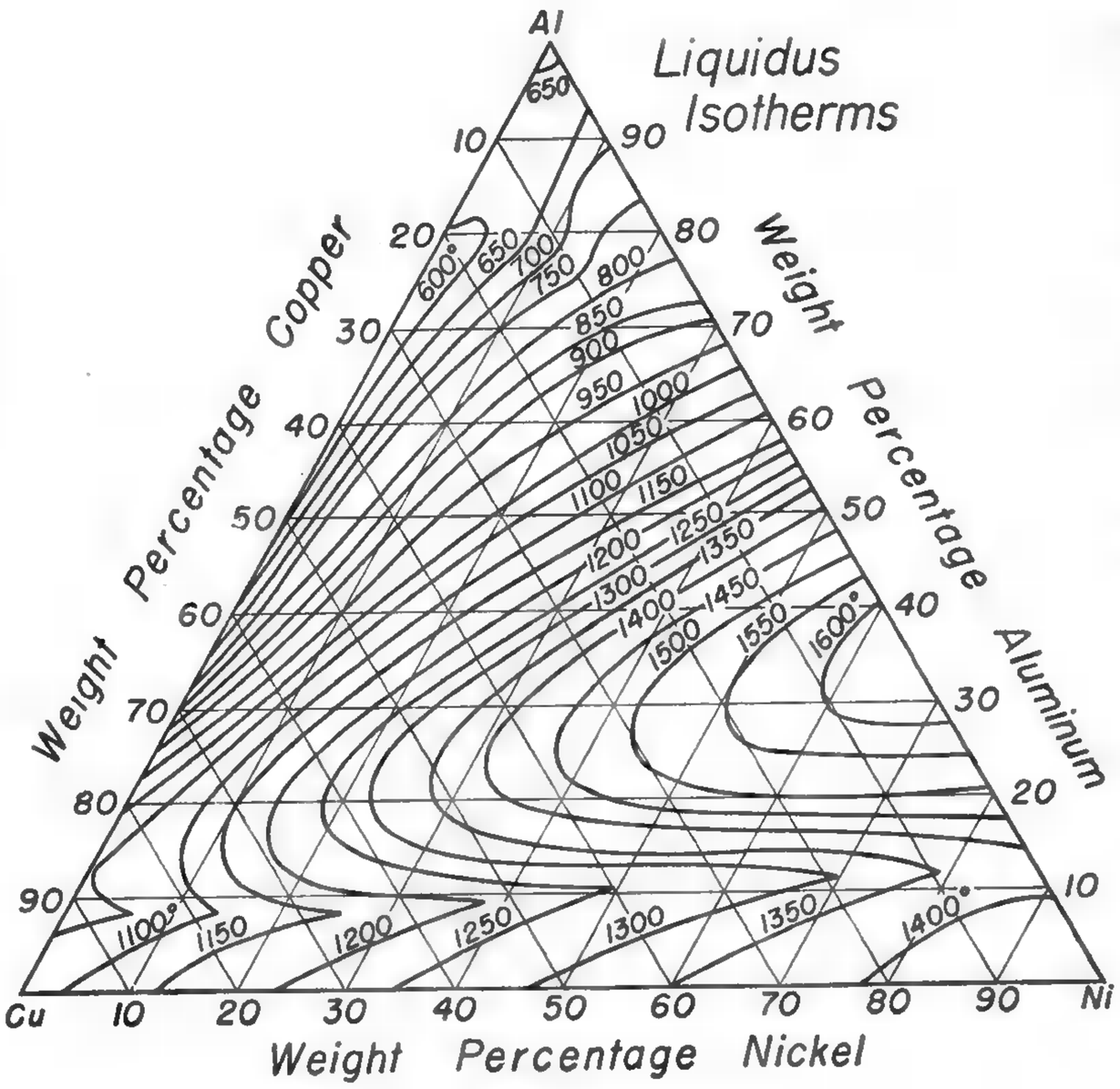
The Vickers hardness of annealed Ag-Pd-Pt alloys is plotted on the ternary concentration plane on page 1129 of this Handbook.

* The Dentists' Supply Company, York, Pa.



Al-Cu-Ni Aluminum-Copper-Nickel

By David I. Sinizer*



Evidence for the presence of a ternary eutectic at 32.5% Cu, 0.9% Ni, remainder aluminum, at 546.6 C, has been presented.[1,2]

At temperatures above 750 C the copper-rich β and the nickel-rich β_2 phases are isomorphous but immiscibility occurs below this temperature. The γ field is divided into three separate sections: γ, γ_1 and γ_2, each of which has a different superstructure.

The τ phase, which does not occur in any of the three binary systems, corresponds to an ideal formula Cu_3NiAl_6 and has a deformed body-centered cubic crystal structure.

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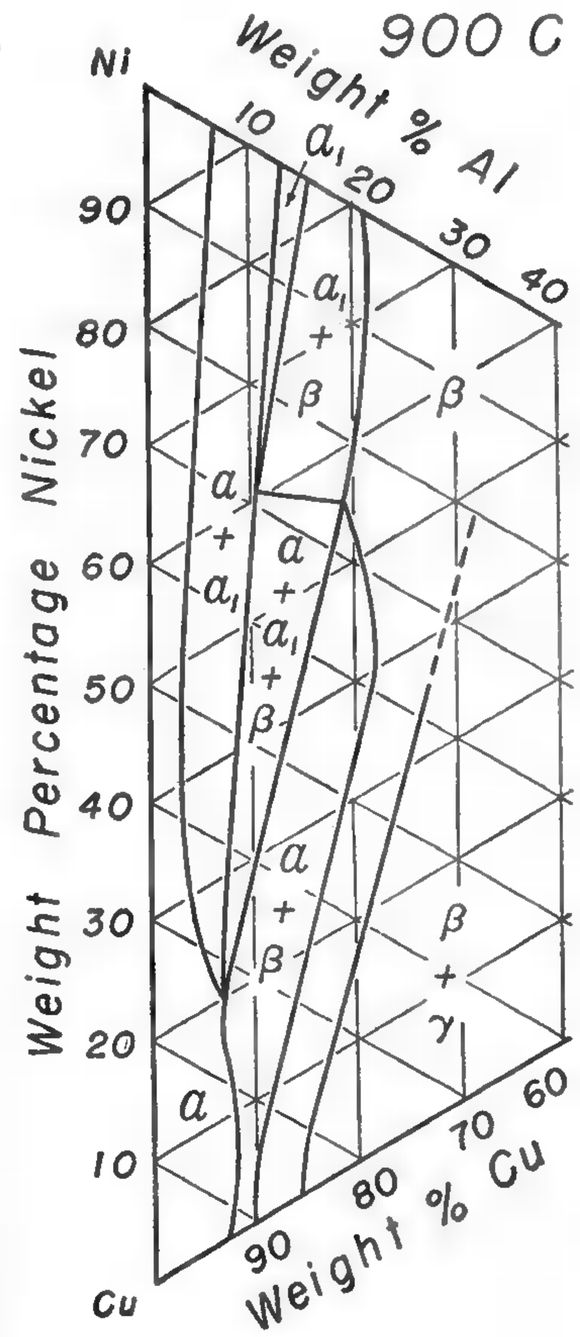
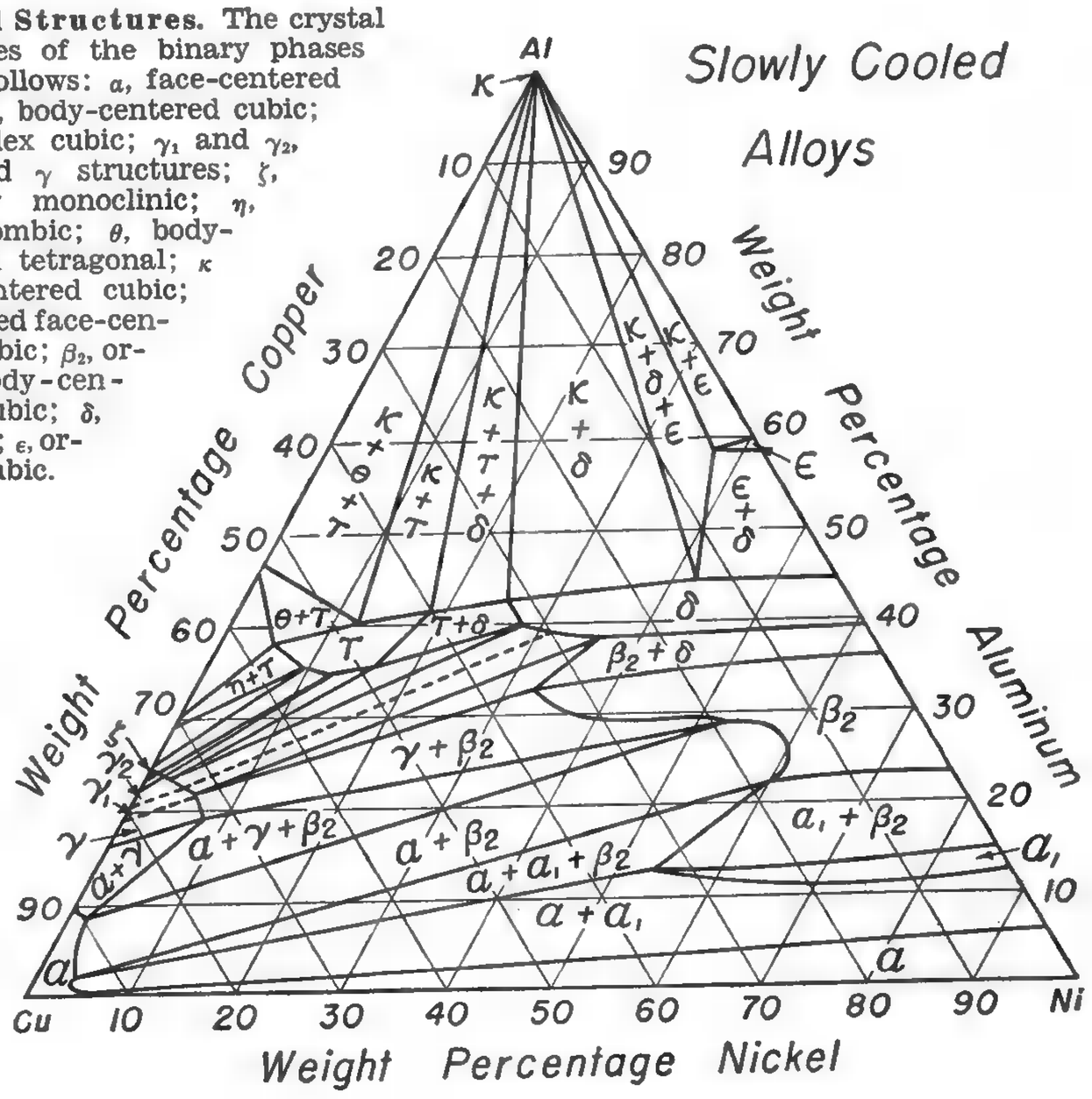
* Metallurgist, The International Nickel Company, Inc., Research Laboratory, Bayonne, N.J. Present address, Massachusetts Institute of Technology, Cambridge, Mass.

* Editor's Note. Alexander[4] investigated the constitution of about 80 copper-nickel-rich alloys by thermal, microscopic and X-ray methods. His results were reported as seven horizontal sections and ten vertical sections through the ternary space model. The horizontal sections include the liquidus, the solidus, and the phase fields at 900, 800, 700, 600 and 500 C. The vertical sections include 3, 6, 10, 20, 40 and 60% Ni; 4, 10 and 14% Al; and the section between β (Cu_3Al) and NiAl.



Crystal Structures. The crystal structures of the binary phases are as follows: α, face-centered cubic; β, body-centered cubic; γ, complex cubic; γ_1 and γ_2, deformed γ structures; ζ, probably monoclinic; η, orthorhombic; θ, body-centered tetragonal; κ face-centered cubic; α_1, ordered face-centered cubic; β_2, ordered body-centered cubic; δ, trigonal; ϵ, orthorhombic.



Al-Cu-Zn Aluminum-Copper-Zinc

By Cyril Stanley Smith*

Despite the importance of these alloys, large areas of the ternary diagram are still uncertain. The liquidus surface shown is based on that of Bauer and Hansen,[1] and Gebhardt[2] for the commercial brass and zinc portions respectively, smoothed into the data of Jares,[3] Hanson and Gayler,[4] and the well-established binary diagrams. The lines dividing the various liquidus surfaces are essentially those of Jares, except for the elimination of the line from the β (Al-Zn) phase, which is now known not to exist in the binary system and may not exist in the ternary system. At the ternary eutectic temperature (375 C) the following four phases are in equilibrium:

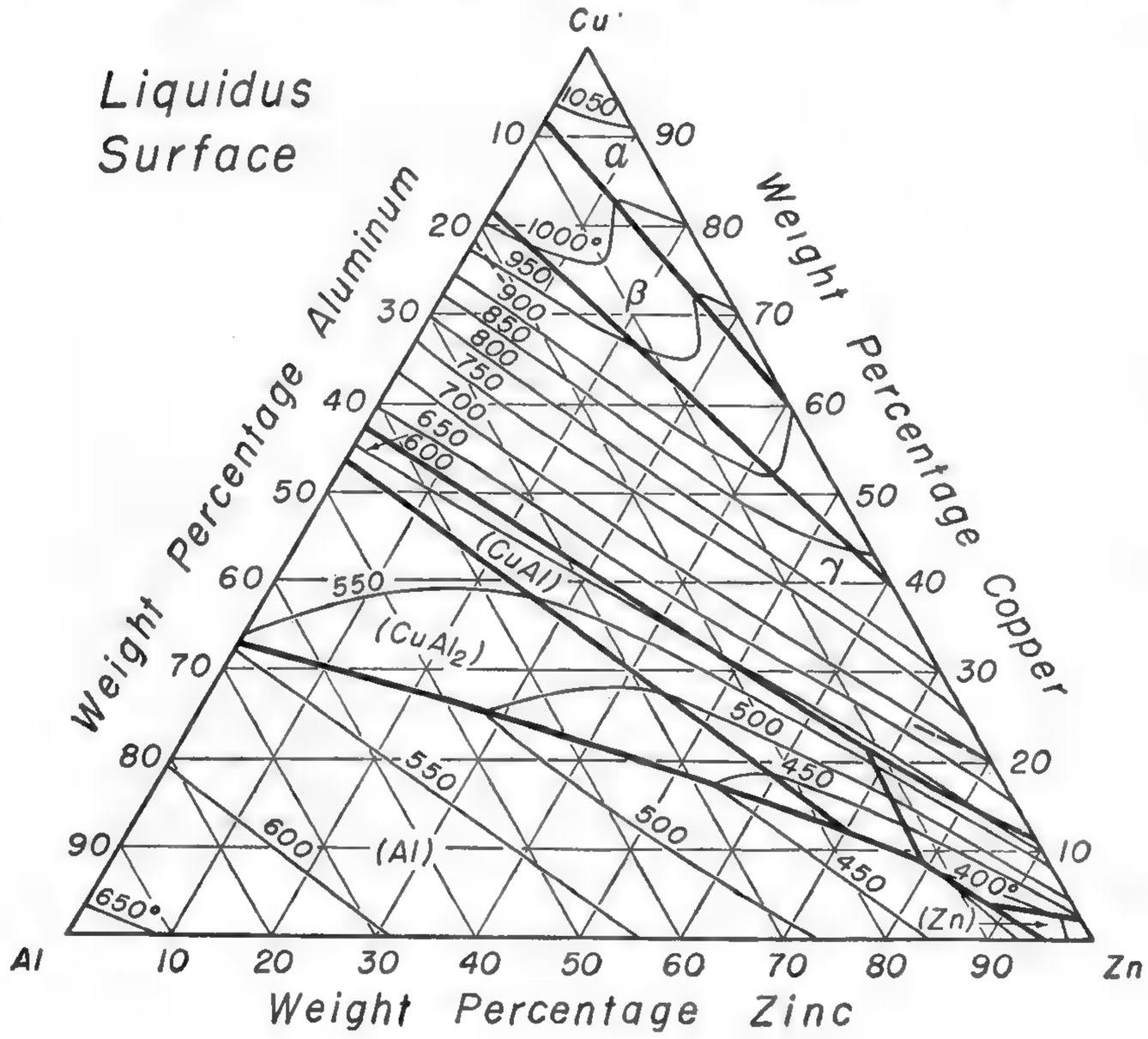
Liquid	7.0% Al	3.9% Cu
Zn-rich solid solution.	1.3% Al	2.9% Cu
Al-rich solid solution..	19.5% Al	1.8% Cu
Epsilon Cu-Zn	1.4% Al	15.2% Cu

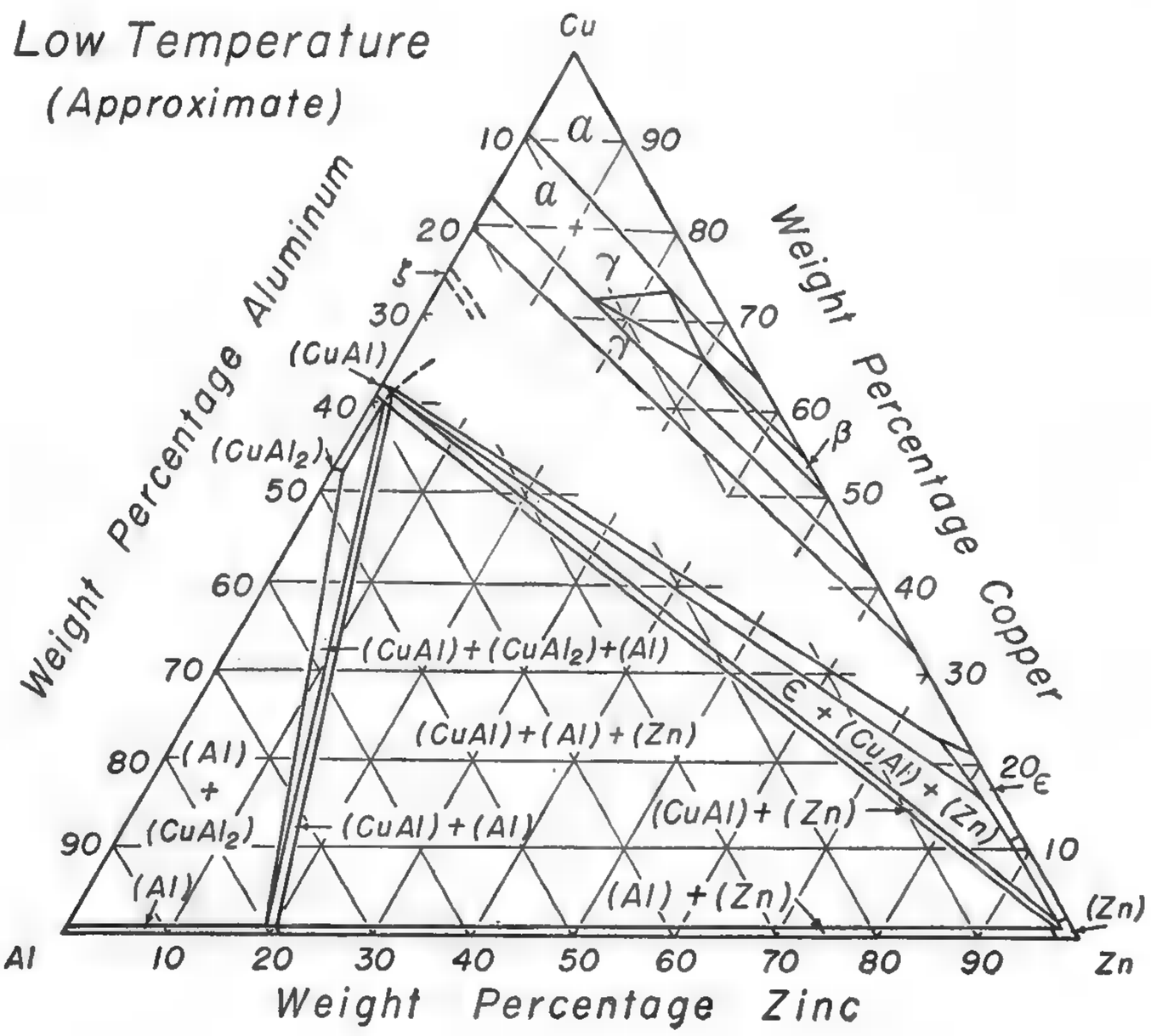
At lower temperatures the aluminum-rich phase decomposes; the influence of copper on the extent of this decomposition is almost unknown except for the temperature at which the copper-saturated, high-zinc branch decomposes, which Gebhardt[2] gives as 274 C (2 deg higher than in the binary) at about 1% Cu.

The solubility of copper and aluminum in solid zinc was established by the work of Burkhardt,[6] Gebhardt,[2] and Löhberg.[7] The maximum solubility at the eutectic temperature (375 C) is 1.3% Al, 2.9% Cu. This decreases to about 0.9% Al and 1.9% Cu at 274 C, and is probably lower at lower temperatures.

The constitution is shown also at the lowest temperatures at which reaction rates are important—410 C for the high-copper end, following Bauer and Hansen;[1] 200 C for alloys with less copper than corresponds to the γ phase, following Hanson and Gayler.[4] It is to be noted that the more careful work at the extreme zinc corner does not fit in with Hanson and Gayler's work, for the (CuAl) phase is not found in equilibrium with (Zn), and the ϵ(Cu-Zn) phase is found to coexist with the (Zn) and the (Al) phases.

The a, β, and γ phases of the binary copper-aluminum and copper-zinc diagrams are isomorphous and extend across the diagram in bands of constant electron/atom ratio. The crystal structure of the γ phase is intermediate (Bradley and Gregory[8]). The eutectoid decomposition of β(Cu-Al) extends into the ternary diagram and decreases in temperature with added zinc, reaching the point shown at 410 C, below which temperature the transformation is very sluggish and commercially unimportant.





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Al-Fe-Ni Aluminum-Iron-Nickel

By L. L. Wyman*

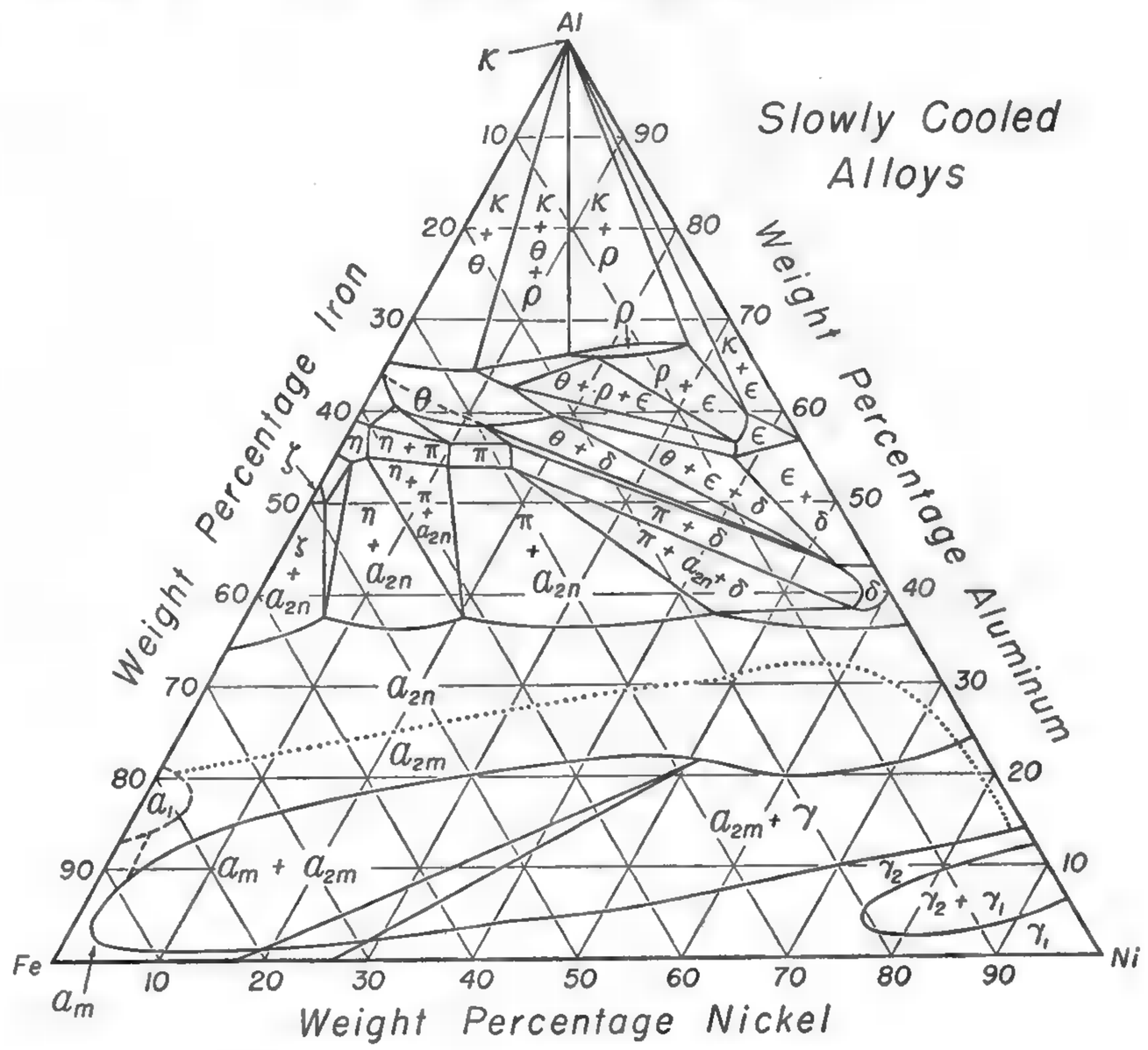
Recent work[1,2] on the low-aluminum alloys has somewhat modified the low-temperature phase limits in this system, and has attributed the increase in coercive force to the formation of $a_{2m} + \gamma$ from a_m rather than the a to γ reaction proposed earlier.[3,4] The γ phase apparently breaks up further into $a_m + a_{2m}$.

The aluminum-rich alloy region has been constructed entirely on the basis of X-ray powder analysis.[5] More recent work[6] has shown that prolonged annealing at 600 C shifts the phase boundaries to the left, in the aluminum corner.

The phases on the aluminum-iron side of the diagram have been labeled the same as in the binary aluminum-iron diagram on page 1161 of this Handbook. The correlation among the phase designations used in the Al-Fe-Ni diagram and in the several closely related systems in this Handbook, is given in the table in the left-hand column. The π and ρ phases occur only in the ternary system.

Correlation of Phase Designations

Al-Fe-Ni	Al-Fe	Al-Ni	Fe-Ni	Al-Cu-Ni
a_m	a_m	...	a	...
a_1	a_1	...	...	...
a_{2m}	a_{2m}	...	...	...
a_{2n}	a_{2n}	δ	...	β_2
ζ	ζ	...	...	...
η	η	...	...	...
θ	θ	...	...	...
κ	κ	a	...	κ
ϵ	...	β	...	ϵ
δ	...	γ	...	δ
γ_2	...	ϵ	...	a_1
γ_1	...	ζ	γ	a



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Al-Fe-Si Aluminum-Iron-Silicon

By W. L. Fink* and L. A. Willey*

Because all commercial aluminum alloys contain iron and silicon as impurities, the aluminum corner of the ternary system is of considerable importance. In addition to the aluminum solid solution, silicon solid solution and the binary intermediate phase $FeAl_3$, two ternary intermediate phases, commonly termed α(Fe-Si) and β(Fe-Si), may appear in the aluminum-rich alloys. The α(Fe-Si) phase forms primarily or by peritectic reaction between $FeAl_3$ and liquid; β(Fe-Si) forms primarily or by peritectic reaction between α(Fe-Si) and liquid. Whether or not these phases have fixed or variable compositions has not been definitely established.[1]

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Al-Mg-Mn Aluminum-Magnesium-Manganese

By G. F. Sager* and B. J Nelson*

A peritectic reaction occurs between $MnAl_4$ and $MnAl_6$, and these, together with Al_3Mg_2, have been observed metallographically in a matrix of aluminum-rich solid solution.[1] A metastable ternary eutectic is found at 26.4% Mg, 2.35% Mn and 437 C.

The solubility of manganese in solid aluminum containing 2% Mg is 0.26% at 500 C, 0.45% at 550 C and 0.80% at 600 C. The solubility of manganese in liquid magnesium containing 8% Al is less than 0.15% at 650 C, 0.3% at 700 C, and 1.4% at 800 C.

In the range of 5% Mg and 0 to 2% Mn, all alloys with more than a trace of manganese are entirely $a + MnAl_6$.

Liquidus temperatures for a and $MnAl_6$ are:[3]

$$T_{(a)} = 660 - 5.28\,(\%\ Mg) - 0.76\,(\%\ Mn) + \tfrac{1}{2}\sqrt{(\%\ Mg)\ (\%\ Mn)}$$

$$T_{(MnAl_6)} = 601.0 + 0.5\,(\%\ Mg) + 29.2\,(\%\ Mn)$$

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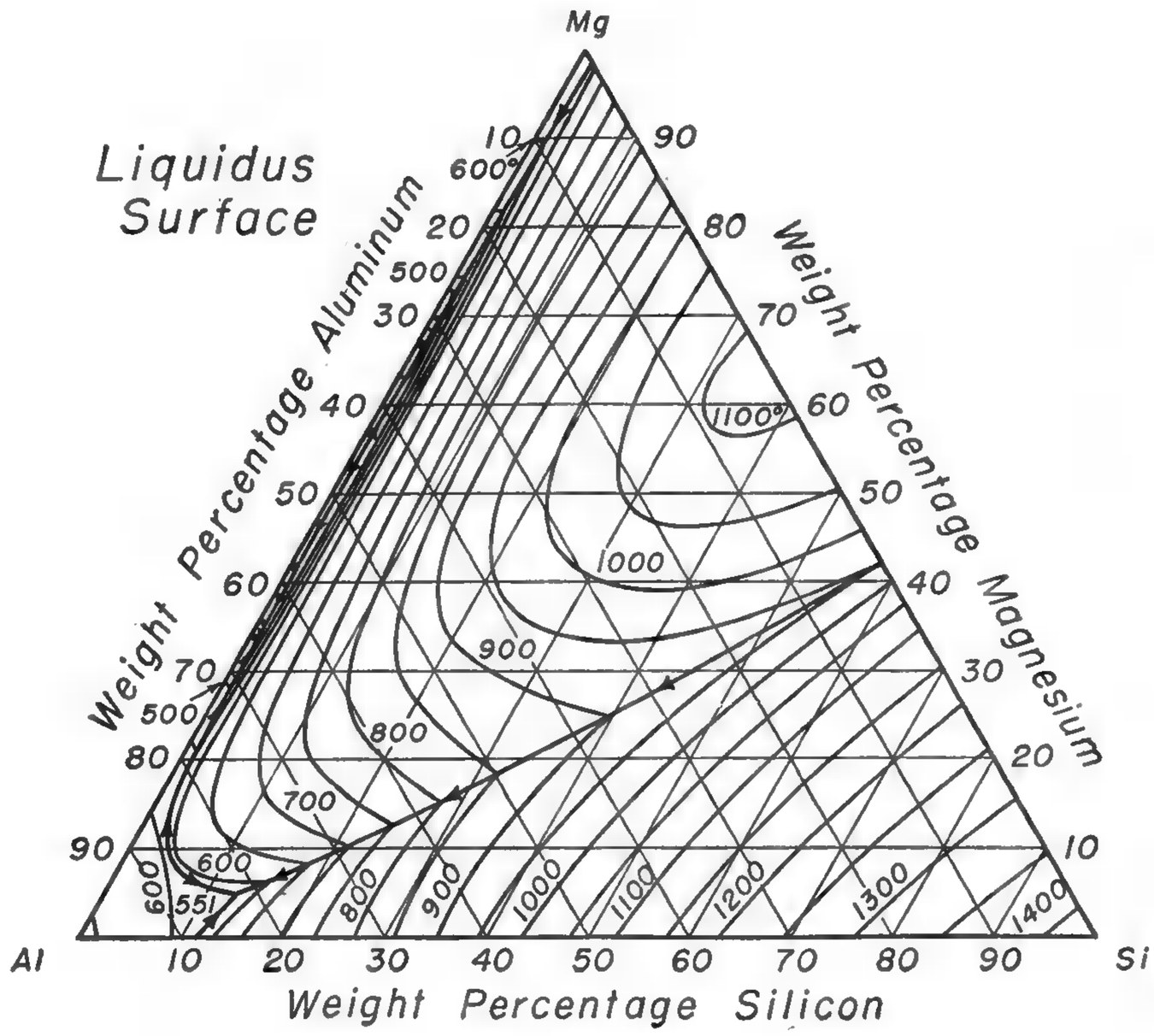
Al-Mg-Si Aluminum-Magnesium-Silicon

By W. L. Fink* and L. A. Willey*

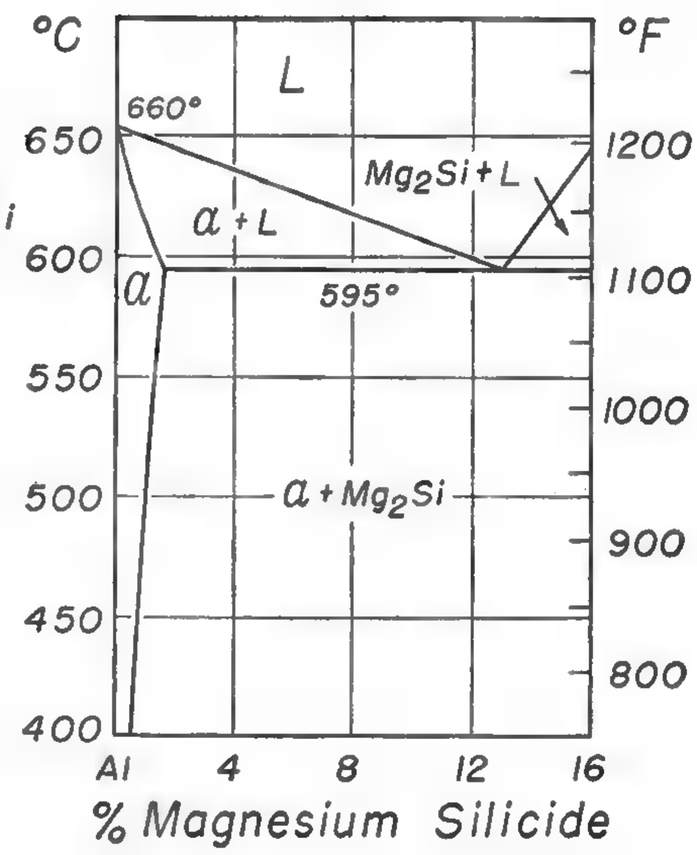


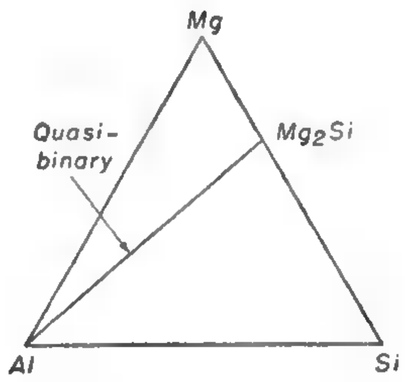
The single binary intermetallic phase in the magnesium-silicon system forms quasi-binary systems with aluminum and with the binary intermetallic phases of the aluminum-magnesium system. No ternary intermetallic phases are formed.

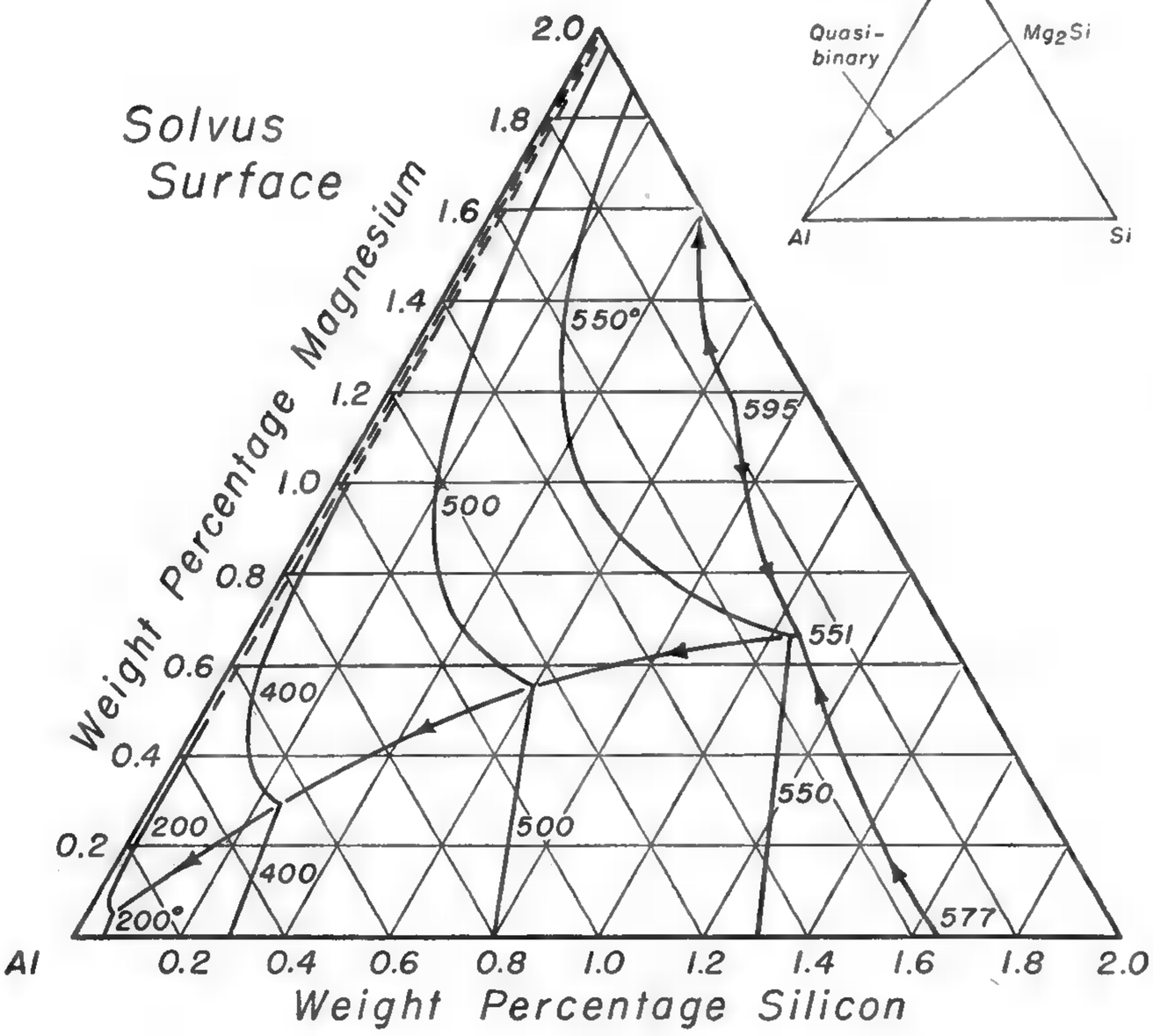
The solubility of magnesium silicide in solid aluminum is as follows:

Temperature, °C	595	500	400	300
Percentage Mg_2Si	1.85	1.05	0.53	0.30

Several commercial wrought alloys of aluminum with magnesium and silicon as the major alloying additions are used extensively (*see* pages 819 to 822). The relatively high strength of these alloys is obtained by precipitation hardening. Alloys with the magnesium and silicon contents in the ratio for the formation of Mg_2Si are more common, although alloys with either excess silicon or magnesium are also used. Excess magnesium lowers the strength by decreasing the solid solubility of Mg_2Si in aluminum.







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Al-Mg-Zn Aluminum-Magnesium-Zinc

By W. L. Fink* and L. A. Willey*

The liquidus surface, the solidus surface (except for isotherms that have been omitted for lack of data) and the phase fields at 100 C for the complete aluminum-magnesium-zinc system and the solvus surface for the aluminum corner of the system are shown.

It will be noted that the only ternary intermetallic phase, λ, extends halfway across the system (20 to 70% Zn) and is therefore not adequately described by the usual designation $Mg_3Zn_3Al_2$.[1,2,3,4] This phase is body-centered cubic with a lattice parameter of 14.29 kX.[4]

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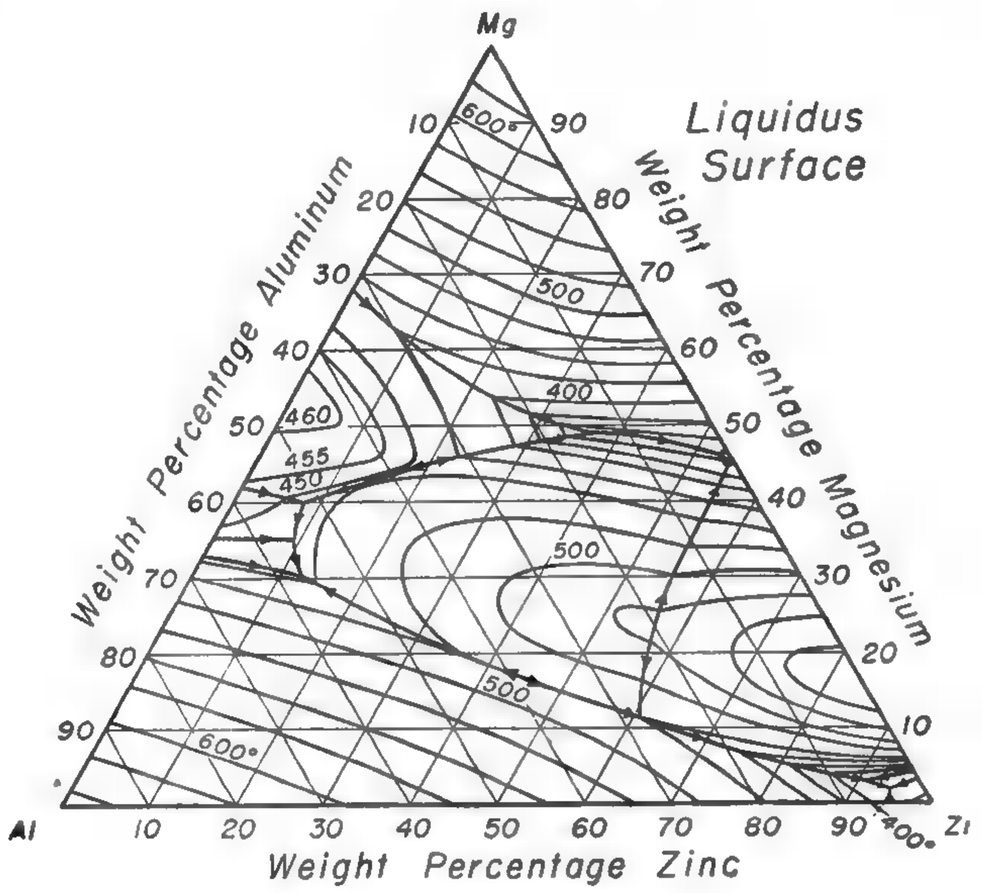

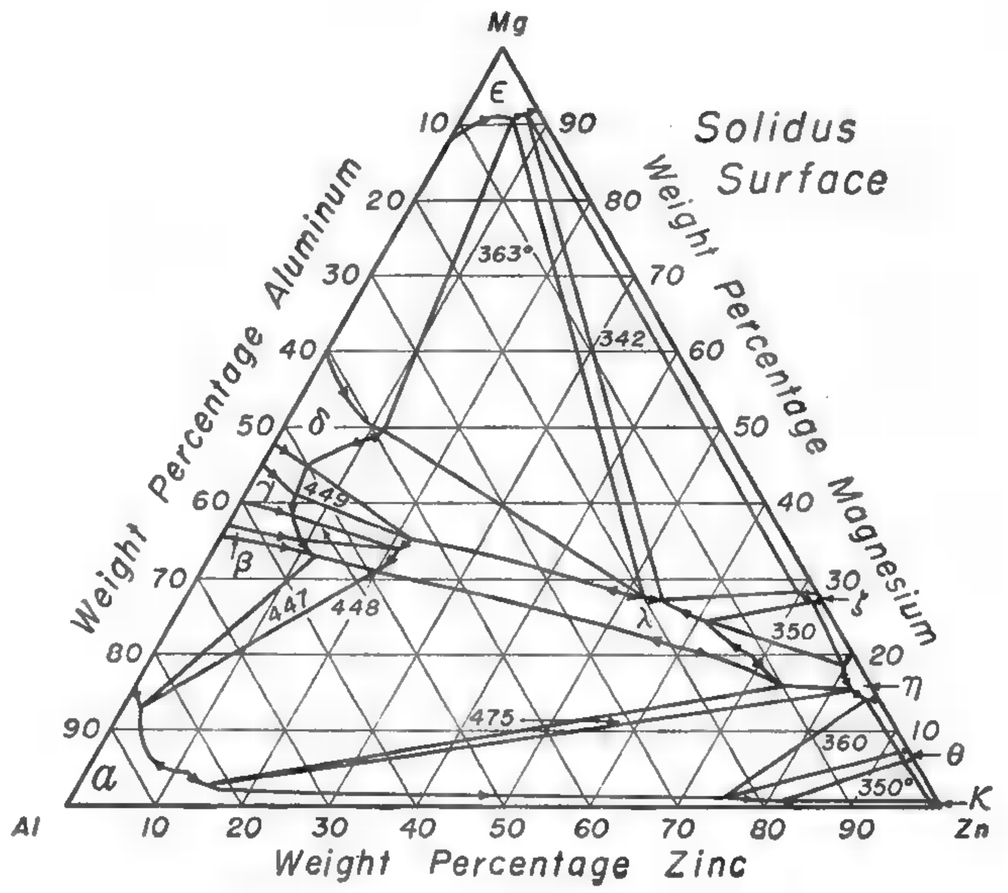

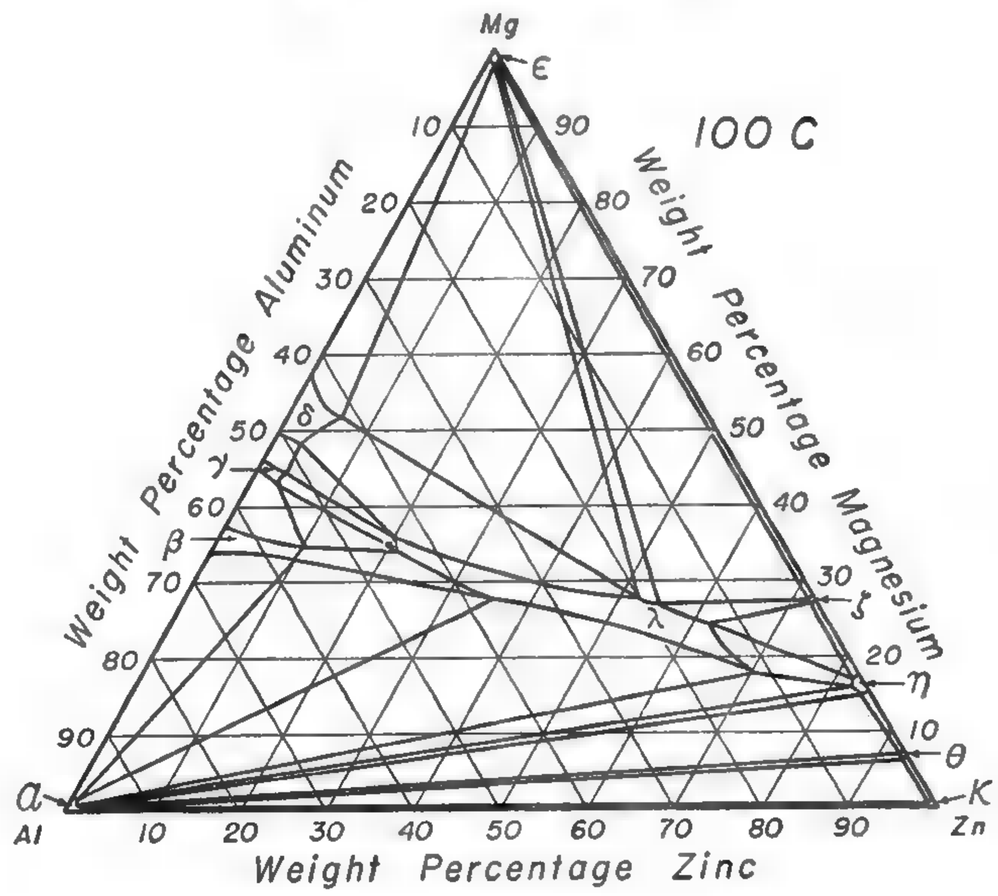

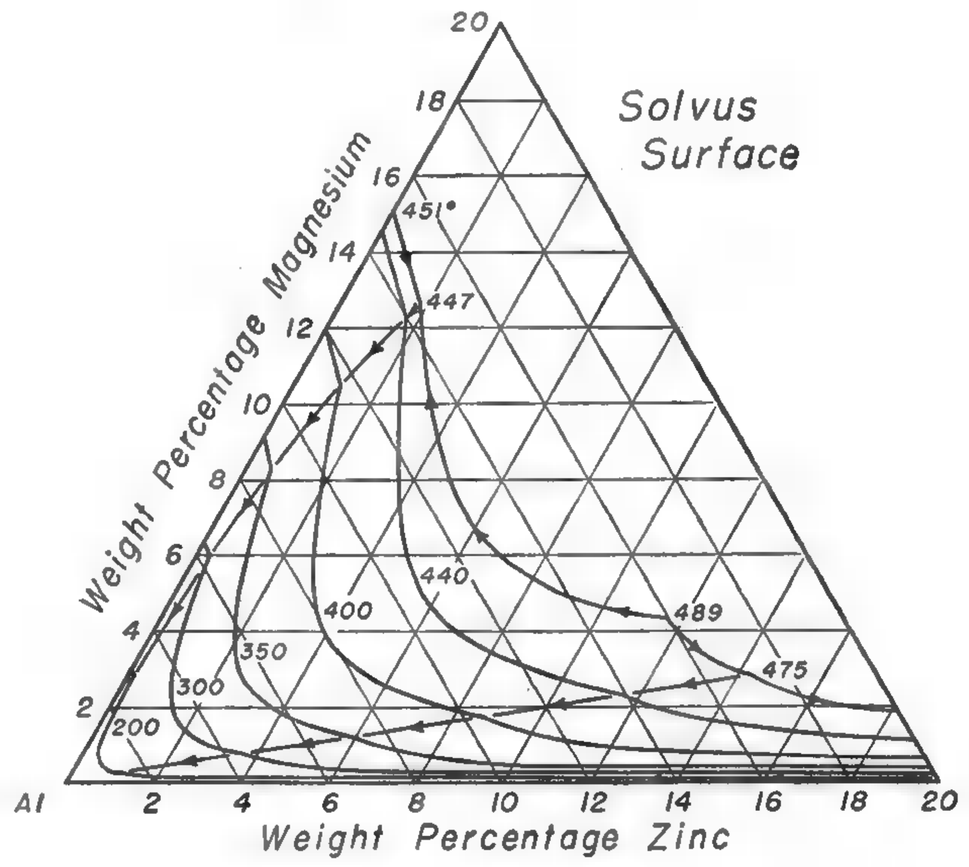

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Al-Mn-Si Aluminum-Manganese-Silicon

H. W. L. Phillips [J Inst Metals, 69, 291 (1943)] studied slowly cooled aluminum-rich alloys containing from 0 to 8% Mn and from 0 to 10% Si. Four invariant points were observed:

(i) 2% Mn, 1.3% Si, 649 C (Liquid, Al, $MnAl_4$, αMnSi)
(ii) 3.4% Mn, 0.5% Si, 660 C (Liquid, $MnAl_4$, $MnAl_6$, βMnSi)
(iii) 2.7% Mn, 1.3% Si, 658 C (Liquid, $MnAl_6$, αMnSi, βMnSi)
(iv) 0.75% Mn, 11.75% Si, 573 C (Liquid, Al, Si, αMnSi)

The following sections of the ternary diagram are given in Phillips' paper: the liquidus surface, the surfaces of secondary separation, the constituents in slowly cooled alloys, and vertical sections at 1.5% Mn, 6% Mn, 1.0% Si, and 4.0% Si.

Al-Mn-Zn Aluminum-Manganese-Zinc

Butchers, Raynor and Hume-Rothery [J Inst Metals, 69, 217 (1943)] have studied the aluminum-rich alloys containing from 0 to 3% Mn and from 0 to 10% Zn. These alloys — similar to the aluminum-rich Al-Mg-Mn alloys — are of two classes, in which the primary separations are aluminum solid solution and $MnAl_6$ respectively.

The temperatures of the liquidus surface at which aluminum-rich solid solution forms are given by the equation:

$$T_{(Al)} = 660 - 0.76\,(\%\ Mn) - 1.66\,(\%\ Zn)$$

The temperatures of the liquidus surface at which $MnAl_6$ forms are given by the equation:

$$T_{(MnAl_6)} = 601.0 + 29.1\,(\%\ Mn) + 0.25\,(\%\ Zn)$$

Be-Cu-Ni Beryllium-Copper-Nickel

By E. N. Skinner*

The fragmentary data available concern only the copper-rich and the nickel-rich portions of the ternary diagram.

Small amounts of nickel reduce[1,2] and, at about 2% Ni, completely obliterate the eutectoidal β-phase domain in the copper-beryllium binary diagram. The temperature of this eutectoid reaction, $\beta \rightleftarrows \alpha + \gamma$, is simultaneously raised from 573 C to the temperature of the one invariant reaction found that involves the liquid phase:

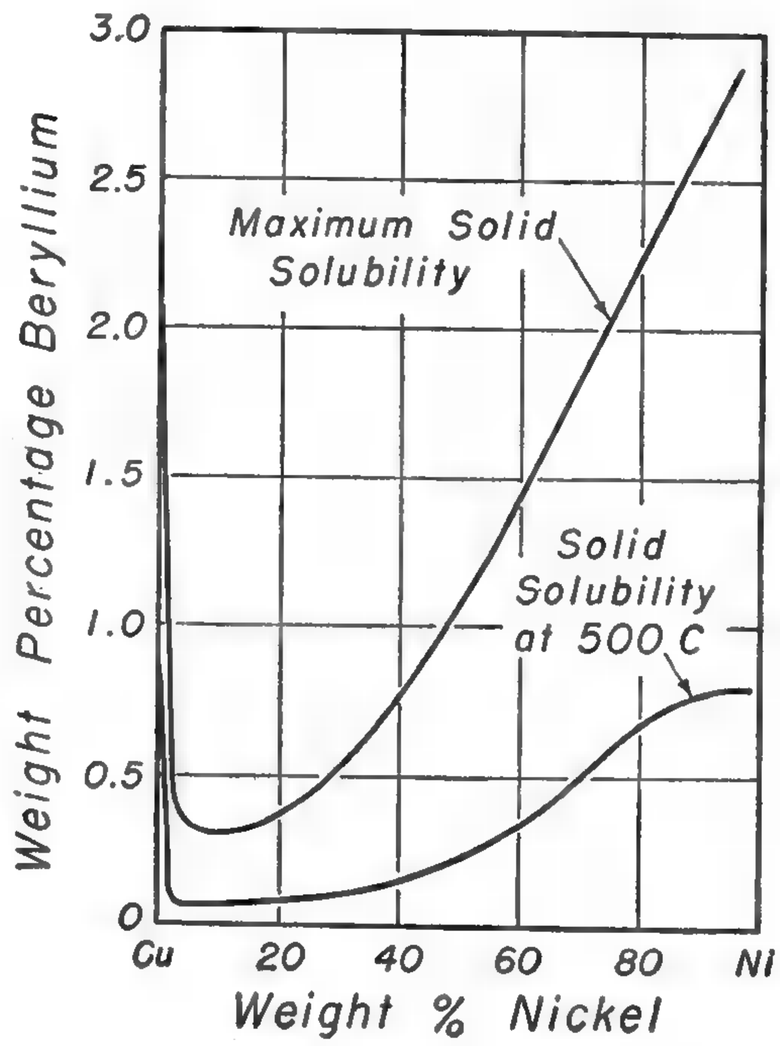
$$L + \gamma \rightleftarrows \alpha + \beta \text{ at } 868 \text{ C}$$

L = 4.4% Be, 0.8% Ni	α = 0.8% Be, 1.6% Ni
γ = ∽ 13.7% Be, 59% Ni	β = 5.7% Be, ∽ 2% Ni

With further additions of nickel, no new phasial equilibriums appear, other than the progressive shift of the eutectic temperature and composition up to that of the nickel-beryllium binary diagram. The γ phase, CuBe in the copper-beryllium binary system, is continuous with and structurally analogous to NiBe.

The two curves indicate the maximum solid solubility (immediately below the solidus) and the solid solubility at 500 C. The sharp decrease at low nickel contents reflects the extinction of the β phase.

The original investigation[1] contains no mention of the shift in eutectic temperature with variation in copper-nickel ratio. Unpublished results* indicate that this eutectic temperature is 1105 C at 68% Ni, 30% Cu, 2% Be.



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C-Cr-Fe Carbon-Chromium-Iron

By W. D. Forgeng*

The general features of the carbon-chromium-iron system are well established. The section between Fe_3C and Cr_7C_3 is apparently a quasi-binary system, and the sections of the diagram have been constructed on this basis.

The carbide phases designated as C_1, C_2, and C_3 have the following formulas and composition limits:

C_1, $(Fe,Cr)_3C$ or cementite containing up to 15% Cr
C_2, $(Cr,Fe)_7C_3$ or trigonal chromium carbide containing up to 55% Fe
C_3, $(Cr,Fe)_4C$ or cubic chromium carbide containing up to 25% Fe

The other phases have been designated as follows: L, liquid; α, ferrite; γ, austenite; σ, sigma (FeCr).

Three of the four four-phase equilibriums that exist in this system are indicated at the points *A*, *B*, and *C* of the diagram that shows the liquidus surface. The equilibriums at *A* and *B* are of the transition-plane type; the equilibrium at *C* is of the eutectic type. The ternary eutectic point at *C* lies close to the plane of the iron-carbon system. The fourth nonvariant equilibrium, which is not shown in any of the horizontal sections included here, is of considerable practical importance and occurs at about 800 C. This equilibrium involves the phases α, γ, $(Fe,Cr)_3C$ and $(Cr,Fe)_7C_3$. The coordinates of the α and γ corners of this quadrangle are at 0.05% C, 2.6% Cr, and at 0.7% C, 2% Cr, respectively. Therefore, the carbide $(Cr,Fe)_7C_3$ is stable in medium-carbon steels containing more than 2% Cr, and the behavior of such steels during heat treatment is different from that of plain carbon steels.

Alloys with less than 2% Cr are similar in constitution to the iron-carbon alloys and differ only so far as three-phase regions can exist over a range of temperature and composition, rather than at a fixed point. With increasing chromium content, the single-phase γ region becomes smaller and disappears entirely at about 20% Cr. In addition, the temperature limits of this region become narrower at the higher chromium contents. From a practical standpoint, this means that steels containing from about 10 to 18% Cr must be heated to temperatures between 900 and 1000 C if full hardening is to be obtained during subsequent quenching, and that, for maximum hardening by transformation of the γ phase, the carbon content of a steel must lie within the limits of the γ region for a given chromium content. It should also be noted that the carbon content of the "eutectoid" is decreased by increasing the chromium content and at 12% Cr, the "eutectoid" contains only about 0.35% C. The α solid solution of the equilibrium $\alpha + C_2 + C_3$ becomes richer in iron at lower temperatures and consequently the carbide $(Cr,Fe)_4C$ may appear in alloys with as little as 10% Cr.

At chromium contents between 20 and 30%, hardening by transformation of the γ phase becomes less pronounced, and since alloys with 30% Cr contain only α, C_2 and C_3, such alloys cannot be hardened by heat treatment.

The solubility of carbon in the α phase of iron-rich alloys, at temperatures just below the solidus, increases from about 0.1% at 12% Cr to about 0.2% at 20 to 30% Cr.

In alloys containing more than about 35% Cr, the α solid solution is gradually converted to the hard and brittle σ phase by holding the alloys in the temperature range between 600 and 900 C for long periods.

For information about the constitution of chromium steels, see the article on page 458 in this Handbook.

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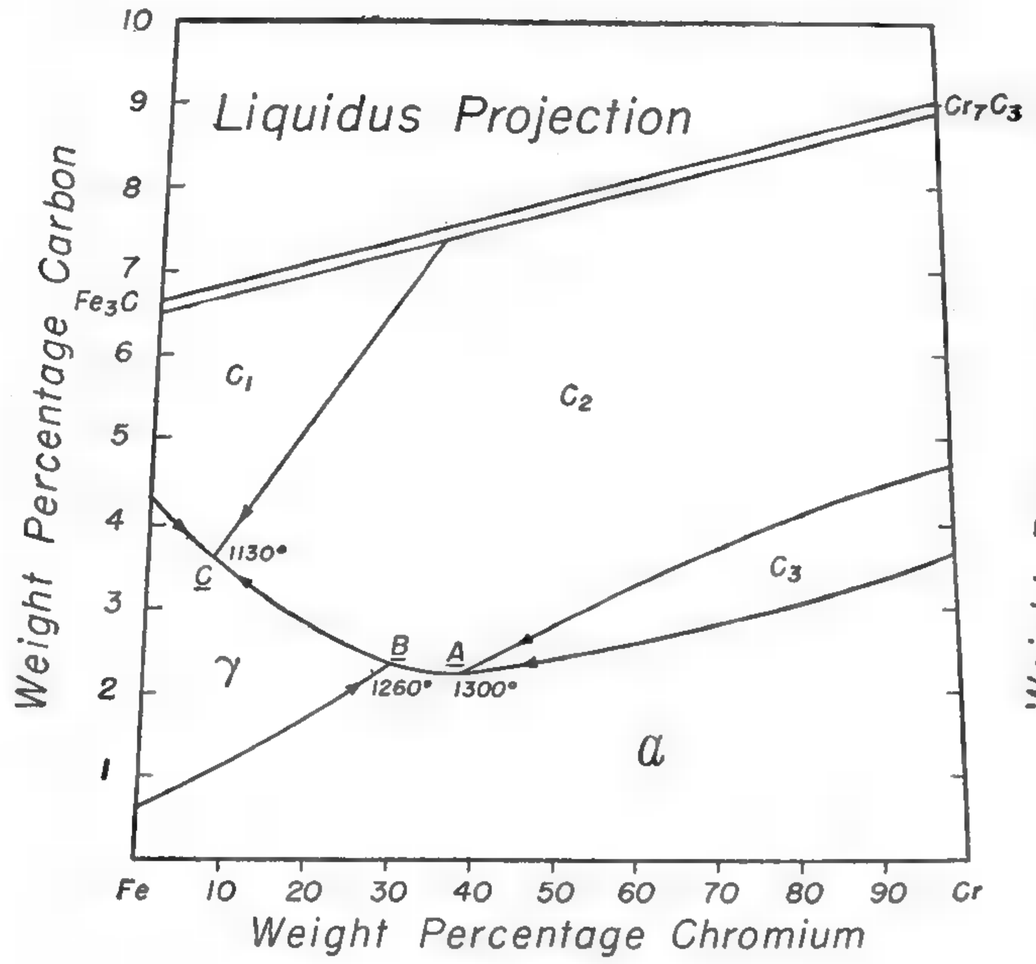
Liquidus Projection
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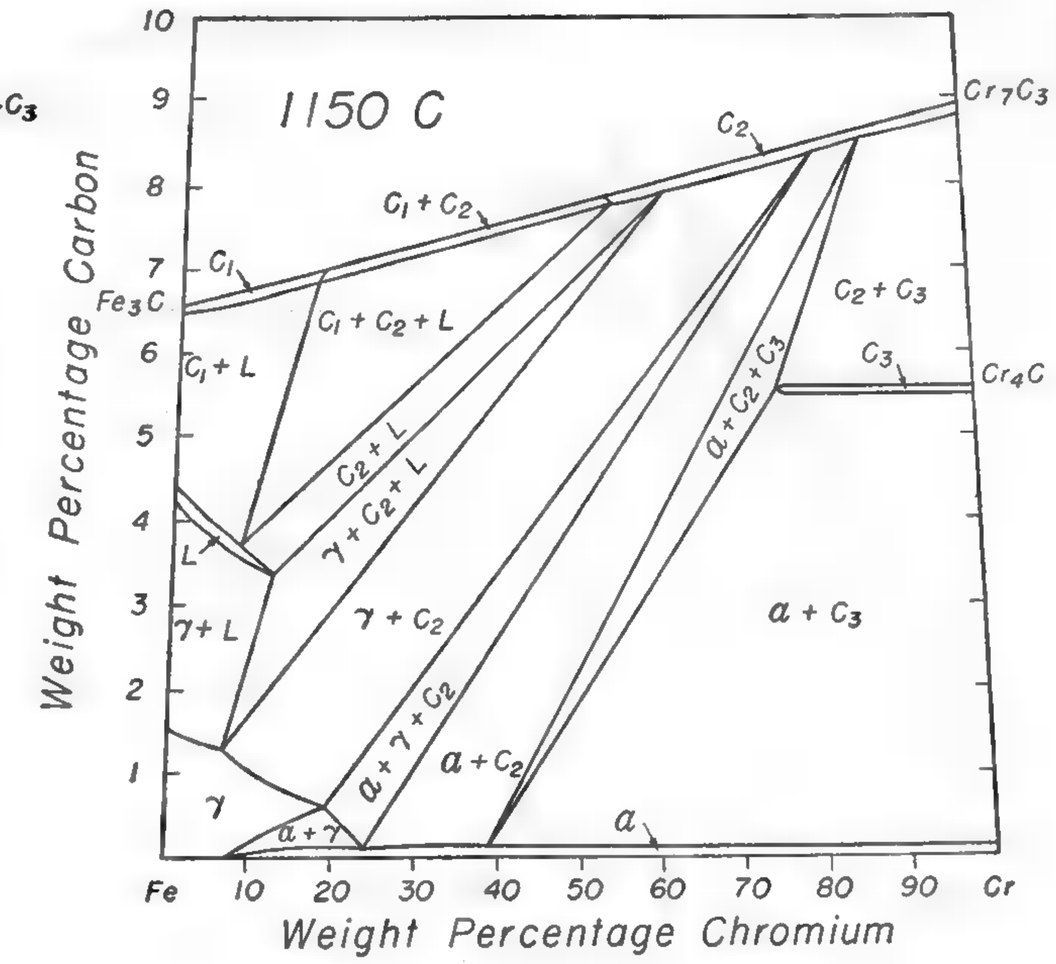
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Cr_7C_3
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L
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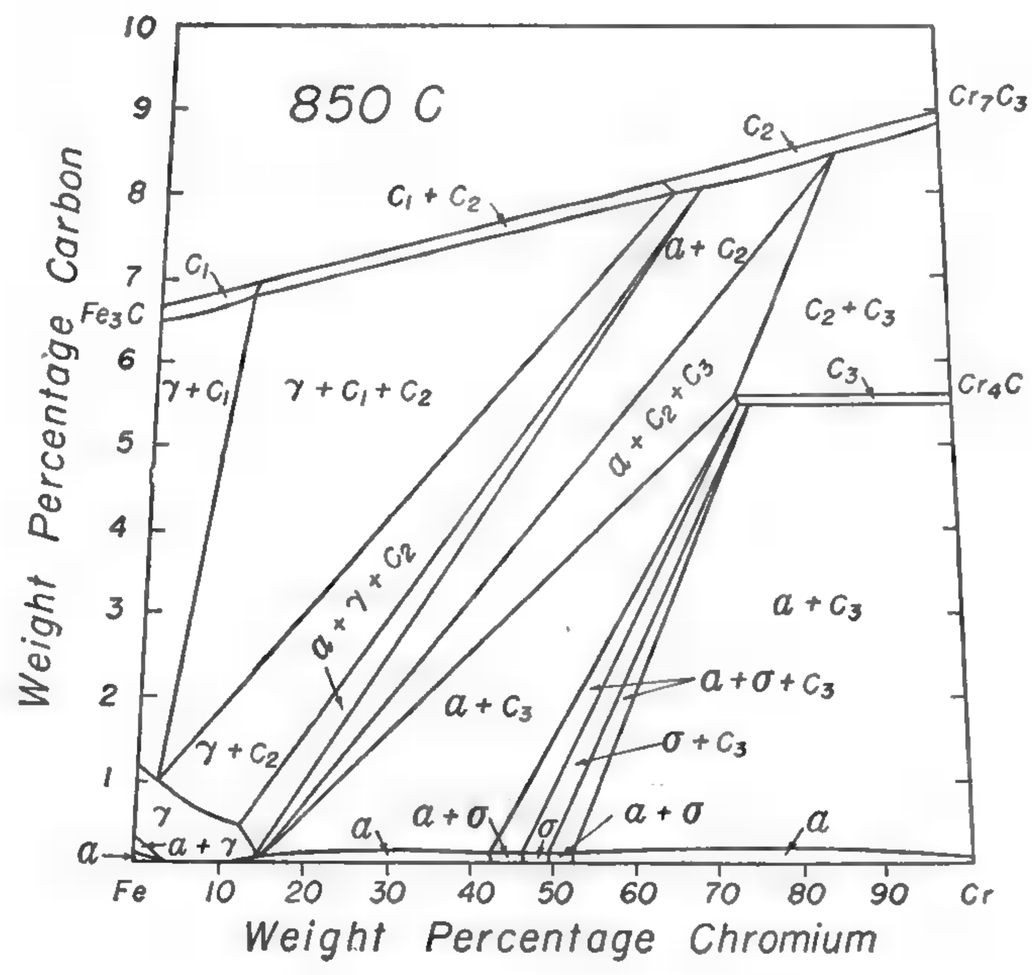
$\gamma + C_2$
$\alpha + C_3$
$\alpha + \gamma + C_2$
$\alpha + C_2$
$\alpha + \gamma$
γ
α
Weight Percentage Carbon
Weight Percentage Chromium
Fe
Cr


850 C
Cr_7C_3
C_2
$C_1 + C_2$
C_1
Fe_3C
$\alpha + C_2$
$C_2 + C_3$
C_3
Cr_4C
$\gamma + C_1$
$\gamma + C_1 + C_2$
$\alpha + C_2 + C_3$
$\alpha + \gamma + C_2$
$\alpha + C_3$
$\gamma + C_2$
$\alpha + \sigma + C_3$
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γ
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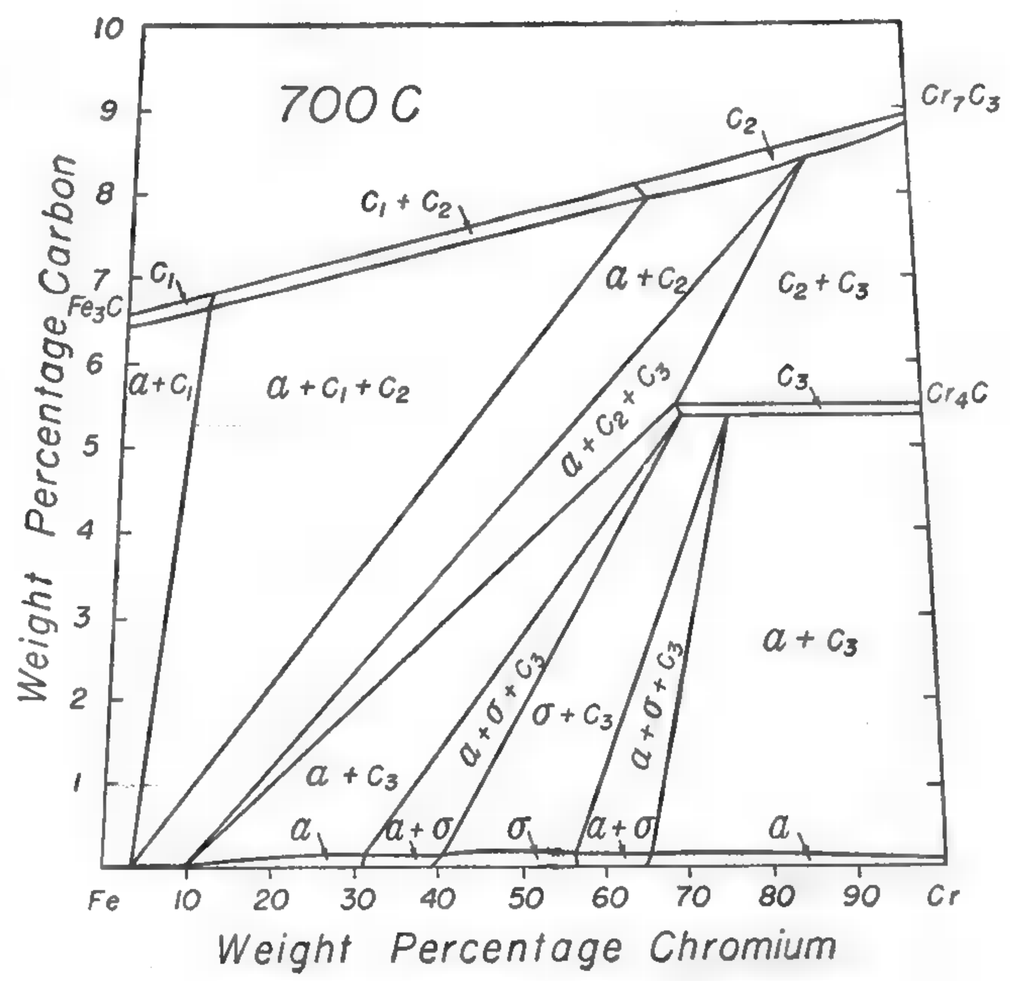
α
$\alpha + \sigma$
σ
Weight Percentage Carbon
Weight Percentage Chromium
Fe
Cr


700 C
Cr_7C_3
C_2
$C_1 + C_2$
C_1
Fe_3C
$\alpha + C_2$
$C_2 + C_3$
C_3
Cr_4C
$\alpha + C_1$
$\alpha + C_1 + C_2$
$\alpha + C_2 + C_3$
$\alpha + C_3$
$\alpha + \sigma + C_3$
$\sigma + C_3$
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α
$\alpha + \sigma$
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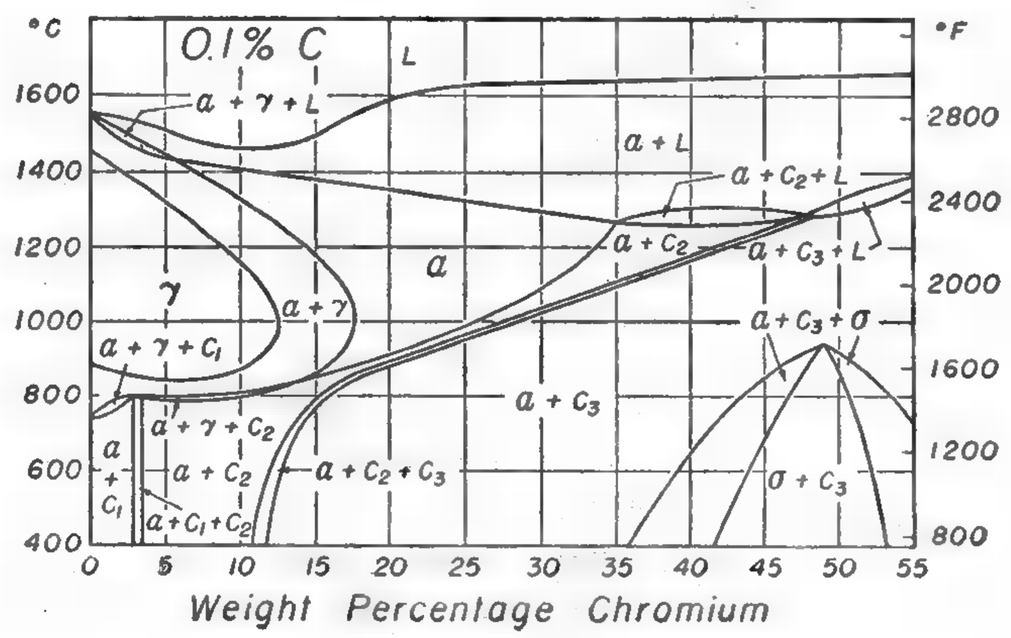
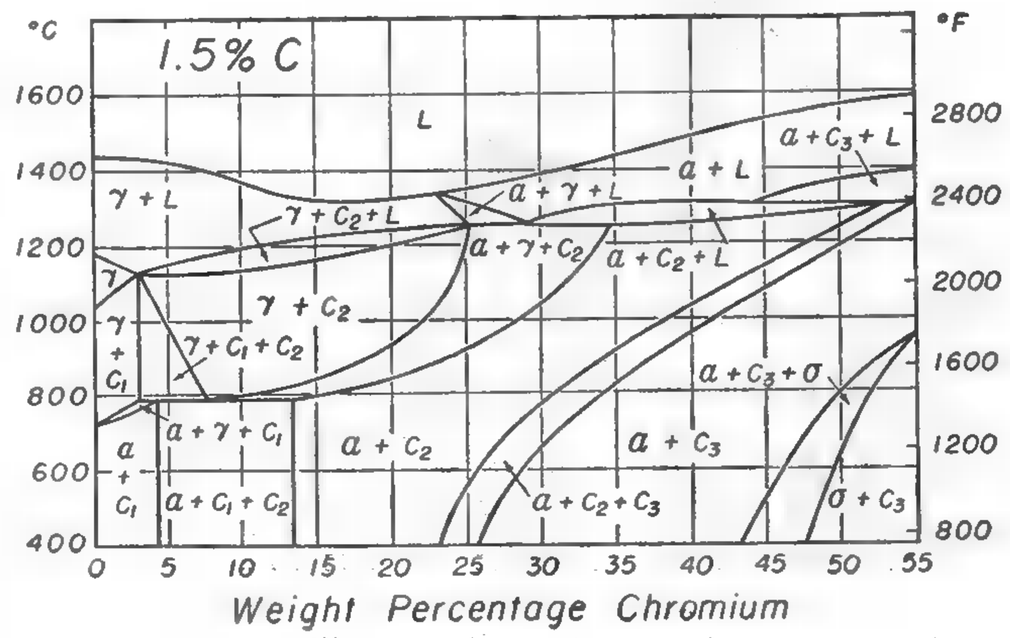
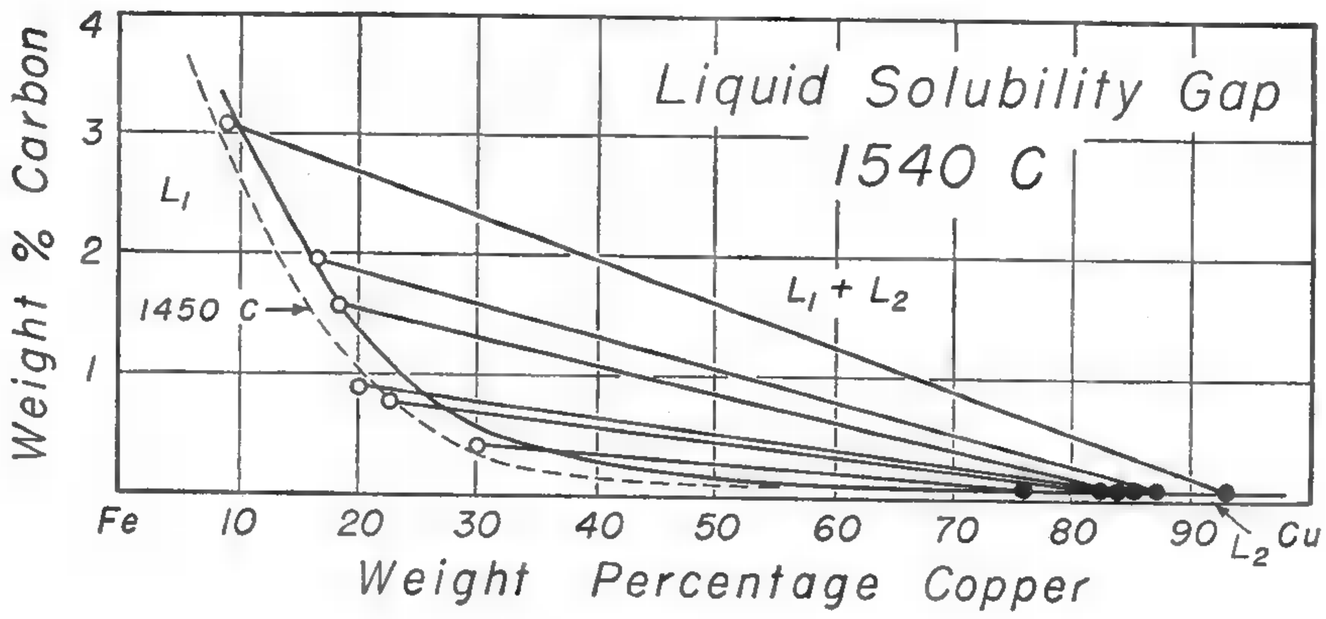
α
Weight Percentage Carbon
Weight Percentage Chromium
Fe
Cr

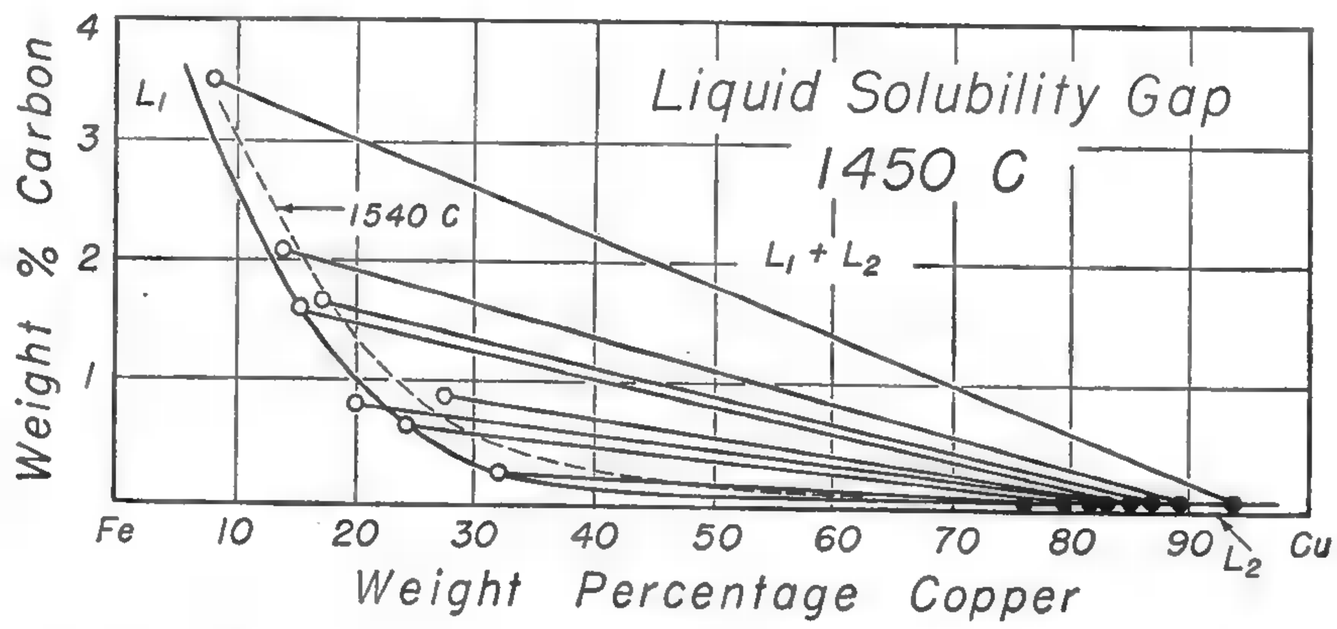

0.1% C
L
$\alpha + \gamma + L$
$\alpha + L$
$\alpha + C_2 + L$
$\alpha + C_2$
$\alpha + C_3 + L$
α
γ
$\alpha + \gamma$
$\alpha + \gamma + C_1$
$\alpha + C_3$
$\alpha + C_3 + \sigma$
$\alpha + \gamma + C_2$
$\alpha + C_2 + C_3$
$\sigma + C_3$
$\alpha + C_1 + C_2$
°C
°F
Weight Percentage Chromium

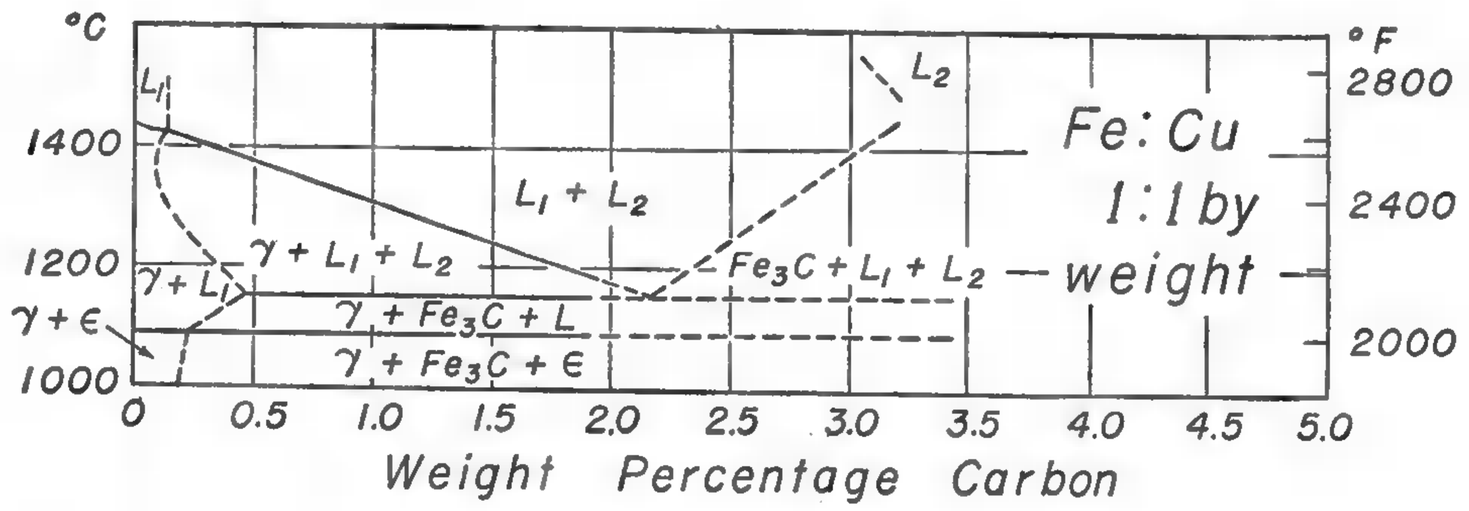

1.5% C
L
$\gamma + L$
$\alpha + \gamma + L$
$\alpha + L$
$\alpha + C_3 + L$
$\gamma + C_2 + L$
$\alpha + \gamma + C_2$
$\alpha + C_2 + L$
γ
$\gamma + C_2$
$\gamma + C_1 + C_2$
$\alpha + C_3 + \sigma$
$\alpha + \gamma + C_1$
$\alpha + C_2$
$\alpha + C_3$
$\alpha + C_2 + C_3$
$\sigma + C_3$
$\alpha + C_1 + C_2$
°C
°F
Weight Percentage Chromium

C-Cu-Fe Carbon-Copper-Iron

By B. N. Daniloff*







The following phases have been proved to exist in the system: L_1, iron-rich liquid; L_2, copper-rich liquid; α, γ, δ and ϵ solid solutions, and iron carbide. Evidence of graphite has also been reported[5] at higher concentrations of carbon and copper.

Maddocks and Claussen[3] determined the intersection of the two-liquid region with the liquidus surface. Their work shows that the liquid immiscibility line does not intersect the iron-copper temperature-concentration plane. This is confirmed by the work of Iwasé[2] whose isothermal sections at 1450 and 1540 C are shown. According to Iwasé, about 0.02% C is sufficient to introduce liquid immiscibility in alloys containing 50% Fe and 50% Cu. The mutual liquid solubility increases with temperature.

The vertical section through the 50% Fe – 50% Cu line, obtained by Maddocks,[3] shows that the monotectic and peritectic four-phase planes exist separately, the former at 1150 C and the latter at 1094 C. The iron-carbon eutectic temperature is raised to 1150 C by the addition of copper, and the monotectic four-phase point is at about 4.2% C and 2.5% Cu.

* San Francisco Naval Shipyard, San Francisco

The δ-γ transformation temperature of the iron-carbon system is raised by the addition of copper.[6]

The ϵ phase probably dissolves some carbon, although quantitative data are lacking.

The extent of the γ phase has not been accurately established. According to Ishiwara[1] the maximum extent of the γ solid solution is at 1.7% C and about 6% Cu. The γ region is limited below by the three surfaces representing primary separation of the α phase, ϵ phase and cementite. The ternary eutectoid point, according to Ishiwara, is at about 700 C and its composition about 0.9% C and 1.9% Cu.

It has been reported[4] that copper dissolves 0.0001% C at 1100 C and 0.003% C at 1700 C.

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1 T. Ishiwara, T. Yonekura and T. Ishigaki, Science Repts Tôhoku Imp Univ, 15, 81 (1926)
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3 W. R. Maddocks and G. E. Claussen, Iron Steel Inst (London), Special Rept No. 14, 1936, p 97
4 M. B. Bever and C. F. Floe, Trans AIME, 166, 128 (1946)
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6 J. H. Andrew, G. T. C. Bottomley, W. R. Maddocks and R. T. Percival, Iron Steel Inst (London), Special Rept No. 23, 1938, p 5

C-Fe-Mn Carbon-Iron-Manganese

By Cyril Wells*

In the ternary alloys, the α phase is a solid solution of carbon and manganese in α iron and the γ phase is a solid solution of carbon and manganese in γ iron. The phase designated C is a carbide of the form $(Fe,Mn)_3C$ in which as many as one-quarter of the iron atoms in the orthorhombic cementite crystal structure may be replaced by manganese.

Manganese atoms dissolved in α or γ replace some iron atoms. Carbon atoms dissolved in α or γ are present in interstices.

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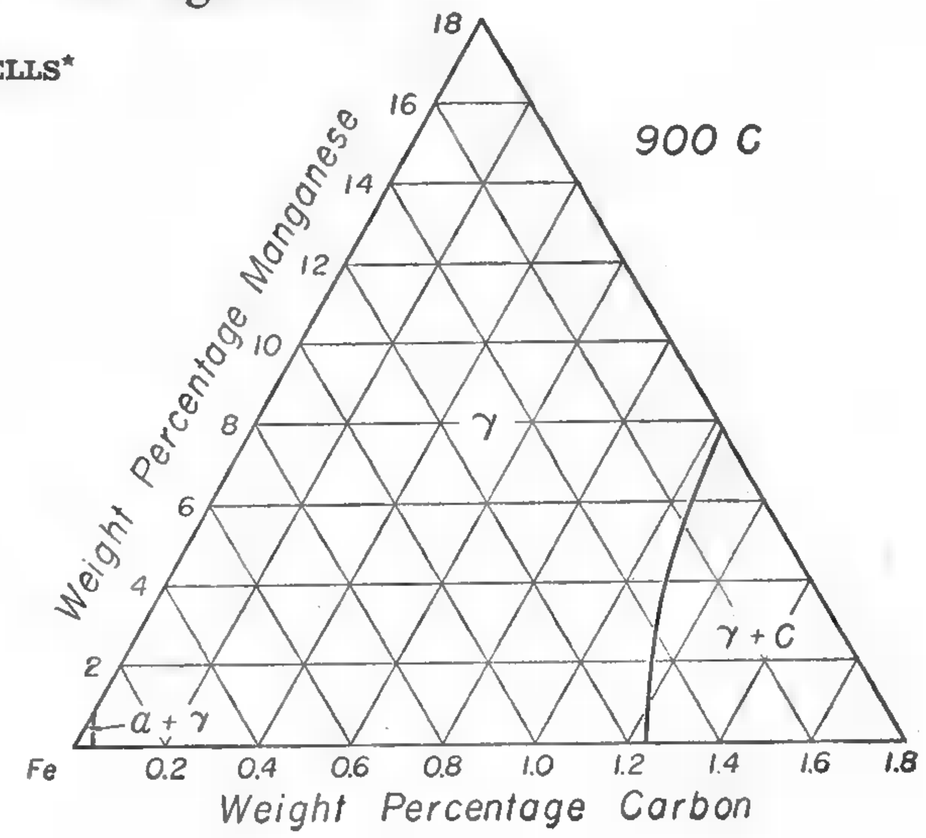
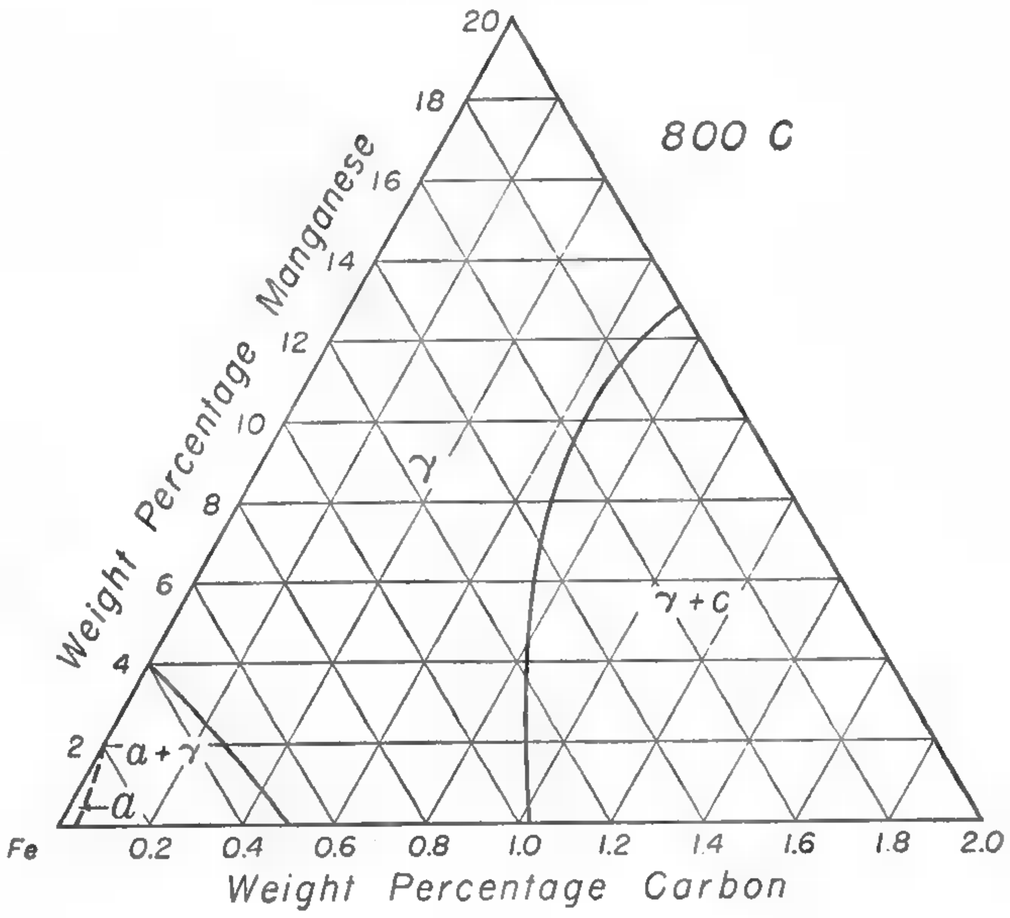
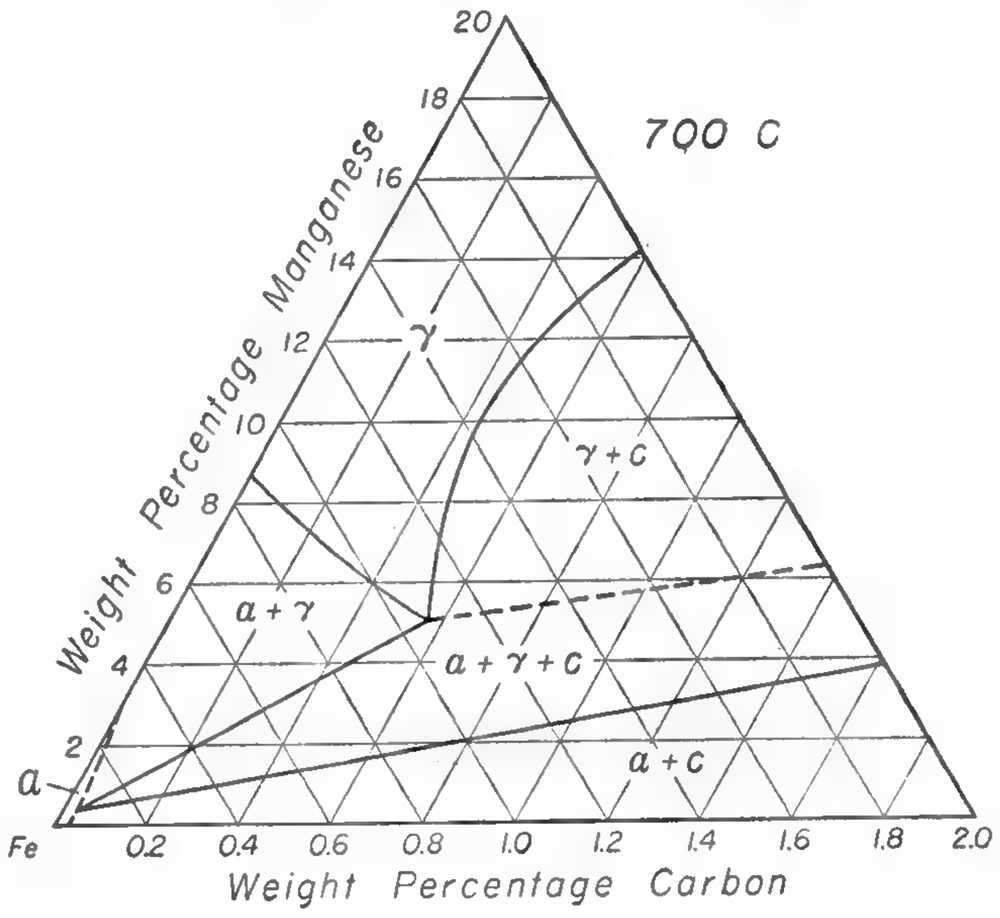
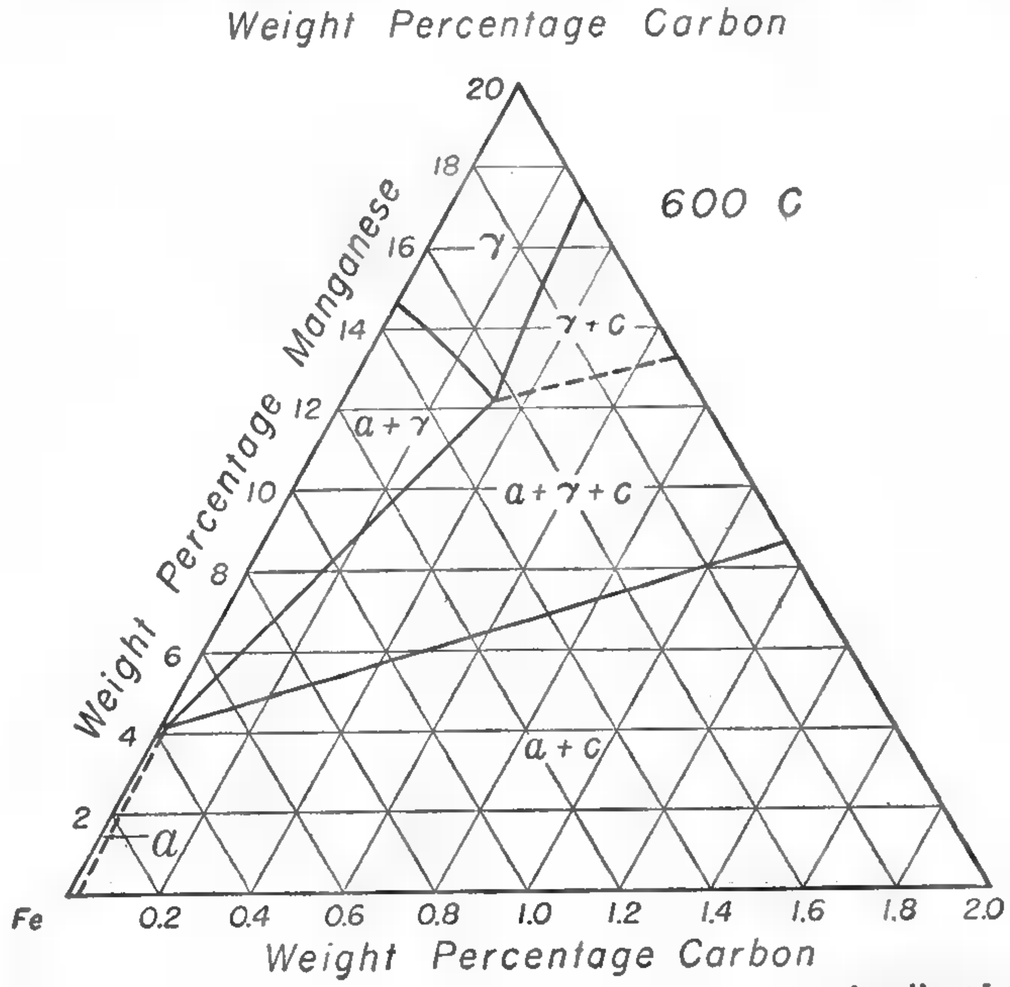
A. R. Troiano and F. T. McGuire, Trans ASM, 31, 340 (1943)

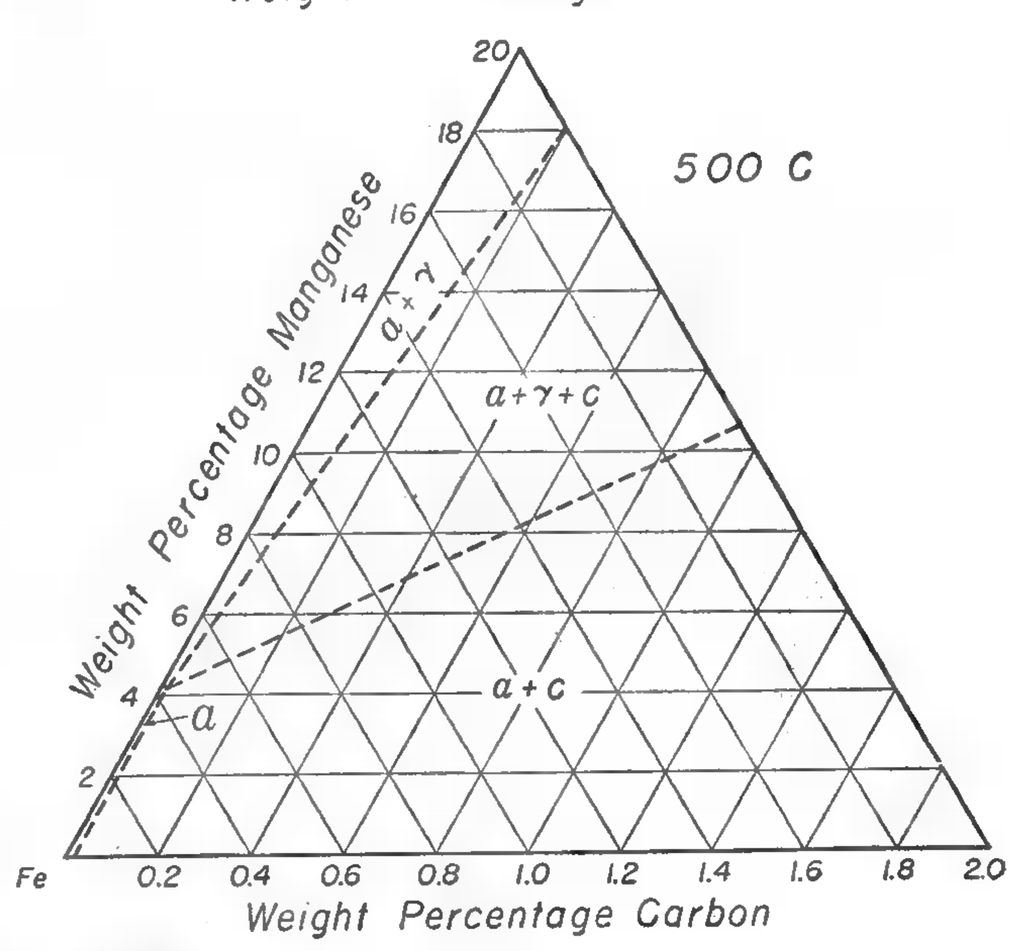
* Metals Research Laboratory, Carnegie Institute of Technology, Pittsburgh











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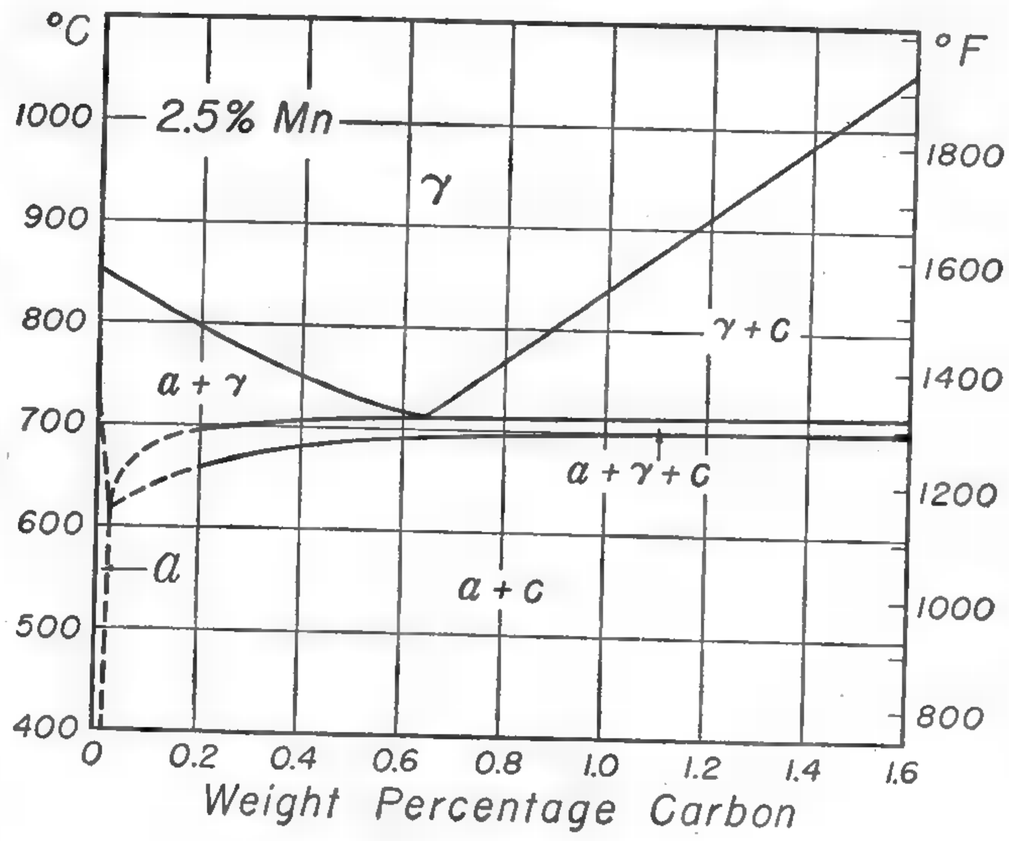
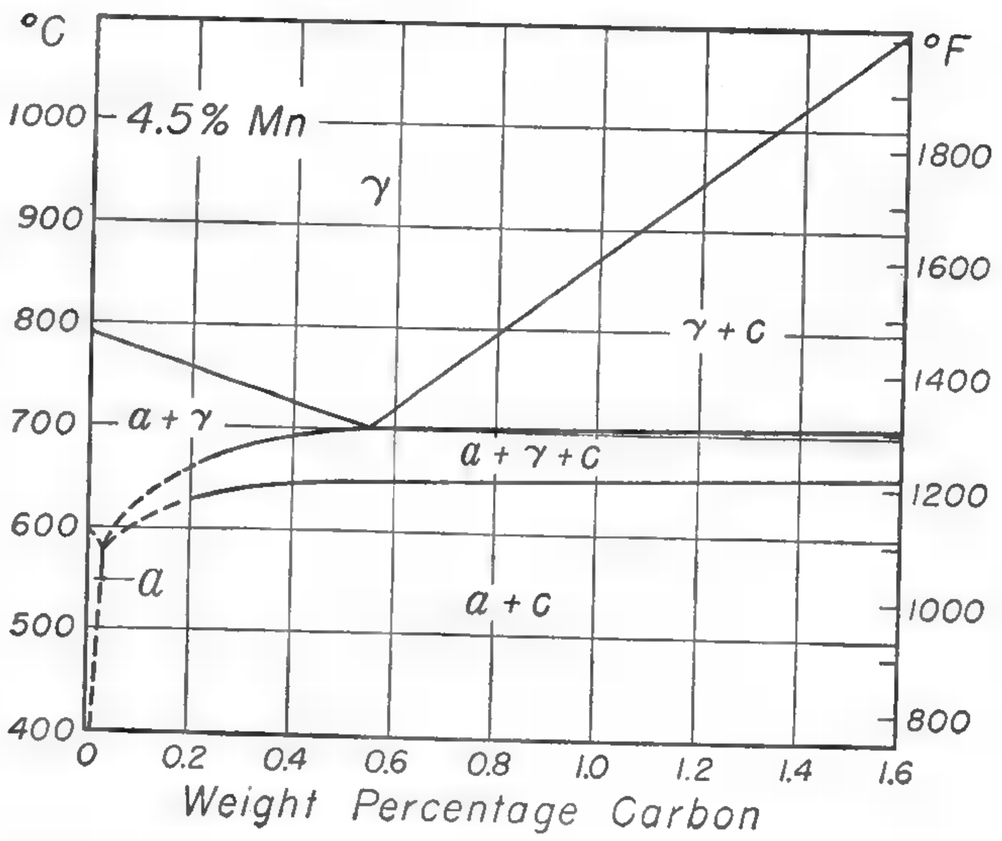
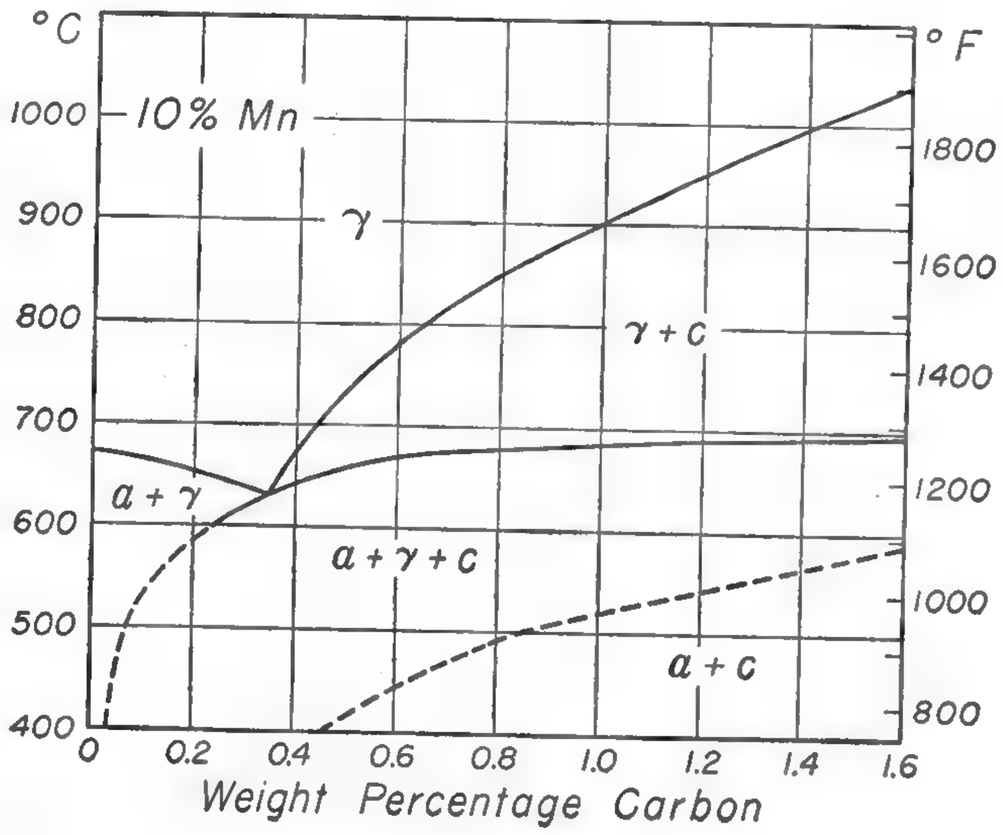
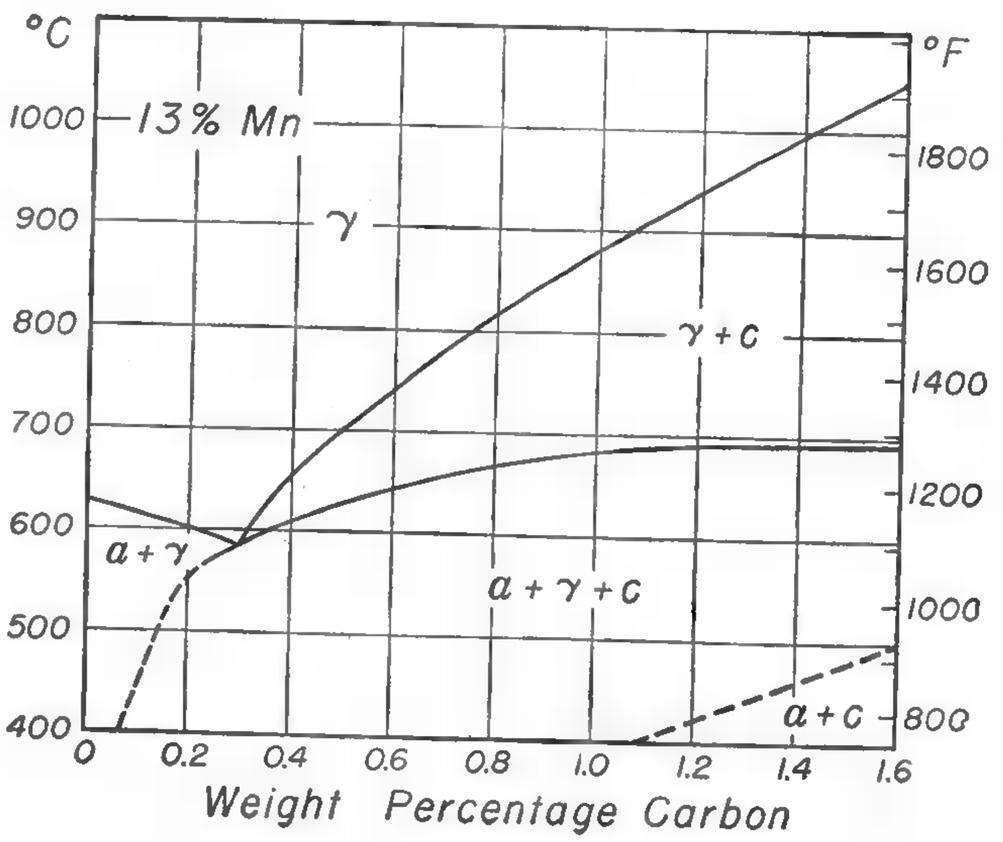








C-Fe-Mo Carbon-Iron-Molybdenum

By W. P. Sykes*

The complete diagram, as determined by Takei,[1] includes the iron-molybdenum side, and extends to Fe_3C and Mo_2C. The diagram is based on studies of 156 alloys. Some of the more important details included in the following paragraphs were taken from Marsh's review of Takei's data.[2]

Phase	Explanation
a	Solid solution of Mo and C in *a* Fe
γ	Solid solution of Mo and C in γ Fe
C	Fe_3C (capable of dissolving Mo, C, and Fe)
ω	Double carbide of Fe and Mo
ε	Fe_3Mo_2 dissolving Fe and C
η	FeMo dissolving Fe and C
θ	Mo_2C (capable of dissolving Fe and Mo)
δ	Solid solution of Fe and C in Mo

The double carbide, ω, is formed by peritectic reaction:

$$L + Mo_2C \rightleftarrows \omega$$

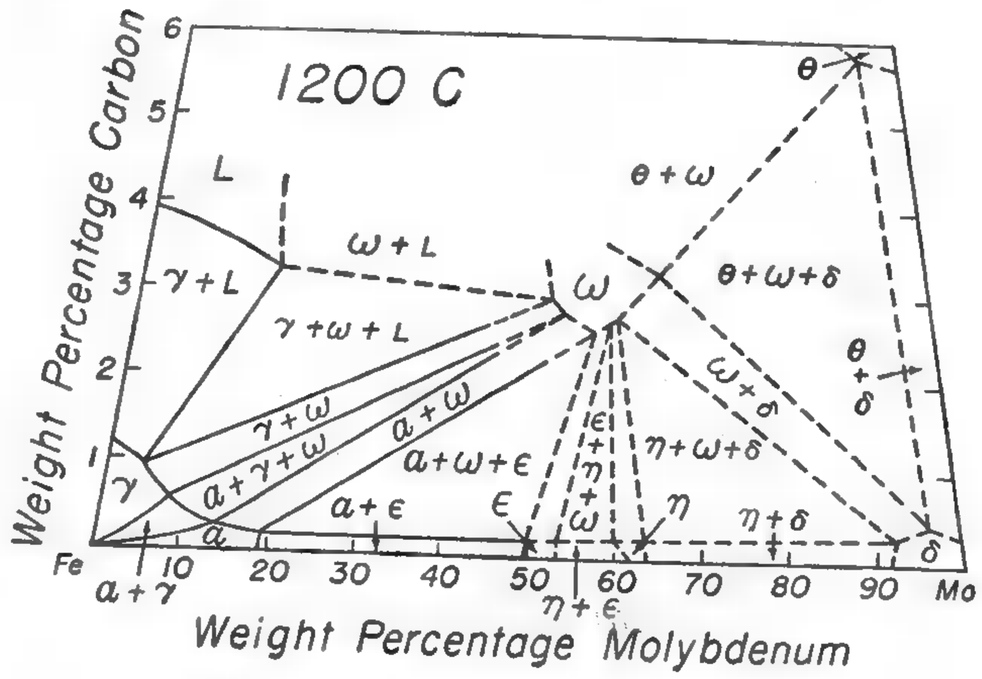
This phase forms eutectics with the binary phases.

The γ phase is decomposed by the peritecto-eutectoid reaction:

$$\gamma + \omega \rightleftarrows Fe_3C + a$$

The γ phase never coexists with the ε phase.

The η phase is decomposed by a eutectoid reaction as in the binary iron-molybdenum system.



* Lamp Department, General Electric Company, Cleveland

In the isothermal sections shown here the regions adjacent to the iron-molybdenum axis are not drawn to scale. This procedure shows clearly the shapes of these regions but gives an erroneous impression of magnitudes.

The sections at constant molybdenum contents, parallel to the carbon side, cannot be used to estimate relative proportions and compositions of the phases present, but these sections do show the identity of the phases.

Because of the existence of the ω phase the horizontal line corresponding to the iron-carbon eutectoid horizontal represents four-phase equilibrium $(\alpha + \gamma + \omega + C)$, which must be nonvariant in a system of three components. The three-phase field, corresponding to the "pearlite interval" in the iron-carbon-silicon system, is therefore eliminated in this system.

For information about the constitution of molybdenum steels, see Fig. 1 to 14 on pages 469 to 471.

References

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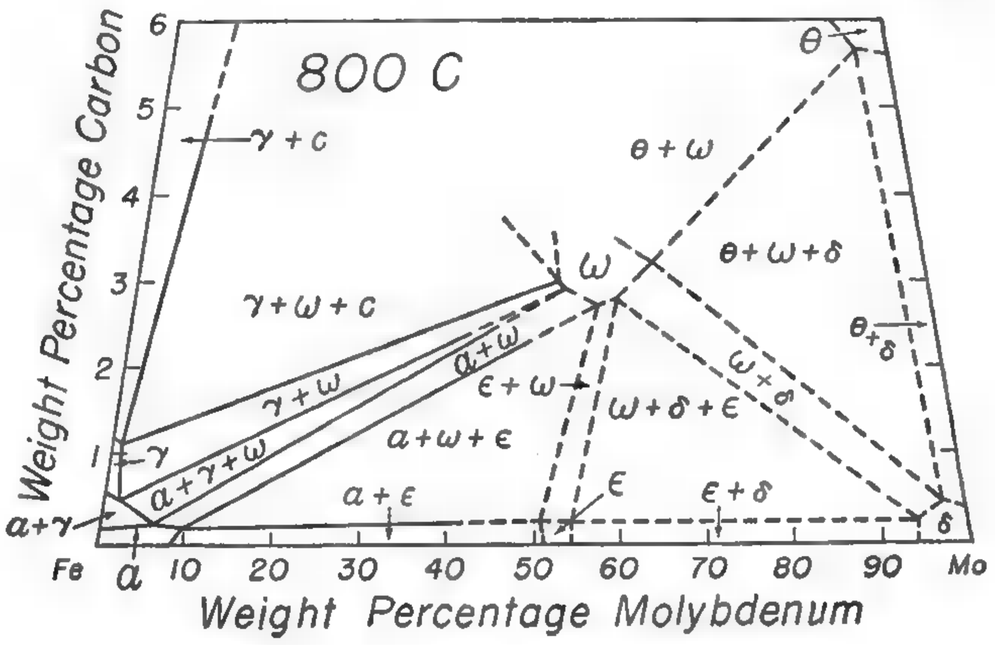
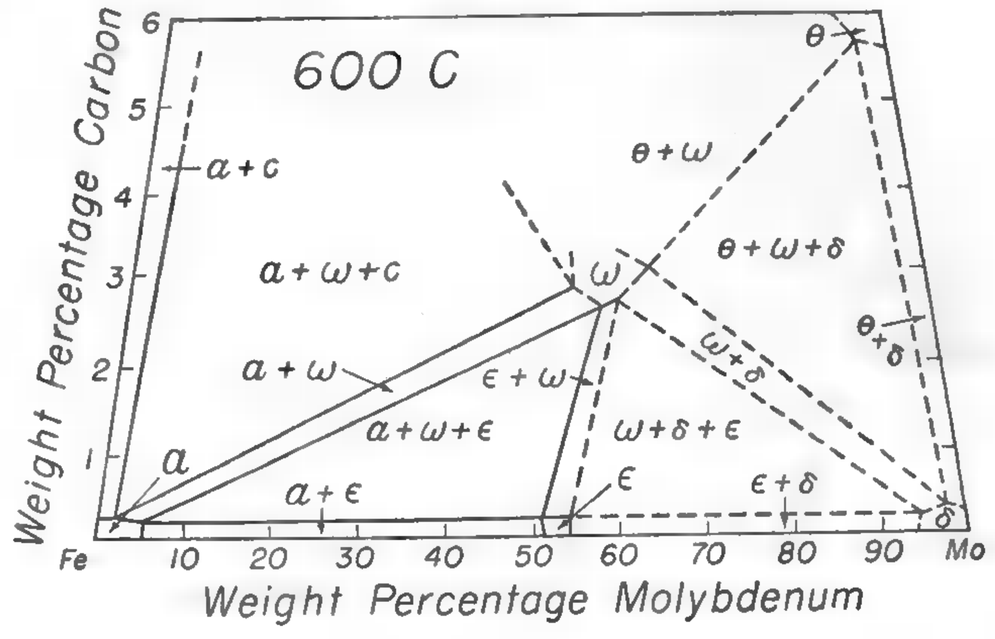
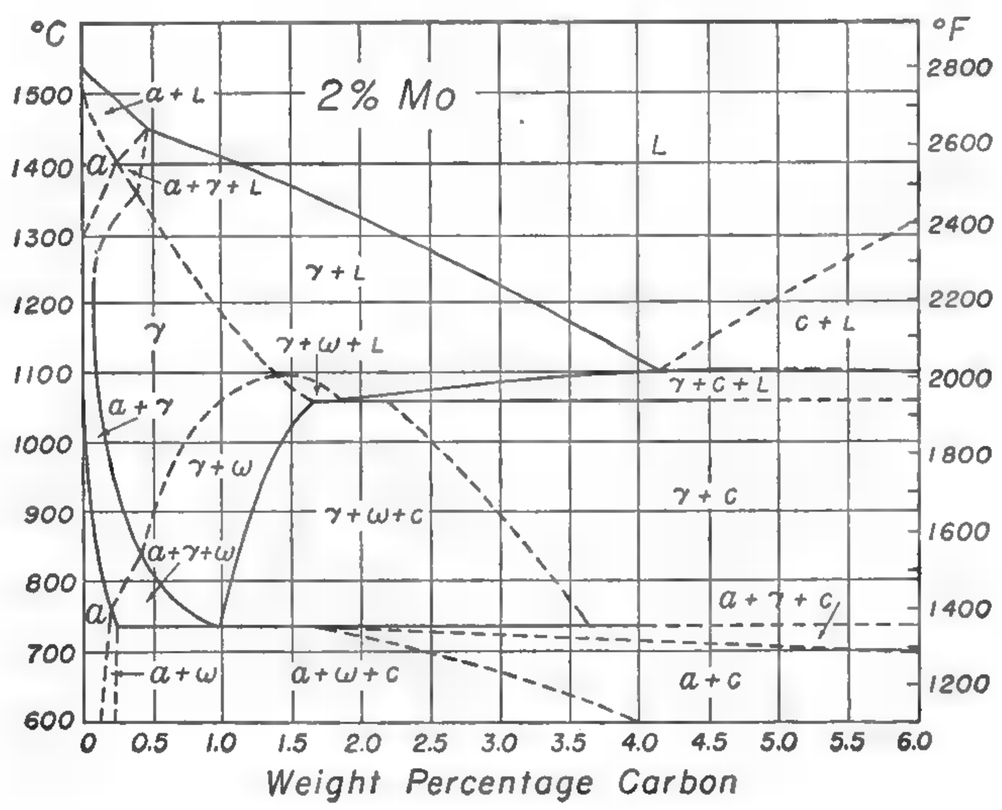
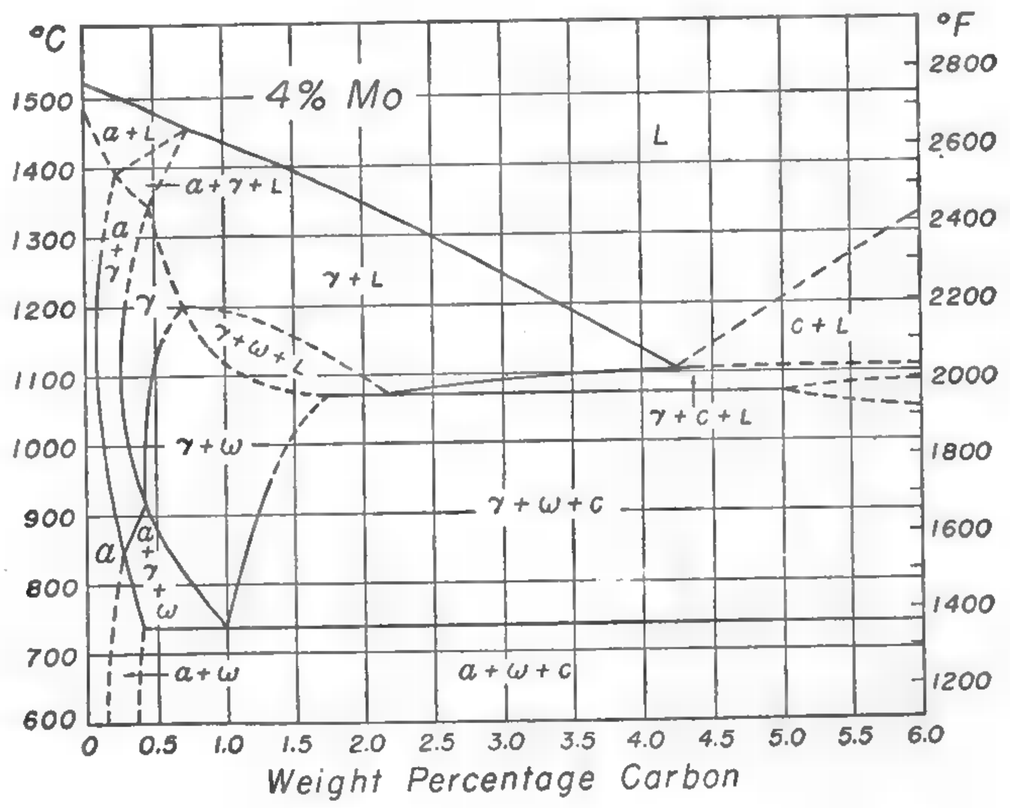
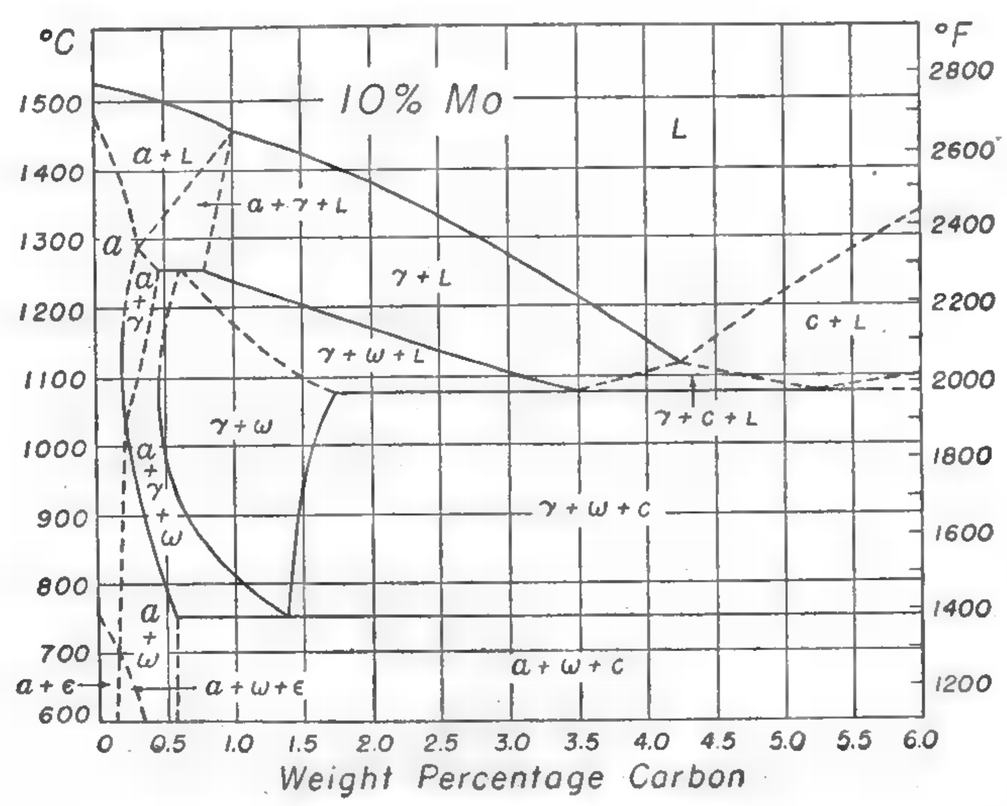
2 J. S. Marsh, Appendix 1, "Alloys of Iron and Molybdenum", Engineering Foundation, McGraw-Hill Book Co., New York, 1932

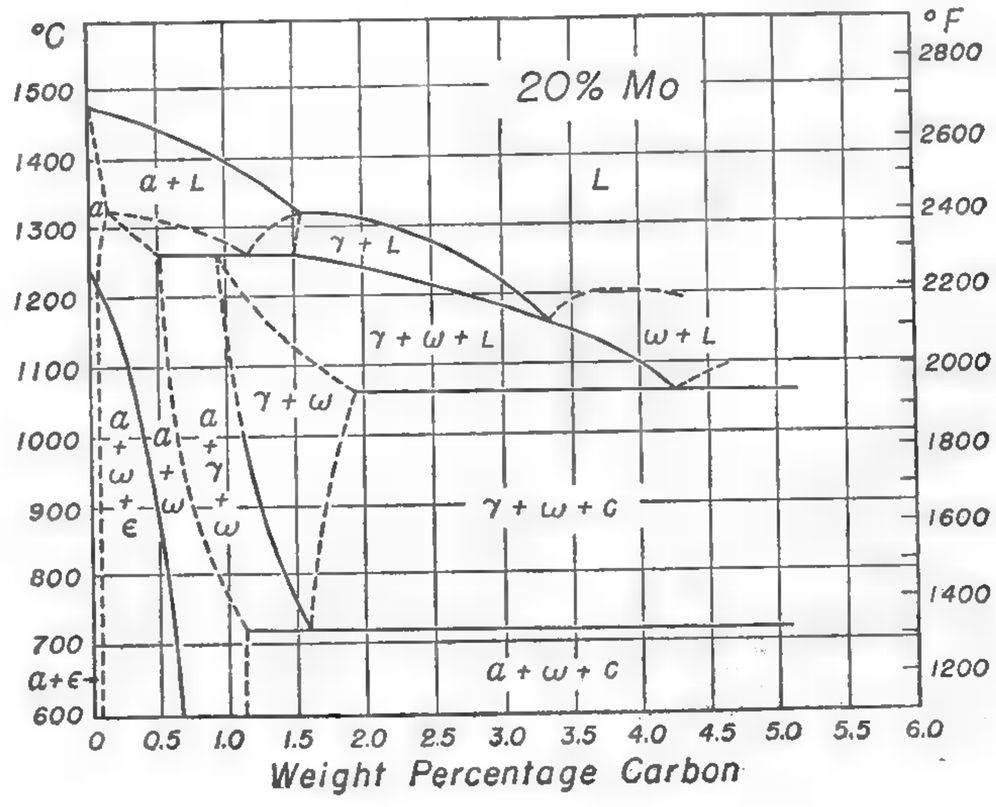












C-Fe-Ni Carbon-Iron-Nickel

By C. M. Schwitter*

The uncertainty surrounding the true equilibrium system makes it inadvisable to present any diagram as authoritative. Reference may be made to the efforts of Marsh[1] to construct a diagram from available information. He concluded that "all possibility of arriving at a most probable iron-carbon-nickel diagram collapses because of . . . . inadequate experimental work on the ternary system."

A practical approach to a structural diagram is contained in the article entitled "Nickel in Steel", on page 473 of this Handbook. This is based on the work of Eash and Pilling[2] from a study of the microstructures developed in slowly cooled cast bars.

Although the equilibrium diagram is in doubt, certain effects of nickel on the iron-carbon system are fairly well known. Nickel is completely soluble in the liquid phase and remains in solid solution in both gamma and alpha iron. In the low-carbon hypoeutectic region of the iron-carbon system, the liquidus temperature appears to be lowered slightly by nickel, but the eutectic temperature is raised approximately 3 °C per 1% Ni over the range 0 to 50% Ni, and the carbon content of the eutectic is decreased about 0.03 to 0.06% for each 1% Ni over the same range. It also appears that the spread between the liquidus and solidus decreases slightly with nickel content over most of the range.

The effect of nickel up to 5 or 6% on the hypoeutectoid region of the iron-carbon system has been established by Scott[3] for commercial nickel steels. The A_3 transformation is lowered about 20 °C per 1% Ni. Each per cent of nickel lowers the A_1 or eutectoid temperature 10.6 °C, and reduces the carbon content of the eutectoid by 0.042%.

* The International Nickel Company, Inc., New York

References

1 J. S. Marsh, "Alloys of Iron and Nickel", Vol I, Engineering Foundation, McGraw-Hill Book Co., New York, 1938, p 56–82
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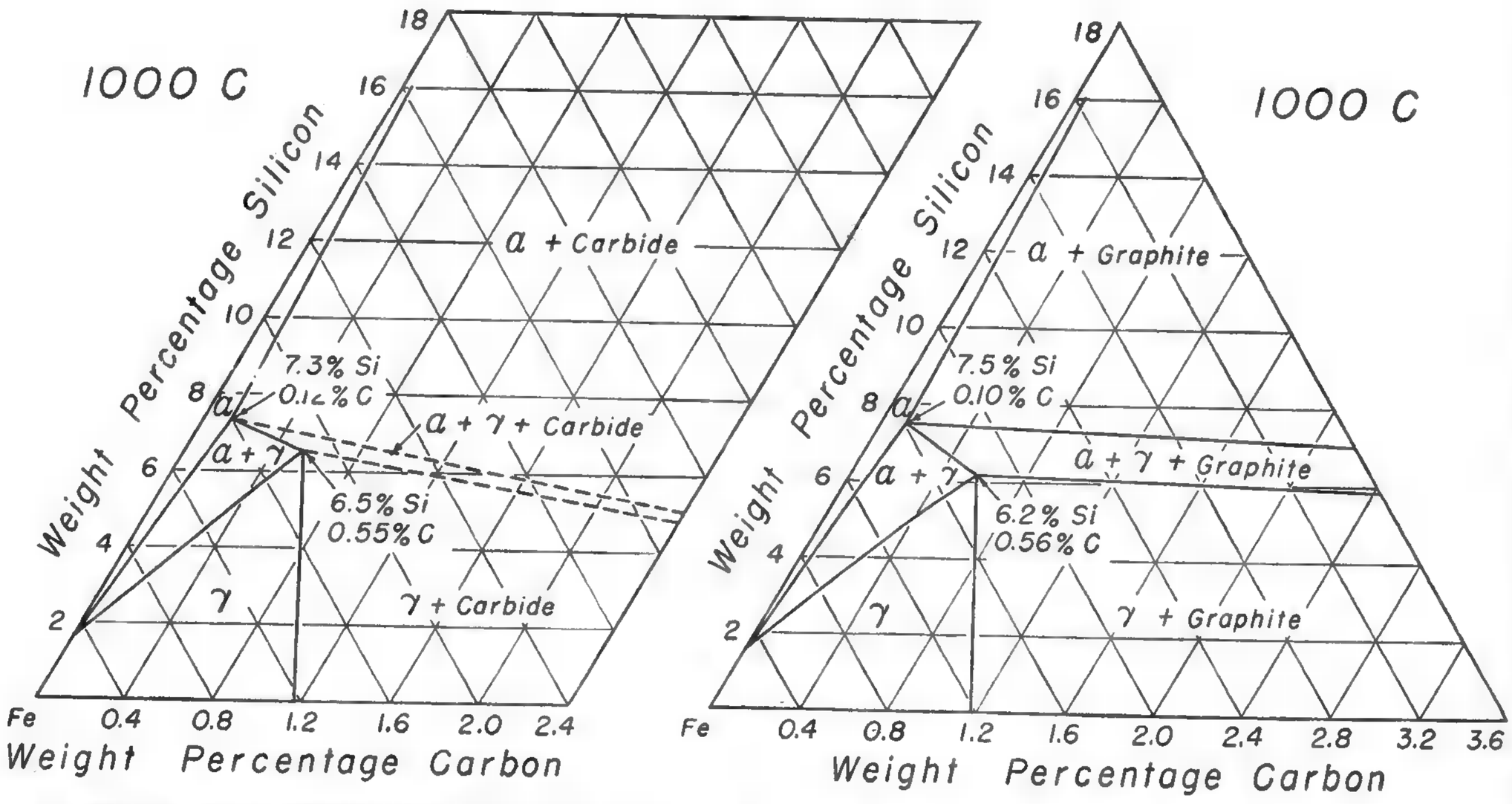
C-Fe-Si Carbon-Iron-Silicon

By Earl S. Greiner*



In view of the uncertainty concerning the stability of Fe_3C that has dissolved some silicon, two types of equilibrium for the iron-carbon-silicon alloys are considered:

(*a*) Fe-Si-(Fe,Si carbide)
(*b*) Fe-Si-C (as graphite)

An isothermal section of the iron-rich Fe-Si-(Fe,Si carbide) system at 1000 C, derived from data of Kriz and Poboril,[1] and a similar section at the same temperature for the Fe-Si-C(graphite) system are shown. At low temperature the isothermal section for the iron-rich alloys of the Fe-Si-(Fe,Si carbide) system will presumably consist of the α and α + (Fe,Si carbide) phase areas, and that for the Fe-Si-C(graphite) system will consist of the α and α + C(graphite) phase areas.

Additional data on the constitution of carbon-iron-silicon alloys can be obtained from the articles "Silicon in Steel", page 476, and "Cast Iron", page 505 in this Handbook.

* Bell Telephone Laboratories, Murray Hill, N.J.

References

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5 E. Jänecke, Z Metallkunde, 32, 142 (1940); and 33, 186 (1941)
6 R. L. Rickett and N. C. Fick, Trans AIME, 167, 346 (1946)

C-Fe-Ti Carbon-Iron-Titanium

By M. F. Hawkes*

There is evidence for a pseudobinary eutectic system between TiC and Fe_3C. The solubilities of titanium in Fe_3C and of iron in TiC are apparently very small.

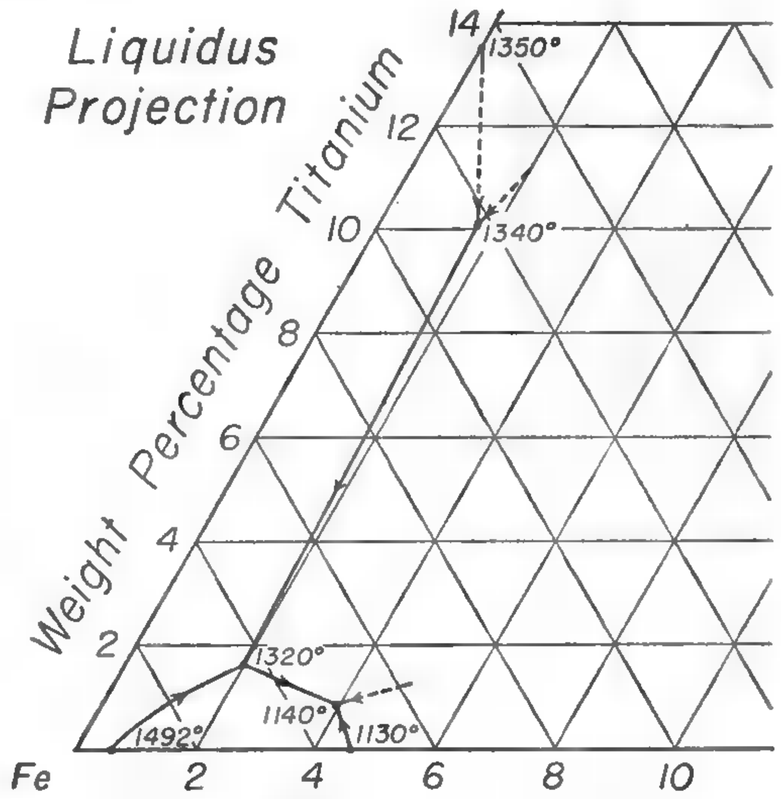
The value of 1350 C for the Fe-Fe_2Ti eutectic (instead of 1310 C as shown in the iron-titanium diagram in this Handbook) is used in order to preserve the relationships among the various quaternary equilibriums as developed by Tofaute and Büttinghaus.[1] Diffusion studies by Gaeff[2] lend support to this value, which is higher than most other investigators have reported.

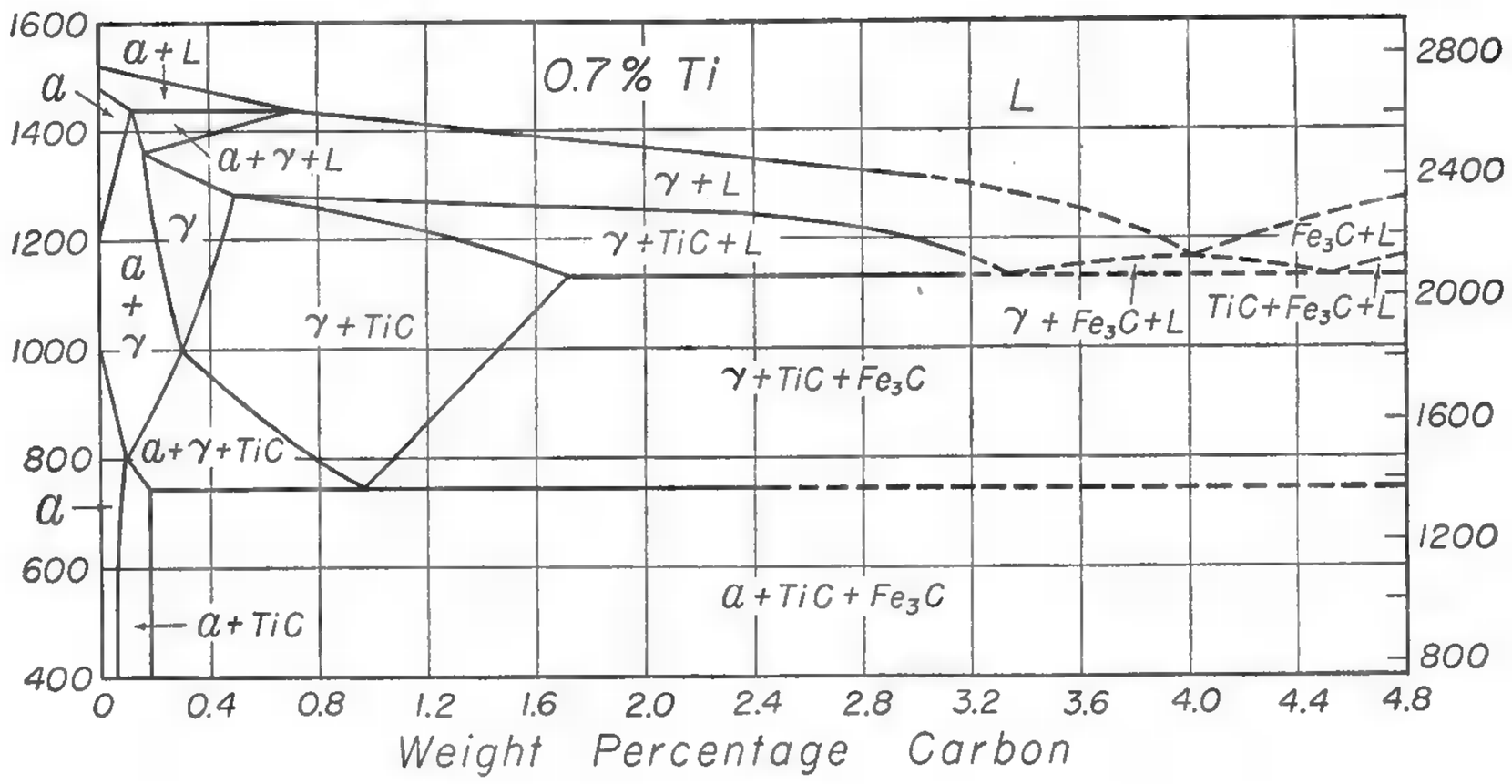
The first intermediate phase in the iron-titanium system is designated here as Fe_2Ti. Tofaute and Büttinghaus had assumed, from the work of previous investigators, that this phase is Fe_3Ti, but there is reason to doubt the correctness of such an assumption. In the discussion of the iron-titanium system in this Handbook (*see* page 1219), references are cited which lead to the conclusion that Fe_2Ti represents the composition of this phase more accurately than Fe_3Ti.

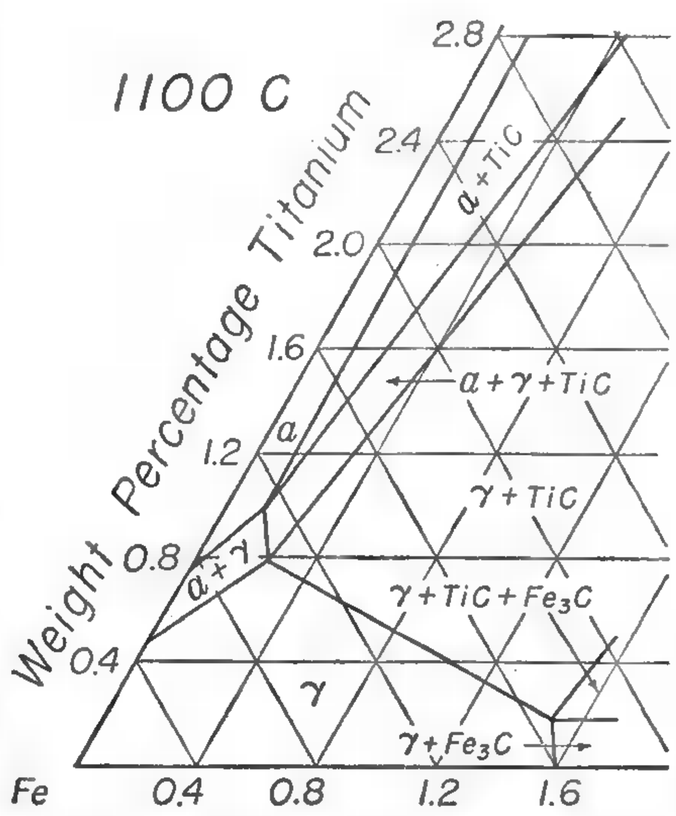
References

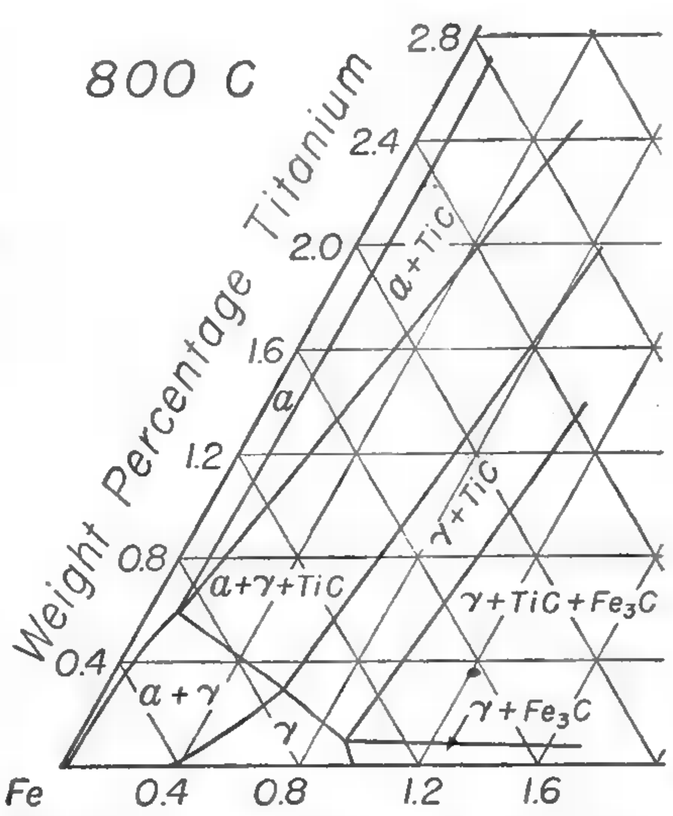
1 W. Tofaute and A. Büttinghaus, Arch Eisenhüttenw, 12, 33 (1938)
2 I. Gaeff, Metallurg, 10, 19 (1934)

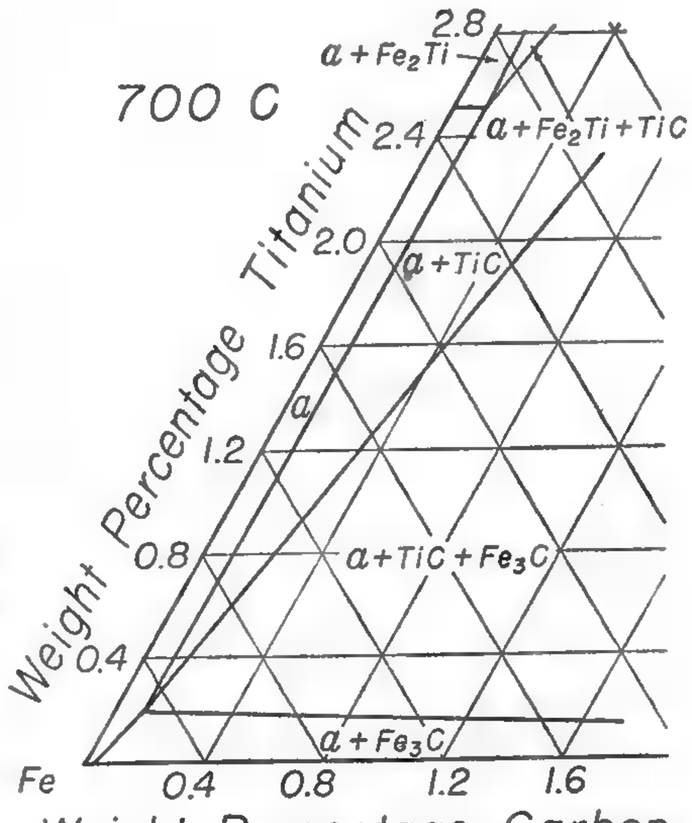
* Carnegie Institute of Technology, Pittsburgh





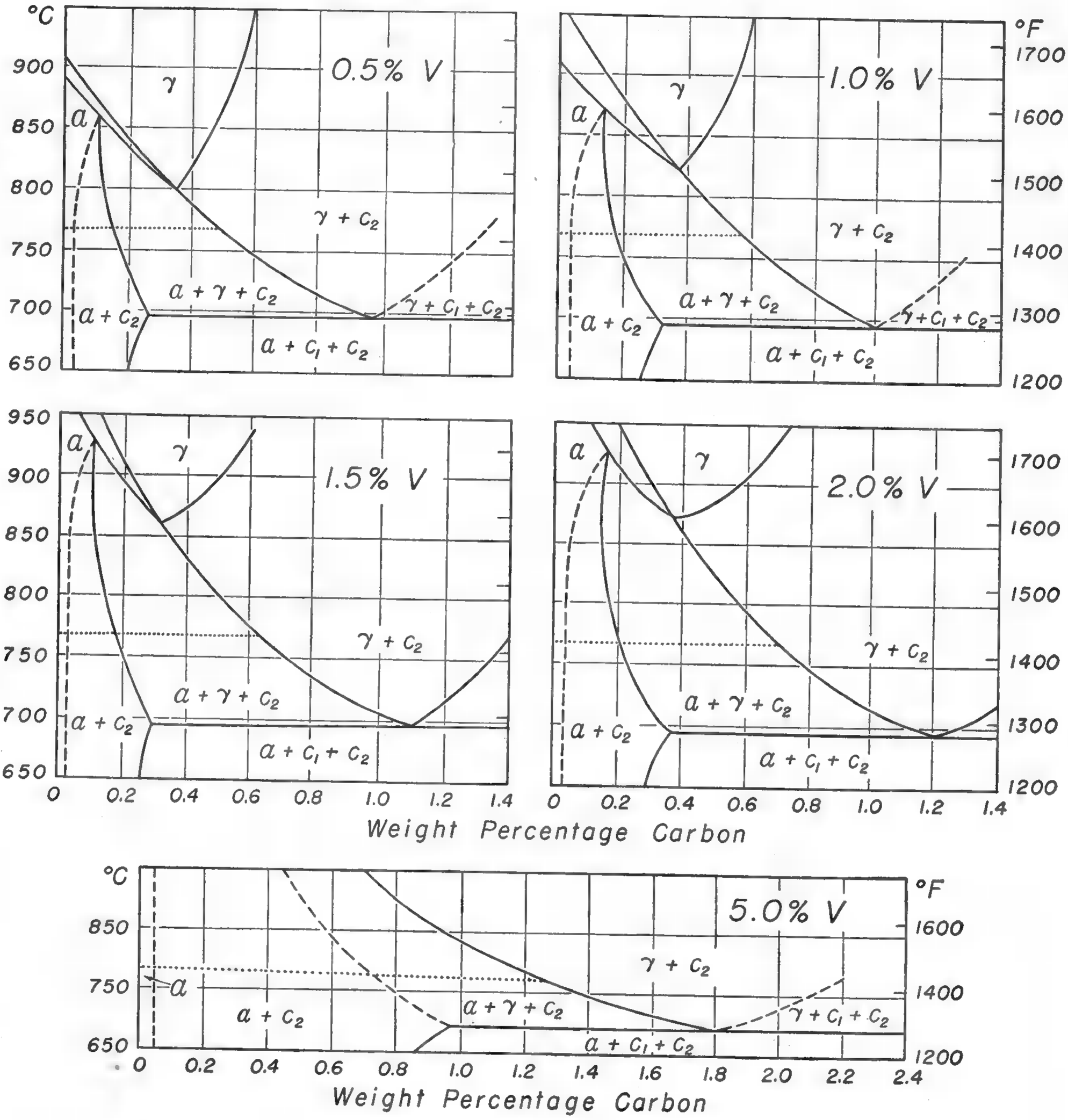






C-Fe-V Carbon-Iron-Vanadium

By Jerome Strauss* and Carl L. Shapiro*



The vertical sections presented by Wever, Rose and Eggers[1] are shown. The phases indicated by C_1 and C_2 here were designated Fe_3C and V_4C_3, respectively, in the original.[1]

The extension of the gamma field by carbon may be compensated by adding vanadium in approximately the ratio of vanadium to carbon in V_4C_3.[2] The solubility of carbon in γ is decreased by the addition of vanadium.[1,3]

Vanadium carbides not shown in the diagram may exist but no double carbide with iron is known.[4,5,6,7]

Vogel and Martin[8] claim that vanadium increases the solubility of carbon in ferrite.

* Vice President and Technical Director, Vanadium Corporation of America, New York
* President, Acryvin Corporation of America, Astoria, L. I., N. Y.

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C-Fe-W Carbon-Iron-Tungsten

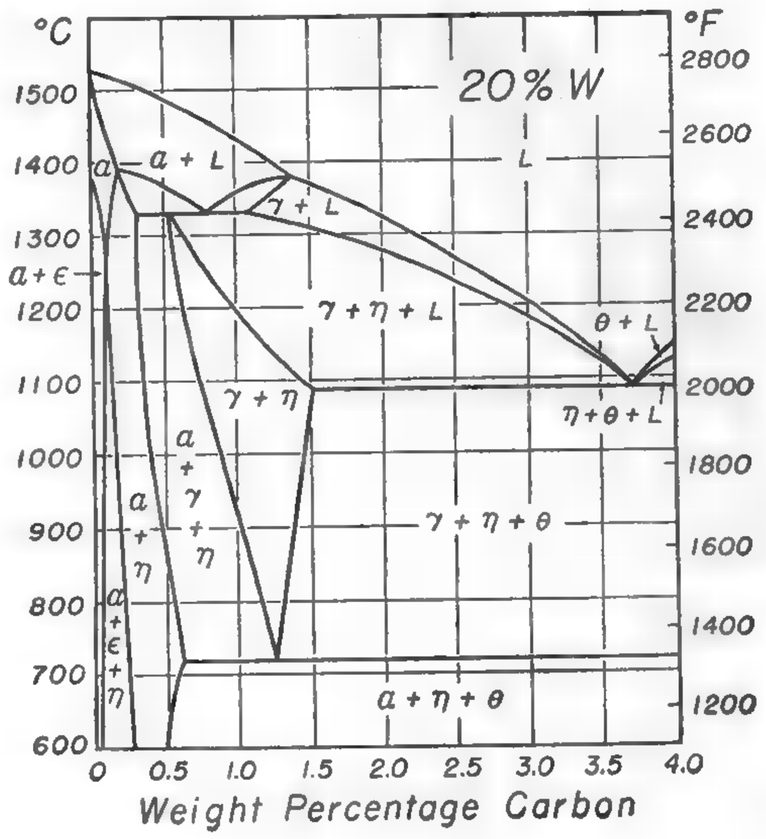
By G. A. Roberts* and A. H. Grobe*

Takeda[1] postulates that $(Fe,W)_6C$ is metastable with respect to WC as Fe_3C is with respect to graphite. Therefore, the diagrams here represent metastable conditions.

According to many investigators, the stable carbides are WC and W_2C. However, as these carbides are seldom formed in ordinary heat treating operations, the more commonly observed, complex carbide has been shown in the ternary sections. The section of the diagram between tungsten and Fe_3C is a quasi-binary section.

Westgren and Phragmén[2] report $(Fe,W)_6C$ to be face-centered cubic with 112 atoms per unit cell and a lattice parameter of approximately 11.08 kX. The carbide probably varies in composition between Fe_3W_3C at 1.64% C and Fe_4W_2C at 1.99% C.

Both Fe_2W and Fe_3W_2 have been reported as stable phases in the iron-tungsten system. For this ternary diagram, only Fe_3W_2 (labeled epsilon) has been shown.



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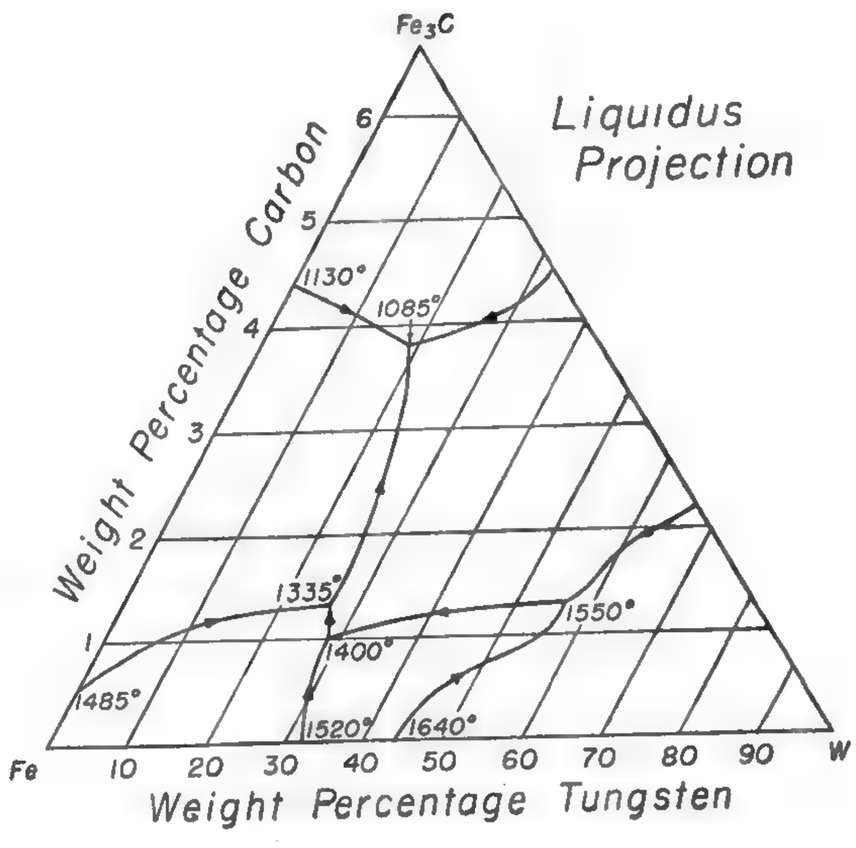
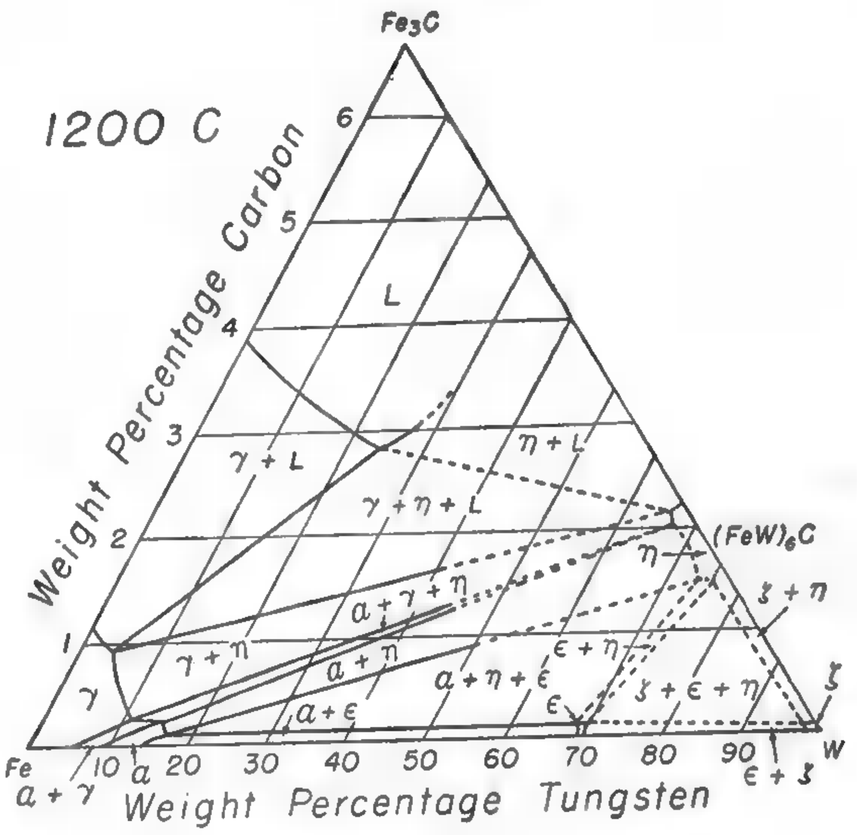
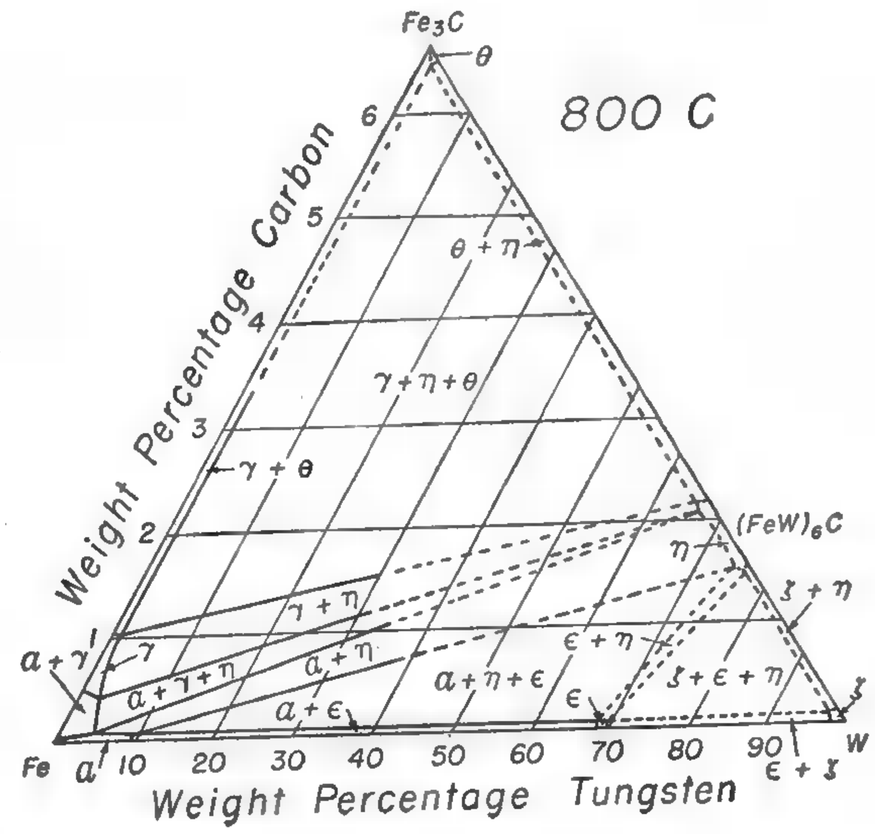
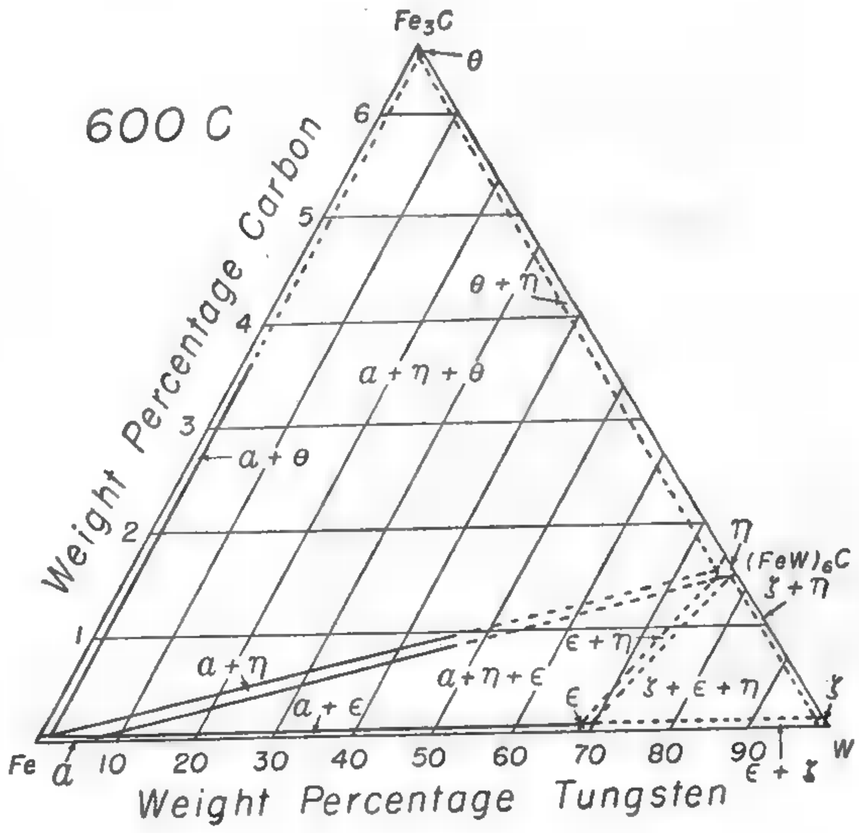
* Vanadium-Alloys Steel Company, Latrobe, Pa.









Cd-Sb-Sn Cadmium-Antimony-Tin

By W. T. Pell-Walpole*

The alloys of industrial interest in this system are confined to the tin-rich region, and detailed investigation has been limited to alloys containing up to 14% Sb and 45% Cd.

The constitution is depicted by (*a*) contour maps of the liquidus, the solidus, the surfaces of secondary separation, and the invariant reactions; (*b*) the isothermal sections for four temperatures; (*c*) two vertical sections of the most important group of alloys; and (*d*) a contour map showing the ternary limits of the α phase.

The phase nomenclature has been selected to be consistent with that used for the binary cadmium-tin system; that is, α, β, γ designate the phases originating in that binary system; the compound phases are referred to by δ and ϵ, or by their approximate chemical formulas, SbSn and CdSb respectively.

The five areas of the liquidus surface correspond to the primary separation of the phases, as follow:

Area *ABCDE* — α
DEFG — β
BCKL — SbSn
FGIH — γ
CDGIJK — CdSb

The surfaces of secondary separation are:

Area *ABCD* $\alpha + L \rightarrow \beta$
EFGHI SbSn $+ L \rightarrow \alpha$
JK'LM, *MLNO* $L \rightarrow \beta + \gamma$
GHP, *GPQ* $L \rightarrow$ CdSb + SbSn
BCGF, *CGQR* $L \rightarrow \alpha +$ CdSb
CRTL, *KK'LC* $L \rightarrow \beta +$ CdSb
TLU, *NLU* $L \rightarrow \gamma +$ CdSb

The solidus map has ten areas representing the solidification of single phases or phase combinations, as follow:

Area *ABCDE* Solidification of α from *L*
BCFG Lower surface of the reaction SbSn $+ L \rightarrow \alpha$
CFH Simultaneous solidification of α + CdSb + SbSn at 227 C
DCHI Solidification of α + CdSb from *L*
DEJK Lower surface of reaction $\alpha + L \rightarrow \beta$
JKNM Solidification of β from *L*
DKLI Simultaneous solidification of $\alpha + \beta$ + CdSb at 209 C
MNQR Lower surface of eutectic $L \rightarrow \gamma + \beta$
NOPQ Simultaneous separation of $\beta + \gamma$ + CdSb at 180 C

The area *OPRS*, shown in the same diagram as the invariant reactions, represents the inclined plane along which the eutectoid decomposition $\beta \rightarrow \alpha + \gamma$ occurs.

The ternary peritectic reactions that occur in equilibrium at 227 and 209 C are readily suppressed with normal rates of cooling; hence metastable phase combinations are common in as-cast alloys.

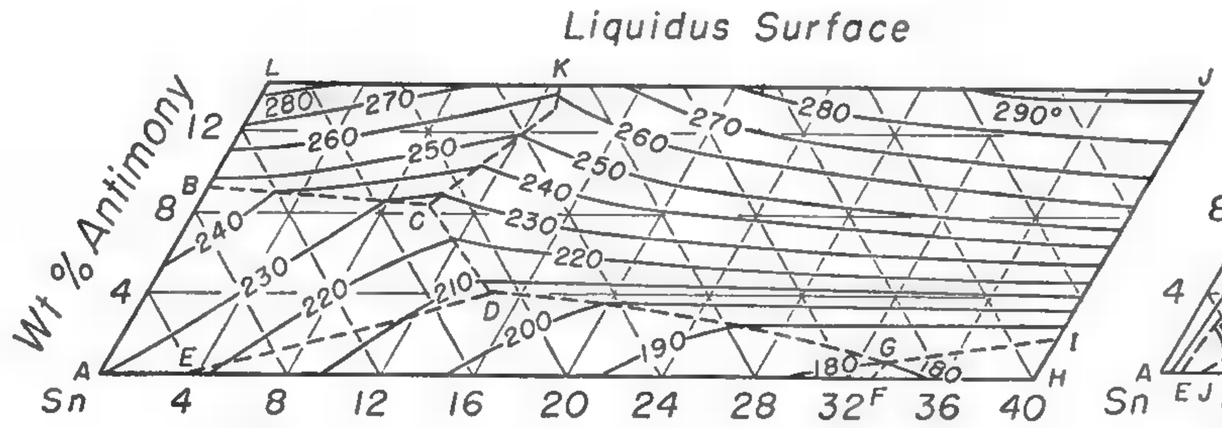
The β phase may be retained at room temperature by quenching, but gradually decomposes on standing. The eutectoid decomposition temperature is subject to marked undercooling and superheating.

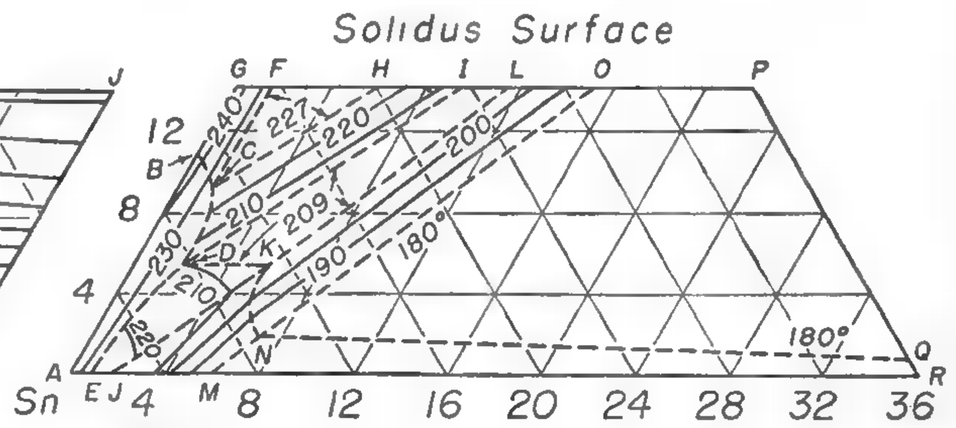
Crystal Structures and Composition Limits of Solid Phases

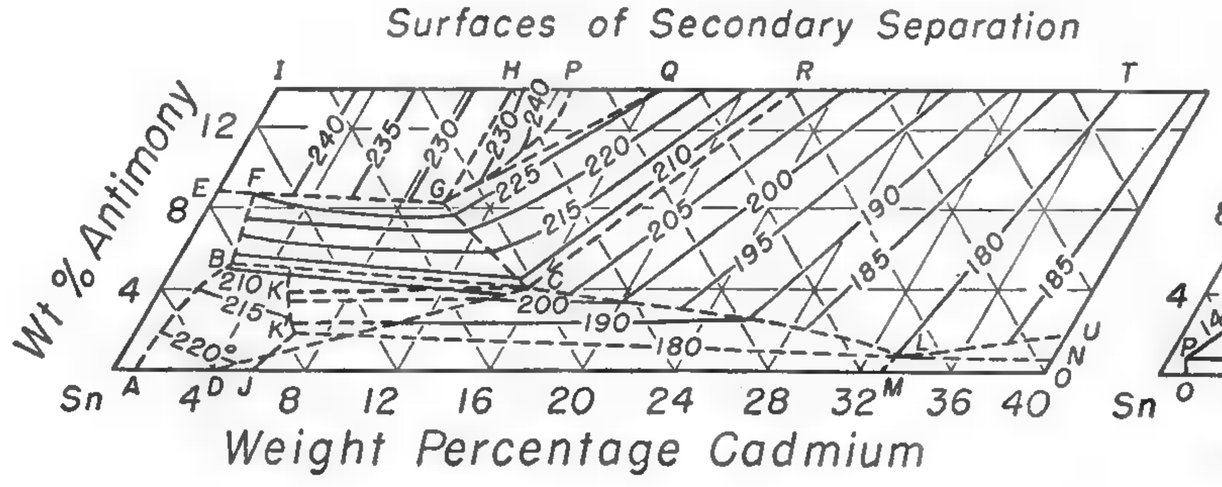
Phase	Structure	Maximum Solubility Limits
α	Tetragonal	9 % Sb, 1.5% Cd at 227 C 5.5% Sb, 2.4% Cd at 209 C
β	Undetermined	5.1% Sb, 5.5% Cd at 209 C 2.0% Sb, 7.0% Cd at 180 C
γ	Close-packed hexagonal	Undetermined
SbSn	NaCl type	Undetermined
CdSb	Rhombic	Undetermined

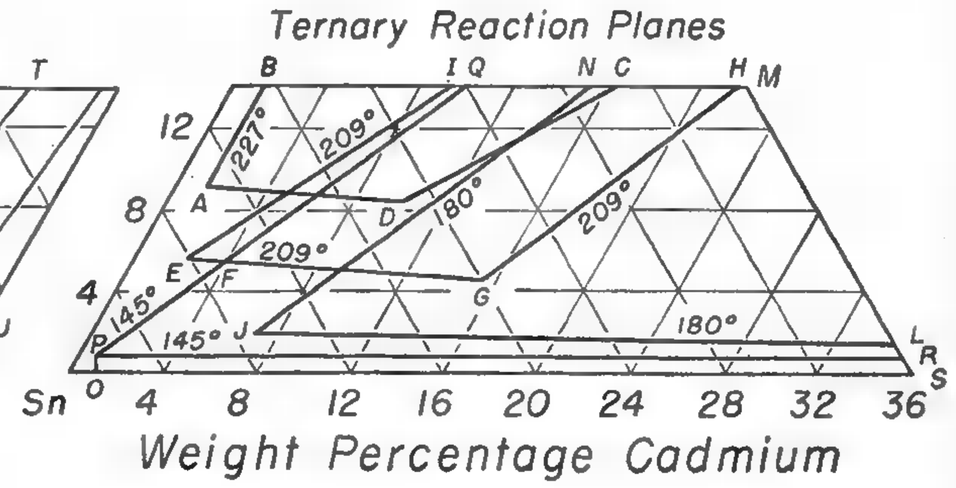
Four invariant reactions occur, as shown in the section labeled Ternary Reaction Planes:

Area *ABCD:* SbSn + *L* (10% Cd, 8.2% Sb) $\rightleftarrows$ CdSb + α (1.5% Cd, 9% Sb) at 227 C
Area *EFGHI:* α (2.4% Cd, 5.5% Sb) + *L* (15.4% Cd, 4.3% Sb) $\rightleftarrows$ CdSb + β (5.5% Cd, 5.1% Sb) at 209 C
Area *JLMN:* *L* (33% Sb, 1% Cd) + CdSb $\rightleftarrows$ β (7% Cd, 2% Sb) + γ (cadmium-rich) at 180 C
Area *PQMR:* β (5.3% Cd, 0.8% Sb) $\rightleftarrows$ α (0.7% Cd, 1.0% Sb) + CdSb + γ (cadmium-rich) at 145 C

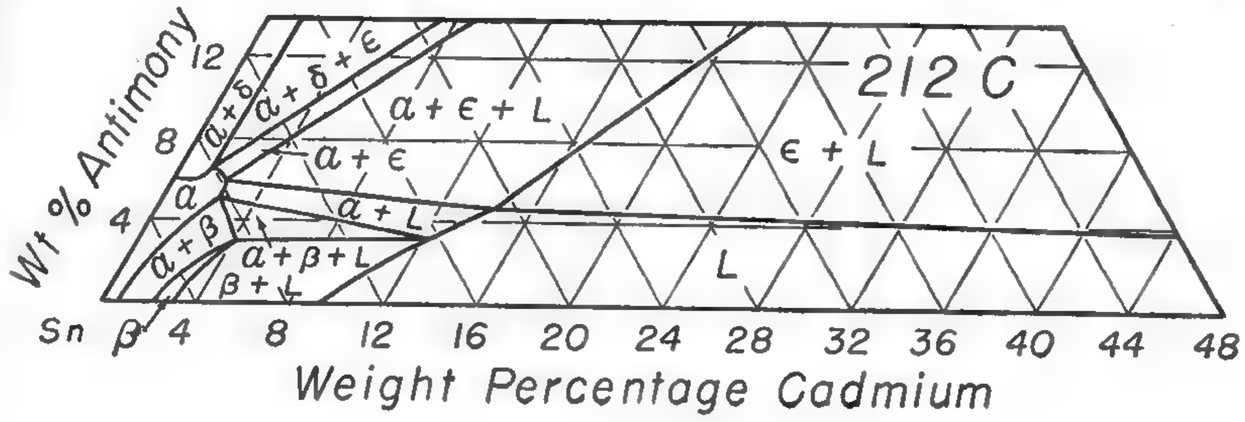


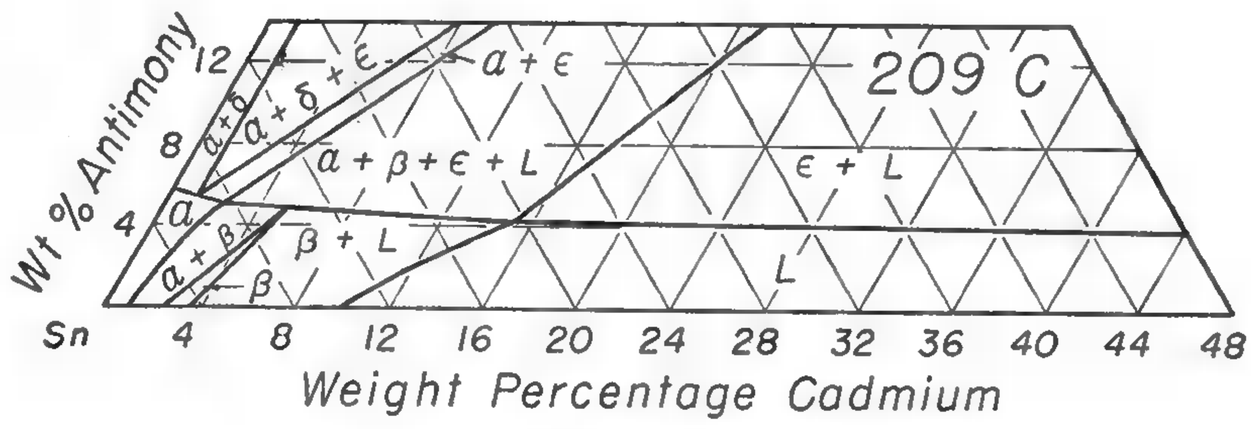


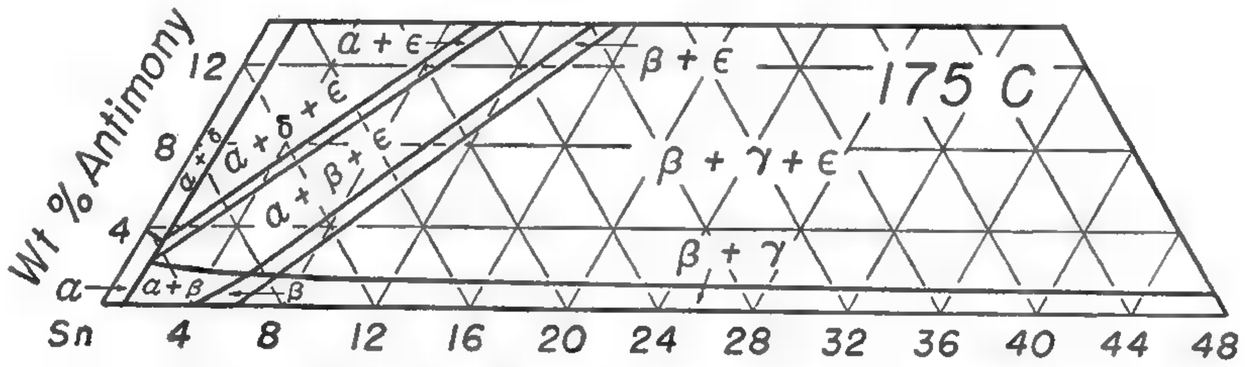


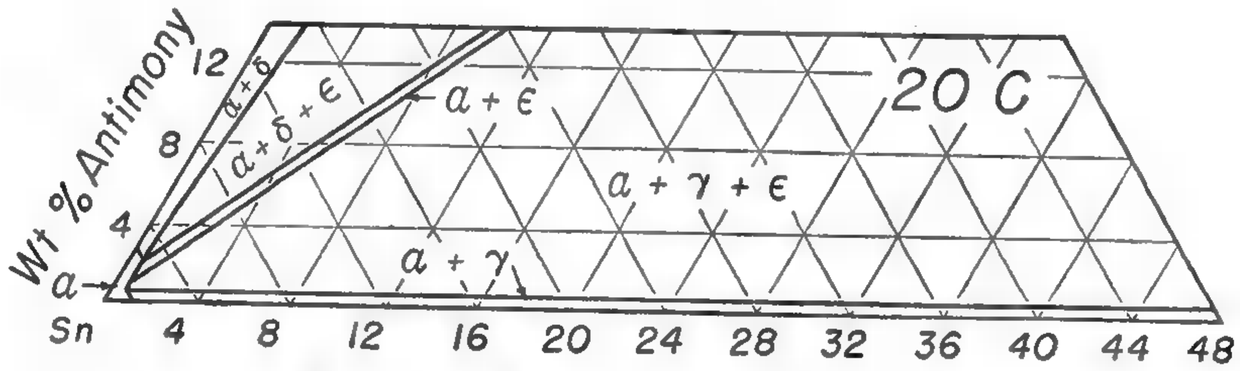


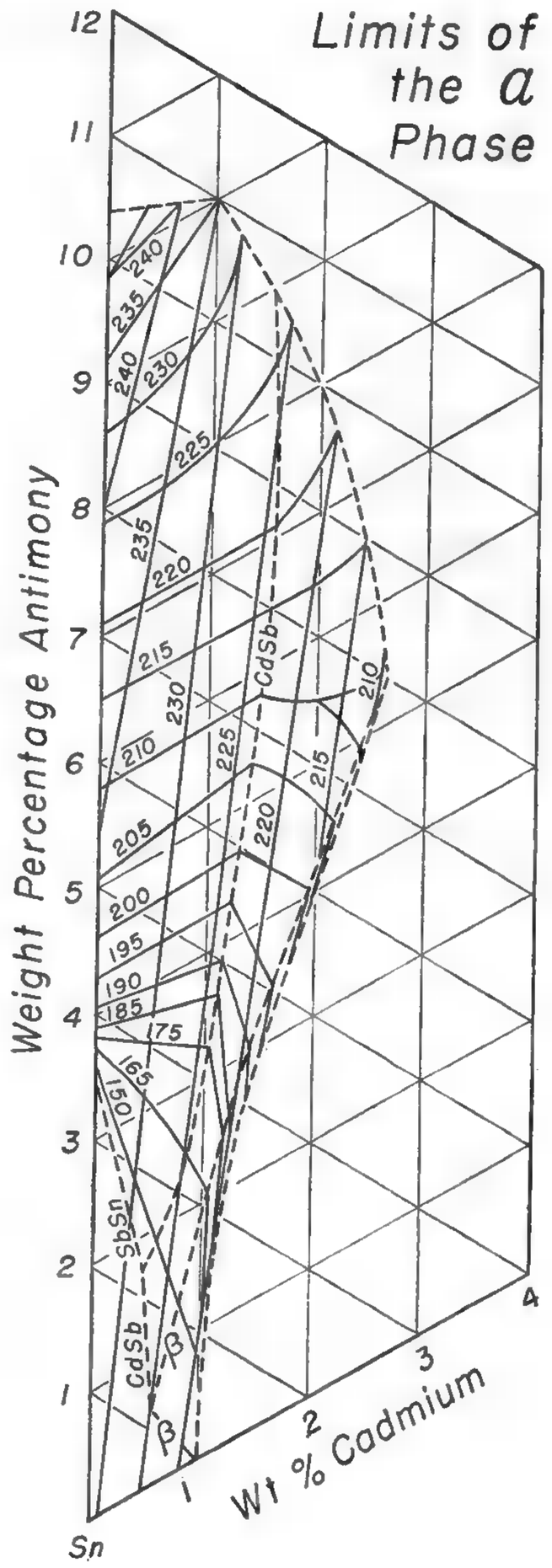
* Tin Research Institute, London, England

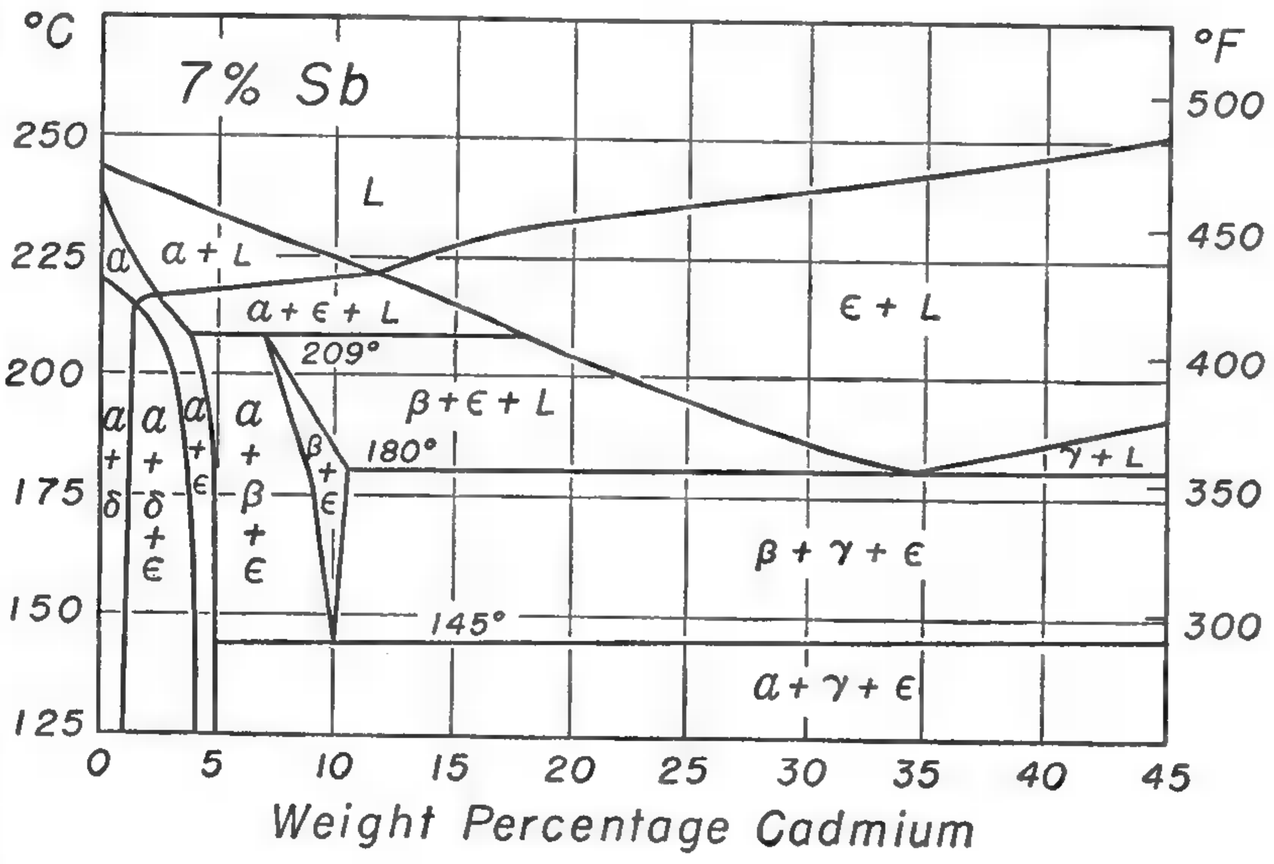

212 C
α + δ + ε
α + ε + L
α + ε
α + L
α + β + L
β + L
α + β
α
ε + L
L
Wt % Antimony
Sn β 4 8 12 16 20 24 28 32 36 40 44 48
Weight Percentage Cadmium

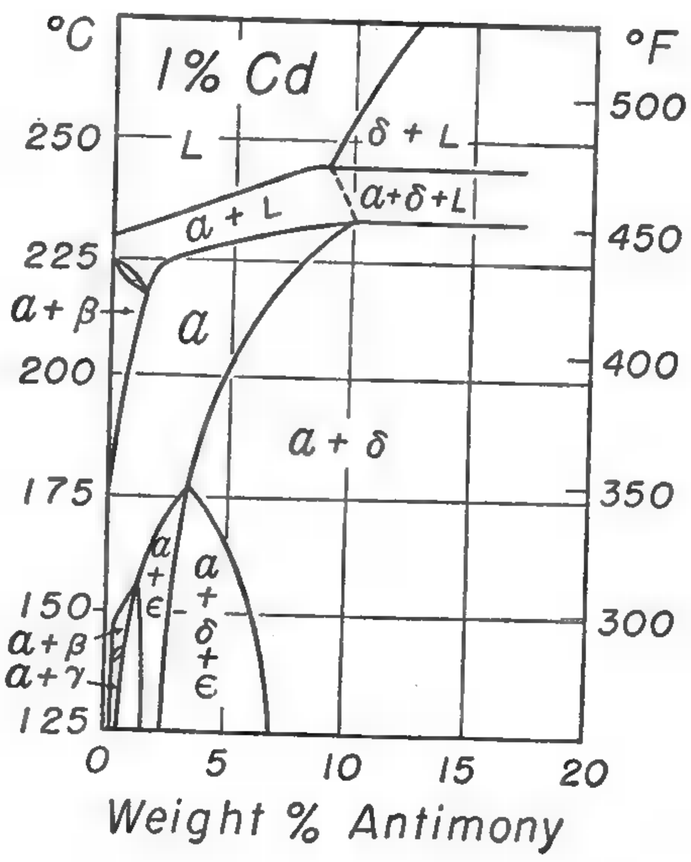

209 C
α + δ + ε
α + ε
α + β + ε + L
β + L
α + β
α
β
ε + L
L
Wt % Antimony
Sn 4 8 12 16 20 24 28 32 36 40 44 48
Weight Percentage Cadmium


175 C
α + ε
α + δ + ε
α + β + ε
β + ε
β + γ + ε
β + γ
α + β
β
α
Wt % Antimony
Sn 4 8 12 16 20 24 28 32 36 40 44 48
Weight Percentage Cadmium


20 C
α + δ + ε
α + ε
α + γ + ε
α + γ
α
Wt % Antimony
Sn 4 8 12 16 20 24 28 32 36 40 44 48
Weight Percentage Cadmium


Limits of the α Phase
240
235
230
225
220
215
210
205
200
195
190
185
175
165
150
CdSb
USbS
CdSb
β
Weight Percentage Antimony
Wt % Cadmium
Sn


7% Sb
L
α + L
α + ε + L
209°
β + ε + L
180°
γ + L
ε + L
145°
α + γ + ε
β + γ + ε
α
α + δ
α + δ + ε
α + β + ε
β + ε
°C
°F
250
225
200
175
150
125
500
450
400
350
300
0 5 10 15 20 25 30 35 40 45
Weight Percentage Cadmium


1% Cd
L
δ + L
α + δ + L
α + L
α
α + β
α + δ
α + ε
α + δ + ε
α + γ
°C
°F
250
225
200
175
150
125
500
450
400
350
300
0 5 10 15 20
Weight % Antimony

Cr-Fe-Ni Chromium-Iron-Nickel

By E. C. Bain* and R. H. Aborn*

The principal feature of this ternary system is its characteristic phase shifts caused by the allotropy of iron.

The maximum separation of liquidus and solidus in ternary alloys that contain up to 50% Cr reaches 100 °C in a 30% Fe, 48% Cr, 22% Ni alloy, but in iron-rich alloys of the stainless steel type this separation does not exceed 40 °C.[1]

The α and γ solid solutions in the iron-rich region of the diagram are generally termed "ferrite" and "austenite" respectively.

The alpha (ferrite) stabilizing influence of chromium (*see* Fe-Cr system) is predominant at very high and low temperatures, whereas the gamma (austenite) stabilizing influence of nickel (*see* Fe-Ni system) is predominant at intermediate temperatures. The outstanding feature, however, is the pronounced reluctance of metastable austenite to transform when once established at higher temperature. The temperature range in which the stable gamma (austenite) region is broadest[2] lies between 900 and 1300 C but the range for any one alloy is often considerably narrower and will vary with composition.

The addition of nickel appears to raise the upper temperature limit of stability of sigma, the brittle iron-chromium compound (*see* Fe-Cr system), to about 920 C and in so doing as much as 8% Ni may be dissolved.[3] Although sigma is shown in equilibrium with gamma (austenite) within certain composition limits, sigma forms more usually from alpha (ferrite). The sluggishness of sigma formation in Cr-Fe-Ni alloys is even greater than in Fe-Cr alloys, so the constitution of the ternary alloys with respect to sigma is uncertain below about 650 C.

Since many commercial alloys, particularly those of the stainless steel type, contain about 0.1% C, the structural constituents present in such alloys (up to 50% Cr or 50% Ni) after rapid cooling from temperatures of maximum austenite formation, are shown also.

* Carnegie-Illinois Steel Corporation, Pittsburgh
* United States Steel Corporation, Research Laboratory, Kearny, N.J.

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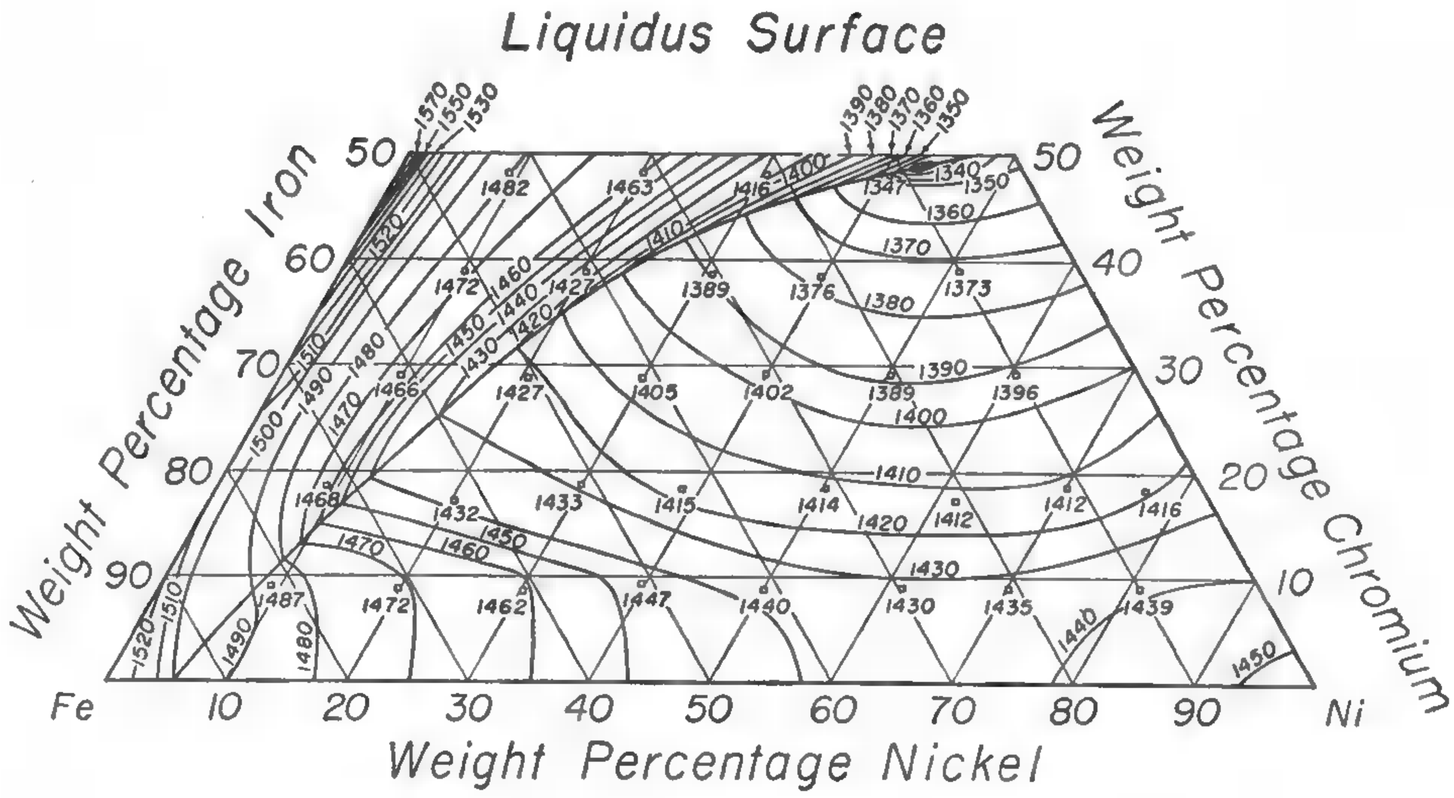
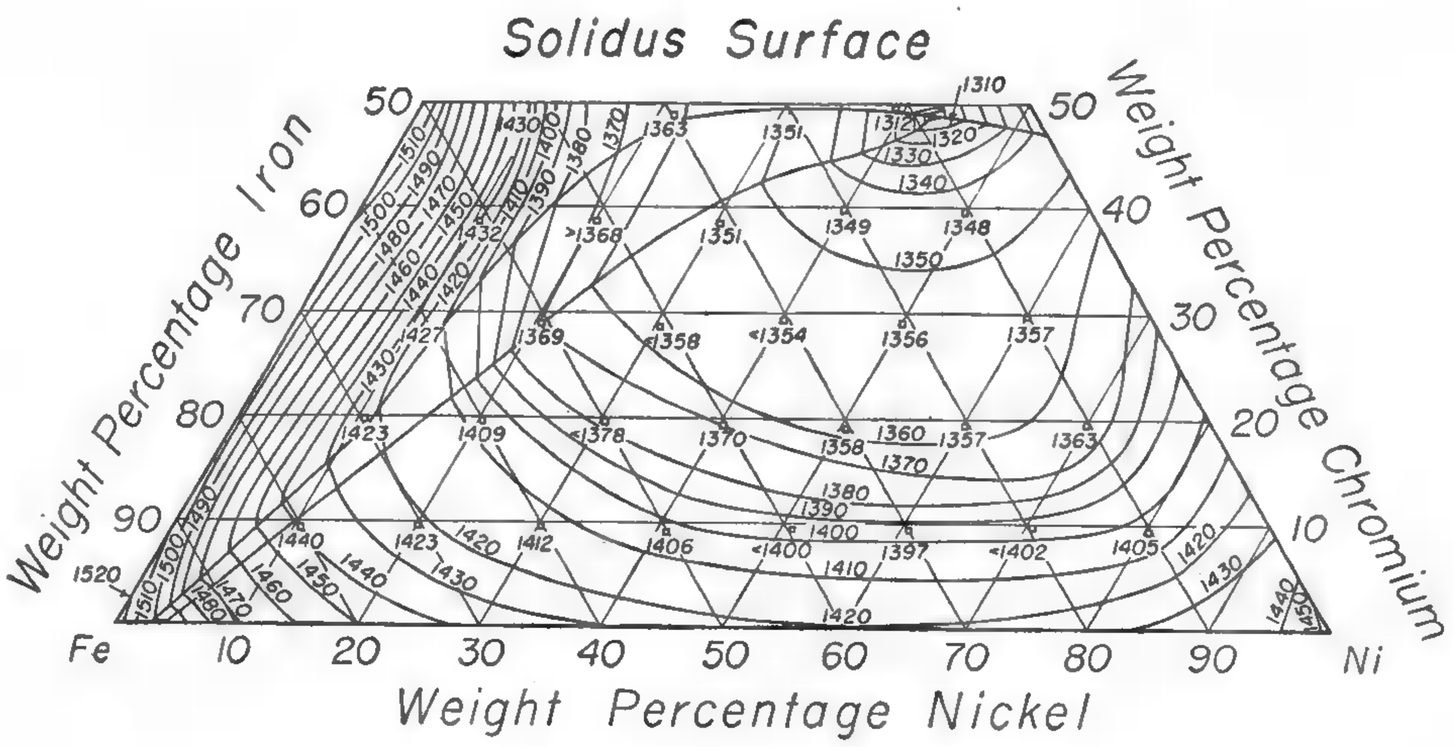
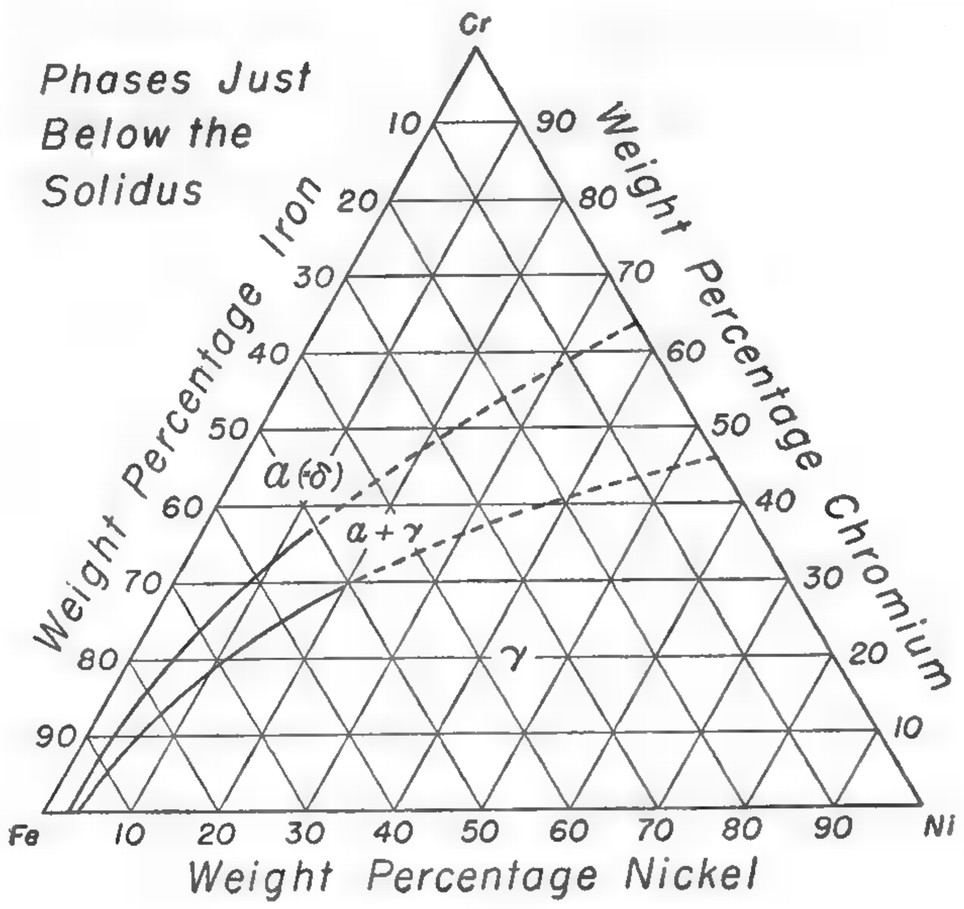
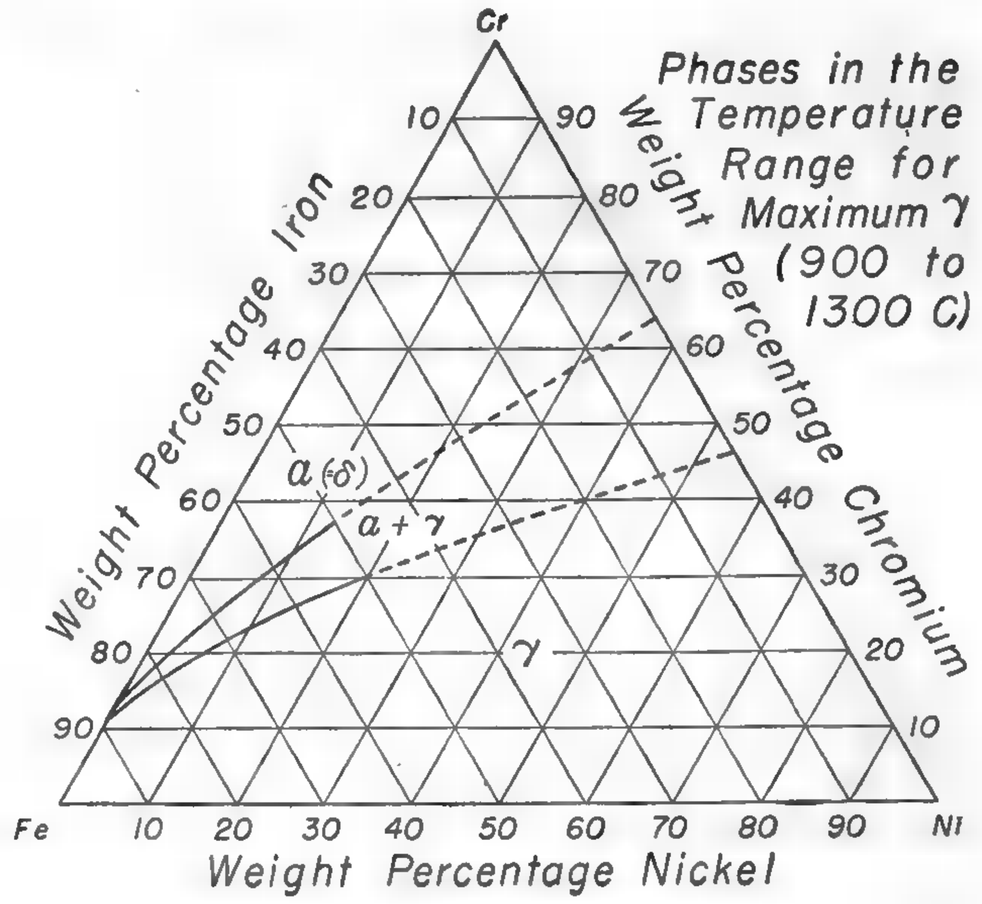
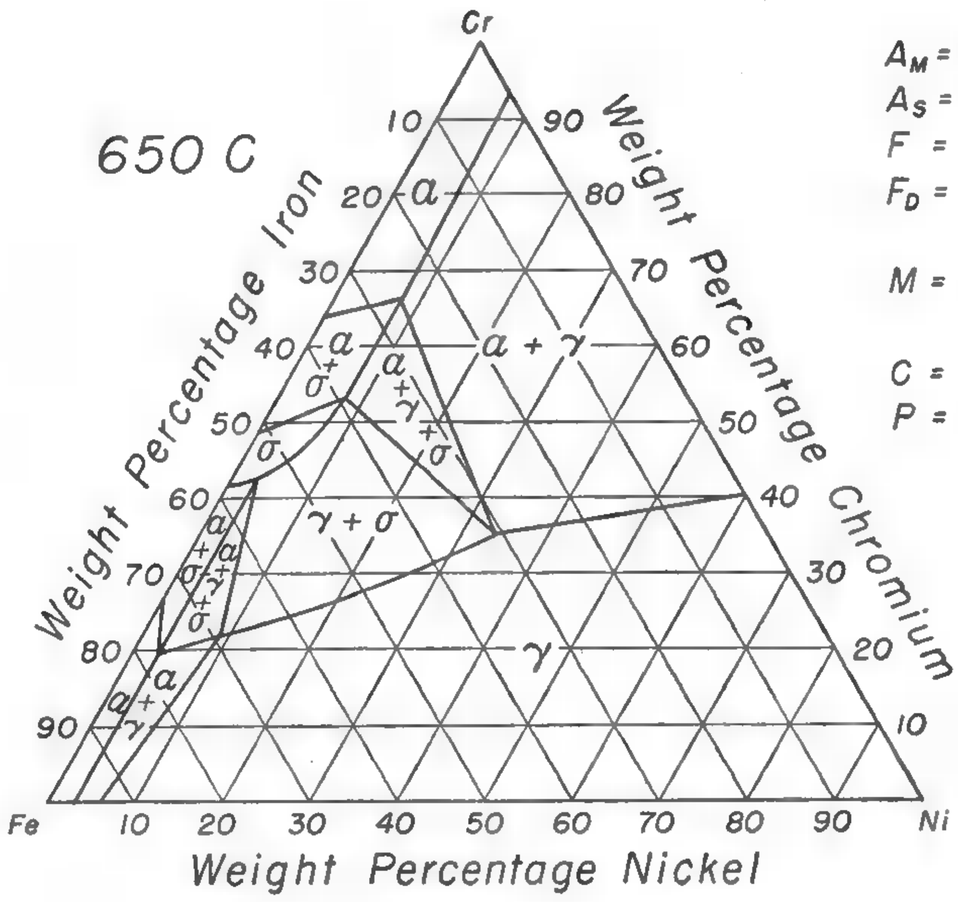




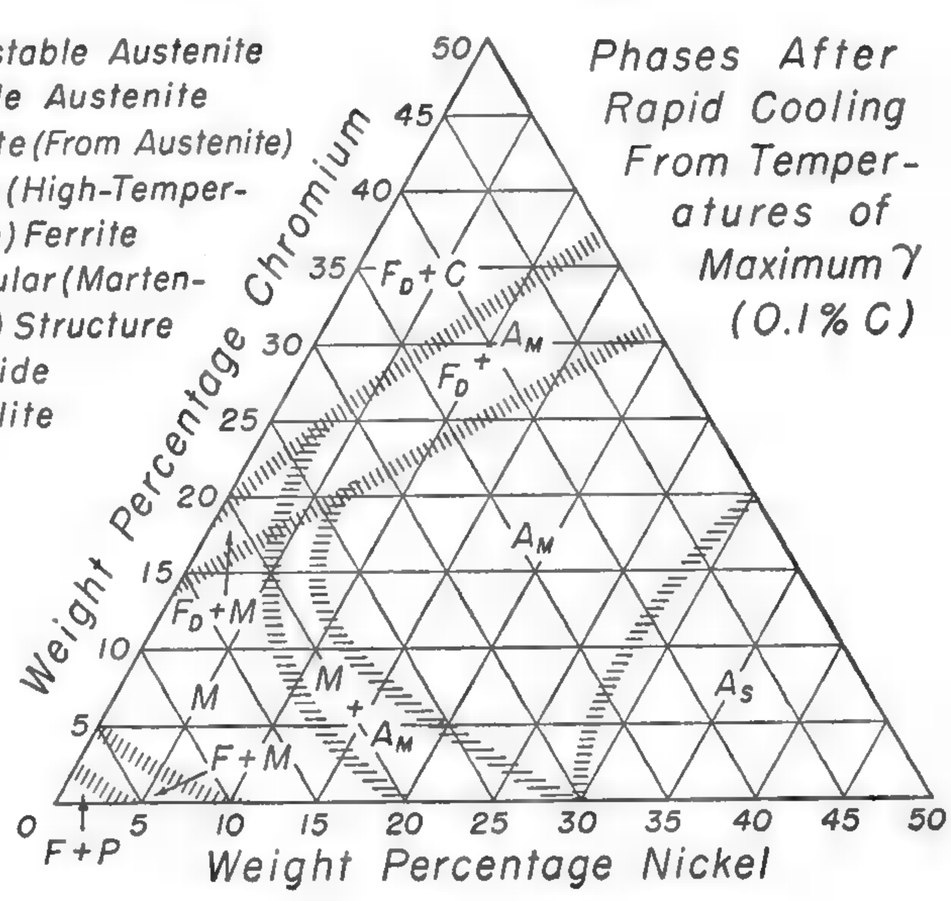
(Other diagrams are on the next page.)





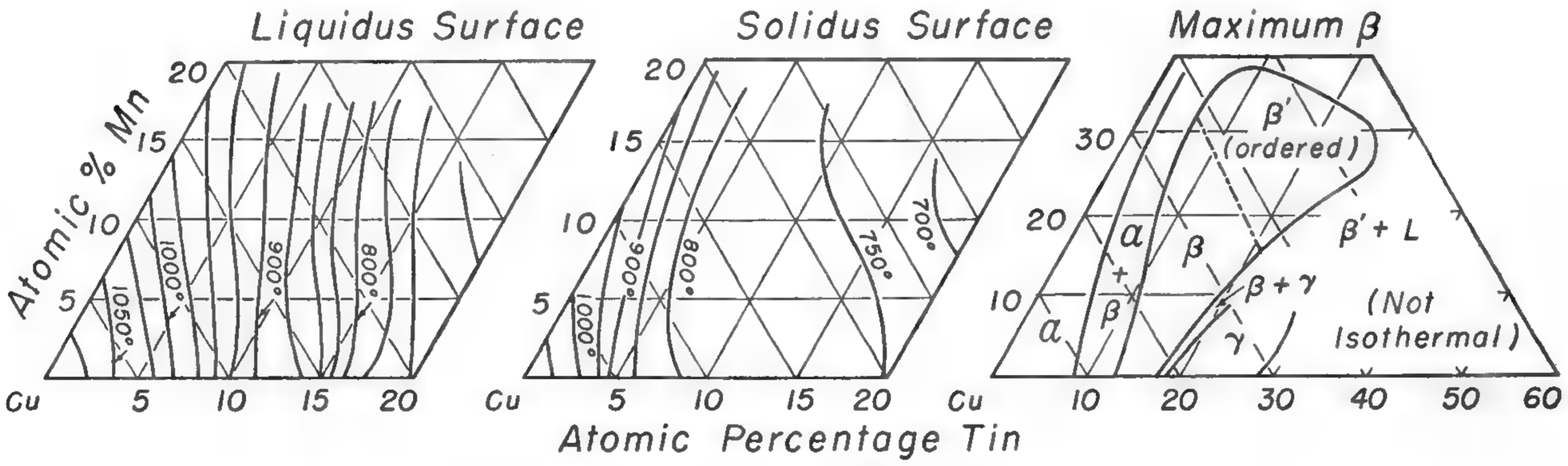


A_M = Metastable Austenite
A_S = Stable Austenite
F = Ferrite (From Austenite)
F_D = Delta (High-Temperature) Ferrite
M = Acicular (Martensitic) Structure
C = Carbide
P = Pearlite



Cu-Mn-Sn Copper-Manganese-Tin

By Louis A. Carapella*



(Text and references are on the next page.)

* Senior Industrial Fellow, Mellon Institute of Industrial Research, Pittsburgh

The contours of both the liquidus and solidus isotherms for the copper-rich portion of the system are illustrated.[1] The same phases that exist in the binary bronze system appear to persist up to 15% Mn, along with the "*X* constituent", which might be Cu_5MnSn_2.[2] The β phase was reported[1] to have a narrow range of homogeneity—a deduction later contradicted by X-ray, microscopic and magnetometric examination of alloys containing up to 40% Mn.[3]

The maximum range of the β phase is outlined in the last figure.[3] At higher manganese and tin contents, β becomes ordered, even at high temperatures. Both β and β' are unstable below 600 C, but they may be retained at room temperature by drastic quenching.

The ordered β' phase is ferromagnetic; the maximum effect occurs at the composition Cu_2MnSn, which has a magnetic saturation moment exceeding that of pure nickel.

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Cu-Ni-Sn Copper-Nickel-Tin

By J. T. Eash*

The liquidus contours of the copper-rich alloys and isothermal sections at 780, 700 and 300 C are shown. The solid phases are isometric in structure with the exception of η, which is probably derived from the hexagonal phase of the copper-tin system.

* Research Laboratory, The International Nickel Company, Inc., Bayonne, N.J.

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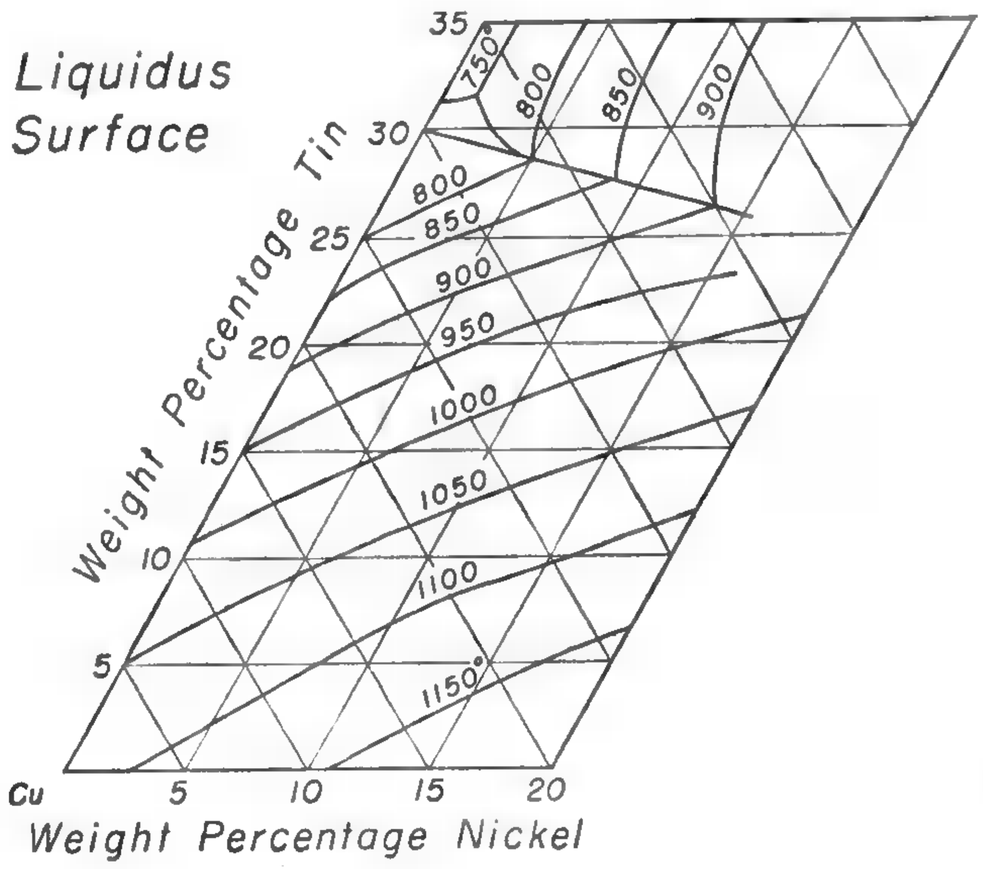

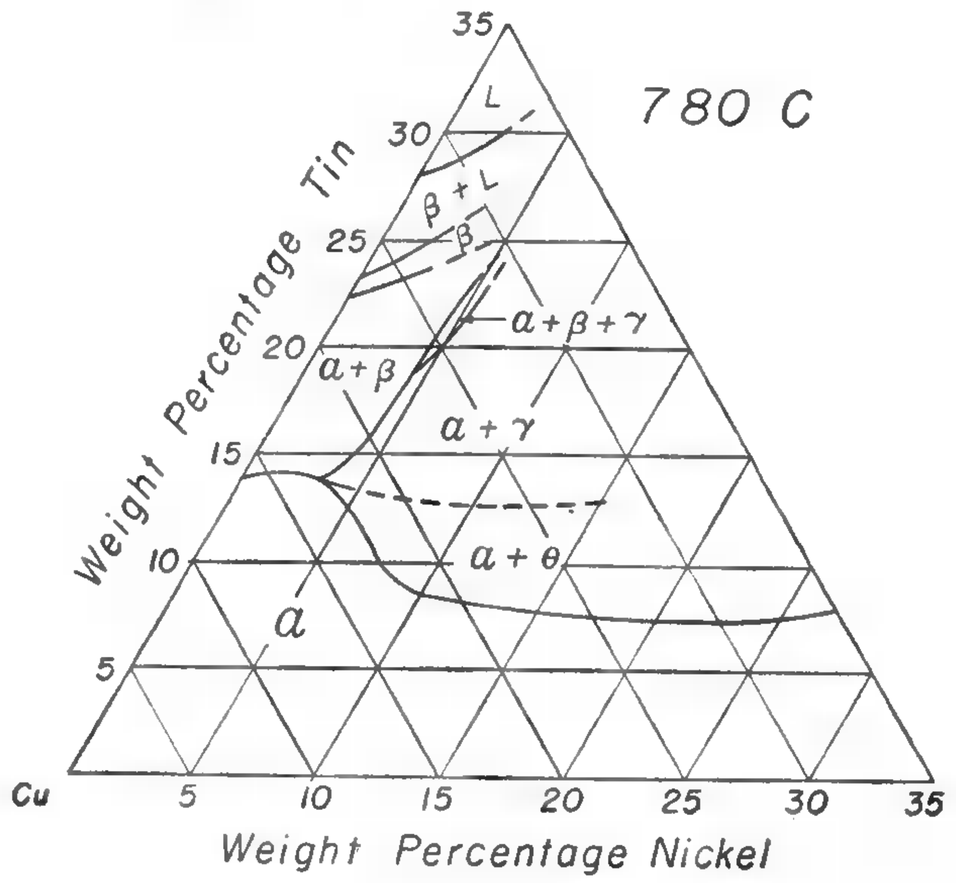

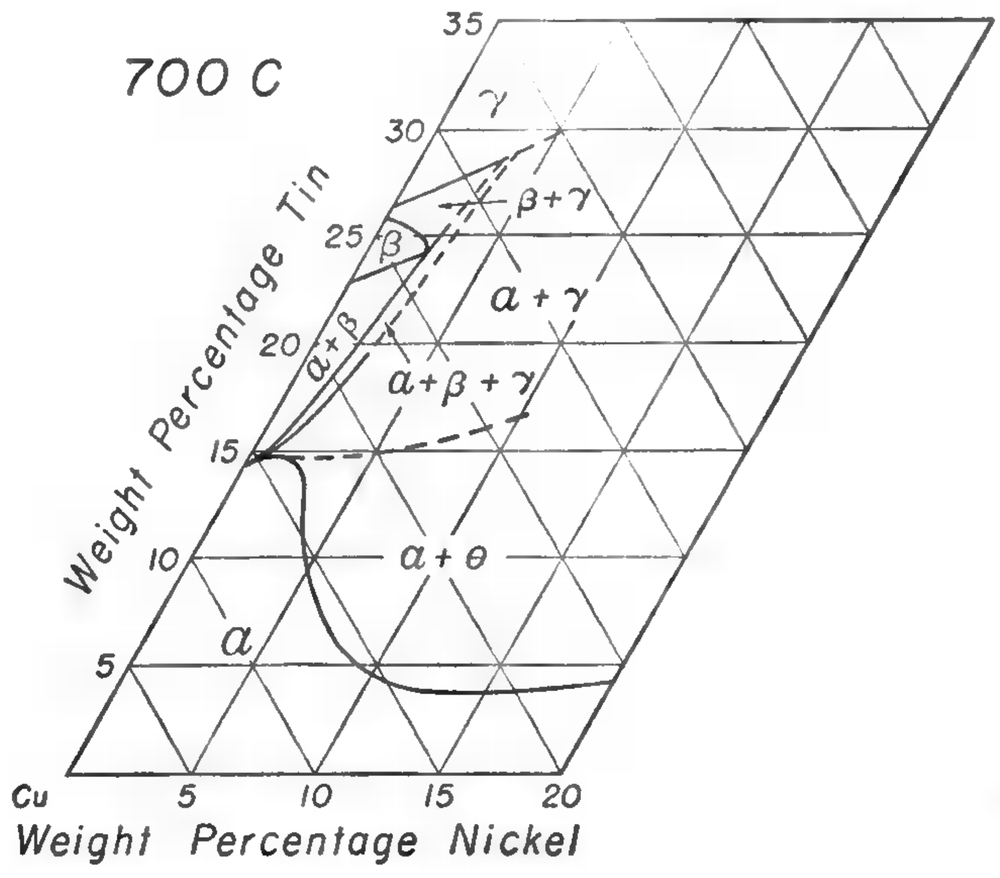

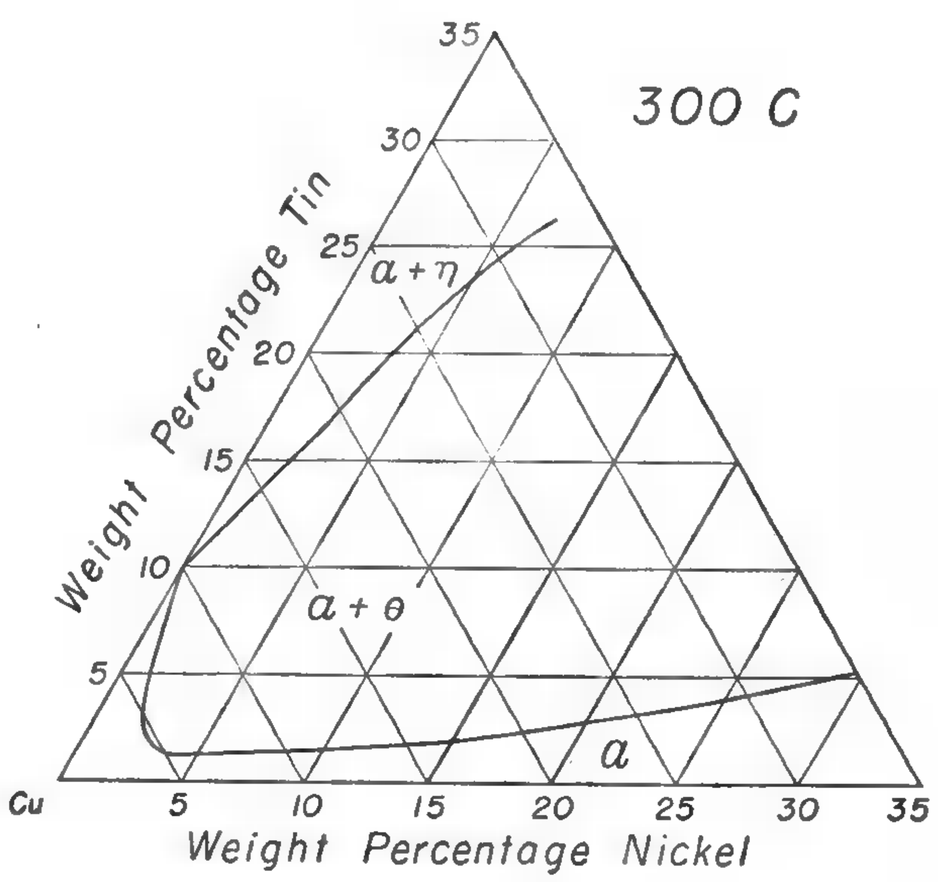

Cu-Ni-Zn Copper-Nickel-Zinc

By T. E. Kihlgren*

The diagrams presented are those of J. Schramm,[6] reorientated so that the base line will represent the binary copper-zinc alloys, since the commercially important nickel silvers are essentially brasses containing up to 25% Ni. The η phase domain of the ternary system is extremely small; the solubility at 100 C of nickel in zinc is of the order of 0.02% and of copper in zinc about 0.3%.

Crystal Structure of Phases

α—Face-centered cubic
β—Body-centered cubic
β'—Body-centered cubic with superstructure (corresponds to low-temperature phase of Cu-Zn system)
β_1—Body-centered tetragonal, AuCu type (corresponds to the low-temperature phase of the Ni-Zn system)
γ—Cubic, low symmetry, 52 atoms per unit cell
δ—Hexagonal
ϵ—Close-packed hexagonal
η—Close-packed hexagonal

* Research Laboratory, The International Nickel Company, Inc., Bayonne, N.J.

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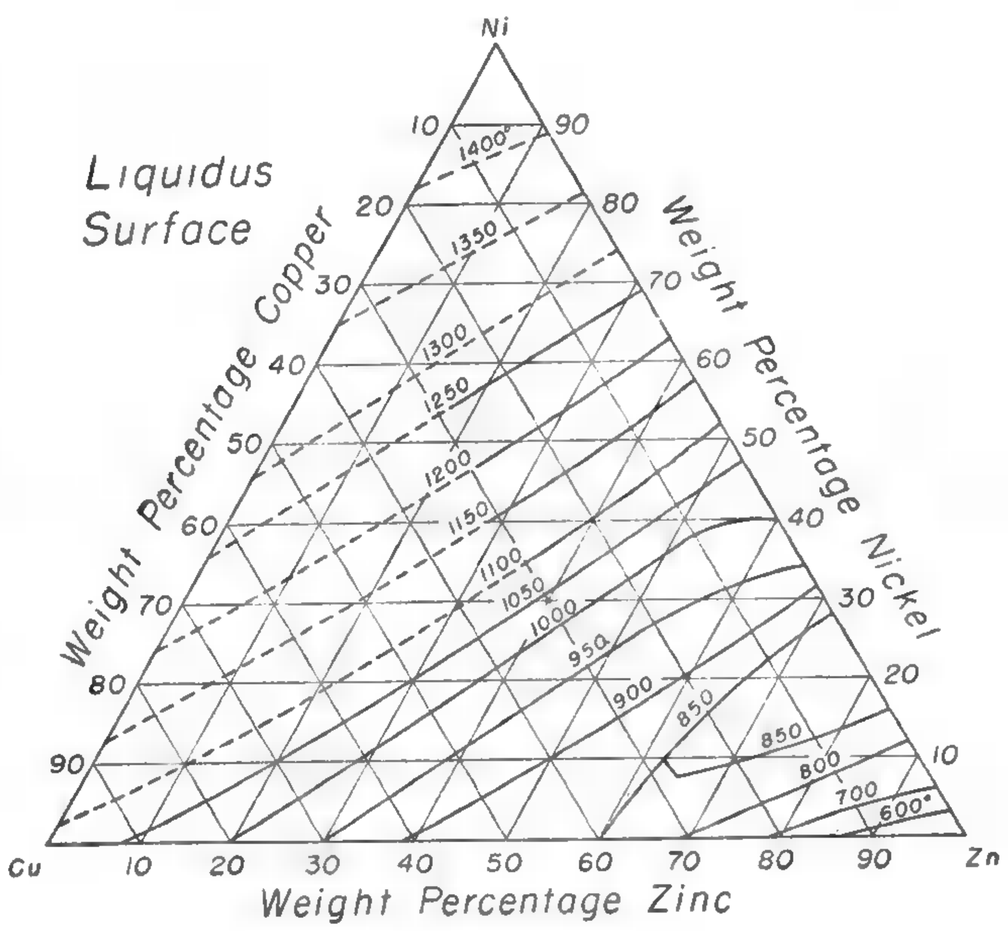
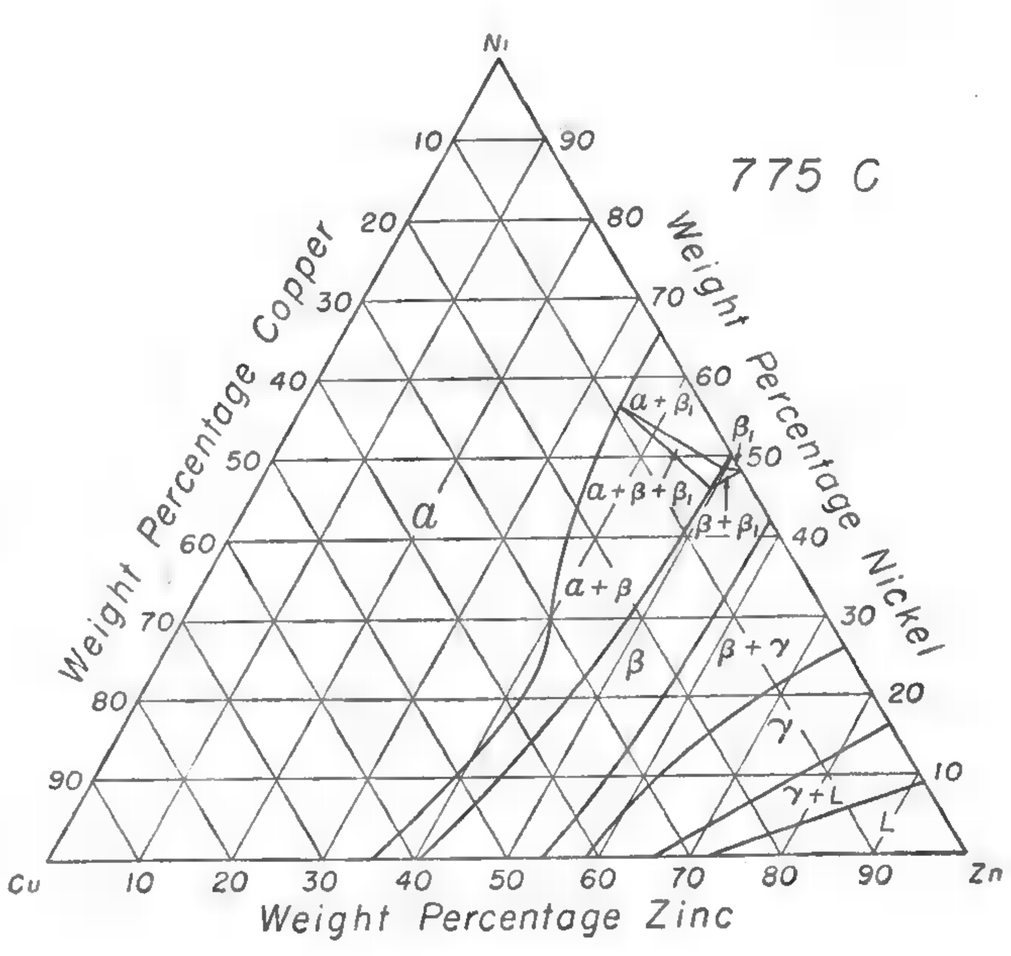
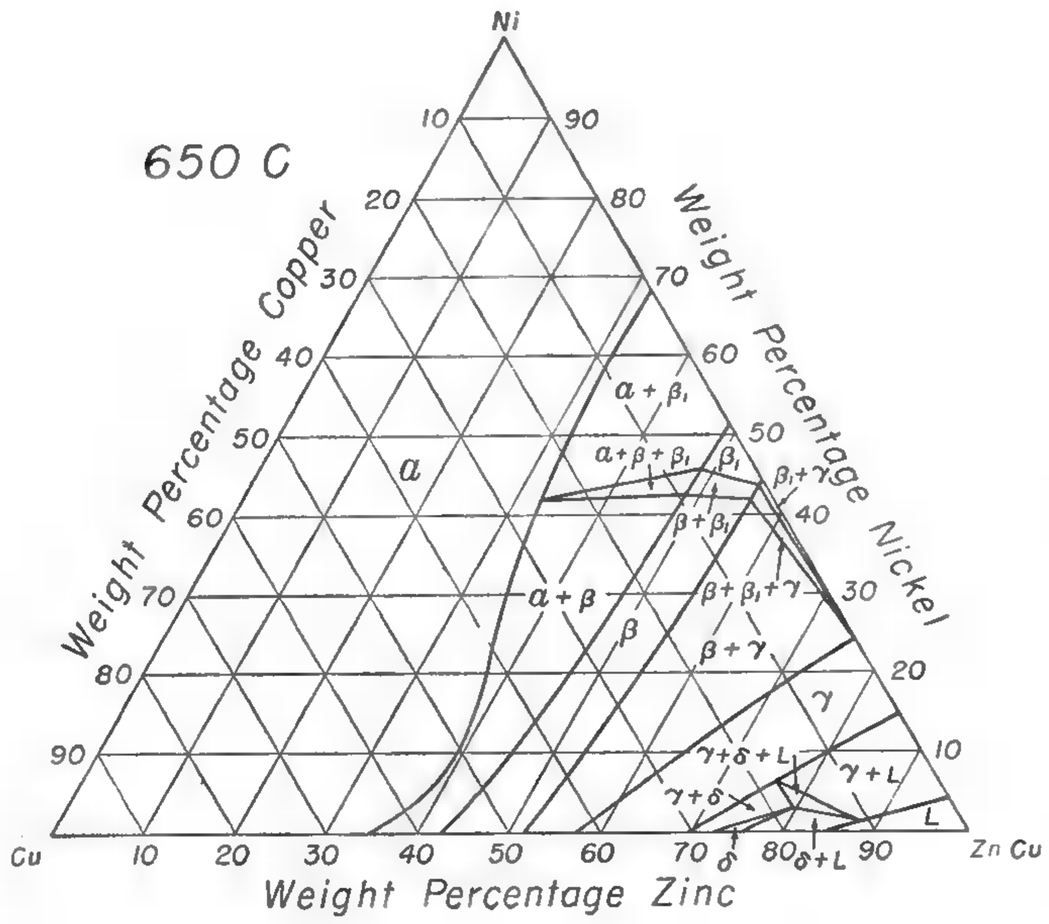
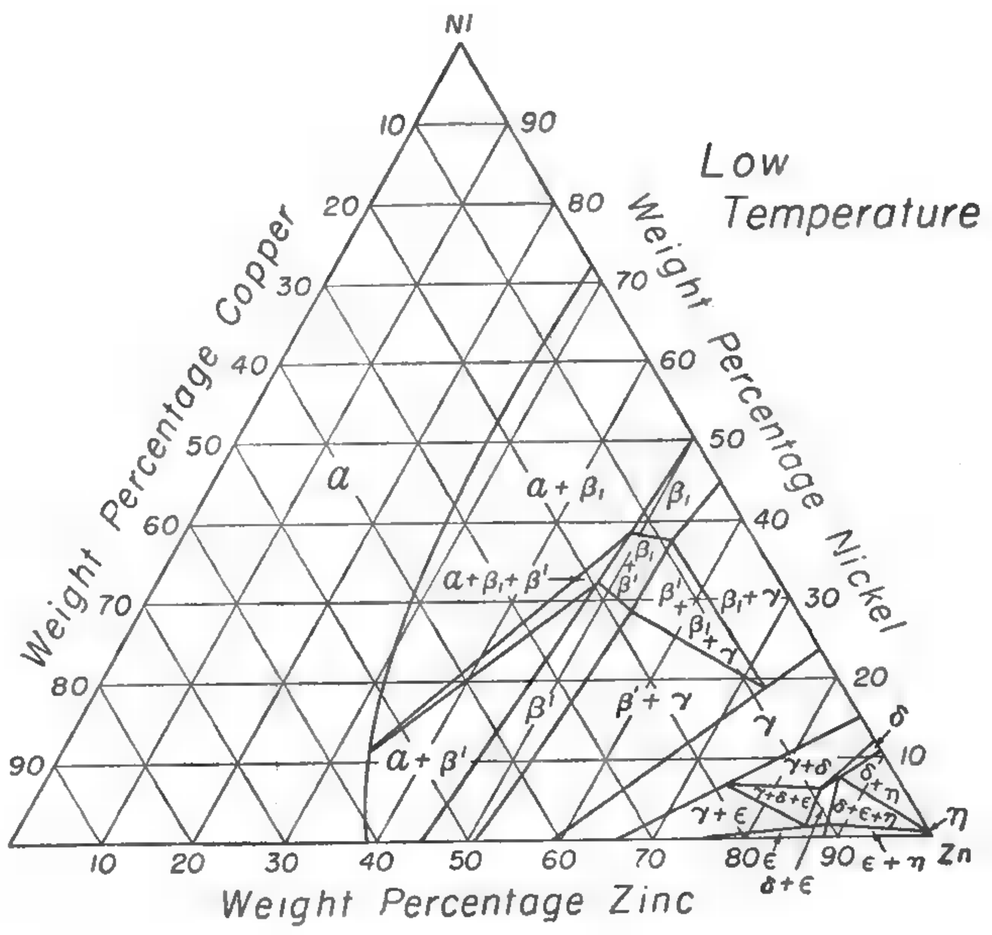








Cu-Sb-Sn Copper-Antimony-Tin

By J. M. Blalock, Jr.*

Although the tin-rich alloys of tin, copper and antimony are very important commercially, and have been the subject of considerable study, there is insufficient published information concerning the constitution of the entire system. By metallographic means, Ellis and Karelitz[1] correlated the physical properties with the microstructures of the tin-rich alloys. The only study of the entire system is that of Tasaki,[2] and the accompanying data are based entirely on his work. It is significant, however, that there is good agreement between the two investigations in the area included in both.

Because Tasaki's work is based mostly on the results of thermal analysis, it is probable that the contours of the liquidus surface are correct. Because of the sluggishness with which these alloys approach equilibrium in the solid state, it is likely that the second diagram indicates the phases to be expected in cast alloys, rather than true equilibrium at room temperature.

Tasaki identified one ternary compound metallographically ($Cu_{12}Sn_7Sb_3$ at 38.9% Cu, 42.3% Sn, 18.8% Sb). With the help of the accompanying tabulations the reactions at the liquidus surface may be easily followed. The cusps in the isotherms lying between points *H* and *E* seem to indicate that there is a reaction along a line joining these cusps, but Tasaki was unable to find any other evidence of such a reaction and concluded that there is none.

Because of the complexity of the three binary systems involved, it is logical to expect phase relationships in the solid ternary alloys to be complicated also, and phase boundaries have not been definitely established. By designating most of the phases in the second diagram with "primes", Tasaki indicated that these phases probably undergo changes in the solid state. The κ phase is the only phase which Tasaki identified as being a product of a transformation taking place below the solidus; it seems likely that ζ is one of the phases participating in this transformation. It was definitely established that the solubility of antimony in Cu_6Sn_5 decreases with temperature; therefore these alloys may be susceptible to age hardening.

References

1 O. W. Ellis and G. B. Karelitz, Trans ASME, 50, Part 1, MSP-11 (1928)

2 M. Tasaki, Mem Coll Sci Kyoto Imp Univ, 12, 227 (1929)

* General Chemical Division, Allied Chemical & Dye Corporation, Chicago

Primary Crystallization

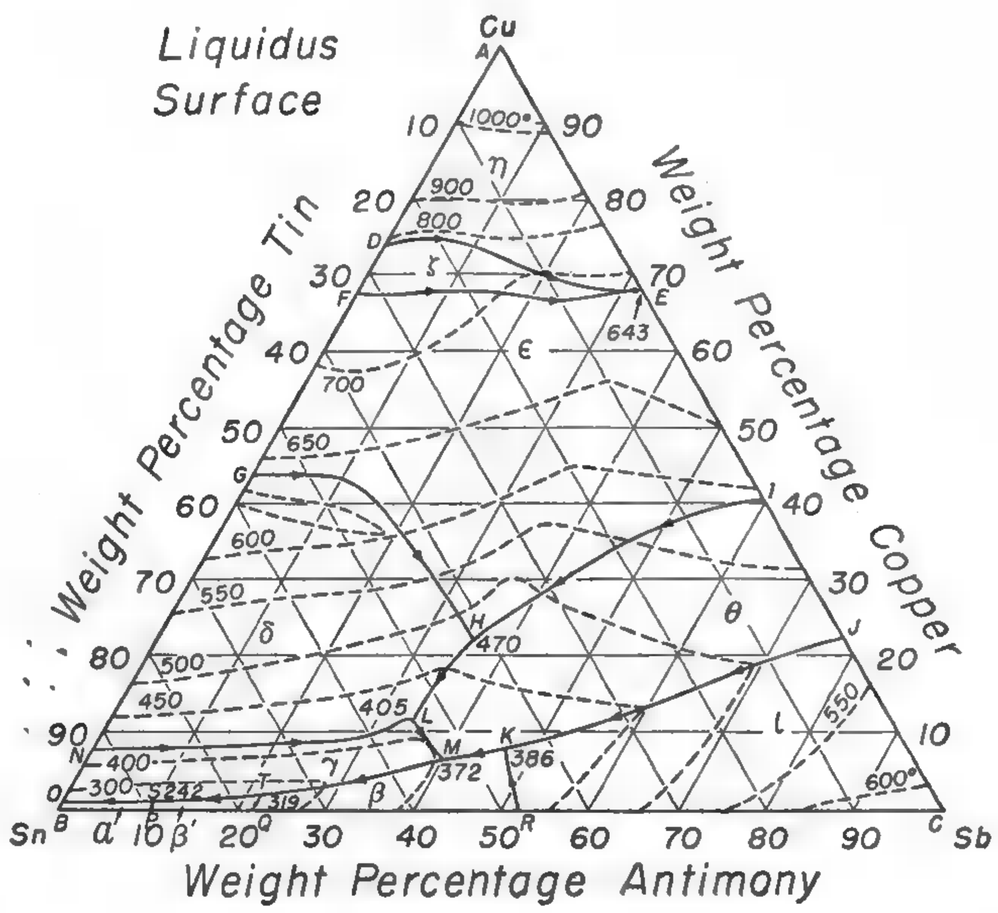
Area of Primary Crystallization	Phase Precipitated	Description
OSPB	α	Sn-rich ternary solid solution
QTMKR	β	Ternary solid solution of Cu in β of Sb-Sn system
PSTQ	β'	Ternary solid solution of Cu in β' of Sb-Sn system
NLMO	γ	ϵ of the Cu-Sn system (Cu_6Sn_5) with some dissolved Sn
GNLH	δ	Cu_3Sn with some dissolved Sn and Sb at higher temperatures
FEIHG	ϵ	Ternary solid solution field between γ(Cu-Sb) and γ(Cu-Sn)
DFE	ζ	Ternary solid solution of Sb in β of Cu-Sn system
ADE	η	Cu-rich ternary solid solution
IHLMKJ	θ	Cu_2Sb
JKRC	ι	Sb-rich ternary solid solution

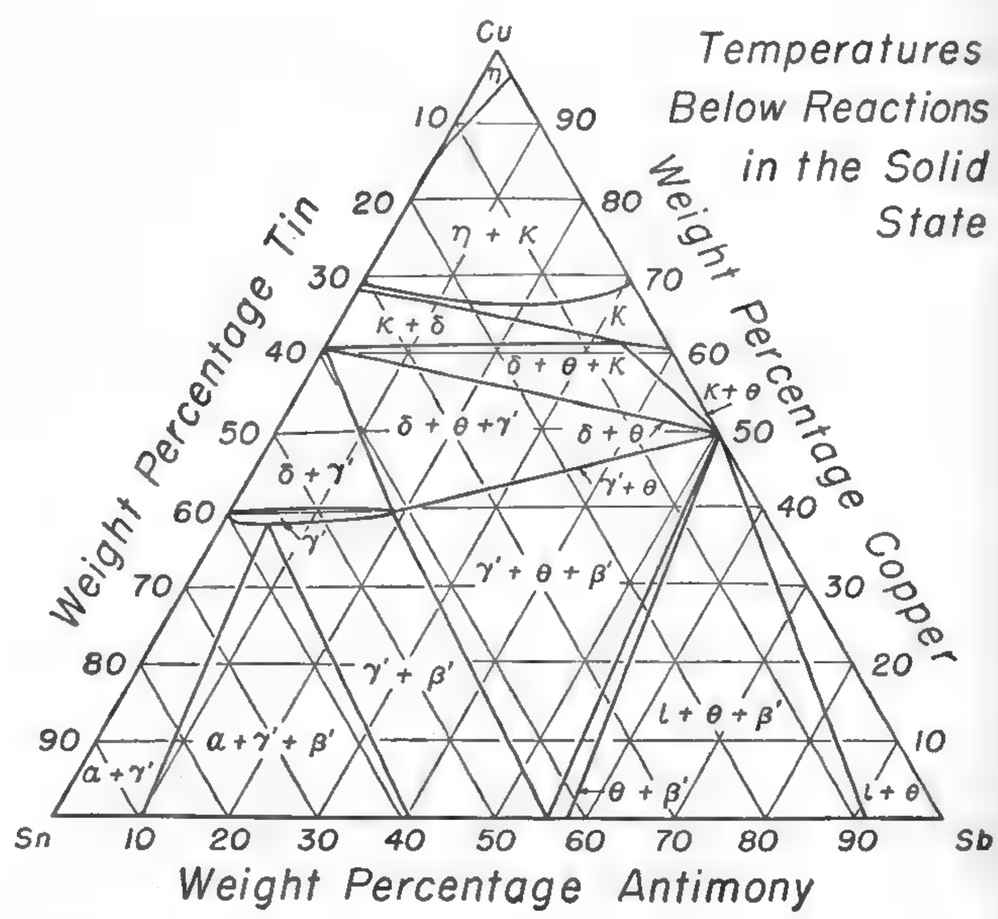
Monovariant Equilibriums

Reaction Line	Reaction	Type of Reaction
DE	$L + \eta \leftrightarrows \zeta$	Peritectic
FE	$L + \zeta \leftrightarrows \epsilon$	Peritectic
GH	$L + \epsilon \leftrightarrows \delta$	Peritectic
HI	$L + \epsilon \leftrightarrows \theta$	Peritectic
HL	$L \leftrightarrows \delta + \theta$	Eutectic
NL	$L + \delta \leftrightarrows \gamma$	Peritectic
LM	$L + \theta \leftrightarrows \gamma$	Peritectic
JK	$L \leftrightarrows \iota + \theta$	Eutectic
KM	$L + \theta \leftrightarrows \beta$	Peritectic
KR	$L + \iota \leftrightarrows \beta$	Peritectic
MT	$L \leftrightarrows \beta + \gamma$	Eutectic
QT	$L + \beta \leftrightarrows \beta'$	Peritectic
TS	$L \leftrightarrows \beta' + \gamma$	Eutectic
PS	$L + \beta' \leftrightarrows \alpha$	Peritectic
OS	$L \leftrightarrows \alpha + \gamma$	Eutectic

Invariant Points

Point	Reaction	Type of Reaction	Temp, deg Cent
E	$L \leftrightarrows \eta + \zeta + \epsilon$	Eutectic	643
H	$L + \epsilon \leftrightarrows \delta + \theta$	Peritectic	470
L	$L + \delta \leftrightarrows \gamma + \theta$	Peritectic	405
K	$L + \iota \leftrightarrows \beta + \theta$	Peritectic	386
M	$L + \theta \leftrightarrows \beta + \gamma$	Peritectic	372
T	$L + \beta \leftrightarrows \gamma + \beta'$	Peritectic	319
S	$L + \beta' \leftrightarrows \alpha + \gamma$	Peritectic	242





Cu-Sn-Zn Copper-Tin-Zinc

By Cyril Stanley Smith*

There is no detailed information on the alloys containing less than 50% Cu. The liquidus is based on reference 1, smoothed into the results from reference 2, near the copper-zinc side. The constitution at 500 C, mainly from reference 2, is given in the isothermal section. The α and β phases extend continuously between the two binary fields. β (or the related γ) in the binary copper-tin system decomposes eutectoidally to $\alpha + \delta$ at 520 C, and the eutectoid extends nearly to the copper-zinc side, decreasing in temperature as the zinc content increases. The phase marked γ probably represents a continuous series of solid solutions between γ(Cu-Zn) and δ(Cu-Sn), which have the same structure.

The decrease in solubility at 300 C shown by the dotted line of the isothermal section, occurs only after extremely long annealing of heavily cold worked samples, and for most industrial purposes the 500 C line represents the effective solubility.

* Director, Institute for the Study of Metals, University of Chicago, Chicago

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1 G. Tammann and M. Hansen, Z anorg Chem, 138, 137 (1924)
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3 S. L. Hoyt and P. H. M. P. Brinton, J Inst Metals, 10, 235 (1913), and 14, 178 (1915)
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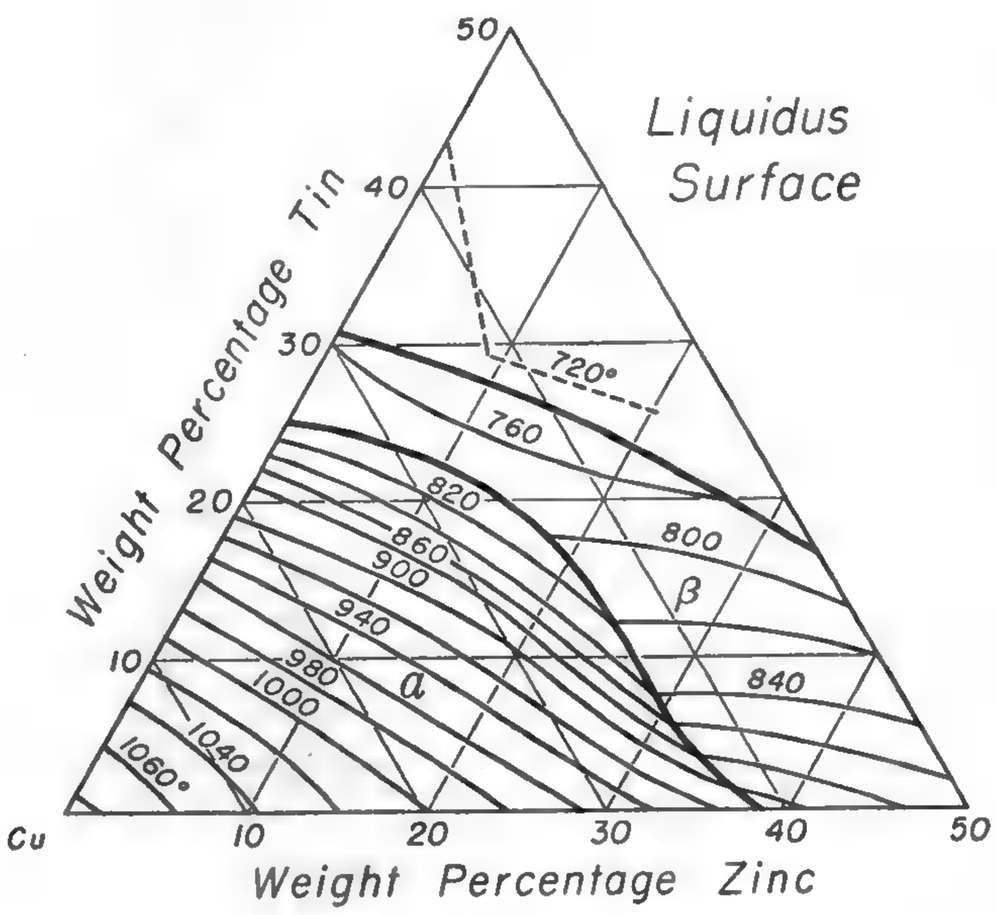
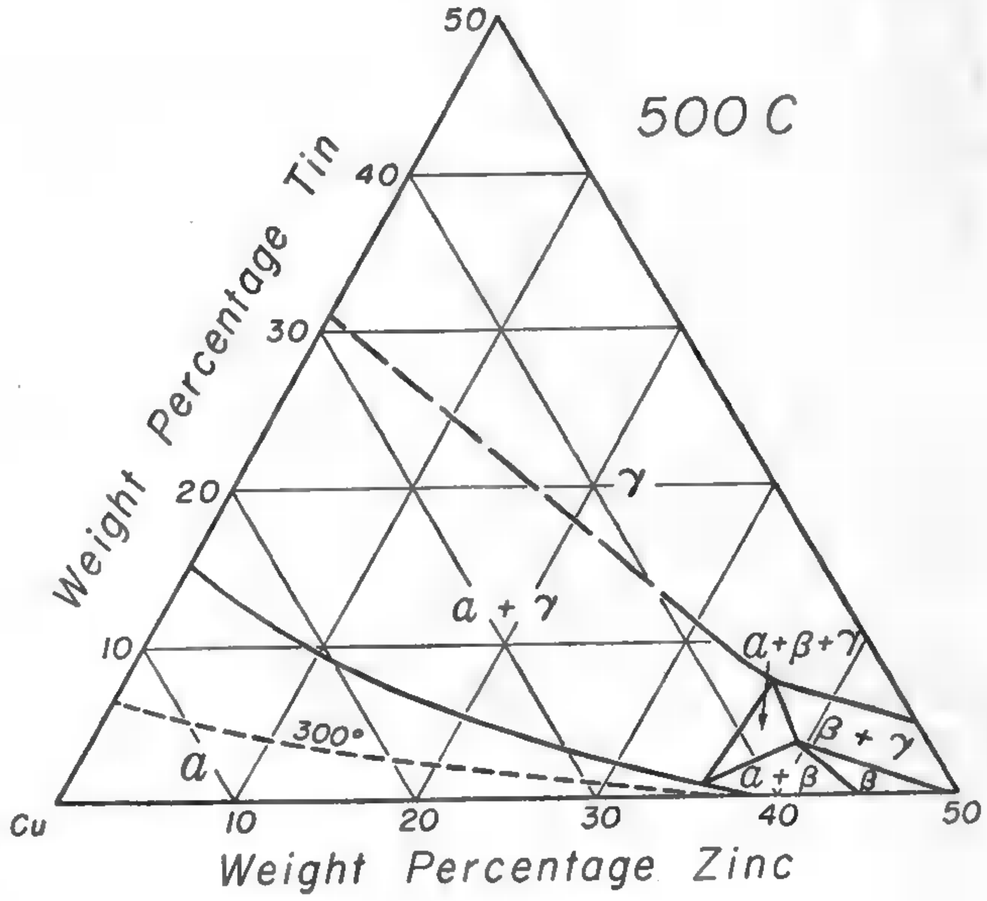




Fe-Mn-O Iron-Manganese-Oxygen

Andrew, Maddocks and Howat [J Iron Steel Inst, 124, 283 (1931)] investigated the section between the compositions FeO and MnO. The liquidus and solidus are slightly curved lines, about 20 C apart, joining the melting temperatures of wüstite and MnO (1410 and 1585 C respectively). It is known that FeO does not exist as a pure substance. Assuming that the "FeO" of these investigators was wüstite containing about 25% O, the thermal effect observed at about 1170 C might have been caused by precipitation of Fe_3O_4 from wüstite (*see* Fe-O system, page 1212).

Fe-Mn-S Iron-Manganese-Sulfur

Vogel and Hotop [Arch Eisenhüttenw, 11, 41 (1937)] investigated the system up to the line joining FeS and MnS. In the manganese-sulfur system, the liquid miscibility gap extends from 0.3 to 33.5% S at 1580 C; MnS melts at 1600 ± 10 C; and there is a eutectic at 1230 C near the manganese side. A ternary eutectic point at 1000 C nearly coincides with the binary eutectic point of the iron-sulfur system (*see* page 1215). There are two maximums of three-phase equilibrium, which largely determine the conditions of solidification.

Fe-Mn-Si Iron-Manganese-Silicon

By Louis A. Carapella*

The thermal and microscopic investigations of Vogel and Bedarff[1] show a ternary system with seven surfaces of primary solidification in which, with decreasing temperature, the following phases are in equilibrium with the melt: the ternary solid solutions of delta manganese, gamma manganese, gamma iron, and alpha iron, the compound FeSi, and the solid solutions of FeSi-MnSi and Mn_5Si_3-$Fe_{12}Si_{11}Mn_5$ respectively. There are also four surfaces of secondary separation, at 1160, 1120, 1020 and 1010 C, and two invariant reactions in the solid state, at 1000 and 720 C.

There are three quasi-binary systems: FeSi – MnSi, Mn_5Si_3 – $Fe_{12}Si_{11}Mn_5$ and FeSi – $Fe_{12}Si_{11}Mn_5$. The last-named system is simple eutectiferous with a eutectic near the ternary compound and at about 1210 C. The other two quasi-binary systems have narrow ranges of solidification and continuous series of solid solutions. Both Vogel and Bedarff[1] and Jänecke[2] have presented isothermal sections for 400 C. Neither of these sections is compatible with present knowledge of the binary Fe-Mn and Fe-Si systems at 400 C.

References

1 R. Vogel and H. Bedarff, Arch Eisenhüttenw, 10, 501 (1937)
2 E. Jänecke, Arch Eisenhüttenw, 11, 409 (1938)

* Mellon Institute of Industrial Research, Pittsburgh

Fe-Mo-Ni Iron-Molybdenum-Nickel

Köster [Arch Eisenhüttenw, 8, 169 (1934)] investigated the ternary system by thermal and micrographic methods in the region iron-Fe_3Mo_2-MoNi-nickel. Fe_3Mo_2 and MoNi form a continuous series of solid solutions. The solubility of α and γ in this solid solution increases with increasing temperature, and precipitation hardening is possible in certain of these alloys. The magnetic transformation surface intersects the γ solid solution surface at 20 C at the points 60% Ni, 17% Mo, 23% Fe and 19% Ni, 10% Mo, and 71% Fe. For data on the mechanical properties of heat-resistant Ni-Mo-Fe castings, see pages 577 and 578 in this Handbook.

Fe-Ni-S Iron-Nickel-Sulfur

Vogel and Tonn[1] investigated the system iron-nickel-Ni_3S_2-FeS above 480 C, and determined the Curie points. Guertler and Savelsberg[2] reported the compounds $2FeS \cdot Ni_3S_2$ and $2FeS \cdot Ni_2S$, both of which decompose, on cooling, into a mixture of FeS and Ni_6S_5 with the liberation of a small amount of nickel. Hawley and co-workers[3] reported that pentlandite is a solid solution series varying from 55% NiS, 45% FeS to nearly 90% NiS, 10% FeS.

References. (1) R. Vogel and W. Tonn, Arch Eisenhüttenw, 3, 769 (1929). (2) W. Guertler and W. Savelsberg, Metall u Erz, 29, 84 (1932). (3) J. E. Hawley, G. L. Colgrove and H. F. Zurbrigg, Econ Geol, 38, 335 (1943)

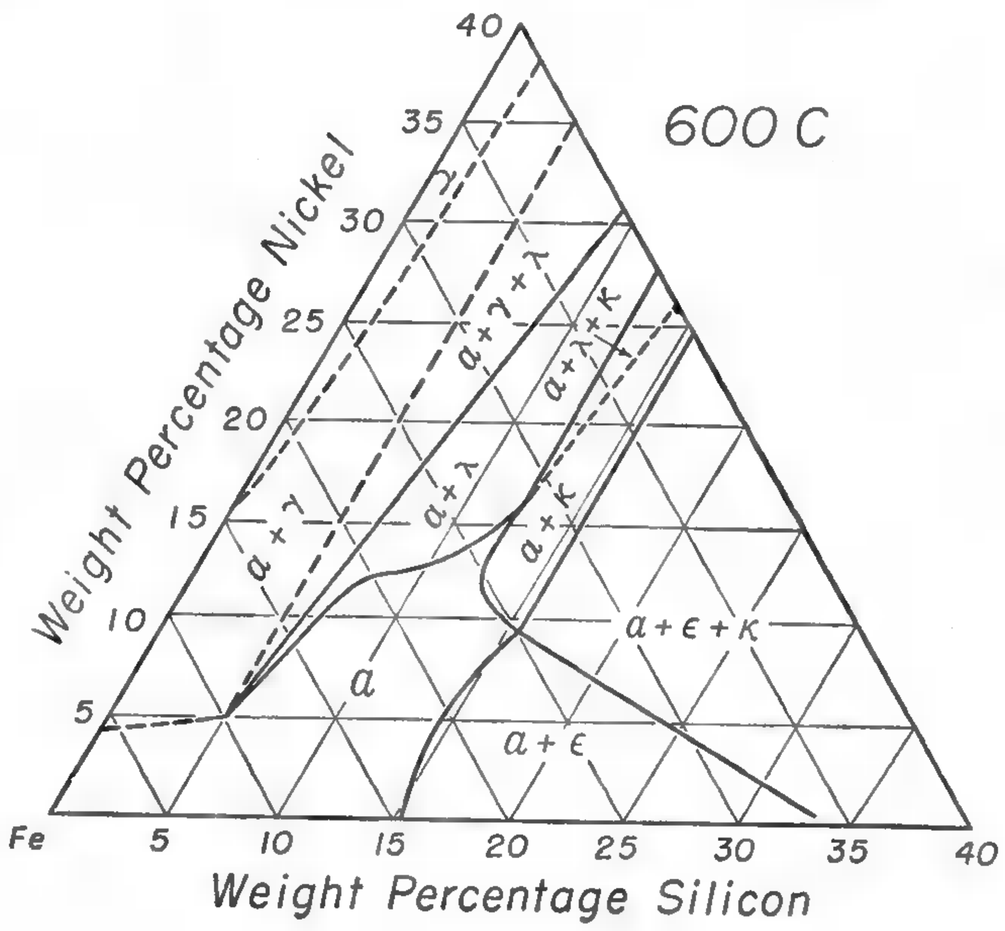
Fe-Ni-Si Iron-Nickel-Silicon

The constitution of the iron-rich iron-nickel-silicon alloys at 600 C was investigated by Greiner and Jette [Trans AIME, 152, 48 (1943)], using X-ray diffraction methods. Most of the alloys were annealed for either 28 or 56 days at 595 or 600 C.

The α, γ and ϵ phases have the same structures as corresponding phases in the binary iron-nickel and iron-silicon alloys.

The λ phase was reported as cubic with $a = 6.131$ kX. The κ phase was reported as tetragonal with $a = 8.308$ kX and $c = 9.012$ kX. Because the λ and κ phases were observed only in duplex alloys, these structures were presented as tentative.

The surface representing the lattice constants of the alpha phase alloys is not a plane.



The Ternary Limits of the Alpha Phase at 600 C

Nickel Atomic %	Nickel Weight %	Silicon Atomic %	Silicon Weight %
	$\alpha/\alpha + \gamma + \lambda$		
4.5	5.0	9.2	4.8
	$\alpha/\alpha + \lambda$		
7.3	8.1	11.2	5.9
8.2	9.1	11.5	6.1
10.9	12.2	13.7	7.3
10.9	12.2	16.1	8.7
11.4	13.2	19.0	10.5
	$\alpha/\alpha + \lambda + \kappa$		
13.6	16.0	22.4	12.6
	$\alpha/\alpha + \kappa$		
13.3	15.6	22.3	12.5
10.1	11.9	22.2	12.5
9.8	11.6	22.7	12.8
8.9	10.6	24.4	13.9
	$\alpha/\alpha + \epsilon + \kappa$		
7.9	9.5	26.8	15.5
	$\alpha/\alpha + \epsilon$		
6.8	8.2	26.1	15.0
4.2	5.1	25.5	14.7
3.5	4.2	25.1	14.4
2.6	3.1	25.1	14.4
1.7	2.0	25.6	14.7

Fe-Ni-Ti Iron-Nickel-Titanium

By Louis A. Carapella*

There is a ternary eutectic at about 20% Ti, 42% Ni and 1105 C. Ni_3Ti and Fe_2Ti form a quasi-binary system, with a eutectic point at 25% Ti, 41% Ni and 1320 C. The maximum solid solubility of Fe_2Ti in Ni_3Ti is about 18%.

References

1 R. Vogel and H. J. Wallbaum, Arch Eisenhüttenw, 12, 299 (1938)
2 R. Vogel, Z Metallkunde, 33, 376 (1941)
For data on age hardening, see page 604 in this Handbook.

* Mellon Institute of Industrial Research, Pittsburgh

Mg-Mn-Zn Magnesium-Manganese-Zinc

By G. F. Sager† and B. J Nelson†

There is a ternary eutectic at 3.2% Mg, 0.07% Mn and 369 C.[1] The solubility of manganese in liquid magnesium containing 6% Zn is approximately 1% at 650 C, 1.7% at 720 C and 3% at 800 C.[2]

References

1 E. Weisse, A. Blumenthal and H. Hanemann, Z Metallkunde, 34, 221 (1942)
2 N. Tiner, Trans AIME, 161, 351 (1945)

† Aluminum Research Laboratories, New Kensington, Pa.

Fe-Ni-W Iron-Nickel-Tungsten

The diagram determined by Winkler and Vogel [Arch Eisenhüttenw, 6, 165 (1932)] has four surfaces of primary crystallization, denoting solidification of α, γ, Fe_3W_2, and a tungsten-rich solid solution, S. Two four-phase equilibriums occur: liquid + $\alpha \rightleftarrows \gamma + Fe_3W_2$ at 1465 C, and liquid + $Fe_3W_2 \rightleftarrows \gamma + S$ at 1455 C. There are three univariant solidification reactions. The ternary limits of the α and γ phases are wide at high temperature, but restricted at low temperature. The γ phase can exist in equilibrium with each of the following: Fe_3W_2, Ni_6W, and the tungsten-rich phase, S. Other transformations were noted.—Louis A. Carapella

Mo-Ni-Si Molybdenum-Nickel-Silicon

H. Pfautsch [Z Metallkunde, 17, 48 (1925)] investigated the effect of silicon on nickel-molybdenum alloys. He found evidence for two ternary phases, Ni_4MoSi_2 and Ni_3Mo_2Si, which melt between 2100 and 2200 C. Ni_4MoSi_2 transforms at about 850 C. Details are given concerning the resistance of the alloys to caustic soda, ammonia, sodium sulfide, hydrochloric acid, nitric acid, tartaric acid, and other liquids. It was reported that silicon increases the corrosion resistance of nickel-molybdenum alloys in hydrochloric acid. The hardness of the alloys is reported also. [This information is from an abstract in J Inst Metals, 35, 554 (1926).]

Pb-Sb-Sn Lead-Antimony-Tin

By R. I. Jaffee* and H. P. Nielsen*

For the liquidus surface, the lead corner has been drawn from Weaver's data,[2] and elsewhere the diagram is from the data of Iwasé and Aoki.[1] Using the nomenclature of these investigators, the following are the fields of primary crystallization: antimony-rich solution, α, in *APKE;* SbSn solution, β, in *PRSMX;* tin-rich solution, γ, in *RCWS;* and lead-rich solution, δ, in *EXMSWB*. There are two invariant points in the system: a ternary eutectic at *X*, where α, β, and δ crystallize simultaneously at 239 C, and a peritectic point at *S* where β reacts with liquid to form $\gamma + \delta$. Along *PX* the peritectic reaction of α with liquid to form β takes place. Another peritectic reaction takes place along the line *RS*, where β reacts with liquid to form γ. Eutectic separation of δ and α takes place along *EX*, of δ and β along *XMS*, and of δ and γ along *SW*. There is a maximum in *XS*, the eutectic line of δ and β, at *M*, which is coincident with the intersection of *XS* with the pseudobinary line from Pb to SbSn.

Summarizing, the reactions that take place at the invariant points and along the boundary lines are:

X	:	$L_X \rightleftarrows \alpha + \beta + \delta$	(239 C)
S	:	$L_S + \beta \rightleftarrows \delta + \gamma$	(189 C)
PX	:	$L + \alpha \rightleftarrows \beta$	
RS	:	$L + \beta \rightleftarrows \gamma$	
EX	:	$L \rightleftarrows \alpha + \delta$	
XS	:	$L \rightleftarrows \delta + \beta$	
SW	:	$L \rightleftarrows \delta + \gamma$	

The locations of the invariant points *X* and *S*, and the point *M*, as found by the various investigators, are:

Point	Investigator	Percentage Tin	Percentage Antimony	Percentage Lead	Temperature, deg Cent
Eutectic, *X*	Iwasé and Aoki[1]	3.5	11.5	85	240
	Weaver[2]	4	12	84	239
Peritectic, *S*	Loebe[3]	60.5	3.0	36.5	191
	Campbell and Elder[4]	57.5	2.5	40.0	189
	Campbell[5]	57.5	2.5	40.0	189
	Heyn and Bauer[6]	53.5	4.0	42.5	184
	Iwasé and Aoki[1]	57.5	2.5	40.0	189
Pseudobinary Eutectic, *M*	Iwasé and Aoki[1]	10	10	80	245
	Weaver[2]	10	10	80	246.5

Concerning the eutectic in the pseudobinary system, Pb-SbSn, Loebe,[3] Campbell,[5] and the early investigators took it to be a peritectic point and reported its composition as 10% Sn, 10% Sb, 80% Pb. Iwasé and Aoki first noticed the maximum in *XS* at this composition, and Weaver, who checked their observation, pointed out the significance of the maximum, and constructed a diagram of the pseudobinary system from thermal data. The early investigators may have missed the ternary eutectic because of inadequate etching methods. Weaver used an electrolytic etch in 10% hydrochloric acid, which clearly distinguished between the α and β phases.

Solid solubilities of the four phases at the temperatures of the invariant points were determined microscopically by Iwasé and Aoki, and they reported the locations of the two-phase and three-phase fields at these temperatures. Their determinations are for alloys annealed 10 days or more, and would not apply to alloys in the cast condition. Weaver has given data on the phase fields in the lead corner for cast alloys. For cast alloys, the boundary between the $\alpha + \beta + \delta$ field and the $\beta + \delta$ field is closer to the pseudobinary line than it is for annealed alloys.

Lead-base lead-antimony-tin alloys are used extensively for bearings and for type metal, because of the low melting points, good casting characteristics, and the relatively high hardness of the alloys. Compositions and properties are given elsewhere in this Handbook (*see especially* "Bearing Materials", page 745; "Type Metals", page 957; and the data sheets for lead-base babbitts, page 965). The structure of these commercial alloys usually consists of hard particles of antimony (α) or SbSn (β) in a matrix of ternary eutectic.

Antimony is frequently added to lead-tin solders in amounts up to 6% of the tin content, for the purpose of increasing the shear strength of the soldered joints. The beneficial effect of antimony is found with solders containing appreciable amounts of tin. An excessive content of antimony causes the formation of SbSn (β), which is considered detrimental in solders.

References

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2 F. D. Weaver, J Inst Metals, 56, 209 (1935)
3 R. Loebe, Metallurgie, 8, 7, 33 (1911)
4 W. Campbell and F. C. Elder, School Mines Quarterly, Columbia Univ, 32, 244 (1911)
5 W. Campbell, Metallurgie, 9, 422 (1912)
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8 O. Bauer and M. Hansen, Z Metallkunde, 26, 39 (1934)
9 E. Hertel and A. Demmer, Metallwirtschaft, 10, 125 (1931)

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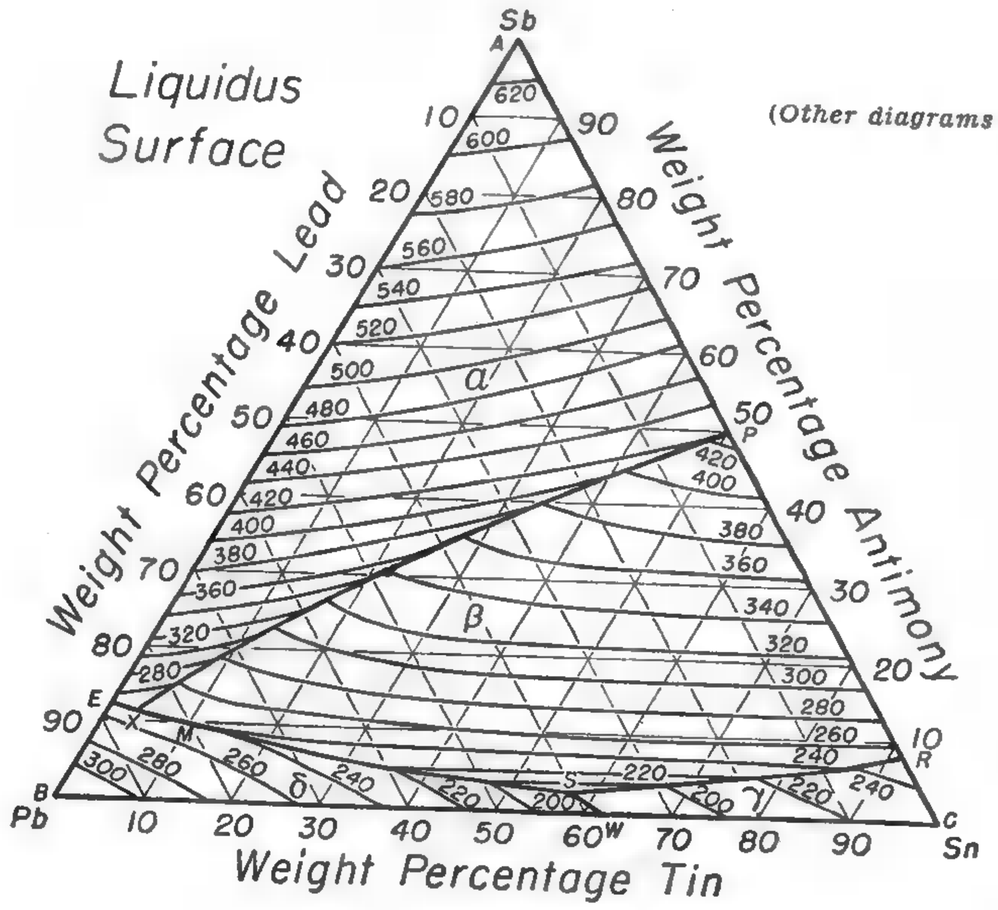
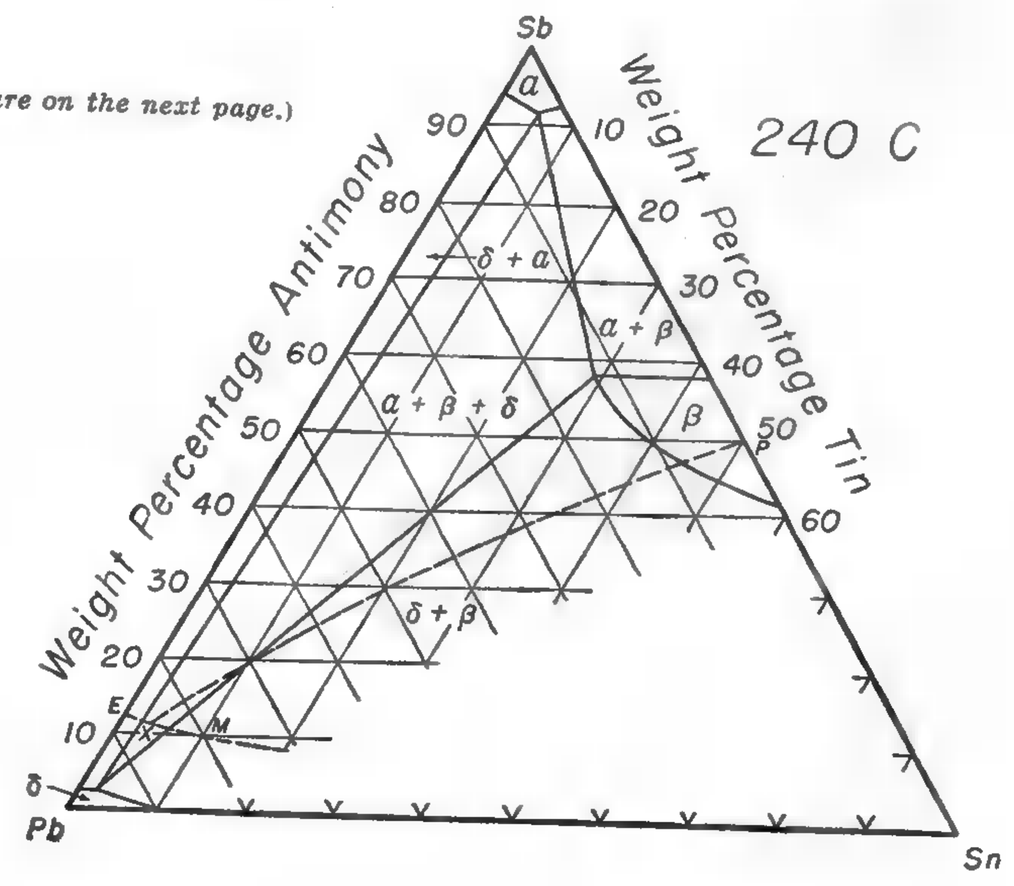
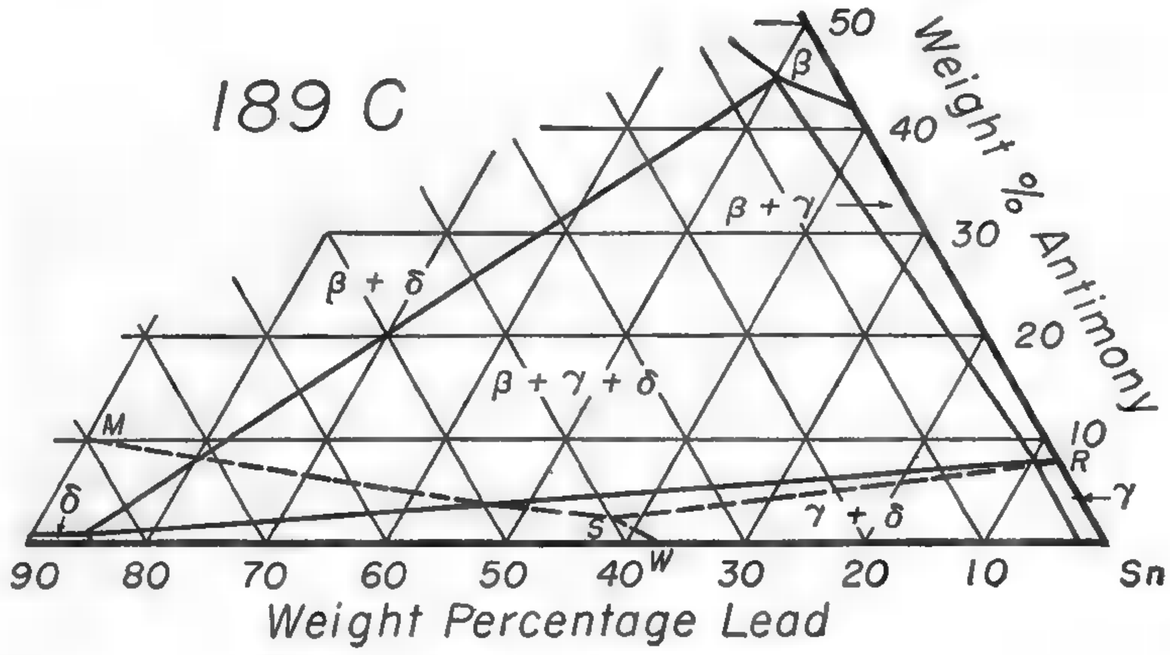
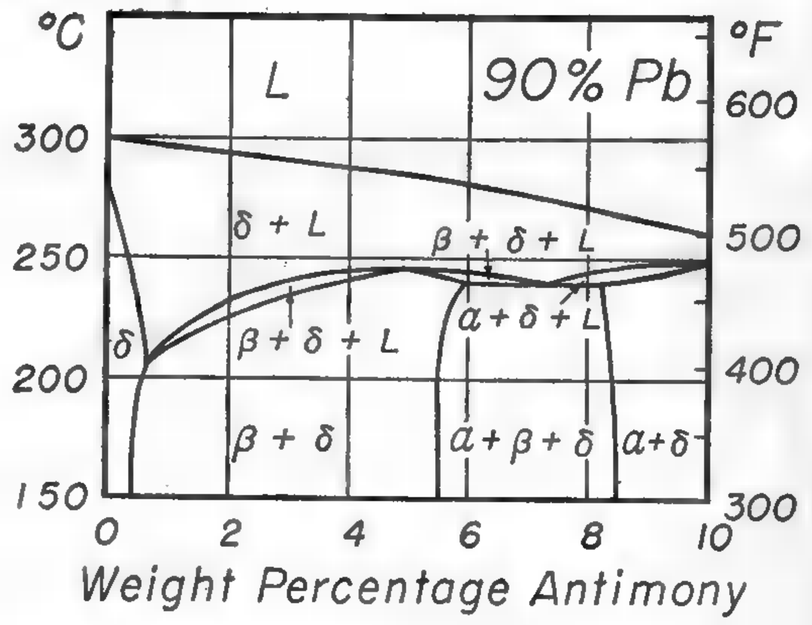
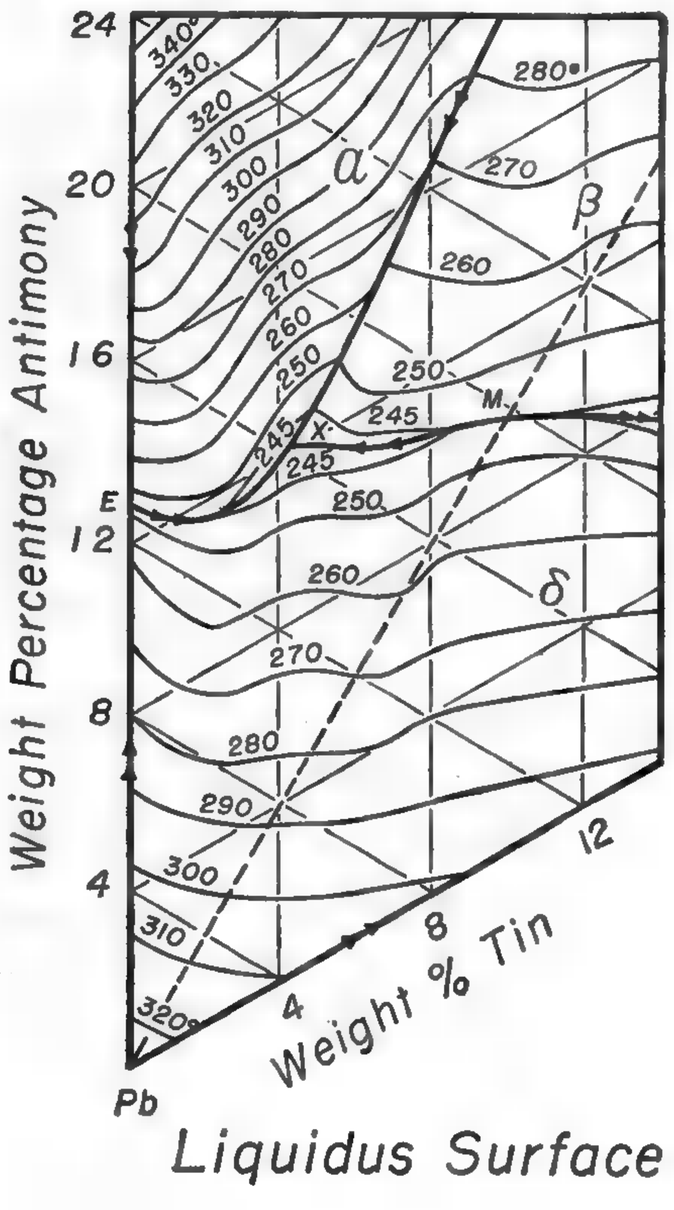


(Other diagrams are on the next page.)

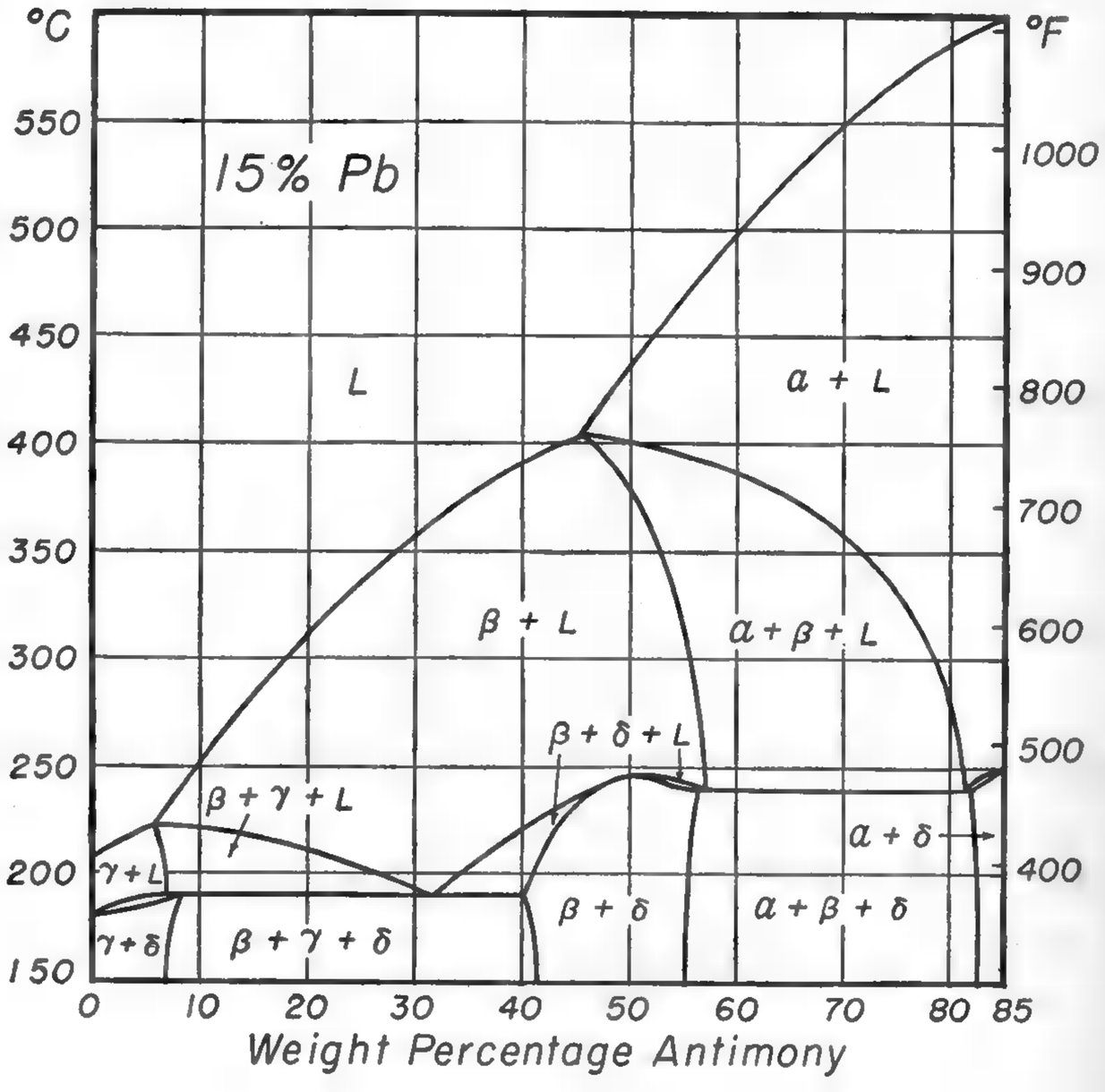




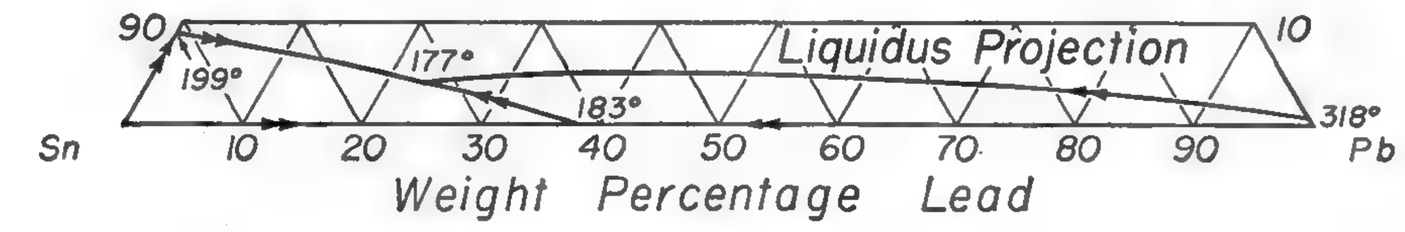


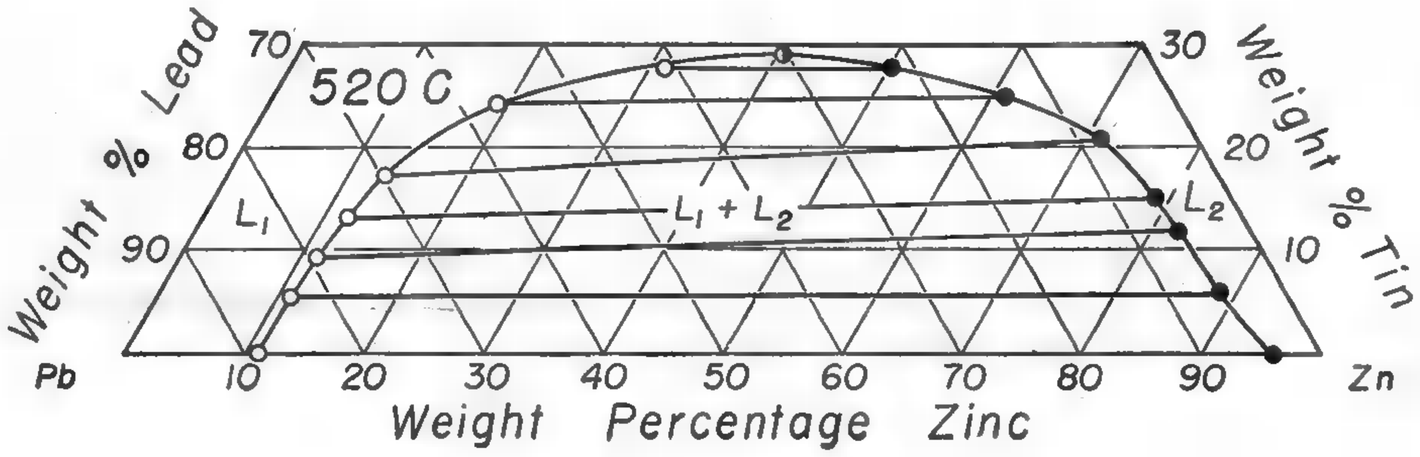


Liquidus Surface



Pb-Sn-Zn Lead-Tin-Zinc





The liquid miscibility gap of the lead-zinc system extends into the ternary system to a tin content of 29% at 520 C[1] (*see cut*). Isotherms have been determined also for higher[2] and for lower[3] temperatures. The miscibility gap lies entirely in the solidification field of zinc. The ternary eutectic point is at 24% Pb, 5% Zn, 71% Sn and 177 C[3] (*see cut*).

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INDEX★

THIS INDEX contains three principal types of entry: materials (chiefly metals and alloys), processes, and properties.

Materials are indexed more completely than processes and properties. The various steels are listed separately, alphabetized according to adjectives; for example, *Austenitic manganese steel, Carbon steel, High-carbon high-chromium tool steel, Martensitic stainless steel,* etc. Nonferrous alloys are listed (1) under the common names, such as *Cartridge brass, White gold* and (2) under the names of the components, with the basis metal given first, as *Copper-zinc, Gold-nickel-copper-zinc.* Numerical trade designations are grouped under the name of the basis metal. For example, 4340 steel is listed under *Steel, SAE-AISI designations;* 17 S aluminum alloy is listed under *Aluminum alloys, trade designations.* Designations of government specifications for nonferrous metals and alloys are indexed on the last page, 1332.

Specific information about the processing of a certain metal is indexed as subordinate entries under the name of the metal. For example, extrusion of tin alloys is indexed as *Tin alloys, extrusion.* Under the name of a process, general information is referred to, and specific information about processing a certain metal may be listed again, depending on the importance of the discussion. Processes such as cold heading, precision casting and press forging are indexed according to the adjective rather than the noun.

Properties of a specific material are listed as subordinate entries under the name of the material. General comparisons or tabulations of a property for a group of materials are indexed under the name of the property.

The letter (T) or (F) in parentheses after an index entry means that the information referred to is in a Table or Figure, respectively, on one of the pages mentioned.

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ADDENDA (*April 15, 1948*)

Chromium

IN A RECENT publication on electrodeposited chromium [A. Brenner, P. Burkhead and C. Jennings, J Research Nat Bur Standards, **40**, 31 (1948)] the following values are reported for some properties of the annealed metal. Hardness, 200 Knoop; modulus of elasticity, 36,000,000 psi; tensile strength, 70,000 psi; electrical resistivity, 13.0 microhm-cm at 28 C; melting point, 1890 ± 10 C. The effects of heat treatment and oxygen content on most of these properties were studied. These data were published after the compilation on pages 1135 and 1136 of this Handbook had been printed.

Selenium

RECENT publications indicate that the electrical resistivity of annealed selenium at room temperature, in the dark, is of the order of 100,000 ohm-cm, a value considerably higher than that given on page 1140 in this Handbook. The electrical resistivity of selenium is affected by light and other factors. Data are given in the following publications. F. de Boer, Philips Res Rep, **2**, 352 (1947); B. D. Cullity, Metals Tech, **15**, TP 2313 (Jan 1948); and W. E. Blackburn, J Applied Phys, **19**, 51 (1948). None of these articles was available when the compilation of properties on page 1140 of this Handbook was printed.

Trade Names

ALTHOUGH this Handbook contains many trade names, it is not a general source for the identification of proprietary designations. The most complete list of alloy trade names is "Engineering Alloys", revised edition, by N. E. Woldman and R. J. Metzlar, American Society for Metals, 1945. Trade names of 1700 tool materials are listed in "A Directory of Tool, Metal-Cutting, and Die Steels, and Sintered Carbides", 19th edition, by T. W. Lippert, Iron Age, 1947. For trade names of processes and equipment, as well as alloys, the reader may refer to "10,000 Trade Names", by T. W. Lippert, Iron Age, 1947.

INDEX OF GOVERNMENT SPECIFICATION NUMBERS FOR NONFERROUS METALS AND ALLOYS

INDEXED BELOW are designating numbers for the following government specifications: Army-Navy Aeronautical, Federal, Navy, Army, and Air Force. The pages referred to are those on which the nonferrous data sheets are given. In each entry, the common name or trade designation of the alloy is included parenthetically for identification.

Joint Army-Navy specifications and specifications of the Navy Bureau of Ordnance and Bureau of Aeronautics are not indexed below, although a few of these are listed under item A4 in the nonferrous data sheets.

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GUIDE TO THE USE OF THE NONFERROUS DATA SHEETS

In this edition of the Metals Handbook, nearly all the specific data for nonferrous metals and alloys have been presented according to a new, semitabular arrangement. This data sheet form has been used so that the reader can easily find information of the same kind for various alloys by following key numbers, which are the same throughout the Nonferrous Section. General information concerning melting, shaping, treating, metallography, and corrosion is included in articles that deal collectively with groups of similar alloys; only specific information is presented in the nonferrous data sheets.

The outline for the data sheet form was made inclusive enough so that there would be a place for every type of information that might be important for some metal or alloy. Only about half the key numbers have been used frequently in the Nonferrous Section, and the most important of these items are listed below. Other key numbers are given in the index; for example, see Supraconductivity *in the index.*

A Designations
- *1* Common name
- *2* Trade name
- *3* ASTM number
- *4* Government number
- *5* Other designations
- *6* Foreign equivalents

B Applications
- *1* Typical uses
- *2* Precautions in use

C Mass
- *1* Density
- *2* Density vs temperature
- *3* Compressibility
- *4* Density vs deformation
- *5* Solidification shrinkage

D Thermal Properties
- *1* Liquidus temperature
- *2* Solidus temperature
- *6* Thermal expansion
- *11* Specific heat
- *13* Heat of fusion
- *16* Thermal conductivity
- *19* Recrystallization temperature

E Electrical Properties
- *1* Volume conductivity (% of standard copper)
- *2* Electrical resistivity
- *5* Temperature coefficient of electrical resistivity

F Optical Properties
- *1* Reflectivity
- *4* Color
- *5* Emissivity

G Magnetic Properties
- *1* Influence of treatments
- *2* Magnetic susceptibility
- *3* Magnetic permeability

H Velocity of Sound

I Chemical Properties
- *1* General corrosion
- *2* Resistance to specific chemical agents

J Structure
- *1* Crystal structure
- *2* Slip plane
- *3* Twinning plane

K Mechanical Properties

Various tabular and graphical arrangements have been used for presenting typical values of the most important mechanical properties. Unless otherwise stated, the numbers given are average values and should not be used for purposes of specification.

- *4* Machinability index
- *9* Damping capacity

L Testing
- *1* Metallography (included only for metals not dealt with in an article on metallography)
- *2* Radiography
- *3* Corrosion tests
- *4* Mechanical tests (included only when some special method of testing is involved)

M Composition Limits
- *1* Quotations from commercial specifications
- *2* Consequences of exceeding impurity limits

N Working Data
- *1* Melting temperature
- *2* Casting temperature
- *3* Alloying practice
- *4* Preferred deoxidizers
- *5* Type of flux
- *6* Precautions in melting
- *7* Hot working temperature
- *8* Shortness temperature
- *9* Annealing temperature
- *10* Maximum reduction between anneals
- *11* Suitable forming methods
- *12* Precautions in forming
- *15* Heat treatment
- *17* Suitable joining methods

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Wrought Alloys 811
Casting Alloys 824
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